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Opportunities for hydrogen in commercial aviation

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Acknowledgments

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present. CSIRO recognizes that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science.

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We are grateful for the time and input of the stakeholders from industry, government, academia who were consulted throughout this project. A full list of stakeholders consulted may be found in Appendix C.

CSIRO Foreword

The global aviation industry has been disrupted by the COVID-19 pandemic on a scale not seen in its century of operation. But while many fleets of aircraft are grounded and travel is postponed, the industry has a unique opportunity to change its path when travel begins to return. Achieving meaningful emissions reduction in Australia will depend on us following the global market trend towards zero-emissions energy across all sectors, including sustainable transport. This report charts a new course for aviation to soar towards its emissions targets with hydrogen.

As the national science agency, CSIRO has already been using innovative science and technology to solve challenges both across the aviation industry and to kick-start an Australian hydrogen industry. Working with many partners, our research has spanned publishing a pioneering biofuels report, developing innovative coatings technology for aircraft, and now in new areas including space technologies. In hydrogen, CSIRO recognises Australia is exceptionally well placed to act early, with vast energy resources which can support other nations' efforts to transition to lower-emissions alternatives. This is where science delivers results – hydrogen energy systems can form the basis of a new export industry in Australia, as well as help the world navigate this energy market transition. Last year we also welcomed a National Hydrogen Strategy to guide the nation's efforts.

The growing hydrogen industry is dependent on many factors, including increasing technology maturity, significant reductions in the cost of renewable energy and the growing acceptance of its potential to achieve deep decarbonisation. Until now, the challenges with transitioning hydrogen from the lab to commercial reality have largely been related to economics and infrastructure. This meant that, for a long time, hydrogen energy applications have remained in the realm of research and development.

But in 2018, a small CSIRO pilot plant in Queensland, Australia, refuelled fuel cell cars using high-purity hydrogen sourced from ammonia, for the first time. With early attention given to fuel cell vehicles and electricity generation, we can now broaden our focus to impacts in the aviation sector. Costs have come down, technologies have matured, and global economies are asking questions – so now's the time for rapid scale-up.

This report takes a long-term view of recovery and prosperity for the sector by identifying decarbonisation opportunities that are available to us now and into the future. Through sustained partnerships – such as the thirty-year relationship we have with Boeing – we're able to explore these concepts more deeply. Our collective goals are to foster innovation, fast-track the deployment of emerging technologies and, in this case, provide a way forward for a sustainable aviation industry. International leadership is critical to connect key players and capabilities across the value chain, and our customer collaborations help to frame this dialogue and develop a path for hydrogen, both in Australia and globally.

Collaboration will see large-scale and interconnected hydrogen value chains unfold, and CSIRO is the natural bridge connecting industry with the research community to deliver expert advice, technology, innovation, engineering and prototyping. Our research and partnerships will enable science and technology to support the development of a whole new sustainable and resilient industry that supports a green recovery.

Dr Larry Marshall
Chief Executive
CSIRO

Boeing Foreword

For over a century, innovation and technology have enabled aviation growth. Boeing is committed to building a more sustainable future for our industry and our planet, and we, along with the broader aviation sector, are committed to achieving the aviation industry goal of halving CO_2 net emissions by 2050 relative to 2005 levels.

Science and technology continue to play a key role in ensuring the long term sustainability of our business, and we are proud to continue our 30-year relationship with CSIRO, one of our most innovative and trusted partners. Our many successes include collaborations across robotics and automation, artificial intelligence, and the development of novel materials for niche and extreme environments.

In 2018 CSIRO published its National Hydrogen Roadmap which served as a blueprint for the development of the hydrogen industry in Australia, and we thank them for extending this analysis to the global aviation sector.

Boeing has made significant improvements in efficiency and reducing emissions from our products. However, we also recognize that sustainable aviation fuels are a necessary contributor to the decarbonisation of aviation and are committed to furthering their development. We expect it will take multiple solutions to decarbonize our fuel supply. With strong developments in the hydrogen industry in recent years, there is now a distinct opportunity for hydrogen technologies to contribute to the aviation sector energy transition across different elements of the value chain.

From using green hydrogen in the production of sustainable fuels, to enabling the production of electrofuels, to using hydrogen as a fuel, this report demonstrates several options for further research and exploration.

We hope this analysis sheds light on the numerous opportunities and helps prioritize the enabling investments to be made by industry, research institutes and governments.

We look forward to collaborating further with the industry to enable sustainable aviation growth for all.

Michael Edwards
General Manager
Boeing Australia

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Glossary

APU	Auxiliary power unit
ASTM	American Society for Testing and Materials
ATJ	Alcohol to jet
Behind-the-meter	Electricity generated on site that does not travel through the grid, avoiding metering
BoP	Balance of plant
Capacity factor	Energy output of an energy asset at full nameplate capacity over a determined period
CO_2	Carbon dioxide
CSP	Concentrated solar power
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRI	Commercial readiness index
DAC	Direct air capture
DFW	Dallas Fort Worth airport
DME	Dimethyl ether
Drop-in fuel	A synthetic fuel that is compatible and interchangeable with a conventional fuel, e.g. synthetic jet fuel
Electrofuel	A drop-in fuel produced from hydrogen derived from electrolysis and captured CO_2
ETS	Emissions trading scheme
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FC	Fuel cell
FT	Fischer-Tropsch
GHG	Greenhouse gas
GPU	Ground power unit: supplies power to maintenance and aircraft on the ground
GSE	Ground support equipment: services aircraft between flights
HEFA	Hydroprocessed Esters and Fatty Acids, a biofuel derived from oil and fats
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
IEA	International Energy Agency
LCA	Life cycle assessment
KBBL	Thousand barrels
LCOH	Levelized cost of hydrogen
LCOT	Levelized cost of transport
LDI	Lean direct injection
MeOH	Methanol
MOF	Metal organic framework
NOx	Nitrogen oxides, polluting emissions that can cause acid rain and smog
O&M	Operating and maintenance
OEM	Original equipment manufacturer
PEM	Polymer electrolyte membrane
Power to liquids	Process of generating liquid fuel using zero carbon electricity, water and CO_2
PV	Photovoltaics
RD&D	Research, Development & Demonstration
RTK	Revenue tonne-kilometres
RWGS	Reverse Water Gas Shift reaction
SABRE	Synergistic Air-Breathing Rocket Engine
SAE	Society of Automotive Engineers
SAF	Sustainable aviation fuels
SMR	Steam methane reforming
SOE	Solid oxide electrolyzer
SPK	Synthetic paraffin kerosene
Syngas	Synthesis gas; A mixture of carbon monoxide and hydrogen
TRL	Technology readiness level

1 Executive summary

Trends in commercial aviation

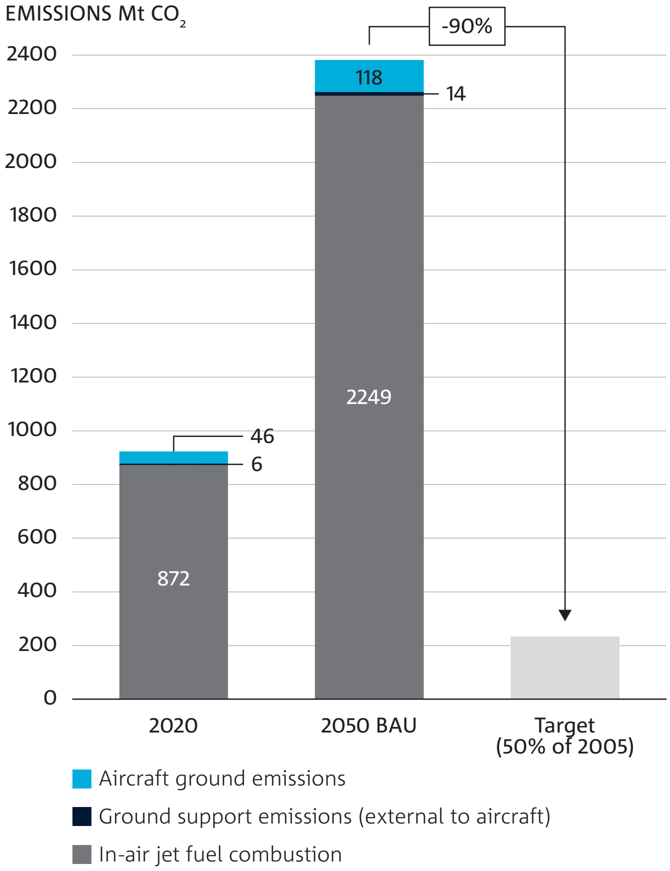
The commercial aviation sector is facing the ongoing challenge of reconciling increasingly stringent environmental regulations and emissions commitments with expected growth in passenger demand.

In 2009, the International Air Transport Association (IATA) adopted a target of a 50% reduction on 2005 CO_2 emissions levels by 2050, with no increase in net emissions after 2020.[1] Although the 2050 target is yet to be codified by the UN International Civil Aviation Organization (ICAO), it has been widely adopted by the aviation industry as the primary emissions abatement goal. During this time however, IATA expects global aviation demand to double to 8.2 billion passengers per year by 2037.

Industry emissions targets are being complemented by a growing concern among the global community over the environmental impacts of aviation, contributing to the emergence of trends such as 'flight shaming' and encouraging airlines to re-assess the consequent impact on their business models.

To date, the aviation sector has achieved greater than 2% annual fuel efficiency improvements and is expected to continue to meet established targets of 1-1.5% due to ongoing technological and operational developments. However, when combined with forecast passenger growth, business as usual (BAU) projections show three-fold growth in CO_2 emissions by 2050.

The observed limitations of efficiency improvements in meeting industry emissions abatement targets has prompted a stronger focus on the adoption of sustainable aviation fuels (SAF). In this context, while there is considerable scope for continued development of biofuels as a 'drop-in' jet fuel, current uptake has been minimal, making up less than 0.1% of jet fuel consumption in 2018.[2] This has led to further consideration of alternatives such as 'clean hydrogen' and other hydrogen-based fuels.



BAU emissions projections with 1.5% efficiency improvements per annum against the 2050 target[3]

Opportunities for Clean Hydrogen

Clean hydrogen is derived primarily from the electrolysis of water using zero or low emissions electricity

In recent years there has been a notable acceleration in the development of the hydrogen industry. This has been driven by a confluence of factors including technology maturity, significant reductions in the cost of renewable energy and the growing acceptance of its potential as one of the only ways to achieve deeper decarbonization both in and outside of the electricity sector. With considerably more focus given to other forms of transport to date, this report considers the role that hydrogen can play in helping decarbonize the aviation sector.

1 International Air Transport Association (2020) *Climate Change*. Available at https://www.iata.org/en/policy/environment/climate-change/

2 The emissions boundary in this assessment has been restricted to CO_2 generated from use of liquid fuels within the airport boundary and jet fuel to power aircraft.

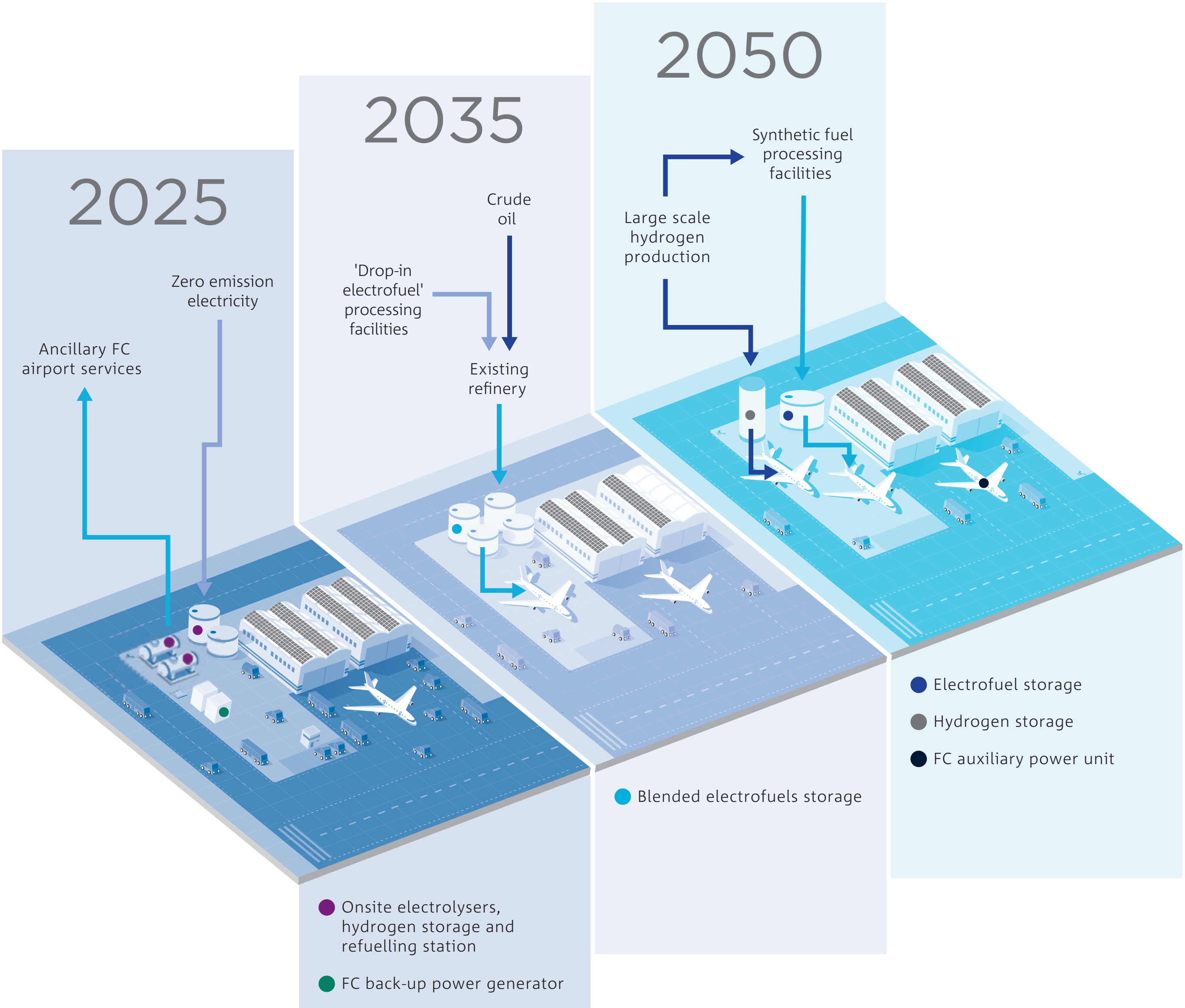
3 Le Feuvre, P (2019) *Are aviation biofuels ready for take off?* International Energy Agency.

These applications are broken down into three primary technology categories with an implicit time component that reflects the expected development periods required before significant uptake can be achieved. This includes:

'On/adjacent airport': Replacement of on-airport ground support equipment (GSE) currently running on liquid fuels and batteries with hydrogen powered fuel cell alternatives. Hydrogen used for treating crude or bio-crude oil to produce jet fuel with a lower carbon intensity is also considered as an early stage application.

Existing infrastructure: On-aircraft (or 'on-platform') applications that require no change to existing infrastructure. This concerns the production of synthetic jet fuel or 'power-to-liquids' (herein referred to as 'electrofuels').

Emerging infrastructure: On-aircraft applications for hydrogen (and other hydrogen augmented fuels) that involve a redesign of existing airframes and supporting infrastructure.

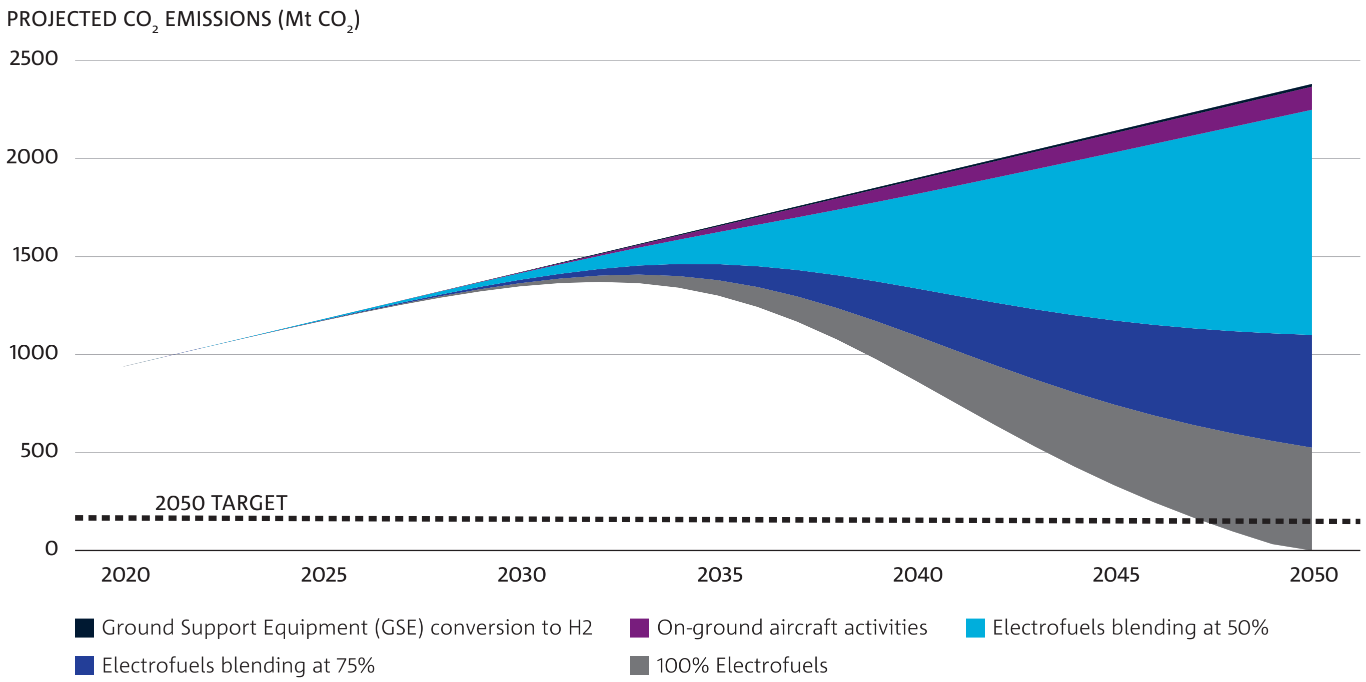


Hydrogen technologies within the aviation sector

Investment priorities

Drawing on the investment priorities set out in this analysis, the figure below illustrates the potential CO_2 abatement that could be achieved via the incorporation of hydrogen into the commercial aviation sector. While the focus of this report is on hydrogen, it does not purport to overlook the potential for other SAF, particularly given the scale of investment required to meet aviation sector energy demand.

The accelerated roll-out of jet aircraft powered by pure hydrogen is not expected to occur until after 2050 and is therefore not included in this CO_2 abatement profile.



Potential CO_2 emissions abatement using hydrogen-based technologies

On/adjacent airport

Although not a material contributor in terms of sector-wide emissions reduction, most fuel cell GSE are expected to provide more economical solutions on a total cost of ownership basis than diesel/gasoline incumbents. They therefore represent a near-term opportunity to catalyze the introduction of hydrogen into the commercial aviation sector.

One of the primary obstacles associated with the roll-out of fuel cell GSE will be achieving an adequate scale of hydrogen production while balancing supply and demand. This is particularly challenging considering the variety of equipment requiring upgrade. In the early stages of development, a reasonable degree of scale can be achieved with a lower risk profile by prioritizing fuel cell powered 'off-the-shelf' technologies such as forklifts, cars, buses and stationary power. Concurrent efforts may then be focused on discrete upgrades to special purpose GSE. With expected reductions in the cost of hydrogen, those GSE with the highest ratio of fuel use to capital cost (e.g. baggage loaders, pushback tugs) will be more economical on a total cost of ownership basis and should be prioritized accordingly.

Despite the longer-term competitiveness of several high-use fuel cell GSE, the capital cost associated with asset turnover presents a more immediate barrier to development. Implementation of policy mechanisms that absorb some of the capital cost and underwrite initial investment risk will be important in facilitating technology uptake. Detailed analysis regarding fleet demand profiles, power requirements and remaining asset life will also be critical in determining the preferred solution for various assets (i.e. retrofit vs purchase of new build systems). This level of analysis will increase the scope for a more coordinated program roll-out.

The challenge associated with complex contractual arrangements between airports, airlines and GSE service providers can be avoided by initially targeting airports with a majority tenant that is responsible for all GSE operations. A more efficient business model would likely see airport operators (via delegation to specialist third parties) assume responsibility for hydrogen production and storage infrastructure. This could allow for an increase in production capacity necessary to service airport adjacent industries such as taxi fleet, buses and freight.

With a lack of existing regulatory frameworks supporting the use of hydrogen in airports, key aviation sector entities such as IATA will play an essential role in developing the requisite standards, manuals and guidelines that can be easily incorporated into local regulations governing hydrogen use. Combined with transparent demonstration projects and public engagement, this will also be crucial in helping stakeholders such as the insurance sector become fully aware of the risks and in turn, the avoidance of exorbitant premiums.

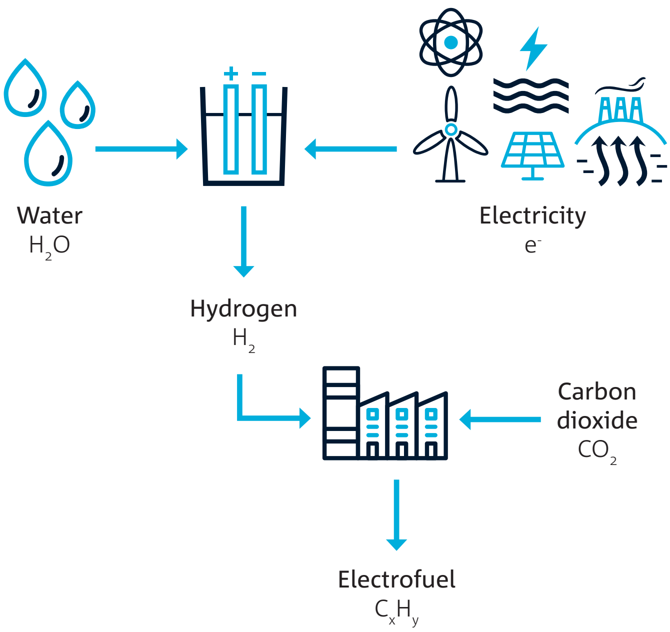
Given the technology maturity and commercial competitiveness of fuel cell GSE on a total cost of ownership basis, it is expected that implementation of these investment priorities could see the rate of uptake accelerate after 2025, replacing all GSE in or around 2035.

Existing infrastructure (Electrofuels)

Electrofuels: Given that all crude refined products consist primarily of hydrocarbons, it follows that renewable hydrogen can be reacted with a stream of CO_2 from waste gas or air (i.e. direct air capture) to produce a ‘drop-in’ carbon-neutral jet fuel.

Given the low rate of asset turnover within the aviation sector, electrofuels represent one of the primary ways in which hydrogen can be used to achieve meaningful decarbonization before 2050 without extensive changes in infrastructure.

While to date there has been no end-to-end commercial demonstration of electrofuel synthesis, there is a strong technology and regulatory base that can be built upon. That said, given the extent of the infrastructure required to meet global aviation demand (e.g. 1,000’s of MW of electrolysis), scaling the electrofuel industry will require a coordinated effort on the part of the broader industry (including upstream oil & gas), governments and research institutions globally.



One of the more effective mechanisms supporting such a coordinated effort could be the implementation of electrofuel blending quotas imposed on jet fuel producers that increase over time, commensurate with industry resources and capacity. Such blending quotas could be determined by key advisory bodies in conjunction with electrofuel manufacturers and then be provided as guidance to governments to enforce on local suppliers. Consistency across jurisdictions will also be important in preventing market distortion.

The increase in production plant scales that follow higher blending quotas will lead to a natural decrease in cost that is also driven by factors such as renewable energy economies of scale, the industrialization of electrolyzer manufacture and improvements in the capacity and cost of CO_2 capture. At larger scales, given the sensitivity of the fuel synthesis process to maintaining a high rate of asset utilization and low electricity price, selection of sites with strong dedicated renewable and dispatchable low emissions energy sources will also be critical. The flexibility required suggests that direct air capture of CO_2 will play an important role in the long-term viability of the industry.

Notwithstanding these developments, electrofuels are unlikely to be commercially competitive with conventional (kerosene based) jet fuel. While they start at 8 times (8x) the current cost of kerosene and only reach 1.25 – 2.5x (the projected cost of kerosene) once a 50% blend is achieved, blending at this rate is likely to only occur after 2040 given the lead times required. While airlines will need to continue to find new ways to limit this impact on their business models, in the early stages of development there is likely to be a key role for governments in absorbing some of the premium associated with use of electrofuels. In this context, it is also critical that existing aviation carbon offset schemes do not divert investment away from longer-term developments in electrofuels.

With strategic global investment, it is possible for large scale electrofuel production to be de-risked after 2030, allowing for an accelerated uptake thereafter.

Emerging infrastructure

Despite the emissions abatement achieved through the uptake of synthetic fuel blends, the continued roll-out of increasingly stringent environmental regulations could see a potential move away from conventional jet fuel closer to 2050. Given its unique properties, hydrogen could play a key role in facilitating this transition in relation to both propulsion and non-propulsion aircraft applications.

Non-propulsion applications

Whereas continued electrification of non-propulsion systems and their consequent ability to be supported by an on-board fuel cell will require on-going analysis, use of hydrogen-based systems for applications such as auxiliary power (i.e. Auxiliary Power Units) and the taxiing phases of flight may present as nearer-term opportunities.

However, incorporating such systems onto jet aircraft is likely to carry a mass penalty that is twice as much as traditional APUs, mostly due to the weight of the storage tank (when hydrogen is compressed at 700bar). While the mass penalty could be reduced using cryogenic hydrogen storage, this will result in higher costs due to the need for liquefaction and material changes in airframe design to ensure that the requisite storage temperatures are maintained. Therefore, although the use of fuel cell systems would significantly lower local ground emissions, round trip economics and emissions would be worsened due to the higher quantities of jet fuel required to support the additional aircraft weight.

Reducing overall mass via the introduction of next generation fuel cells and storage tanks are the subject of ongoing RD&D within the hydrogen industry and this could well be accelerated should such investment be prioritized by the aviation sector. However, this alone is unlikely to result in the weight reduction required to compete with incumbent systems. Rather, the most significant improvements may be achieved by optimizing the integration of fuel cells early in the conceptual design phase of aircraft.

Therefore**, given the slow rate of asset turnover, minimizing ground emissions from aircraft before 2050 will require a renewed focus on the development of hydrogen fuel cell Ground Power Units (GPU) and electric taxiing systems that are external to aircraft**. While extensive work is required to overcome the safety and operational challenges associated with increased levels of capital equipment on or near runways, it is reasonable to expect that the uptake of such GSE could accelerate after 2030, effectively minimizing ground-based emissions from aircraft by 2045.

Propulsion applications

There is significant potential for hydrogen fuel cells (for propulsion) to disrupt the current turboprop market (i.e. shorter haul flights up to 1000 miles (1600km) and 100 passengers). However, **given the power density (kW/lb or kW/kg) limitations of fuel cell systems, they are unlikely to provide economical solutions for long distance flights with heavy payloads that currently rely on the use of traditional jet engines**.

For combustion in jet engines, hydrogen-augmented fuels such as ammonia and methanol (i.e. non-drop-in electrofuels) are likely to require less extensive changes to airframe and engine design. However, when compared to kerosene, these fuels have a poor energy density by volume and with the exception of liquefied natural gas (LNG), poorer energy densities by mass, which limits their competitiveness in long haul travel. **For the carbonaceous fuels in particular, poorer energy densities, combined with CO_2 emissions upon combustion bring into question the motivation for changing existing infrastructure to accommodate non-drop-in fuels, particularly when minimal gains are expected in the overall cost of production (compared to drop-in electrofuels).**

In contrast, cryogenic hydrogen has a superior energy density by mass compared with kerosene and produces no CO_2 emissions upon combustion. Aside from challenges relating to storage and handling, the primary obstacle stems from its poor volumetric density. This may encourage a move away from conventional aircraft design to models such as the 'blended-wing-body' which show promise in improved aerodynamic efficiency and can accommodate larger volumes of fuel.

To facilitate the uptake of hydrogen planes closer to 2050, a considerable amount of research is required in the immediate term regarding changes in engine design and the development of on-aircraft infrastructure such as light-weight cryogenic storage tanks that minimize hydrogen boil-off (i.e. vaporization). In terms of supporting infrastructure, the widespread use of such aircraft will require hydrogen volumes in the order of thousands of tons of hydrogen per day to be delivered to major airports. A likely scenario could involve the distribution of hydrogen via pipeline with liquefaction facilities set up on or near the airport boundary. Hydrogen production infrastructure dedicated to the electrofuels industry could also be gradually diverted to support an increasing demand for hydrogen-fueled aircraft.

While it is possible for hydrogen to be supplied to aircraft via hydrant systems (as per current refueling models), significant RD&D is required to ensure safe and efficient refueling times by simultaneously increasing flow rates and preventing hydrogen leakage. This infrastructure model could be rolled out strategically, initially by targeting airports that support the most popular flight paths with gradual expansion thereafter.

Summary of investment priorities 2020–2030

TIMELINE	2020-2025	2025-2030
On/airport applications	■ Continue to roll out public hydrogen refueling at major airports ■ Develop business cases for fuel cell GSE beginning with 'off the shelf' technologies. Techno-economic assessments should consider both onsite production and imported hydrogen ■ Develop demonstration projects that highlight safety of hydrogen on airports (e.g. hydrogen buses) ■ Undertake demonstration of special purpose GSE ■ Airports to engage major tenanting airlines to determine business models for hydrogen infrastructure upgrade, including focus on servicing adjacent industries ■ Entities such as IATA to develop manuals and guidelines regarding hydrogen use in airports ■ Implement a policy mechanism that absorbs part of capital cost associated with turnover and underwrites supply and demand risk	■ Continue to develop effective solutions for GSE retrofit and performance testing ■ Assess demand profiles, asset life and power requirements of high use GSE to determine strategy for widespread roll-out ■ Assess logistics, business models and safety considerations regarding fuel cell Ground Power Units and extended use of external taxiing systems
Existing infrastructure	■ Establish detailed life-cycle-analysis frameworks to better understand emissions abatement achieved through use of electrofuels and other SAF ■ Develop end-to-end commercial demonstration of various electrofuel synthesis pathways using different sources of low emissions energy and CO_2 ■ Airlines continue to pursue new business models designed to incentivize consumers to purchase SAF ■ Identify key global locations with strong energy resources, hydrogen storage and existing oil and gas infrastructure that could accommodate large-scale electrofuels production ■ Progress development in high-temperature electrolysis and direct air capture technologies ■ Continue to improve mechanisms for certification of SAF production ■ Electrofuel manufacturers to provide regulators with ongoing access to plant output and quality data	■ Explore the development of blending quotas commensurate with available capacity and resources ■ Continue to implement subsidies to absorb premium associated with the use of electrofuels ■ Develop joint ventures between electrofuel manufacturers, oil refineries and airlines to secure offtake ■ Ensure carbon offset schemes do not divert investment away from development of SAF such as electrofuels ■ Continue to educate the public on benefits of use of electrofuels
Emerging infrastructure	■ Assess the cost of cryogenic hydrogen against drop-in electrofuels and other SAF on a $ per energy basis ■ Adapt further investigation of increased aircraft architecture electrification to include the role of fuel cells in meeting demand ■ Develop airframe concepts that optimize fuel cell integration at the component level to improve system weight ■ Continue to develop emerging airframe designs such as blended-wing-body with a view to accommodating cryogenic hydrogen storage ■ Continue development of engine designs that combust pure hydrogen while maintaining stable combustion temperatures ■ Progress development in on-board cryogenic storage materials, pumps and heat exchangers	■ Develop regulatory framework supporting the use of hydrogen fuel cells for both propulsion and non-propulsion applications ■ Pursue development of efficient cryogenic hydrogen refueling systems that maintain flight turnaround times and minimize hydrogen leakage ■ Develop long-term strategy for the divergence of large-scale hydrogen production infrastructure from electrofuels to hydrogen aircraft

■ Policy/regulatory ■ Commercial ■ RD&D ■ Social

2 Introduction

2.1 Commercial aviation sector trends

The commercial aviation sector is facing the ongoing challenge of reconciling increasingly stringent environmental regulations and emissions commitments with expected growth in passenger demand.

In 2009, the International Air Transport Association (IATA) adopted a target of a 50% reduction on 2005 CO_2 emissions levels by 2050 with no increase in net emissions after 2020.[4] Although the 2050 target is yet to be codified by the UN International Civil Aviation Organization (ICAO), it has been widely adopted by the aviation industry as the primary emissions abatement goal. Similarly, in 2012, all flights within the European Union were included under the coalition's emissions trading scheme (ETS). Over the next few decades however, and largely driven by rising wealth in Asia, IATA expects that global passenger demand could double to 8.2 billion per year by 2037.[5]

Industry emissions targets are being complemented by a growing concern amongst the global community over the environmental impacts of aviation. The emergence of movements such as 'flight shaming' has led to a month-on-month decline for 2019 in passenger numbers in countries such as Sweden[6] and is forcing airlines to re-assess the effect on their business models. This trend is at least partially responsible for several airlines such as Qantas and British Airways' owner IAG, committing to net-zero CO_2 emissions by 2050.

To date, the aviation sector has achieved greater than 2%[7] annual fuel efficiency improvements and is expected to continue to meet established targets of 1-1.5% due to ongoing technological and operational developments. Those that are relatively easy to implement include the roll-out of aircraft with lighter structures, higher engine efficiencies and reduced drag.[8] Operational efficiencies that stem from improvements in flight patterns, fleet management and aircraft traffic can also lead to significant reductions in fuel consumption.

4.6%

Average annual projected passenger traffic growth

104 billion

Annual global commercial jet fuel consumption in gallons

9%

Average yield of jet fuel from a barrel of crude oil

3.2x

How much more energy is consumed by the aviation industry than the nation of Australia

4 International Air Transport Association (IATA) (2020) *Climate Change*. Available at https://www.iata.org/en/policy/environment/climate-change/

5 IATA (2018) *IATA Forecast Predicts 8.2 billion Air Travelers in 2037*. Available at https://www.iata.org/en/pressroom/pr/2018-10-24-02

6 BBC (2020) *Sweden sees rare fall in air passengers, as flight-shaming takes off*. Available at https://www.bbc.com/news/world-europe-51067440

7 The Boeing Company (2019) Global Environment Report. The Boeing Company

8 Mrazova M (2013) *Future directions of fuel efficiency in aviation*, INCAS BULLETIN

Figure 1 represents the projected CO_2 emissions profile for the global commercial aviation sector, accounting for improvements in efficiency and increases in passenger demand against the 2050 target adopted by IATA. Note that this is not representative of 'CO_2 equivalent' (CO_2-e) which includes non-CO_2 greenhouse gases such as methane. The emissions boundary in this assessment has been restricted to CO_2 generated from the use of liquid fuels within the airport boundary and jet fuel to power aircraft (i.e. all airport power and heat demand is not in scope).

The observed limitations of efficiency improvements in meeting industry abatement targets has prompted a stronger focus on the adoption of sustainable aviation fuels (SAF). In this context, while there is considerable scope for further development of biofuels as a 'drop-in' jet fuel, current uptake has been minimal, making up less than 0.1% of jet fuel consumption in 2018.[9] This has increased the scope for consideration of alternatives such as 'clean' hydrogen and other hydrogen-based fuels.

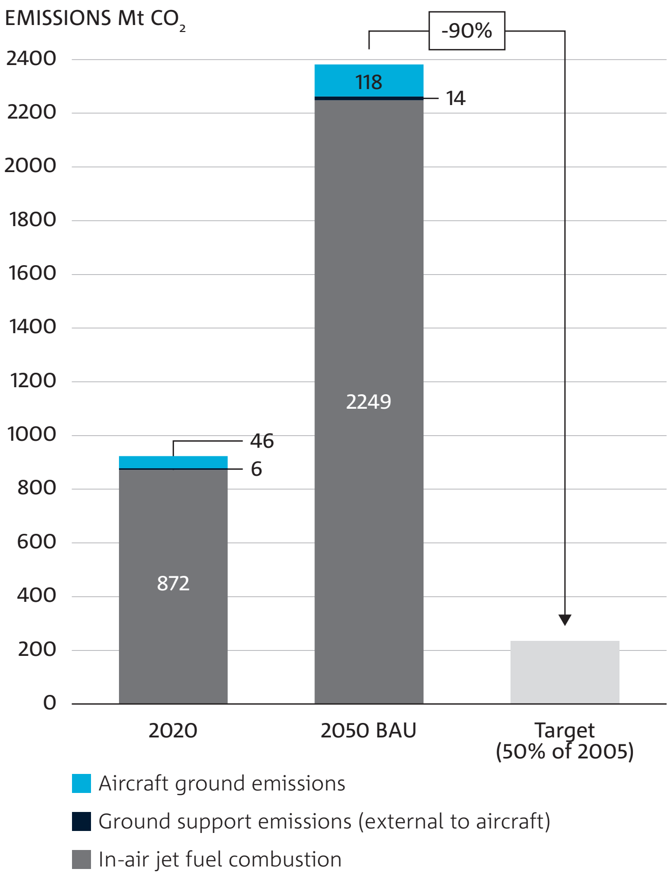


Figure 1. Global aviation sector projected business as usual (BAU) emissions to 2050 in Mt CO_2 including forecast passenger growth and annual efficiency improvements (1.5%)

2.2 Applications for hydrogen in commercial aviation

In recent years there has been a notable acceleration in the development of the hydrogen industry. This has been driven by a confluence of factors including technology maturity, significant reductions in the cost of renewable energy and the growing acceptance of its potential as one of the only ways to achieve deeper decarbonization both in and outside of the electricity sector.[10] With considerably more focus given to other forms of transport to date, this report considers the role that hydrogen can play in helping decarbonize the aviation sector.

This report categorizes the applications for hydrogen within commercial aviation across three primary areas and the analysis has been structured accordingly:

- **On/adjacent airport applications (Section 3):** Considers the role for hydrogen powered fuel cells in all on-airport activities (i.e. ground support equipment) that currently rely on batteries and liquid fuels (e.g. diesel and gasoline). The section also considers the scope for hydrogen used for treating crude or bio-crude oil to produce jet fuel with a lower carbon intensity.
- **Existing infrastructure (Section 4):** Considers the on-aircraft (or 'on-platform') applications that require no change to existing infrastructure. This concerns the production of synthetic jet fuel or 'power-to-liquids' (herein referred to as electrofuels), which involves using hydrogen and CO_2 to produce 'drop-in' jet fuel.
- **Emerging infrastructure (Section 5):** Considers on-aircraft applications for hydrogen that would involve a change to existing aircraft design. This section is subdivided into 'fuel cells for non-propulsion applications' and 'hydrogen for propulsion'.

9 Le Feuvre, P (2019) *Are aviation biofuels ready for take off?* International Energy Agency

10 Refer to *National Hydrogen Roadmap,* CSIRO for further discussion on industry development

By separating the sections in the manner described, there is an implicit time component that reflects the expected development periods required for each of the technology categories. The consequent time with which there could be a meaningful uptake of each technology is depicted in Figure 2.

Given the overarching need to achieve meaningful emissions abatement within the aviation sector, the primary focus of this report is on the technology solutions that support larger emissions-intensive jet aircraft (i.e. greater than 100 seats and range beyond 500km). While smaller propeller aircraft (i.e. turboprops), helicopters and urban taxis all present favorable applications for hydrogen, deeper analysis is not within the scope of this report.

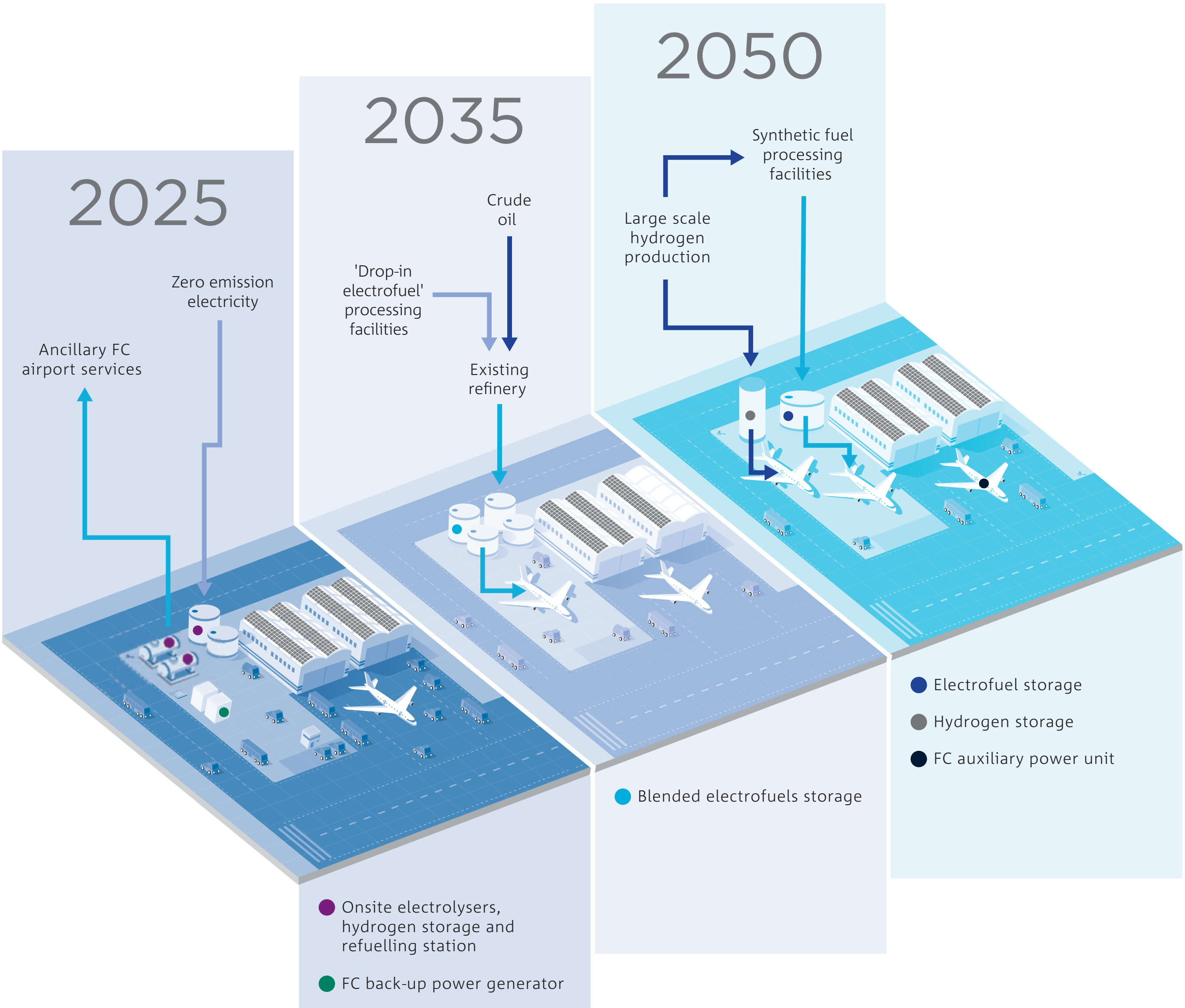


Figure 2. Hydrogen technologies within the aviation sector

2.3 Analysis approach

In many ways, this report represents an extension to, and should be read in conjunction with the *National Hydrogen Roadmap* and the *Hydrogen Research Development & Demonstration Report* released by CSIRO in 2018 and 2019 respectively.

As per the *Roadmap*, the technologies that underpin the applications for hydrogen identified in Section 3 (On/adjacent airport) and 4 (Existing infrastructure) are first assessed in terms of cost and maturity according to the Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) framework set out in Figure 3. This represents the 'base case' scenario for 2020.

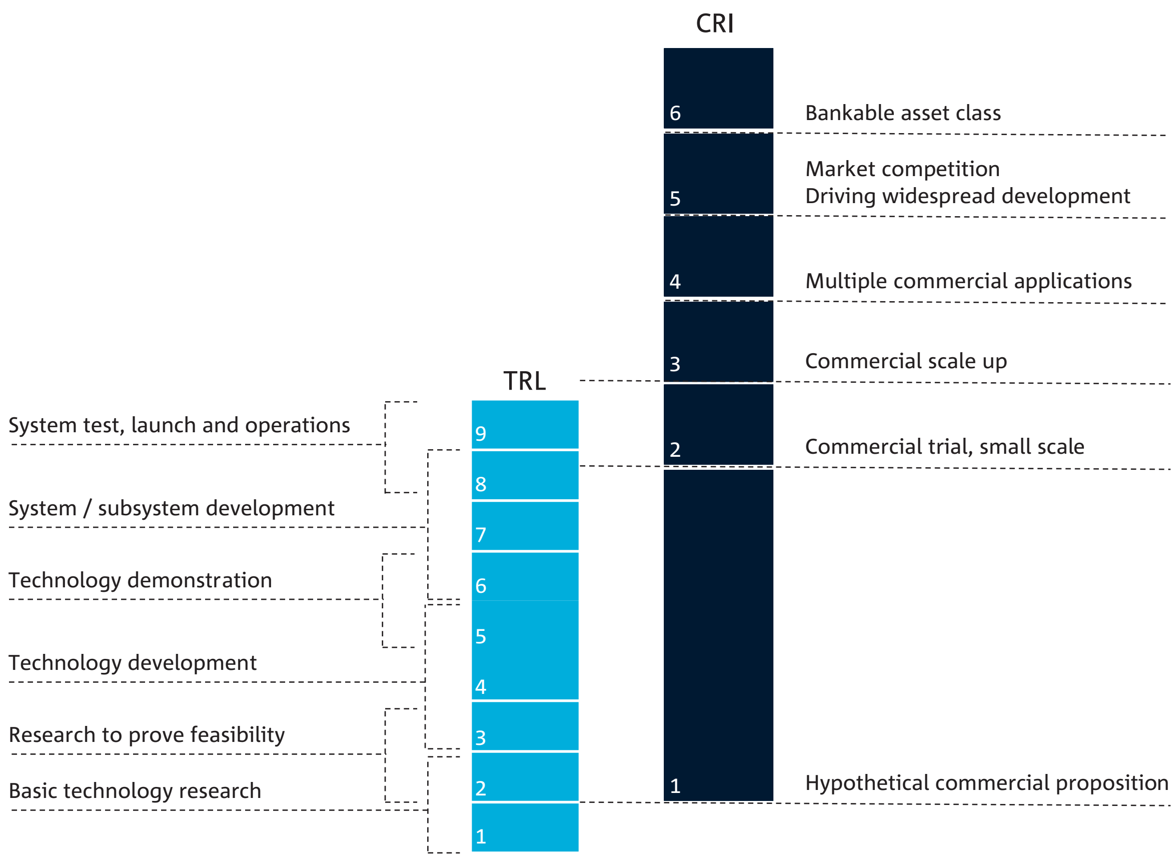


Figure 3. TRL and CRI assessment framework[11]

11 Available at https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf

The analysis then focuses on the investment priorities needed to develop each of the technologies further and achieve the cost reductions necessary to create an economically sustainable industry (i.e. CRI 6). The investment priorities align to the following 4 categories:

1. **Commercial:** Includes an assessment of the commercial models, implications and opportunities.
2. **Policy/Regulatory:** Includes an assessment of where policy is needed to stimulate relevant markets together with the technical/economic regulations that are required to facilitate deployment of relevant technologies.
3. **Research Development & Demonstration (RD&D):** Includes an assessment of where incremental improvements to mature technologies are needed as well as the potential for less mature technologies (non-exhaustive) to provide the next wave of development. Demonstration projects needed to overcome first-of-kind risk are also considered.
4. **Social license:** Includes an assessment of the initiatives required to ensure communities are properly engaged and understand all aspects of hydrogen use.

While not all the investment priorities are inherently quantifiable, they are aggregated to determine a 'best case' scenario that sets out what could be achieved over the 2025, 2035 and 2050 timeframes (Figure 4). The consequent emissions abatement that stems from the uptake of relevant technologies is then set out in Section 6.

Given the long lead times required to develop the technologies set out in Section 5 (emerging infrastructure) as well as the integrated nature of aircraft and aviation infrastructure, a different assessment approach is employed that considers RD&D priorities as they relate to the universal rules within commercial aviation. This includes:

1. **Economics of travel:** Includes payload, fuel/energy efficiency, refueling times
2. **Safety:** Relates primarily to the handing, storage and use of hydrogen and hydrogen augmented fuels
3. **Environmental impact:** Includes emissions, pollution and noise
4. **Hydrogen specific RD&D:** Investment priorities as they relate to hydrogen (as opposed to in-depth analysis of aircraft design and specifications)

These methodologies are designed to help inform investment amongst various stakeholder groups (e.g. industry, government and research) so that the use of hydrogen within the aviation sector can be scaled in a coordinated and strategic manner.

All costs are presented in 2019 US dollars unless explicitly stated otherwise. All other units are presented using both the metric and imperial systems. Note also that while 'hydrogen' is defined as being produced using renewable or low emissions sources, full 'life cycle analysis' (LCA) would require a deeper level of analysis which is not within the scope of this report.

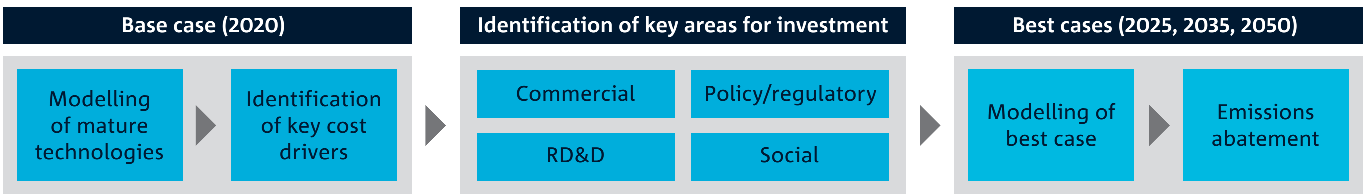


Figure 4. Assessment framework

3 On/adjacent airport applications

On or 'adjacent' airport activities provide a nearer-term opportunity to introduce clean hydrogen into the commercial aviation sector.

On-airport applications refer primarily to the replacement of current operations that rely on liquid fuels and batteries with hydrogen-powered fuel cell alternatives. This transition has the potential to deliver cost savings, reduce dependence on imported fuels and achieve significant abatement in local ground-based emissions. The proliferation of these technologies also provides a starting point for the development of safety standards, regulations and standard operating procedures for the handling of hydrogen within an airport boundary.

In this context, 'adjacent airport opportunities' considers the replacement of hydrogen derived from natural gas (i.e. steam methane reforming) with electrolysis as a means of treating crude and bio-crude in the upstream production of kerosene. While the emissions abatement achieved will be credited to the oil & gas sector, this application will be important in the context of providing jet fuel with a reduced carbon intensity. It may also be critical in supporting the development of synthetic fuels as discussed in Section 4.

3.1 On-airport applications

3.1.1 Applications and supporting technologies

The potential on-airport applications for hydrogen can be broadly categorized according to Table 1.

Ground Support Equipment (GSE)

Airport operations depend heavily on a series of fleet vehicles and power generating technologies which are collectively known as ground support equipment (GSE).

Mobility GSE

Mobility GSE include a series of vehicles that support aircraft servicing, as well as the movement of luggage, freight and people. Technically, all of these operations can be replaced with a hydrogen powered fuel cell system.

Use of hydrogen for materials handling (e.g. forklifts) is already being demonstrated within the warehouse operations of several large logistics companies such as Amazon and Walmart. Here, fuel cell equipment has already been found to be competitive with diesel and battery alternatives on a total cost of ownership basis.[12] When compared to diesel specifically, due to a more limited number of moving parts, additional cost savings can be achieved via reduced maintenance. Fuel cells are also more efficient than diesel engines and do not idle.

Plug Power is one fuel cell equipment manufacturer that is successfully applying its technology to GSE applications, having recently demonstrated use of fuel cell operated baggage tugs at Hamburg Airport. The US military has also been active, as demonstrated by the Hawaii Air National Guard who recently retrofitted a U-30 Aircraft Tow Tractor with a fuel cell power system to tow an 84t aircraft.[13]

Table 1. On-airport applications for hydrogen

CATEGORY		EXAMPLES
Mobility ground support equipment (GSE)	Materials handling	Baggage/cargo tractors, belt loaders, pushback and taxiing tugs/tractors, forklifts
	Transport	Apron bus
	Servicing	Follow-me vehicle, ramp agent, de/anti-icing vehicles, catering vehicles, air conditioning units, refuelers, lavatory service vehicles
Stationary GSE	Power generation	Back-up power, ground power units (GPU)
Heat generation		Airport food burners

12 Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) *National Hydrogen Roadmap*. CSIRO

13 Corpuz O (2019) *Clean energy partnership demonstrates 'alternative' way to move aircraft.* DVIDS

Case Study: Plug Power and Hamburg airport[14,15]

Plug Power was founded in 1997 as a company working to develop fuel cells before selecting a market for their product. The application came in the form of materials handling, with the product offering going commercial in 2014. By providing increased productivity and lower operational costs, Plug Power was able to secure deals with many major warehouse operators including Amazon and Walmart. As of 2019, Plug Power has sold more than 28,000 fuel cell units.[16]

Building on the success of forklift sales, Plug Power is expanding its materials handling offerings by identifying opportunities for GSE at airports. Recently at Hamburg airport, Plug Power partnered with MULAG, a GSE manufacturer, to build fuel cell cargo tow tractors. The successful pilot has led to an order of an additional 60 units and a permanent hydrogen refueling station.

Plug Power has conducted a similar trial at Memphis airport, partnering with FedEx and battery powered GSE manufacturer Charlatte America to test fuel cell baggage tractors. The latest phase of the trial has shifted to Albany International airport to test the technology in colder climates.[17]

Similarly, fuel cell cars and buses are a readily available technology offered by several OEMs such as Toyota and Hyundai. This readiness is being demonstrated in France with a recent announcement by Toulouse-Blagnac Airport that in 2020, it will host a hydrogen production and public refueling station to fuel four buses (provided by SAFRA) that will transport passengers between car parks, terminals and aircraft.[18]

Stationary GSE

Major airports depend heavily on continuous electricity supply and therefore employ a number of back-up power systems which are utilized in the event of a power outage. Ground power units (GPU) are mobile generators that are used to provide power and air-conditioning to the aircraft when the engines are switched off (although a growing trend is for conditioned air to be provided at the gate).[19] Currently, these operations are typically undertaken using diesel generators that could be replaced with fuel cells.

For regional airports with low traffic levels, microgrids or remote energy power systems with an integrated hydrogen and fuel cell solution for energy storage and electricity production may present a competitive primary energy system. This is largely due to the potentially high cost of electricity that stems from either transport of diesel or capital-intensive transmission infrastructure connecting power generation to remote regions. Microgrids may also be deployed in major airports looking to improve security of energy supply (discussed further in Section 3.1.3).

Material GSE

Using Dallas Fort Worth (DFW) airport as a proxy, a list of the most material GSE (based on diesel consumption) at major airports is set out in Table 2. In 2018, DFW was the 15th biggest airport in terms of passenger volume globally.[20]

Heat generation

Many airports are connected to a natural gas pipeline used to service the airport's power or heat generation facilities. Opportunities to blend natural gas with specified concentrations of hydrogen or potentially upgrade to a 100% supply is likely to be part of a broader cross-industry effort rather than undertaken locally at an airport.[21]
It is therefore not considered in detail in this analysis.

Comparison against battery powered GSE

Battery and fuel cell-powered technologies are continuing to provide complementary solutions for mobility operations across different industries looking to transition away from liquid fuels.

Compared with fuel cell equivalents, battery powered GSE currently have a lower capital cost, reduced infrastructure requirements and more power for higher torque motors which can be critical for moving heavy on-airport equipment from rest (e.g. pushback tugs). These systems are already being rolled out for certain GSE, with major upgrades occurring at airports in Seattle, Philadelphia and DFW in 2016. In the same year, Delta Airlines reported that it had converted 15% of its GSE fleet to run off batteries.[22]

14 Kelly-Detwiler P (2019) P*lug Power CEO: Soon Fuel Cells Will be Everywhere, Really*. Forbesd

15 FuelCellsWorks (2019) *Plug Power Teams with German Manufacturer MULAG to Bring New Hydrogen-Powered Ground Support Vehicles to Hamburg Airport*. FuelCellsWorks

16 Plug Power (2019) *Hydrogen fuel cell day: A look back at the plug symposium*. Plug Power Inc.

17 Plug Power (2019) *The results are in*. Available at https://www.plugpower.com/2019/08/4851/

18 FuelCellsWorks (2019) *France: Hydrogen Buses and Station for the Toulouse-Blagnac Airport.* FuelCellsWorks

19 National Academies of Sciences, 2012, Airport Ground Support Equipment (GSE): Emission Reduction Strategies, Inventory, and Tutorial, US

20 Airports Council International (ACI) *(2019) Annual World Airport Traffic Report*. ACI

21 Refer to *National Hydrogen Roadmap,* CSIRO for analysis regarding use of hydrogen in the gas networks.

22 Available at https://afdc.energy.gov/files/u/publication/egse_airports.pdf

Rather, difficulties arise in relation to operating time before recharge, length of recharge times and the consequent need for charging infrastructure to be spread around major airports. This is particularly challenging for older airports with less resilient infrastructure that may be unable to cope with a significant increase in electricity demand during peak operating periods.

A 'battery swap' operating model may be used for high-usage equipment to avoid lengthy charging times. However, this will add to program capital costs and require storage at different points across the apron. In terms of productivity, batteries also suffer from subpar performance in extreme temperature conditions, rendering them unsuitable for certain climates. Lastly, use of battery powered GSE will require workforce re-training due to the change in operations and behavior associated with recharging and equipment downtime. For these reasons, batteries are likely to be more applicable to smaller regional airports with limited operating windows.

For major airports with continuous operations, fuel cell GSE are likely to require minimal change in operational behavior due to the avoidance of longer charging times and/or purchase of additional batteries. This also allows refueling infrastructure to be more centralized (as per existing airport bowsers or 'fuel farms'). The ability to store hydrogen in tanks means that increases in electricity load during peak periods can also be avoided.

Table 2. Estimated material GSE at DFW airport 2019[23]

GSE	DIESEL CONSUMPTION '000 GALLONS/YEAR ('000 LITERS/YEAR)	USE AND HYDROGEN APPLICABILITY
Baggage/cargo tractor	309 (1,170)	These tractors are used to tow baggage and cargo trolleys to and from aircraft. They tend to have long idling periods while the baggage is being handled. This results in wear and tear on the diesel engines and increased emissions. In the case of fuel cell tractors, it would be possible to switch the engine off during baggage handling.
Cars/pickups/vans	6.81 (25.8)	Primarily run on gasoline in the US. Fuel cell alternatives are readily available off-the-shelf technologies.
Belt loaders	160 (606)	Belt loaders enable baggage and payloads to be loaded both on and off aircraft via a conveyor belt. Diesel engines can be retrofitted with a fuel cell system.
Aircraft tractor/tugs	2,234 (8,457)	With a similar design to baggage tractors, aircraft tugs are used to pushback and tow aircraft between locations. Tugs are required for push back at the gates due to the absence of thrust reversers on commercial aircraft. Fuel cell alternatives are already available from Plug Power.
De-icing trucks	652 (2,468)	De-icing trucks store, transport, heat and distribute de-icing fluid to the aircraft surfaces and runways covered in ice. Diesel engines can be retrofitted with a fuel cell system. Heat generated by fuel cells may also be utilized.
Generators/GPUs	335 (1,268)	Generators and ground power units (GPUs) are used to provide power to airport and aircraft (respectively) when the primary power source is not available. Stationary fuel cells power units are readily available.
Forklifts	14.0 (53)	Forklifts are a type of materials handling equipment utilized for general maintenance tasks as well as transferring cargo between locations around the airport. Fuel cell alternatives are already commercially available.
Air Conditioners/ Heaters	864 (3,270)	Air conditioning units supply cooled or heated air to stationary aircraft. Air conditioners are most frequently used when an aircraft is at a terminal or undergoing maintenance. Heaters are designed to prevent the freezing of fluids and lubricants in aircraft engines. Heat generated by fuel cells as a by-product may also be utilized here.
TOTAL	**4,540 (17,186)**	

23 Use has been estimated using the Airport Cooperative Research Program (ACRP) which ties the relationship of number of flights to quantities of GSE

3.1.2 Hydrogen infrastructure

Production

In the context of airports, depending on demand, hydrogen may be produced locally or imported from another proximate source (this trade-off is discussed further in Section 3.1.3). Assuming that hydrogen is produced locally, electrolysis is likely to provide the most favorable technology solution.[24] The potential for hydrogen derived from the reformation of locally produced waste gases in this context is also a notable option if the required feedstocks are available.

Within electrolysis, the two most mature and readily available technology options are alkaline and polymer electrolyte membrane (PEM). Both options have different advantages depending on the nature of use and are expected to continue to improve with respect to operating efficiencies and capital cost.[25] There are however several factors that should be considered by electrolyzer proponents within an airport boundary to achieve the most favorable cost of production.

Capacity factor

The extent to which the electrolyzer plant is used is critical for the overall cost of hydrogen produced. This is particularly the case while electrolyzer capital costs remain high in the early stages of industry development.

To achieve favorable hydrogen costs, the capacity factor should be between 80-90%.

Low-cost renewable/low emissions electricity

Electricity represents a significant cost input for hydrogen production (in the order of 70%). Within an airport boundary, there are a number of ways in which this may be sourced, and the most economic outcomes are likely to stem from the optimization of each:

1. **Dedicated renewables**: Depending on resource availability, there may be scope to build adjacent dedicated renewables (i.e. solar PV and wind) as a 'behind-the-meter' solution with some degree of flexibility. Other renewable energy technologies such as hydropower and geothermal may also be available for certain locations (e.g. Iceland has 15 airports where all electricity demand is met using hydropower[26]). However, within an airport boundary, there is typically considerable underutilized space that may be taken advantage of using solar PV. This includes vacant land and the rooftops of onsite buildings.

   There is some speculation that use of solar PV could be distracting for incoming pilots. However, it is important to note that in contrast to heliostats (mirrors) used for concentrated solar thermal power (CSP), traditional silicon panels primarily absorb rather than reflect light. There is already precedent for solar farms

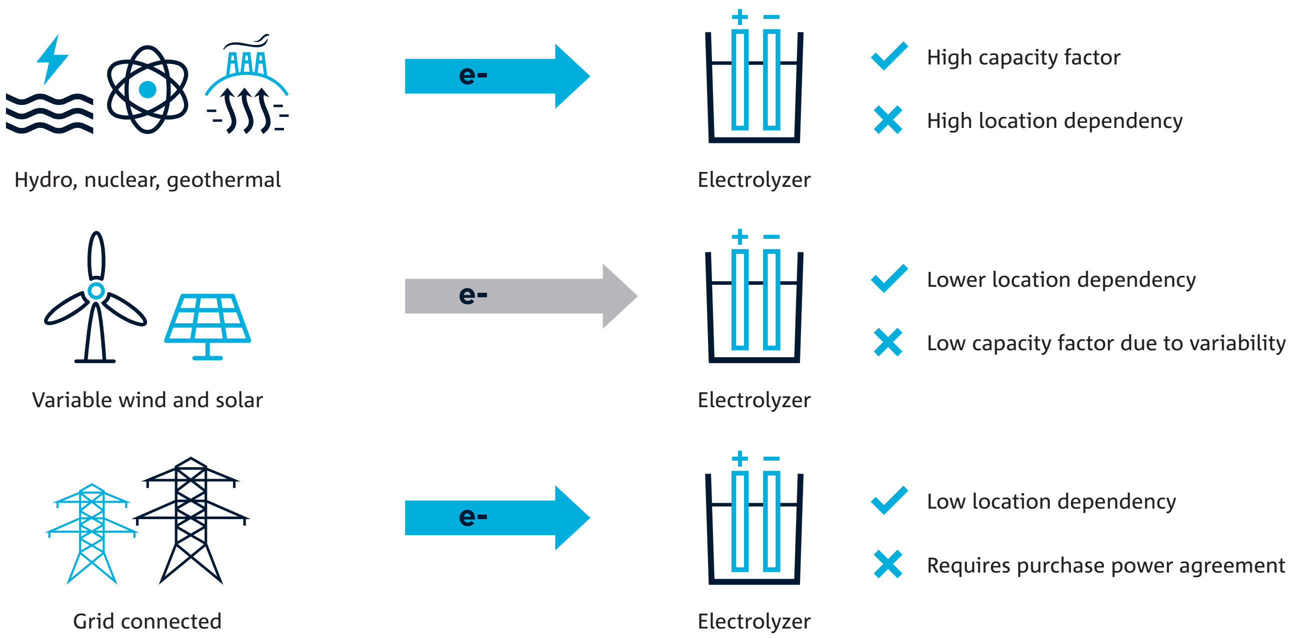


Figure 5. Electricity and capacity factor configurations

24 Clean hydrogen can be produced via a number of different pathways (e.g. electrochemical, thermochemical etc). Refer to the CSIRO National Hydrogen Roadmap for further detail on production technologies

25 Refer to CSIRO *National Hydrogen Roadmap* for further discussion

26 Isavia (2018) *Annual and CSR Report 2018.* https://www.isavia.is/annualreport2018/environment/climate

at airports with Denver International Airport already hosting 2MW and currently implementing plans for expansion.[27] Dependence on solar however will result in a poor capacity factor and so requires optimization with an alternative electricity source.

2. **Grid connection**: Use of a traditional electricity grid connection remains an important consideration in the context of achieving a high capacity factor. Although the electrons purchased from the grid are likely to come from a number of different electricity sources (including coal and natural gas), they can still be considered 'clean' so long as a power purchase agreement is in place between a renewable energy asset operator and an airport offtaker.

   Co-use with onsite renewables will be important in limiting pressure on existing electricity distribution infrastructure. Use of grid electricity during periods of low demand (e.g. overnight) can also indirectly smooth out electricity demand profiles for utilities.

Size of plant

The size of the electrolyzer plant has a substantial impact on the cost of hydrogen. Cost efficiencies can be realized by both increasing the size of the electrolyzer stack as well as the number of stacks in order to achieve greater utilization of balance of plant (BoP). Based on modelling conducted in the *Hydrogen Roadmap*, the greatest improvement in capital cost is achieved when increasing the plant size from 1 to 100MW, with more incremental gains achieved thereafter.

Water

Sourcing a sustainable water supply is a key requirement in the development of hydrogen production infrastructure. Most electrolysis cells require high purity water in order to limit side reactions caused by ions (salts) found in naturally occurring water and, while a number of water sources may be available (e.g. airport adjacent seawater), the higher the treatment requirements, the greater the cost. Despite this variability, water typically makes up less than 2% of the cost of hydrogen production.[28]

Storage and distribution infrastructure

Irrespective of whether hydrogen for GSE is produced within or outside of the airport boundary, use will need to be supported by necessary storage and distribution infrastructure.

Storage

In its uncompressed gaseous state, hydrogen retains a relatively poor volumetric density (lb/ft^3 or kg/m^3). This means that additional technologies must be utilized to increase the amount of hydrogen stored inside a tank of fixed size and improve the overall asset economics. Technologies that allow for a higher volumetric density of hydrogen are typically more expensive (i.e. due to the higher capital cost and energy burden)[29] and are therefore more applicable to situations where demand is high, but there are significant limitations on space (e.g. fuel cell vehicles). The most mature and applicable technologies to be considered in the context of on-airport storage are set out in Table 3. More emerging storage technologies can be referenced in the *Hydrogen RD&D Report*.

Table 3. Applicable hydrogen storage technologies

TECHNOLOGY	DESCRIPTION	HYDROGEN DENSITY[30] LB/FT^3 (KG/M^3)	TRL
Compression (@ 50–150 bar)	A mechanical device increases the pressure of hydrogen in its cylinder. Hydrogen can be compressed and stored in steel cylinders at pressures of up to 200 bar, while composite tanks can store hydrogen at up to 700 bar for transport applications.	0.3–0.7 (3.95–10.9)	9
High pressure (350–700 bar and 25˚C)		1.4–3.1 (23–50)	9
Liquefaction (-253˚C), 1 bar	Hydrogen is liquefied and stored at -253°C at ambient-moderate pressures in cryogenic tanks. The process occurs through a multi-stage process of compression and cooling.	4.4 (70.8)	9
Ammonia (10 bar and 25˚C)	Hydrogen is converted to ammonia via the Haber Bosch process and is liquid at ambient temperatures and mild pressure. Will need to be converted back to hydrogen at the point of use (refer to CSIRO RD&D report for more detail on hydrogen cracking technology).	6.7 (107)	9
Toluene/ methylcyclohexane (ambient conditions)	A type of liquid organic carrier. Hydrogen is reacted with toluene to form methylcyclohexane (MCH) which can be transported at ambient temperature and pressure. The hydrogen is then released through exposure to heat or catalysts.	2.9 (47)	9

27 Day M, Mow B (2018) *Research and Analysis Demonstrate the Lack of Impacts of Glare from Photovoltaic Modules.* NREL

28 Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) *National Hydrogen Roadmap*. CSIRO

29 Refer to National Hydrogen Roadmap for cost comparison between different hydrogen storage technologies

30 Charnock S, Temminghoff M, Srinivasan V, Burke N, Munnings C, Hartley P (2019) *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO

Major or regional airports are unlikely to suffer from limitations on space that would necessitate investment in higher volumetric density storage technologies such as liquefaction and ammonia to meet potential demand. In this context, high pressure (350bar) storage may be preferred.

Distribution

Distribution of hydrogen between the point of origin and use may be achieved using the storage technologies identified above paired with trucking vehicles such as tube trailers. However, should demand continue to increase, depending on the location, the most cost-efficient method would involve the distribution of compressed hydrogen via pipeline. This option comes with the added benefit of an in-built storage mechanism (i.e. linepacking) and could be further utilized to provide multiple distribution points within an airport boundary.

3.1.3 Investment priorities

Commercial

Project roll-out

One of the primary challenges associated with the roll-out of emerging fuel cell based GSE within an airport boundary will be achieving the necessary balance in hydrogen supply and demand. There is added complexity in this context due to the range of different GSE types utilized on the apron, with some able to be substituted by readily available technology (e.g. vehicles and forklifts) and others requiring either retrofit or special purpose new build systems (e.g. belt loaders).

In the early phase of project roll-out, in order to demonstrate an economically competitive end-to-end value chain, it is important to achieve a reasonable degree of scale (e.g. >1MW) without taking on excessive technology risk. To achieve this, the initial uptake of fuel cell GSE may be focused on readily available technologies such as apron vehicles, forklifts and stationary power GSE. At DFW, substitution of existing buses, vehicles, forklifts and stationary power units with fuel cell alternatives would require the development of a ~4MW electrolyzer to meet demand.

Concurrent projects would likely focus on retrofit or new build of special purpose GSE that are used continuously (e.g. baggage tractors) and would therefore require significant volumes of hydrogen.

Upgrade of material special purpose GSE

Decisions regarding the upgrade or retrofit of existing GSE are likely to differ depending on the equipment in question. As a starting point, there are several special-purpose GSE (e.g. aircraft tugs) which are already commercially available. However, particularly in the early stages of commercial scale-up, such technologies are likely to demand a high capital cost.

Where capital costs remain high, retrofit of existing GSE may prove more economical so long as the equipment in question has a sufficient asset life remaining. Note that asset life for some GSE is heavily dependent on use of a diesel combustion engine, suggesting that this could be extended through the addition of a fuel cell and electric drivetrain. However, GSE with a high capital cost (e.g. de-icing trucks) may also have high voltage requirements which makes the retrofit option more challenging due to the greater complexity of engines and operating systems.

As mentioned, with some effort to electrify GSE already taking place across several airports globally, it is important to consider the relative ease with which batteries can be substituted with fuel cells where an electric drivetrain has already been integrated. Companies such as Plug Power and Nuvera offer fuel cell systems that are designed to be retrofitted into battery forklifts with no modifications required. This is achieved through the production and availability of a range of power specifications to fit a variety of models.[31] The experience gained from these companies can be leveraged to provide solutions for niche GSE products.

Another retrofit option involves upgrading diesel and petrol internal combustion engines (ICE) so they can run off hydrogen, as demonstrated at Montréal-Pierre Elliott Trudeau International Airport in 2010. This type of retrofit is relatively straight forward, similar to the replacement of a worn-out engine,[32] and can run on hydrogen that is of lower purity compared to fuel cells. However, controlling NOx emissions is set to be a challenge. Fuel cell alternatives also have superior fuel efficiency and less moving parts.[33]

Multiple service providers

Within a major airport, multiple contracts relating to different ground support operations exist between airlines, third-party service providers and airports. These contractual models are likely to differ between locations and are often dependent on the size of the airport and tenanting airlines. GSE in particular may also be owned or leased.

31 Plug Power Europe (2017) *Hydrogen and Fuel Cells for Material Handling Applications*. Available at https://www.fch.europa.eu/sites/default/files/Ranjieve%20williams.pdf

32 Mwanalushi K (2018) *Fuel for thought*. Available at https://www.airsideint.com/issue-article/fuel-for-thought/

33 US Department of Energy (2019) *Hydrogen Basics.* Available at https://afdc.energy.gov/fuels/hydrogen_basics.html

Europe for example has a directive to ensure more than one provider is available at large airports.[34] In contrast, Chinese and Saudi Arabian airports commonly have a single provider, which in separate cases is controlled by either an airline, an independent operator or the airport as per Pudong International Airport in Shanghai.[35] The level of complexity and variability associated with these contracts increases the difficulty of determining a commercial model that allows for coordinated roll out of fuel cell based GSE.

In the initial stages of development, airports which have a major airline carrier are therefore likely to prove more favorable locations for demonstration and subsequent roll-out of fuel cell GSE. For example, airlines such as Qantas which retain a dominant market share at major Australian airports, typically own the majority of GSE (which are leased to other airlines) as well as diesel fuel farms. They, together with the relevant airport operator are therefore well positioned to conduct an upgrade of specific GSE and pave the way for smaller service providers that are less likely to take on the risk and cost of transition to fuel cells. In terms of risk allocation, it may be preferable for the airport to own and operate the hydrogen refueling infrastructure which could increase the scope for servicing adjacent industries.

Servicing adjacent industries

Given the impact of electrolyzer scale on the overall price of hydrogen, it is important to consider the opportunity that comes with airports serving as hubs for both passenger and freight ground transportation. There is therefore potential to increase electrolyzer capacity and reduce hydrogen demand risk by servicing connecting fuel cell fleet vehicles, buses, trucks and possibly trains in the near future. Such a model could enhance the scope for a specialized third party to build own and operate an electrolyzer plant and have multiple hydrogen offtakes in place with vehicle providers both within and outside the immediate airport boundary.

Similar themes have begun to emerge in other transport sub-sectors. For instance, since 2012, the AC Transit bus depot in San Francisco, California, has been servicing in the order of 13 fuel cell buses. Critically, the onsite hydrogen refueller services its bus fleet as well as the public with one distribution point inside and another outside of the forecourt. Further, several cities have recently introduced public hydrogen refueling stations adjacent to their airports. This includes Japan's major airports in Osaka and Tokyo, LAX (US), Gatwick Airport (UK), Oslo airport (Norway), and forecasted completion of stations at Seoul's Incheon International Airport and Germany's Hamburg and Schönefeld airport in 2020.

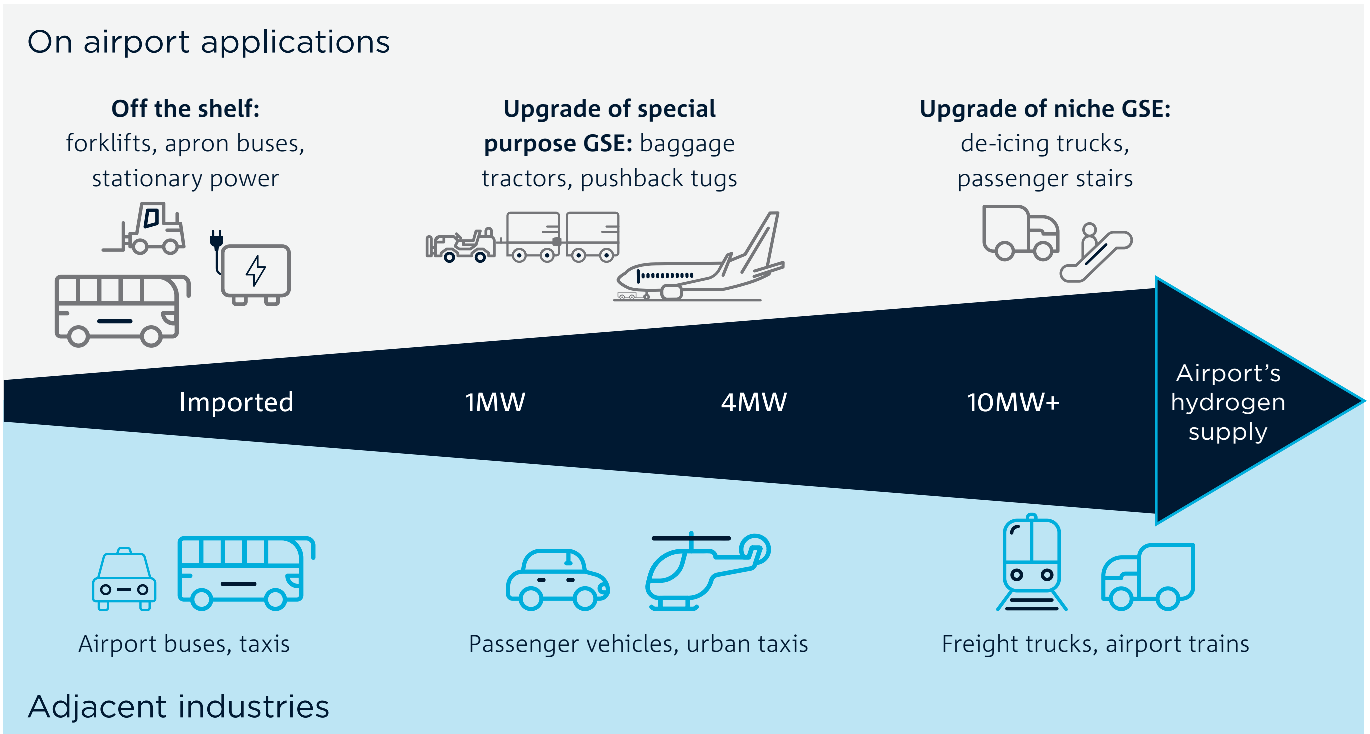


Figure 6. GSE project roll out as hydrogen demand and supply increases

34 European Commission (2020) *Groundhandling.* Available at https://ec.europa.eu/transport/modes/air/airports/ground_handling_market_en

35 Tomová A, Trgiňa L, Novák Sedláčková A (2015) *Ground handling business at non – European biggest world airports as a problem of market structures.* Business, Management and Education

Location

Depending on the airport location and particularly while demand from fuel cell GSE is low, importing hydrogen to the airport may prove more cost-effective. This is particularly the case where existing hydrogen production and/or distribution infrastructure is relatively proximate. The cost efficiencies achieved, primarily through scale at a centralized point of production, must offset the additional cost of hydrogen distribution. Such decisions should also be considered in the context of maintaining security of hydrogen supply, a priority for all airports with continuous operations.

One potential example is Los Angeles Airport (LAX) which as a major transport hub, is also located near a network of existing hydrogen refueling stations. One of these stations makes use of a hydrogen pipeline operated by Air Products located in Torrance, approximately 12km (7mi) from LAX. The remaining distance to the airport could be covered by distribution trucks or a pipeline extension to the airport.

Optimization of input and output products

On or near-airport applications for oxygen should also be considered in order to improve electrolysis economics and provide added benefit to other airport/aircraft operations. Waste heat from electrolysis may also be further utilized for air-conditioning and hot water supply.

Similarly, wastewater from several activities can be treated and used as an input into electrolysis, allowing for a degree of resource circularity to be achieved within the airport boundary. Key wastewater sources include aircraft and vehicle washing as well as airline food preparation and cleaning. Notably, at airports such as Heathrow, oxygen is currently being used to treat wastewater from de-icing activities.[36]

Broader industry benefits

The need for security of energy supply has led several airports globally to consider investment in localized microgrids. In the US, such decisions were provoked by a fire near Atlanta's international airport that destroyed two substations resulting in an 11-hour power outage and the cancellation of 1,200 flights in early 2018. Pittsburgh will be the first airport to be 100% powered by a microgrid supported by both natural gas and solar PV.[37]

Hydrogen and stationary fuel cells have been widely recognized as an important solution for microgrid or stand-alone power systems, particularly when supported by a higher percentage of variable renewable energy resources. This is largely due to the improvements in cost (compared with battery systems) that occur as energy storage requirements increase.

Policy/Regulatory

Incentive programs

Targeted government programs that incentivize the electrification of GSE are likely to be effective in promoting the uptake of fuel cell systems. This may be crucial in helping absorb the capital cost of fuel cell GSE in the earlier stages of development as well as underwriting hydrogen supply and demand risk.

Globally there is precedent for government programs focused on the uptake of zero-emissions vehicles within airports. Crucially however, given that hydrogen has additional infrastructure requirements (as compared with battery-electric) and is not as widely recognized as a zero-emissions option, it should be explicitly promoted within such programs. This was already found to be the case with the Airport Zero Emission Vehicle (ZEV) and Infrastructure Pilot Program implemented in the US in 2012.

Case study: Airport Zero Emission Vehicle (ZEV) and Infrastructure Pilot Program[38]

The pilot program was created by Congress in 2012 and allows FAA issued Airport Improvement Program grants to be used for the purchase of zero-emission vehicles for use on airport and for infrastructure that facilitates fuel delivery. Battery and fuel cell vehicles are considered eligible, as well as the recharging and refueling infrastructure.

The program prioritizes projects in locations that are deemed 'nonattainment' by the EPA in terms of air quality and are the most cost-effective in providing the greatest air quality improvement. Local matching of funds is also required and is considered on a case-by-case basis. The most common projects so far have been the procurement of electric buses with charging infrastructure.

36 Freyberg T (2013) *Wastewater reed bed treatment takes off after Heathrow airport upgrade*. Water Technology

37 Gerdes J (2019) *Microgrids Take off Among Airport Operators.* Greentech Media

38 FAA (2019) Airport Zero Emissions Vehicle and Infrastructure Pilot Program. FAA

Safety regulations and standards

With limited use of hydrogen on airports globally, there is an absence of an established regulatory framework governing its use. While airports are accustomed to dealing with highly flammable materials such as jet fuel, hydrogen has its own risk profile that needs to be managed (detailed risk profile regarding use is set out in Table 13).

That said, it is also important to ensure that the regulatory burdens imposed are commensurate with the level of risk. While hydrogen is a flammable material, adverse perceptions of the associated danger can lead to overburdensome regulation and increase project cost and approval times. Efforts to reduce this risk can be achieved by undertaking the necessary risk assessments and via continued stakeholder consultation as detailed in the subsection on 'social license' below.

In developing relevant regulations, fundamental lessons may be leveraged from current hydrogen storage and use practices across other sectors. This includes refueling infrastructure standards that set targets for key parameters such as temperature, pressure and dispenser safety (e.g. SAE standard J2601).[39]

Primary considerations for airports include ensuring hydrogen storage tanks are a sufficient distance from people and structures such as air intakes, overhead power, open flames and combustible materials. Adequate leak and flame detection is also required due to the odorless and almost invisible flame produced by hydrogen,[40] as is the establishment of allowable distances between fuel cell GSE and aircraft refueling equipment.

In terms of implementation, much of the guidance around the handling of different gases and equipment within the aviation sector is derived from IATA Standards, Manuals and Guidelines. It is therefore important that IATA and other aviation regulatory bodies such as the FAA continue to discuss and integrate hydrogen handling guidance as the number of global demonstration projects increases.

RD&D

As one of the later adopters of hydrogen-based technologies, the aviation sector will have the benefit of being able to leverage much of the ongoing RD&D across different areas of the hydrogen value chain.

Many of these research areas are dealt with in more detail in the *National Hydrogen Roadmap* and *Hydrogen RD&D Report*. However, some of the key research areas directly applicable to airport use are set out below.

Compression and refueling

Refueling hydrogen vehicles at 350 or 700bar is an energy-intensive process and mostly relies on mechanical compressor technologies with a number of moving parts. Mechanical compression is therefore noisy and vulnerable to high maintenance costs.[41] Electrochemical compression (TRL 3)[42] provides an alternative method to compress hydrogen utilizing a polymer exchange membrane and electric currents to achieve high pressures with no moving parts. This process can achieve higher efficiencies, lower maintenance costs and noiseless operation. Further RD&D is required to reduce capital costs and improve management of electric conditions and material integrity.[41]

Fuel cell integration

The process of integrating fuel cells into existing GSE can benefit from a series of RD&D measures. Product development of retrofit solutions are required to provide a range of upgrade options for airports and airlines. Additionally, testing of vehicle components (e.g. fuel cells) in an airport environment will need to be undertaken to ensure durability in high fume areas.

Finally, to aid companies in selecting the most economic electrification pathways, fleet analysis will assist with selection of appropriate fuel cell size and storage pressure in accordance with GSE operating requirements.

Social license

Use of hydrogen powered GSE can play a key role in enabling airport staff and passengers to become familiar with the use of hydrogen within an airport boundary. It is important that familiarization is carried out in a transparent manner to make stakeholders aware of the risks, improve social acceptance and in turn, help ensure that the regulatory framework imposed is commensurate with the risk. An effective means by which this has been achieved in the broader hydrogen industry to date is by clearly highlighting use of hydrogen and fuel cells on buses and vehicles already in operation in order to normalize use.

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39 US Department of Energy (2014) *An Introduction to SAE Hydrogen Fueling Standardization*. DOE

40 H2 Tools (2015) *Safety considerations for Hydrogen and Fuel cell applications.* Pacific Northwest National Laboratory

41 Kee B, Curran D, Zhu H, Braun R, DeCaluwe S, Kee R, Ricote S (2019) *Thermodynamic Insights for Electrochemical Hydrogen Compression with Proton-Conducting Membranes*. Membranes

42 Charnock S, Temminghoff M, Srinivasan V, Burke N, Munnings C, Hartley P (2019) *Hydrogen Research, Development and Demonstration: Technical Repository,* CSIRO

Such initiatives are also important in the context of insurance. A lack of familiarity around the risks of hydrogen could lead both airline and airport insurers to charge exorbitant premiums or refuse to insure assets that utilize hydrogen. Broader industry engagement, rather than just at the airport, is therefore crucial. Ongoing promotion by entities such as IATA will again play an important role in this process.

3.1.4 Modelling summary

As mentioned, depending on the proximity of the hydrogen source, it is likely to be more economical to import hydrogen for initial demonstration projects. However, as demand increases, so too does the scope for onsite electrolysis. Given the availability of fuel cell 'off-the-shelf' technologies that are widely used to service other markets (e.g. cars, forklifts), it is reasonable to expect that such GSE could be replaced around 2025. In the case of DFW airport, this would necessitate a 4MW electrolyzer to meet such demand along with demonstration of other special purpose GSE (e.g. belt loaders). This represents the 'base case' as part of this analysis.

The 'best case', which could involve the complete replacement of all GSE at DFW would require a ~28MW electrolyzer to meet demand after 2030. The 'best case' would also benefit from continuous improvements in electrolyzer capex.

Base and best-case levelized costs of hydrogen (LCOH) for onsite production including compression at 350bar are set out in Table 4. This cost also includes the additional infrastructure required to dispense hydrogen at elevated pressures for refueling.

Table 5 shows the consequent base and best case levelized cost of transport (LCOT in $/hr) for each of the material GSE (refer to Appendix A for methodology). Note that a 25% capex increase has been assumed for special purpose vehicles (e.g. baggage loaders), representing either the cost of retrofit or the manufacture of equipment not currently produced at scale (as compared with conventional GSE). The price of diesel and gasoline has also been assumed to increase in the years to 2030 based on International Energy Agency's World Energy Outlook.[43]

Table 4. Best and base case hydrogen production (DFW)

SCENARIO	ELECTROLYZER SIZE, MW	ELECTRICITY COST, C/KWH	LCOH INCLUDING COMPRESSION @350BAR AND DISPENSING, $/LB ($/KG)	ELECTROLYZER FOOTPRINT, FT^2 (M^2)
Base case (2025 – 2030) (cars/pickups/SUVs/vans + generators/GPUs + forklifts)	4	4	1.53 (3.38)	613 (57)
Best case (2030 +) (all material GSE)	28	4	1.37 (3.03)	3,659 (340)

Table 5. LCOT for material GSE at DFW

GSE TYPE	LCOT CALCULATED USING 2030–2040 DIESEL PRICE TRAJECTORY, $/HR	LCOT CALCULATED USING 2025 H2 PRICE, $/HR	LCOT CALCULATED USING 2030 H2 PRICE, $/HR
Baggage/cargo tractor	17.17	**9.68**	**9.42**
Cars/pickups/SUVs/vans	3.54	4.64	4.60
Belt loaders	26.89	**26.51**	**26.00**
Aircraft tractor/tugs	229.55	**196.01**	**190.41**
De-icing trucks	190.77	209.25	205.52
Generators/GPUs	32.80	**27.27**	**25.90**
Forklifts	8.92	**8.92**	**8.69**
Air Conditioners/Heaters	81.95	**62.14**	**58.74**

43 IEA (2019) *World Energy Outlook*. OECD

As shown, fuel cell-based systems are expected to be competitive for several GSE, particularly those with the highest ratio of fuel use to capital cost (e.g. loaders, pushback tugs). Other GSE such as de-icing trucks that have lower usage rates and a higher capital cost are likely to be less competitive and may therefore not be prioritized as part of an airport upgrade. Further, although the capital cost of apron cars/vans is higher than their diesel equivalents, a lower technology risk profile may still make them attractive for early roll-out.

3.2 Adjacent airport applications

Hydrogen for 'adjacent airport applications' refers to its use in the production of conventional fuels (via fractional distillation) or SAF.

Refining crude oil via fractional distillation[47]

While the composition of crude oil differs by location (primarily in terms of chemical and sulfur content), it fundamentally consists of hydrocarbon molecules with different chain lengths and consequently molecular weights. Fractional distillation is the process by which crude oil is separated into its constituent hydrocarbon groups based on their respective boiling points. The crude oil is heated in furnaces with vapors and liquids travelling through to a distillation unit. As the vapor and liquid in the unit rises, the temperature drops, causing condensation and allowing each of the products to be extracted.

Hydrogen is then used to treat some or all of the extracted products from the fractional distillation process. It can be catalytically reacted with hydrocarbons to remove sulfur, nitrogen and other contaminants to produce a cleaner fuel with fewer pollutants when combusted (i.e. hydrotreating). Hydrogen can also be used to split/upgrade heavier oils into more valuable products such as gasoline (i.e. hydrocracking).

As explored further in Section 4.2, hydrogen is used in a similar fashion for the treatment of SAF. This is particularly the case for biofuels, which can require between 3 and 75 times more hydrogen (depending on the process and feedstock) than conventional crude due to the additional impurities that need to be removed via hydrotreating.[44]

Today, hydrogen supplied to refineries is typically produced via steam methane reforming (SMR) which produces CO_2 as a by-product and can account for 25% of refinery GHG emissions.[45] Although this abatement would not count towards the emissions profile of the aviation sector, replacing SMR with hydrogen derived from electrolysis will enable airlines to utilize a less carbon-intensive fuel.

At the Rhineland refinery in Germany, planning has begun for the 'Refhyne project' which involves the construction of a 10MW electrolyzer which will be integrated into the existing process. Scheduled to begin operation in 2020, it is intended to supply 1,300t of clean hydrogen per year, less than 1% of the 180,000t of hydrogen used currently.[46]

44 IEA Bioenergy (2019) *'DROP-IN' BIOFUELS: The key role that co-processing will play in its production*. IEA Bioenergy

45 United States Environmental Protection Agency (2010) *Available and emerging technologies for reducing greenhouse gas emissions from the petroleum refining industry.* EPA

46 Refhyne (2018) *Launch of Refhyne, world's largest electrolysis plant in Rhineland refinery.* Available at https://refhyne.eu/news-item-heading/

47 U.S. Energy Information Administration (EIA) (2019) *Oil: crude and petroleum products explained*. Available at https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-the-refining-process.php

4 Existing infrastructure (Electrofuels)

A combination of reliable technology and high capital cost has meant that aircraft typically have a low rate of turnover (e.g. a commercial jet has an average asset life of between 25–35 years). Further, according to the International Panel on Climate Change, it can take at least 45 years from the point at which new aviation technology is developed before it replaces its incumbent in operation. This includes at least 5–10 years of technology testing and approvals.[48]

Therefore, in the absence of a global policy regime that expedites fleet turnover, the narrative surrounding pre-2050 options for meaningful decarbonization within the aviation sector center primarily around achievable measures ancillary to the aircraft itself. These measures, as they relate to hydrogen, involve the production of synthetic electrofuels.

4.1 Incumbent jet fuels

A base understanding of conventional jet fuels is required to comprehend the potential for electrofuels in this section as well as other hydrogen augmented fuels assessed in Section 5.

4.1.1 Jet fuel

Conventional jet fuel consists of several different crude oil-based compounds and is therefore defined by its performance specification as opposed to the molecules it is comprised of.[49] This performance specification is governed by the international standard ASTM[50] D1655 and can be broadly defined as:

Kerosene-type: Includes Jet A and Jet A-1 specifications which consist of hydrocarbon molecules with a size distribution of approximately 8 to 16 carbons. These are the most commonly used fuels for commercial flights.[51]

Naptha-type: Includes the Jet B and JP-4 specifications which consist of hydrocarbon molecules with a distribution of 5 to 15 carbons. Jet B is often used for improved performance in colder weather conditions.

However, the composition of jet fuel is more complex than the size distribution of its hydrocarbon molecules, with structure and other additives playing a key part in its operating properties. The specifications for jet fuel are set out in ASTM D1655 (and similar specifications such as DEF STAN 91-091), with a sample of key attributes identified in Table 6.

Table 6. Jet fuel operating properties

PROPERTY	DESCRIPTION	SPECIFICATION
Flash point	The lowest temperature at which can be ignited in the presence of air	38°C minimum
Freezing point	The lowest point after which the fuel changes from a liquid to solid	-47°C minimum
Heat of combustion	The energy released when a fuel is combusted	42.8MJ/kg minimum 19.4MJ/lb
Viscosity	Internal friction within a fluid	8mm^2/s maximum
Sulphur content	Quantity of sulfur within the fuel	0.0030wt% maximum
Density	Mass of fuel per unit of volume	775-840kg/m^3 48-52lb/ft^3

48 Dray L (2014) *Time constants in aviation infrastructure*. Transport Policy

49 Mortenson A, Wenzel H, Rasmussen K, Justesen S, Wormslev E, Porsgaard M (2019) *Nordic GTL a pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO_2*. University of Southern Denmark

50 ASTM International is an international standards organization that publishes voluntary consensus technical standards

51 Ibrahim A, Bohra M, Selam M, Choudhury H, El-Halwagi M, Elbashir N (2016) *Optimization of the Aromatic/Paraffinic Composition of Synthetic Jet Fuels*. Chemical Engineering & Technology

4.1.2 Biofuels

While biofuels are likely to play a key role in decarbonizing the aviation sector, to date there has been limited uptake. Under the ASTM D7566 standard (a subset of ASTM D1655), six biofuel production pathways have so far been approved that are suitable for blending with conventional jet fuel. Currently, the most widely commercialized method is known as hydro-processed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK).[52]

To date, this process has predominantly been used to produce HEFA Diesel for road transport due to the more favorable economics. Shifting to a higher fraction of kerosene requires larger quantities of hydrogen for treatment, reduces the overall yield and comes with less access to incentives.[53] Currently, the largest producer of HEFA-SPK is Neste, with operating refineries in Singapore, the Netherlands and Finland. Upgrades due to be completed in 2022 will bring Neste's HEFA production up to 1 million tonnes per annum.[54]

4.2 Synthetic electrofuels

Given that all crude refined products consist primarily of hydrocarbons, it follows that hydrogen and CO_2 can serve as the base feedstocks for any synthetically produced higher-order liquid fuel.

As discussed in this section, some of the more mature pathways to synthetic fuels rely on an intermediate building block known as 'synthesis gas' or 'syngas'. This involves a mixture of carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen, and is traditionally produced using feedstocks such as natural gas or biogas (i.e. steam methane reforming) and coal or biomass (i.e. gasification). The addition of more hydrogen gas to the mixture enables the 'reverse water gas shift' reaction[55], a process that allows for the production of an adjustable ratio of CO and H_2.

Where traditional fossil fuel feedstocks such as coal or natural gas are used, no meaningful emissions abatement is achieved. Use of such feedstocks are therefore outside the scope of this report. Further, despite their emissions abatement potential, pathways that involve a waste or biomass feedstock are not considered due to the focus of this analysis on the role of hydrogen in aviation.

A high-level illustration of the pathways to electrofuels is set out in Figure 7. Each of the discrete components are then discussed in the subsections below.

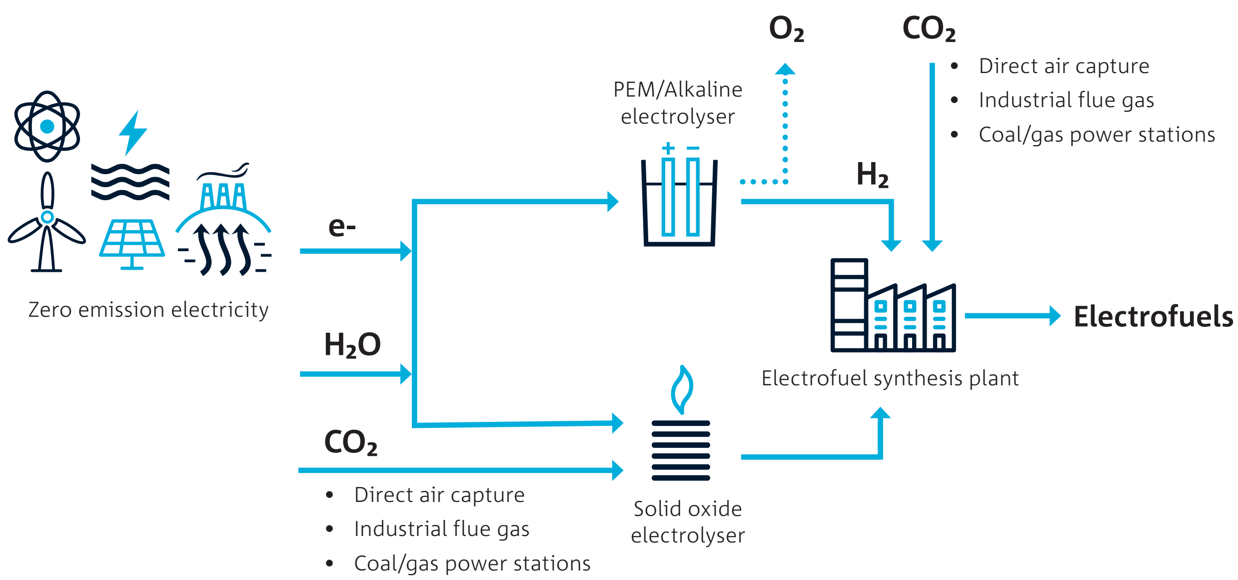


Figure 7. Production of electrofuels

52 Feuvre P (2019) *Commentary: Are aviation biofuels ready for take off?* IEA

53 Van Dyk S, Su J, McMillan J, Saddler J (2019) *'DROP-IN' BIOFUELS: The key role that co-processing will play in its production.* IEA Bioenergy

54 CAAFI (2019) *Neste Makes Final Investment Decision Expanding Renewable Product Production Capacity*. CAAFI

55 Steam methane reforming and gasification are processes that are typically employed to produce hydrogen, largely for industrial processes. To improve the yield of hydrogen, the water gas shift reaction is used, where more water is added to the system to increases the ratio of CO_2 and H_2. Conversely, by adding additional H2, the opposite or reverse gas shift reaction can be achieved which improves the ratio of CO and H_2O.

4.2.1 Available technologies

Hydrogen production

In the early stages of development, hydrogen production for electrofuel synthesis may rely on the more mature electrolysis technologies (i.e. PEM and Alkaline) discussed in Section 3.

However, of increasing importance in this context is the opportunity for high-temperature electrolysis that can utilize waste heat produced in the upstream synthetic fuel synthesis processes described further below. This can be achieved using solid-oxide electrolyzers (SOE), which despite their lower TRL, have the advantage of electrolyzing steam (at higher temperatures) rather than liquid water. This requires a lower energy input which enables a more efficient conversion of electricity to hydrogen. SOEs can also be leveraged for co-electrolysis of CO_2 to directly produce syngas (discussed further in the RD&D priorities set out in Section 4.2.4).

Storage

Electrofuel production plants rely heavily on the constant supply of significant quantities of hydrogen in order to maintain reaction temperatures, efficiencies and improve asset economics. To ensure continuous operation, a hydrogen storage buffer may be needed given the variability in electricity supply when relying primarily on renewable energy sources such as solar PV and wind. In addition to linepacking and the storage technologies considered in Section 3.1.2, depending on the location, underground geological hydrogen storage represents another important option. This is considered further in relation to the RD&D priorities in Section 4.2.4.

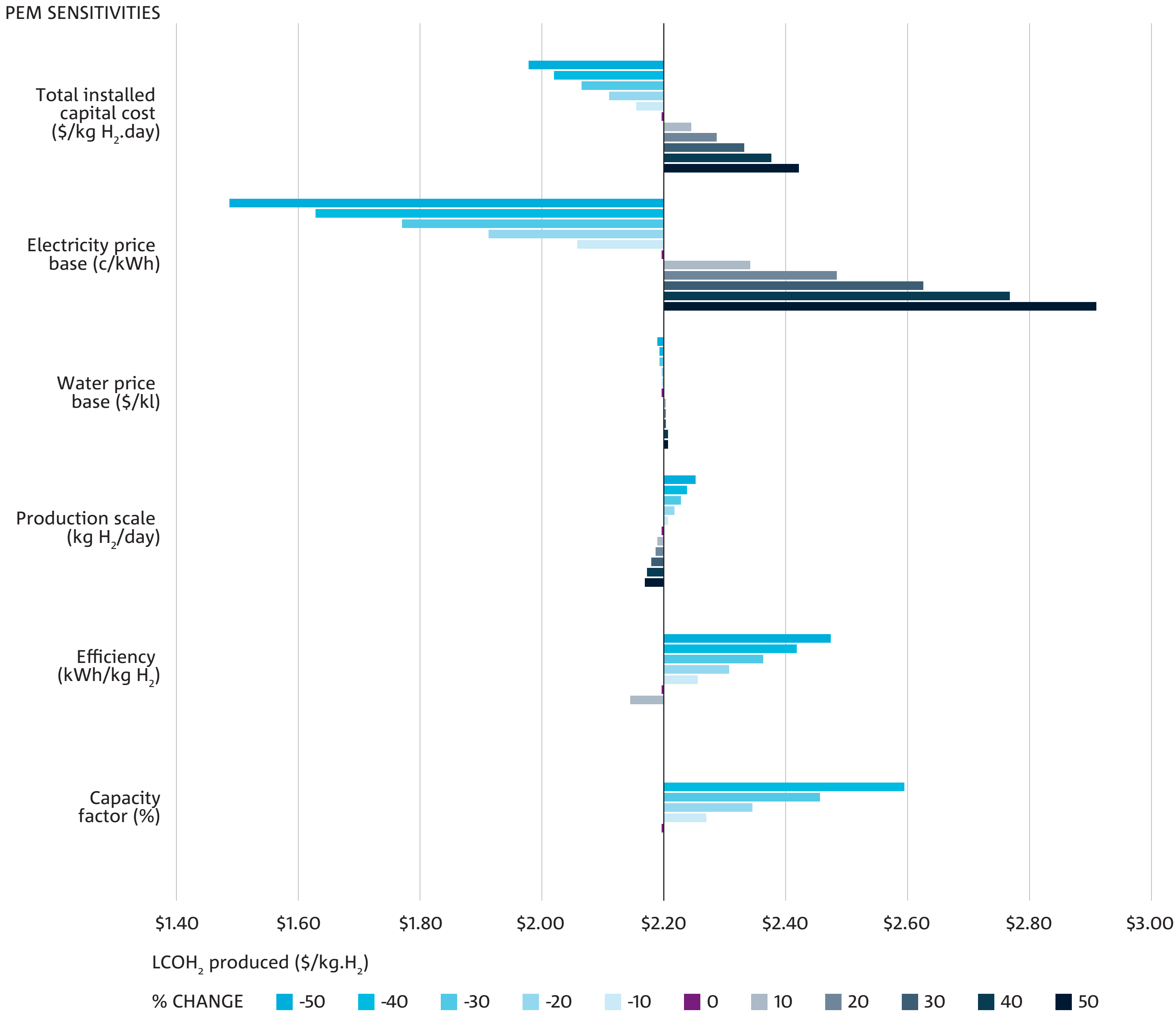
Hydrogen production costs

In first-of-kind commercial plants, asset proponents may be unwilling to take on excessive technology risk across each of the discrete components. Between 2025 and 2030 however, it is expected that 100MW PEM electrolyzer plants could be de-risked technically and commercially. With some degree of effort still required to commercialize SOE, base case production costs for hydrogen are set for a PEM electrolyzer system operating at a 90% capacity factor with a levelized cost of $1.00/lb ($2.20/kg). No additional compression costs have been included here.

Table 7. High-temperature electrolysis technology assessment

TECHNOLOGY	DESCRIPTION	TRL	COMMENTS
Solid-oxide electrolysis (SOE)	SOE uses thermal energy in combination with electrical energy to synthesize hydrogen, using a ceramic solid-oxide electrolyte membrane. By adding CO_2, co-electrolysis of CO_2 and H_2O enables the direct production of syngas.	6–7	Solid oxide electrolysis makes use of heat to significantly reduce the required electrical energy input for hydrogen production.

By varying the cost inputs by certain percentages (shown in the '% change' legend) and assessing the consequent impact on levelized cost (horizontal axis), Figure 8 depicts the material cost drivers for hydrogen production at this scale. As shown, while cost reductions from the base case can still be achieved with improvements in electricity price (assumed to be 3c/kWh) and capital cost, limited improvements are expected to be derived from further increases in plant size (i.e. production scale). This is primarily due to reduced re-utilization of balance of plant when capacities are above 100MW.[56] Depending on the location of the plant and energy source, it is also critical to maintain a high capacity factor. This could be achieved by prioritizing more low emissions dispatchable technologies (e.g. CSP) and potentially a supplemental grid connection.



Summary

- Material cost drivers include capacity factor and electricity
- Minimal gains from increases in production scale beyond 100MW
- Improvements in capital cost still important

Figure 8. Identification of material cost drivers for hydrogen production using PEM

56 Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) *National Hydrogen Roadmap*. CSIRO

CO_2 Capture

The capture of CO_2 is commonly practiced in industry today. Technologies vary depending on the source and purity of the CO_2 but generally begin with the adsorption/absorption or filtering of (purified) CO_2 using specified materials. The CO_2 is then stripped from the material by applying heat or electricity, and the material is then re-used.

As a general rule, the more dilute the stream of CO_2, the higher the cost of capture.[57] The following subsection considers CO_2 capture from concentrated streams as well as direct air capture (DAC) from the atmosphere.

Concentrated CO_2 streams

Coal, gas or biomass power stations (4-80% CO_2) and industrial processes such as cement manufacturing (14-33% CO_2) or oil refining (8% CO_2) produce relatively concentrated streams of CO_2.[58] Notably, fermentation in ethanol production produces a nearly pure (i.e. 99.9%) CO_2 stream.[59]

The primary methods of CO_2 capture and their applicability to these different sources is represented in Table 8.

Table 8. Concentrated CO_2 capture technologies[60,61]

CO_2 CAPTURE TECHNOLOGY	DESCRIPTION	PREFERRED USER	TRL[62]	COMMENTS
Absorption	A gas stream is contacted with a liquid absorbent (solvent), absorbing CO_2 either physically or chemically depending on the solution. Heat is then applied to release CO_2 and the absorbent is recycled in the system.	Process streams, post and pre-combustion capture. Well-suited for post-combustion.	9	Chemical: Amines. Physical: organic molecules.
Adsorption	Involves the intermolecular forces between the CO_2 and the surface of the adsorbent, resulting in CO_2 adhering to the surface. Heat or electricity is then applied to release CO_2.	Can reduce energy and cost of CO_2 capture in post-combustion. Low adsorption capacities in flue gas conditions.	7	Physical: Zeolites, Metal organic frameworks, activated carbon. Chemical: Metal oxides, hydrotalcites, metal salts.
Membrane	Selective membranes enable separation of substances through various mechanisms such as diffusion, molecular sieve and ionic transport.	Process streams – flue gas (post-combustion), natural gas processing, hydrogen (pre-combustion), or oxygen from nitrogen (oxyfuel combustion).	5	Requires high energy for post-combustion CO_2 capture. Efficient for high CO_2 concentration gas streams.

57 Feron P (2019) *Growing interest in CO2-capture from air*. Greenhouse Gasses: Science and Technology

58 Mondal M, Balsora H, Varshney P (2012) *Progress and trends in CO_2capture/separation technologies: A review*. Energy

59 State CO2-EOR Deployment Work Group (2017) C*apturing and Utilizing CO2 from Ethanol: Adding Economic Value and Jobs to Rural Economies and Communities While Reducing Emissions*. Great Plains Institute

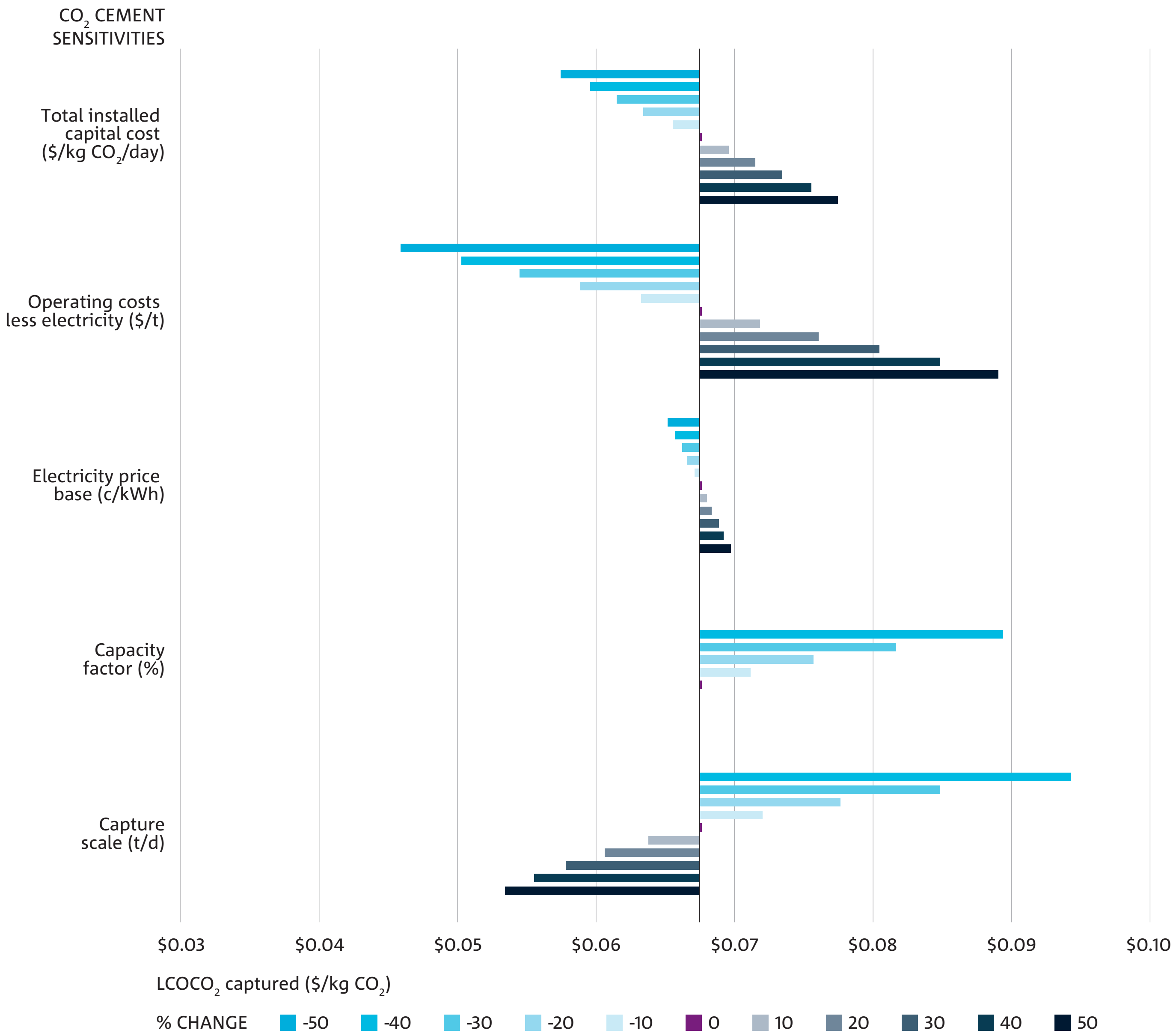
60 Songolzadeh M, Soleimani M, Ravanchi M, Songolzadeh R (2014) *Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions*. The Scientific World Journal

61 IPCC (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press

62 Bui M et al. (2018) *Carbon capture and storage* (CCS): the way forward. Energy & Environmental Science

The cost of CO_2 capture has been modelled based on the use of a monoethanolamine absorber at a cement production plant. Here the base case production capacity is sized so that it is commensurate with hydrogen output from a 100MW PEM electrolyzer. The levelized cost of CO_2 production is $0.03/lb ($0.07/kg).

The material cost drivers are shown in Figure 9 and illustrate that in contrast to hydrogen production, benefits can still be realized via increases in the capture scale of the plant. Ongoing improvements in capital and operating costs through use of cheaper materials with greater absorption and recycling properties will also be critical to achieving further reductions in cost.



Summary

- Further increases in capture scale can improve cost of CO_2.
- Reductions in capital and operating costs also significant.

Figure 9. Material cost drivers for CO_2 capture at a cement plant

Direct Air Capture (CO_2 capture at low concentrations)

DAC is gaining increasing interest as an important and feasible technology solution to achieving meaningful reductions in the concentration of CO_2 in the atmosphere. However, CO_2 exists in the air at low concentrations of 400 parts per million (ppm) or 0.04% and therefore, the energy requirements needed to facilitate this process can be in the order of three times greater than post-combustion CO_2 capture from fossil fuel power generation.[63] Lower gas concentrations will also lead to a requirement for larger adsorber/absorber columns which increases capital and operating costs. The main DAC technologies and some of the companies responsible for their development are set out in Table 9.

Table 9. DAC technologies and associated companies[64]

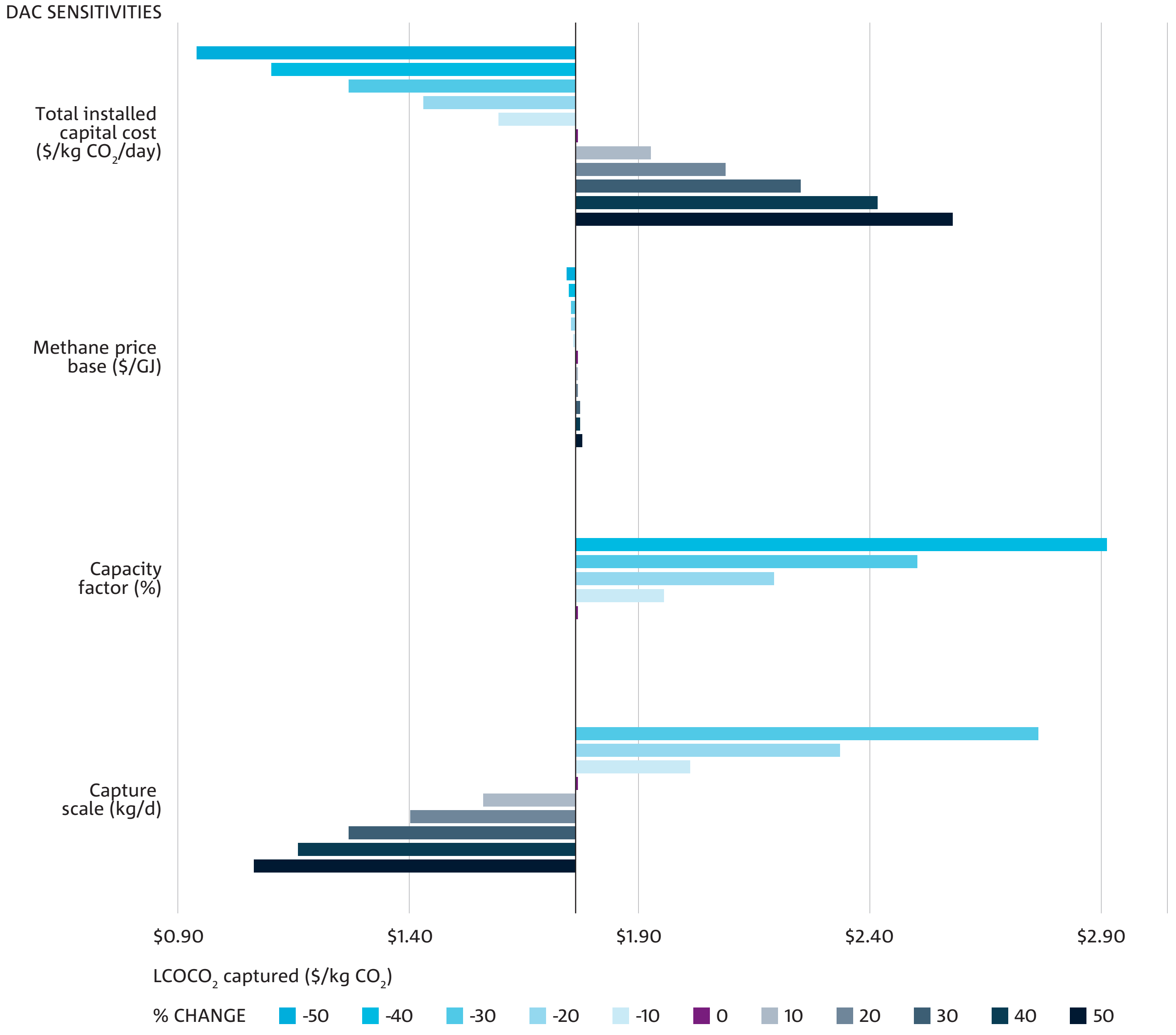
TECHNOLOGY	DESCRIPTION	TRL	COMMENTS
Solution-based absorption and electrodialysis (no heat)	Air is drawn in and CO_2 is absorbed using a sodium hydroxide (NaOH) solution. The resulting sodium carbonate (Na_2CO_3) solution is then acidified using sulfuric acid (H_2SO_4), releasing almost pure CO_2. The NaOH and sulfuric acid are then regenerated through electrodialysis to be used again.	5	Only requires electricity, no thermal energy needed.
Solution-based absorption and calcination (high temp)	CO_2 is absorbed using either a NaOH or potassium hydroxide (KOH) aqueous solution. In the case of KOH, the CO_2 is absorbed to form potassium carbonate (K_2CO_3). In a pellet reactor, the K_2CO_3 is precipitated into calcium carbonate ($CaCO_3$). The $CaCO_3$ is then calcinated at 850°C decomposing into CO_2 and CaO to be collected.	9	*Active: Carbon engineering* Combustion of natural gas is needed to produce the required temperatures for calcination. However, the CO_2 generated is then captured as part of the overall process. Natural gas could be displaced by burning pure hydrogen, using CSP or electrification via renewable electricity
Solid-based adsorption and desorption (low temp)	Two variations of this technology are commercially available. The first (Climeworks) fans ambient air over amine compounds bounded to dry porous granulates as a filter material. Once the material is fully enriched with CO_2, it is regenerated (i.e. the CO_2 is removed) by applying a combination of pressure and temperature swing (~100°C). Global Thermostat has a different structure of amines and regenerates these materials using low-temperature steam.	9	*Active: Climeworks, Global Thermostat* The low thermal requirement can be met by waste heat

63 Feron P (2019) *Growing interest in CO2-capture from air*. Greenhouse Gasses: Science and Technology

64 Viebahn P, Scholz A, Zelt O (2019) *The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis*. Energies

As part of this analysis, modelling has been undertaken using solution-based absorption and calcination (high temperature) as a proxy. Base case capacities for a plant are again limited by a 100MW PEM electrolyzer with the resulting levelized cost of CO_2 production set at $0.80/lb ($1.76/kg).

Material cost drivers for DAC are set out in Figure 10 with notable benefits in levelized cost achieved by increasing capture scale and via use of less capital-intensive equipment. While natural gas is utilized to generate heat requirements for solution-based calcination, it does not represent a key cost driver. Note however that this may change should natural gas be replaced with alternative heat sources (e.g. electrification).



Summary

- Material improvements achievable via increases in capture scale and reductions in capital cost
- Maintaining a high capacity factor also critical
- Natural gas not material cost for heat but likely to change with source

Figure 10. Material cost drivers for DAC

Pathways to electrofuels

Two mature pathways exist to produce electrofuels, Fischer-Tropsch (FT) and Methanol (MeOH). Their respective processes, TRLs, advantages and disadvantages are presented in Table 10.

FT based jet fuels, otherwise referred to as FT Synthetic Paraffin Kerosene (FT-SPK), have been certified as a 'drop-in fuel' in concentrations of up to 50 vol% under standard ASTM D7566 (refer to discussion on biofuels in Section 4.1.2). In practice, this means that once the synthetically derived fuel via FT meets the specifications under ASTM D7566, it may be blended with conventional jet fuel in concentrations up to 50%.

Post blending, so long as the fuel meets the standard in ASTM D1655, it subsequently becomes a certified fuel and requires no additional certifications downstream. Importantly, there is no restriction on feedstock, which allows electrofuels to be subject to the same certification process as long as the fuel is derived from syngas using the prescribed FT pathway.[65] This is distinct from 'splash blending' which involves mixing of FT SPK and conventional jet fuel during aircraft refueling. This is not permitted under the ASTM at any concentrations.

Table 10. Established pathways to electrofuels

PROCESS	DESCRIPTION	TRL	(DIS) ADVANTAGES
Fischer-Tropsch (FT)	Syngas is reacted under a polymerization (exothermic) reaction in the presence of a metal catalyst where carbons derived from the CO are used to produce longer carbon chains. Preferred CO to H_2 ratio is 2:1. Metal catalysts include iron, cobalt, ruthenium and nickel[66]	9	+ ASTM approved pathway up to specified concentrations − Multiple products, less targeted (depending on catalyst) − Tendency to produce lighter hydrocarbons − Catalyst affected by temperature in exothermic reaction − Produces mainly linear hydrocarbons
Methanol (MeOH)	Involves the hydrogenation of CO or CO_2 using a catalyst such as Cu-ZnO – Al_2O_3 to produce methanol (MeOH).[67] The methanol is then reacted further using a zeolite catalyst to produce longer hydrocarbon chains	9	+ Can use CO_2 or CO and therefore does not require RWGS reaction + MeOH produces shorter chain hydrocarbons enabling more targeted fuel production − Currently not certified to any concentrations under the ASTM

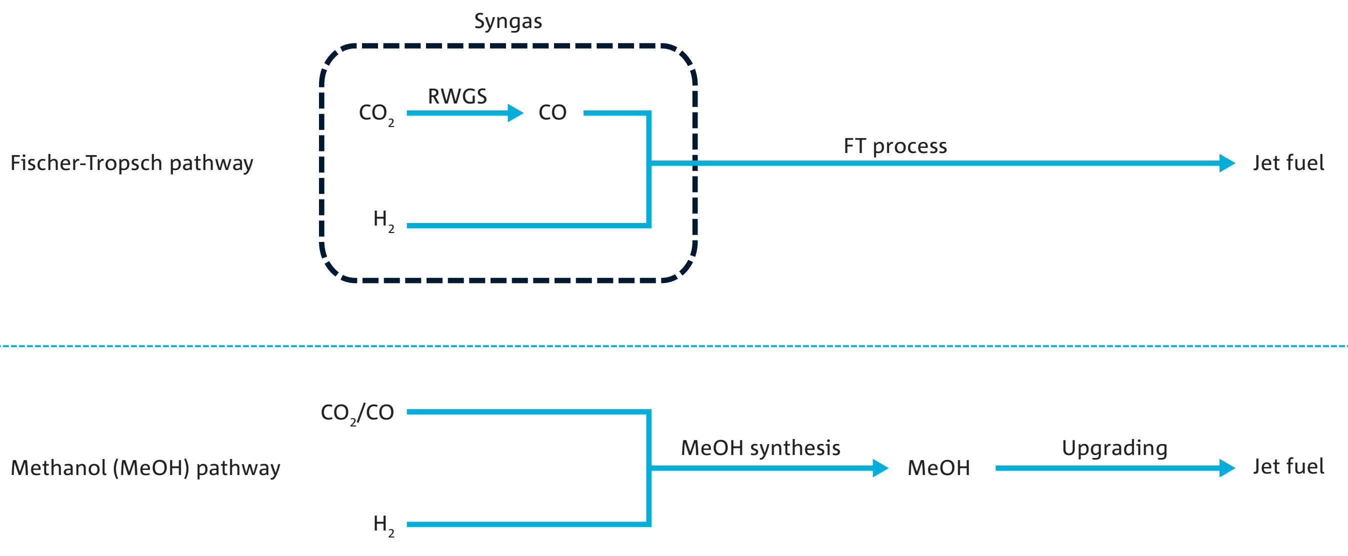


Figure 11. Electrofuel synthesis pathways

65 Schmidt P,Batteiger V, Roth A, Weindorf W, Raksha T (2018) *Power-to-Liquids as Renewable Fuel Option for Aviation: A Review.* Chemie Ingenieur Technik

66 Speight J (2014) *Gasification of Unconventional Feedstocks*. Gulf Professional Publishing

67 Brahmmi R, Kappenstein C, Cernak J, Duprez D (1998) *Copper-zinc catalysts. Use of new bimetallic precursors and comparison with co-precipitation method.* Studies in Surface Science and Catalysis

In Germany, use of the methanol intermediate pathway is receiving greater levels of interest. While more challenging when only pure CO_2 is available, both CO_2 and CO can be used to produce methanol which obviates the need for the RWGS reaction.[68] Methanol also produces shorter chain hydrocarbons and therefore enables a more targeted fuel production process that requires significantly less feedstock when compared to an equivalent volume of fuel produced via FT.

To date there has been little movement regarding industry approval of the MeOH process. It is also important to note the distinction between this process and the currently approved 'alcohol to jet' (ATJ) for biofuels. In ATJ, instead of being converted to syngas as a precursor, ethanol is dehydrated to ethylene and used to produce longer hydrocarbon chains via a series of catalytic reactions.[69]

As shown in Table 10, both pathways to electrofuels are technically mature. However, only discrete elements, as opposed to fully integrated supply chains (i.e. going from hydrogen and CO_2 to ASTM approved aviation fuels) have been demonstrated.[66] This includes the Vulcanol project operated by Carbon Recycling International in Iceland which combines hydrogen derived from electrolysis with CO_2 from a volcano to produce methanol. The plant has been operating since 2012 and produces 4,000t of methanol per year.[70] Producing jet fuel from coal has also been practiced by Sasol in South Africa since 1999 when it produced its first certified 50% synthetic blend of jet fuel via FT. This was followed by the production of 173,000L of synthetic jet fuel in 2009.[71]

Globally there are an increasing number of 'power to other products' (or 'power to X') projects emerging, with over 190 demonstrations in operation or being constructed as at 2019.[72]

Advantages of electrofuels

In addition to their emissions abatement potential, there are a number of ancillary benefits that stem from increased use of electrofuels within aviation. In general, although there is minimal change in NOx levels,[73,74] synthetic fuels produce less particulate matter and no sulphates (SOx) due to the absence of sulfur in the fuel. This is particularly important in reducing local pollution and improving air quality around airports.[75]

Further, SAF more generally, typically contain less trace elements which allows for a cleaner burning, more efficient fuel. While more research is required to determine the benefits associated with electrofuels specifically, studies have reported up to 2% efficiency improvements with FT derived fuels (using a biomass feedstock) depending on the blending concentrations used.[76] This allows for a reduction in total mass of fuel carried and used by aircraft.

Base case costs

The base case costs for production of electrofuels are represented in Table 11 and are reflective of the requirements needed to achieve a quality of fuel certifiable under ASTM D7566. The FT process is modelled as using an iron catalyst which, in terms of total hydrocarbon product, produces 62% jet fuel (by mass), 22% gasoline and a series of other lighter hydrocarbons which are recycled back into the process. Given the current challenges regarding the scalability of DAC as compared with high concentration CO_2 capture, CO_2 costs are based on cement production and overall production capacities are limited by the use of a 100MW PEM electrolyzer.

As shown in Table 11, while the price of electrofuels is significantly higher than conventional fuel (~$110 per barrel (bbl) in 2030), methanol is a more attractive synthesis process. This is primarily due to the need for less feedstock to produce jet fuel via the methanol intermediate as compared with syngas. Thus the methanol pathway has a higher fuel output when limited by a 100MW electrolyzer.

Table 11. Base case costs for jet fuel production via FT and MeOH pathways

PATHWAY	FT -SPK	MEOH-SPK
Cost, $/bbl	792	743

68 Schmidt P,Batteiger V, Roth A, Weindorf W, Raksha T (2016) *Power-to-liquids, potentials and perspectives for the future supply of renewable aviation fuel*. Chemie Ingenieur Technik

69 IEA Bioenergy (2019) *'DROP-IN' BIOFUELS: The key role that co-processing will play in its production*. IEA Bioenergy

70 Hobson C, Marquez C (2018) *Renewable Methanol Report*. Methanol Institute

71 Morgan P (2011) *An overview of Sasol's jet fuel journey.* Sasol

72 Chehade Z, Mansilla C, Lucchese P, Hilliard S, Proost J (2019) *Review and analysis of demonstration projects on power—to-X pathways in the world*. International Journal of Hydrogen Energy

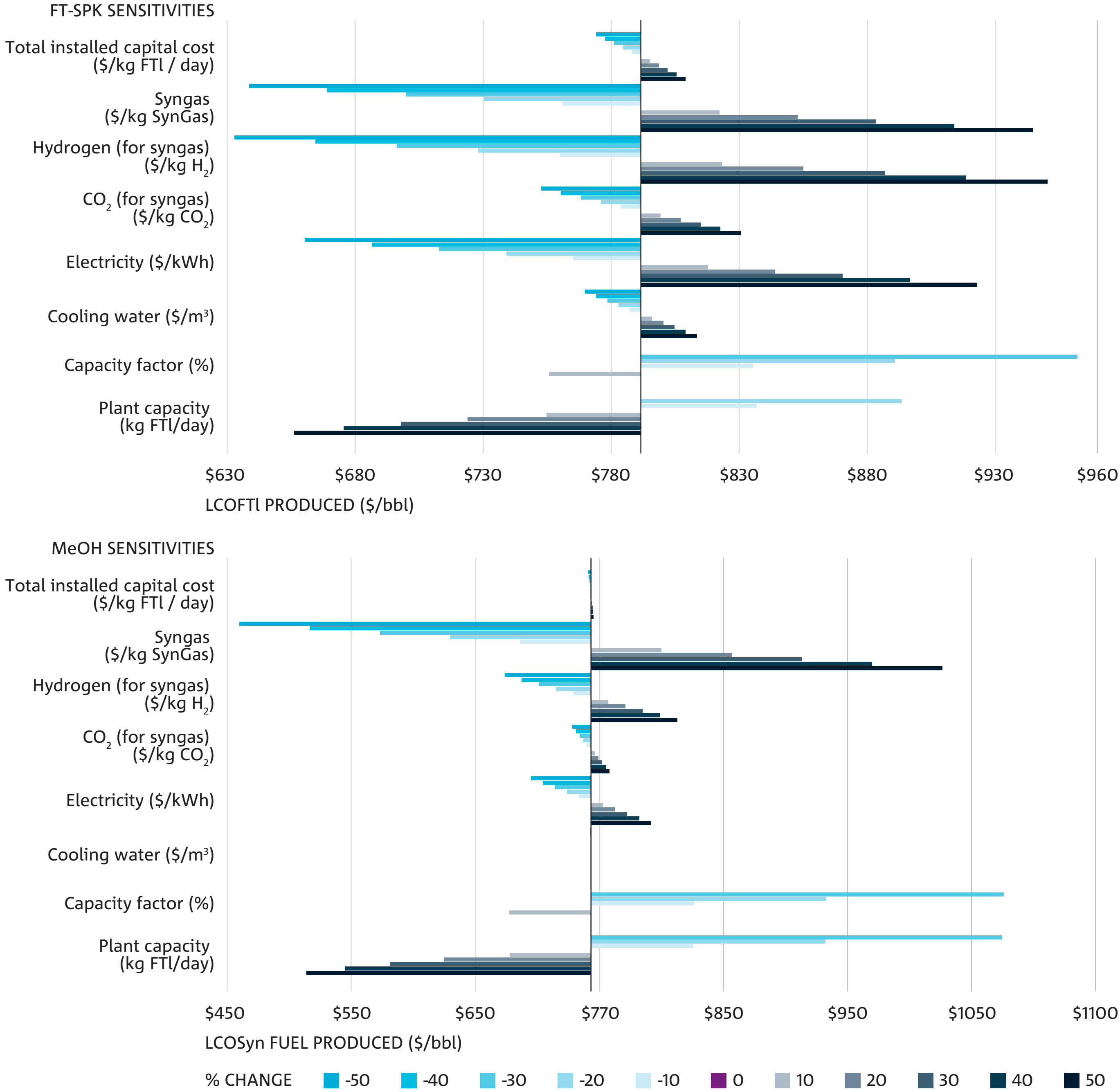
73 Bhagwan R, Habisreuther P, Zarzalis N, Turrini F (2014) *An Experimental Comparison of the Emissions Characteristics of Standard Jet A-1 and Synthetic Fuels*. Flow Turbulence Combust

74 Starik A, Savel'ev A, Favorskii O, Titova N (2018) *Analysis of emission characteristics of gas turbine engines with some alternative fuels*. International Journal of Green Energy

75 Argonne National Labs (2012) *Life Cycle Analysis of Alternative Aviation Fuels in GREET*. US DOE

76 Wolters F, Becker RG, Schaefer M (2012) *Impact of alternative fuels on engine performance and CO2 emissions*. DLR

As observed in Figure 12, for both synthesis pathways, production of the intermediate (i.e. MeOH or syngas) is more significant in terms of cost than the upstream refining required to produce jet fuel. Note however that feedstock costs are more critical for FT than MeOH, again given the difference in quantities required (i.e. jet fuel production via MeOH requires less CO_2, hydrogen and consequently electricity, and so is less sensitive to changes in feedstock price). The cost associated with both synthesis methods will also benefit significantly from increases in plant capacity while maintaining a high capacity factor.



Summary

- Production of 'intermediate' more material than upstream refining to produce jet fuel.
- Feedstock costs more material for FT due to volumes required.
- Increases in plant capacity while maintaining a high capacity factor is critical.

Figure 12. Material cost drivers for electrofuel production via FT and MeOH

4.2.2 Commercial investment priorities

Fuel represents a significant expense for airlines, comprising approximately 30% of total operating costs.[77] Therefore, any increase in the cost of fuel has a significant impact on their operations. The global industry is also broadly characterized as a 'differentiated oligopoly', where although slightly different products are offered (e.g. destinations, benefits, seating, baggage), market share is concentrated within relatively few players who offer the same service and have significant influence over the industry. These industry players also operate with small margins and in healthy competition with one another.[77]

With this market structure in place, sector-wide cost increases that can arise due to changes in fuel price are expected to be passed on to the consumer. However, recent studies have suggested that the differentiated nature of these oligopolies means that only up to 50% of the cost increase is likely to be passed through.[77]

While this next section of the report does not consider the impact of increased pricing on passenger demand, it examines methods to reduce cost pass-through as well as potential industry trends that may serve to levelize the cost of conventional and electrofuels.

Scale

With commercial demonstration of electrofuels in its infancy, there is a long lead time required before production plants reach output levels that result in meaningful blending concentrations. For instance, in May 2019, a European Consortium announced a new study to assess the production of synthetic jet fuel at The Hague Rotterdam Airport. If the demonstration plant is realized, it will be capable of producing 1,000L of electrofuel per day.[78]

For refineries, the overall impact on the price of jet fuel sold is unlikely to be significant at lower blending concentrations, resulting in a limited cost increase for airlines. While this will change as the blending concentration of electrofuels increases, improvements in plant capacity are expected to generate significant reductions in production costs.

As an example, Figure 13 illustrates the impact of scale on the cost of fuel produced via FT (using PEM) as blending concentrations increase for a refinery that produces 10,000 barrels per day (bpd) of kerosene. This is slightly below the industry average of 12,000bpd[79] and is enough kerosene to travel 300,000km on a Boeing 737, or power nearly 27 return flights from NYC to London.

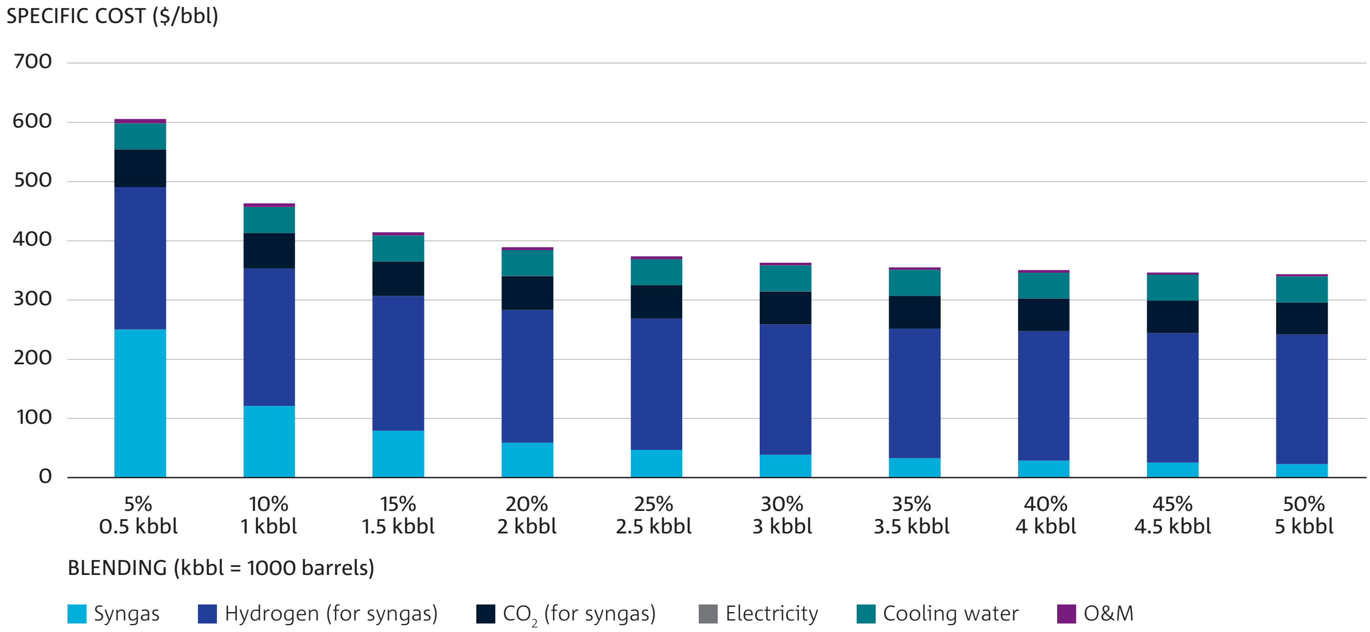


Figure 13. Cost improvements achieved via increases in scale of FT electrofuels plant (base case)

77 Koopmans C, Lieshout R (2014) *Airline cost changes: To what extent are they passed through to the passenger.* Journal of Air Transport Management

78 Sunfire (2019) *The Hague Airport initiates study for the production of renewable jet fuel from air.* Sunfire

79 Calculation based on data from US Energy Information Administration's 2019 Refinery Capacity Report. Available at https://www.eia.gov/petroleum/refinerycapacity/

In this example, the most meaningful reductions in cost stem from increases in the scale of CO_2 capture and syngas production using the RWGS reaction. The following results also reflect the improvements (from the base case) in electricity and electrolyzer capital costs discussed below.

For both the FT and MeOH pathways, the most significant reductions in levelized cost of electrofuels follow production scale increases from 500 to ˜3000bpd. Given that more incremental gains are achieved thereafter, depending on the specific project, the technical and commercial risk associated with construction of larger plants might outweigh the benefit of any additional reductions in capital cost.

Impact on electricity, water and the broader hydrogen industry

The significant quantities of electricity and hydrogen required to support the uptake of synthetic fuels (shown in Figure 14) suggest that use of electrofuels in aviation should be considered in the context of the broader transition to a low carbon economy. It is critical that electricity infrastructure is not diverted from other commercial and residential users given the consequent impact it will have on existing electricity infrastructure, demand and price. Rather, these volumes require the use of dedicated renewables to exclusively support this industry. This is the focus of the Westküste 100 project announced in Germany in July 2019 which is prioritizing production of electrofuels via the methanol pathway.

The quantity of renewable energy required to support a growing electrofuels industry represents a 'game-changer' for the electricity sector. So long as there is sufficient infrastructure to support this scale up (e.g. raw materials and skilled workforce), it is reasonable to expect electricity costs to be in the order of 1–2 c/kWh on average. This will require significant engagement with the broader energy sector.

A similar theme is likely to emerge with respect to the manufacture of electrolyzers. Meeting the required volumes of hydrogen production would signify a tipping point for the industry, resulting in the industrialized and likely automated manufacture of electrolyzers globally. A conservative industry estimate could see electrolyzer capital costs reduced to approximately $600/kW.

Case Study: Westküste 100[80]

The German Government together with 9 other project partners have announced plans to construct 700MW of alkaline electrolyzers to feed a jet fuel production plant using the methanol pathway. The plant is to be located in Northwest Germany at the Heide Oil Refinery. Based on modelling developed as part of this analysis, this could equate to around 3,400bpd of kerosene.

The project will begin with a 30MW pilot by 2025 which will serve the refinery and other nearby chemical companies as scale-up continues. The electrolyzers will utilize excess wind power from wind farms that are forced into curtailment (40% of Germany's wind power was curtailed in 2018). Due to grid and transmission constraints, the consortium is also keeping open the option to construct dedicated offshore wind nearby as the plant is scaled up.

To maximize revenue streams, the project aims to utilize all outputs. The oxygen will be sold as oxyfuel to the nearby cement factory where the CO_2 will be sourced and waste heat from operations will be used by local district heating systems.

80 Collins L (2019) *Offshore wind to power giant green-hydrogen carbon-neutral aviation-fuel plant*. Recharge

Figure 14 depicts the scale of PEM electrolyzers (left-hand axis) and feedstock volumes (right-hand axis) required to support the production of electrofuels at the same blending concentrations shown above. For reference, the 3,000MW associated with a 50% blend (using FT at a 10,000bpd refinery) is roughly 27% of New York City's peak electricity demand of 11,000MW.[81]

While water use is significant, variable sources including desalinated seawater may be used with minimal impact on the overall cost of fuel (as discussed in Section 3.1.2). Further, with respect to both fuel synthesis pathways, approximately 50% of total output (by mass) is water which can be reused in the overall process. For reference, an average coal plant requires approximately 586gal/MWh (2,220L/MWh) with nearly 90% used for cooling.[82] Typical freshwater consumption for a 1,000MW plant in Australia's Latrobe Valley ranges from 35-46t/day.[83]

Conventional Jet fuel pricing

In recent years preceding 2019, the airline industry has benefitted from relatively low-cost jet fuel, hovering around $85/bbl.[84] While this analysis does not purport to predict the future price of jet fuel, there are a number of trends related to the oil & gas sector that may strengthen the business case for the uptake of electrofuels. Some of these trends are considered below.

Changing liquid fuel mix

As demonstrated in Section 3.2, the fractional distillation of crude oil produces a series of products sold in a wide range of markets. Given the integrated nature of this process, the price and volume of products sold can significantly impact the cost of others. It is therefore critical for oil refineries to have a high 'crack spread' (i.e. the price of the products sold vs the price of crude oil) in order to amortize the capital cost of the refining infrastructure and create a robust operating margin.

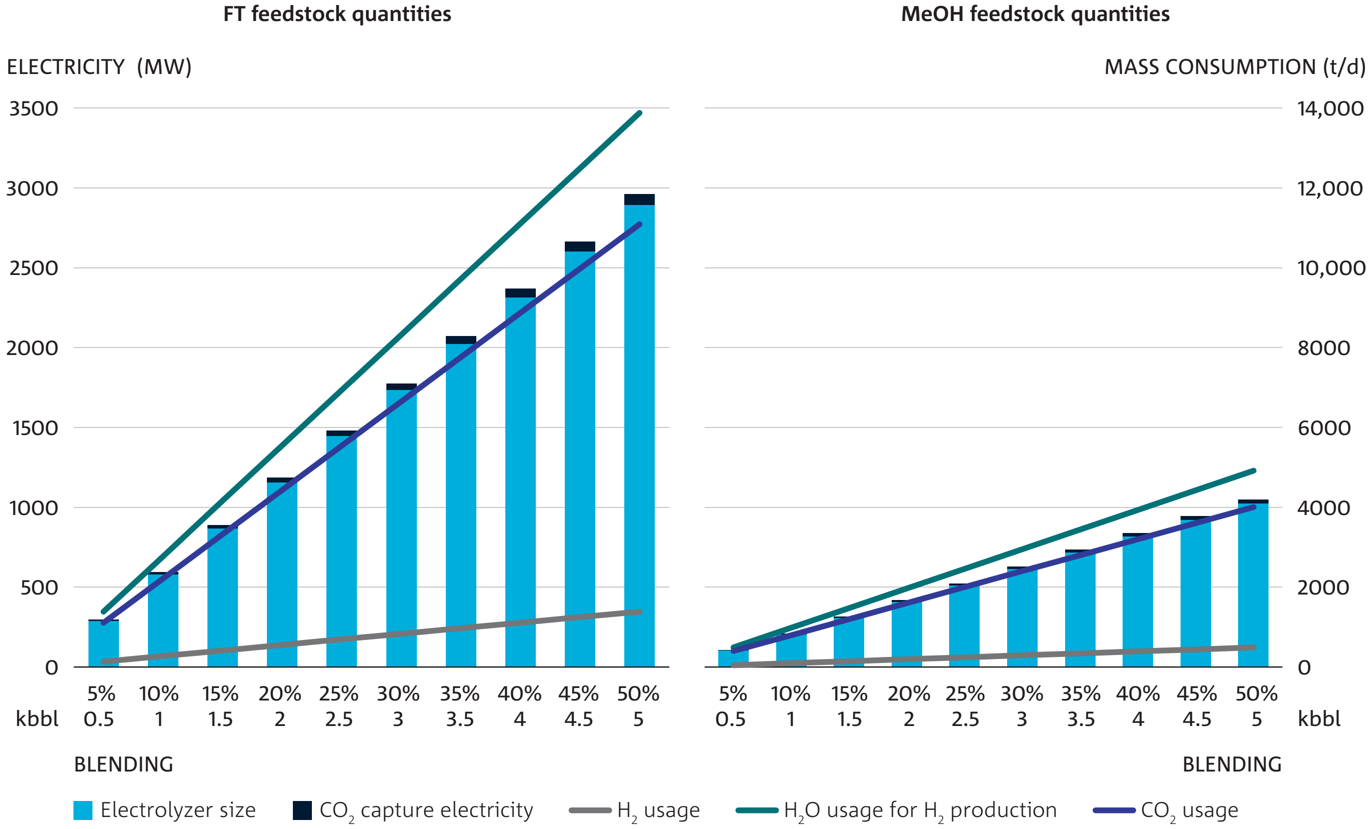


Figure 14. Quantity of electricity needed to support blending concentrations via FT and MeOH

81 Energy Committee of the New York building congress (2016) *Electricity Outlook: Powering New York City's Future*. New York Building Congress

82 Jin Y, Behrens P, Tukker A, Scherer L (2019) *Water use of electricity technologies: A global meta-analysis.* Renewable and Sustainable Energy Reviews

83 Smart A, Aspinall A (2009) *Water and the electricity generation industry: Implications of use.* National Water Commission, Australian Government

84 US Energy Information Administration (2019) *Petroleum & other liquids*. Available at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPJK_PF4_RGC_DPG&f=M

Approximately 70% of a typical refinery output will comprise of diesel (27%) and gasoline (43%), with only 9% comprising of jet fuel.[85] This must be considered in the context of longer-term trends, particularly within the road transport market, wherein an increasing uptake of (hydrogen and battery) electric vehicles over the coming decades could lead to a significant decline in demand for diesel and gasoline. Bunker fuel, which has been one of the dirtier and heavier distillate fuels that has not required significant treatment, is also becoming subject to more stringent pollutant restrictions by regulatory bodies such as the International Maritime Organization (described further in Section in 4.2.3).

These changes could manifest in an increase in the price of jet fuel by reducing overall refinery saleable product volumes and promoting a premium for crude oil with a higher fraction of kerosene that is difficult to source (requiring more expensive drilling practices). It may also force refineries to upgrade existing infrastructure to allow for increased hydrotreating processes and re-processing of lighter hydrocarbons to increase jet fuel yield. This would then lend favorably to the competitiveness of electrofuel plants with the capacity to create more targeted products.

Managing volatility

The market for crude derived fuels is inherently complex, suffering from a variety of physical, economic and political sensitivities that contribute to price volatility. Specific factors include demand spikes, seasonality and supply chain interruptions such as natural disasters, explosions and regional conflict.[86] To manage the price volatility risk associated with jet fuel, it is common for airlines to engage in price hedging through financial instruments such as futures contracts, options and swaps.[87] Hedging strategies vary greatly, with many US airlines no longer employing such practices, and European airlines such as Norwegian, Ryanair and Lufthansa hedging between 85-100% of jet fuel used.[88]

In contrast, electrofuels are likely to suffer from considerably less price volatility given the reliance on hydrogen and CO_2 as primary feedstocks. This obviates the need for costly hedging practices and presents an opportunity to localize supply and improve economic security.

Another means by which airlines can capitalize on a localized targeted feedstock is by vertically integrating their supply through the purchase of an interest in or by entering into a joint venture with an oil refinery and electrofuels manufacturer. This would give the manufacturer a more secure revenue stream, reduce demand risk and increase scope for gradual improvements in plant scale.

Given the need for blending, particularly in the development phase of this industry, it may be that the purchasing airline does not receive the exact electrofuel molecules contracted for. However, simply purchasing electrofuels as part of their overall fuel supply would be counted towards their emissions abatement efforts. This is similar to the mechanism of a Power Purchase Agreement (PPA), wherein a large electricity consumer may have a direct agreement with a wind farm operator but does not receive the green electrons given the existence of the electricity grid as an intermediate.

There is precedent for the vertical integration of fuel supply by airlines, evident in the purchase of the Phillips 66 oil refinery in Delaware (US) by Delta Airlines in 2012. While Delta has benefitted from securitization of supply through the acquisition, one of the primary challenges has stemmed from the need to engage in markets for other crude based products which is outside their core business expertise. Purchasing a targeted electrofuel plant could help minimize this challenge for similar acquisitions in the future.

Case study: Delta Airlines Phillips 66 refinery

In 2012, Delta Airlines purchased an oil refinery in Pennsylvania in order to reduce its exposure to fluctuations in jet fuel prices. To meet this strategic goal, Delta began operations by concentrating on maximizing kerosene output, despite suboptimal margins. When oil and refined fuel prices fell in 2016, the refinery was forced to shift outputs to favor gasoline and diesel fuel which were offering better margins and access to government incentives. Although this helped reduce losses, past prioritization of kerosene refining and the rising costs of transporting crude oil to the east coast caused Delta to suffer a USD125m loss that year.[89] As a result of the mismanagement of refinery outputs, Delta Airlines is attempting to sell a partial stake in the refinery to bring on board more expertise.

85 US Energy Information Administration (2013) *Oil: crude and petroleum products explained.* Canadian Fuels Association

86 Airlines for America (2018) *Jet fuel: From well to wing.* Available at https://www.airlines.org/wp-content/uploads/2018/01/jet-fuel-1.pdf

87 Hu R, Xiao Y, Jiang C (2018) *Jet fuel hedging, operational fuel efficiency improvement and carbon tax.* Transportation Research

88 Dunbar N (2018) *Airlines divided on hedge benefits as oil volatility surges*. EuroFinance

89 Reed D (2018) *Delta Belatedly Is Facing Up To Its One Big Mistake: Investing In An Oil Refinery*. Forbes

New business models

Voluntary purchasing schemes for passengers can help airlines amortize investments in electrofuels. To date however, the voluntary carbon offset programs offered by airlines have had minimal success, with general uptake reported to be below an average of 2%.[90] While this trend has started to improve, the lack of interest thus far has prompted the industry to further explore commercial mechanisms at their disposal to alleviate the cost impact of sustainable aviation fuels on passengers.

Third-party intervention

Corporate customers make up over a quarter of air-travel.[91] This creates an opportunity for the additional cost associated with use of electrofuels to be absorbed by industry to varying degrees. Whether it is motivated by corporate social responsibility or shareholder mandates to reduce company emissions, it is reasonable to expect that corporations with high levels of corporate travel will buy into available fuel programs and work to integrate these costs into overall operational expenditure. Microsoft provides an example of one large multinational company participating in a program that involves direct purchase of SAF for its employees on specified flights.

Case study: Microsoft

Microsoft and KLM Royal Dutch have signed an agreement that will see Microsoft commit to purchase an amount of sustainable aviation fuel equivalent to all flights taken by their employees between the Netherlands and the USA on KLM and Delta Airlines. This is said to reduce CO_2 emissions by up to 80% for these flights when compared to fossil fuel-derived jet fuel.[92]

Frequent flyer miles

Frequent flyer miles represent a low-cost tool at the disposal of airlines that can be used to incentivize consumer behavior. In recent times, airlines such as Qantas have used frequent flyer miles to reward passengers who purchase carbon offsets. This has resulted in a 15% increase in loyalty program members offsetting their flights since the beginning of the program offer.[93]

Co-benefits funded by airports

Another way in which the cost of electrofuels may be amortized is to open the opportunity for airports to pay for the co-benefits associated with their use. Benefits include improved air quality, reduced greenhouse gases and the regional economic benefits that stem from local fuel production.[94]

Location

At smaller scales, given that electrofuel producers are likely to sell their output directly to conventional refineries, opportunities to co-locate plants with refineries should be pursued. This is due to the fact that there is a readily available source of CO_2 from the refining process and significant demand for hydrogen which provides an opportunity to scale electrolysis plants (as per the example of the Refhyne project).

However, as blending concentrations of electrofuels increase, the most important consideration is access to cheap low emissions energy resources given the impact of electricity on the price of hydrogen as shown in Figure 8 and Figure 12. This requirement outweighs the benefit of lower cost, high concentration CO_2 sourced from existing industrial plants and promotes the continued development of DAC technologies due to flexibility it brings in terms of CO_2 source.

Of similar importance is the need to maintain high capacity factors due to the continuous use requirements of the fuel synthesis plants and impact on the overall cost. This can be achieved through dispatchable low emissions/renewable technologies such as nuclear, geothermal, hydropower and CSP depending on the availability of local resources.

A best-case scenario may also involve use for the oxygen produced via electrolysis. One potential option may be for the oxy-combustion[95] of a carbonaceous feedstock (preferentially biomass) for heat/electricity, which also produces a high concentration CO_2 output that can then be captured and used as a feedstock into the synthesis of electrofuels (as per the Westküste 100 case study).

90 Abington T, Carr M, Wilkes W (2019) *Greta Thunberg and 'flight shame' are fuelling a carbon offset boom*. Australian Financial Review

91 Chen D (2013) *US Research: Leisure travel prevails over business travel.* Tourism Review

92 KLM Royal Dutch Airlines (2019) KLM and Microsoft join forces to advance sustainable air travel. KLM

93 Hatch P (2019) *Qantas points push sees green flyers take off.* Sydney Morning Herald

94 Klauber A, Benn A, Hardenbol C, Schiller C, Toussie I, Valk M, Waller J (2017) *Innovative Funding for Sustainable Aviation Fuel at U.S. Airports: Explored at Seattle-Tacoma International. Rocky Mountain Institute*. Rocky Mountain Institute

95 Oxy combustion refers to the combustion of a carbonaceous feedstock in the presence of high concentrations of oxygen as opposed to air

Export

Many countries lack the natural resources required to develop an electrofuels industry and may therefore need to rely on imports from those with a comparative advantage. Countries with existing oil & gas export infrastructure as well as strong renewable resources present as important candidates. Particularly in relation to CSP/solar PV, this includes Saudi Arabia, Qatar, Australia and Chile. However, with more arid climates, such countries may be forced to rely primarily on desalinated water in order to meet demand. As mentioned, while this does not have a significant impact on the overall cost of hydrogen, use may be subject to a number of social license challenges over the coming decades.

Given the difference in natural resources required (i.e. no longer a dependence on crude oil deposits), use of electrofuels may then create additional scope for importing countries to diversify their supply and reduce overall risk. As an example, this could include greater utilization of geothermal and offshore wind resources in northern Europe where there is greater access to renewable sources of water.[96]

4.2.3 Policy/regulatory priorities

Carbon policy

It is unlikely that airlines and oil refineries will make the necessary investments needed to create an electrofuels industry voluntarily. An efficient policy mechanism will therefore be needed to help levelize the cost of electrofuels and conventional jet fuel. While a detailed analysis of the different policy mechanisms available and methods of enforcement are beyond the scope of this report, at their core, all rely on the application of a pecuniary value or penalty on CO_2 or other greenhouse gas (GHG) emissions.

For electrofuels, the situation is unique in that waste CO_2 that would otherwise be emitted (or drawn from the atmosphere) is purchased as an input into the fuel production process. However, that fuel is subsequently combusted during flight resulting in the re-release of CO_2. Although other fuel subsidies can be made available (discussed in Section 4.2.3), rewarding both the emitter (of the CO_2) and the airline purchasing and utilizing the fuel could result in a double-counting of abated emissions which may undermine carbon accounting systems.[97]

This begs the question as to where the CO_2 emissions credit under a relevant policy should sit along the value chain. Indeed this liability can be positioned upstream (i.e. the initial emitter of CO_2) or downstream (i.e. the airline combusting the fuel).

It has been suggested that an upstream approach is more efficient. This is based on the premise that whoever invests the capital in the CO_2 capture assets should be able to realize the benefit of any carbon credit system. In practice, this would mean that if the liability is attached to the emitter, an electrofuel producer could pay a 'zero' or 'negative' price for the CO_2 feedstock which can reduce the cost of the fuel sold (i.e. the emitter pays for the infrastructure required to remove rather than vent CO_2).

Although this would result in the availability of a cheaper synthetic fuel, it would prevent the airline from being able to derive any carbon abatement achieved through the use of a sustainable fuel. Further, given that this represents one of the only opportunities for the airline to reduce its emissions profile, it should be able to realize the available carbon credit.

It follows that the same structure applied to the existing biofuel industry remains appropriate for electrofuels, where combustion of these fuels earns a carbon credit (or in practice, use is associated with a zero-emissions factor[98]). In effect, this also means that the capital and operating cost associated with the capture and utilization of CO_2 upstream is essentially passed through to the airline who consequently pay a premium for an alternative fuel. It is also important to note that while a proxy carbon price levelizes the cost of conventional jet and electrofuels, it still has the effect of increasing the overall cost of fuel which is subsequently passed on to the consumer.

Blended quota mandate

Whereas complicated carbon pricing mechanisms can attract higher transaction costs (e.g. monitoring and compliance), a potentially more straightforward means by which the uptake of synthetic jet fuels can be progressively increased is through the use of government-imposed mandates with prescriptive blending quotas that increase over time (e.g. 2% by 2030). Flexible blending quotas were found to be particularly effective in promoting use of biofuels in Brazil.

96 Renewable water resources can be found at http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

97 Malins C (2017) *What role is there for electrofuels technologies in European transport's low carbon future.* Cerulogy

98 Using the example in Australia's National Greenhouse Account Factors

Case study: Biofuel expansion in Brazil

Brazil is home to one of the world's largest biofuel markets. One of the primary regulatory instruments used to create a market for bioenergy was progressive blending mandates. The ethanol blending mandate has increased from 4.5% in 1977 to 27% in 2015, resulting in the production of 8.7 billion gallons (33 billion liters) of bioethanol in 2018. The mandates set for biodiesel, now at 11%, were so successful that blending quotas were brought forward several years.[99]

Another key aspect of the success of these mandates is their flexible nature. Flexible blending ranges allow for rates to be aligned with supply capacities to avoid bottlenecks. Blending ranges are managed by a multisectoral body that considers government policy goals, commodity prices and installed capacity. A series of regional and federal tax incentives were also employed to encourage production and improve the competitive advantage of ethanol.[100]

One of the key challenges in emerging industries such as synthetic fuels stems from the risk in aligning supply and demand. Therefore, a policy regime with set blending quotas increasing at key milestones can be particularly effective in aligning investment in electrofuel production capacities and in mitigating demand risk from conventional jet fuel suppliers. This is particularly important given the infrastructure requirements associated with scale-up according to different blending rates set out in Figure 14. There are a number of relevant lessons to be learnt from the International Maritime Organization's cap on sulfur content recently enforced on the shipping industry, particularly in relation to allowing enough lead time for the industry to invest in new capital and adjust their operations to accommodate significant changes in regulation.

Case study: International Maritime Organization sulfur cap 2020

The International Maritime Organization has been progressively reducing the acceptable limits on the sulfur content of bunker fuel in order to reduce SOx emissions from combustion. In 2016 it was announced that from January 1 2020, the sulfur content limit on fuel oil will be reduced from 3.50% to 0.50%, a significant reduction from the prior average sulfur content of 2.70%.[101]

This cap has led to heavy fuel oil (the most commonly sold crude based product) no longer being compliant unless scrubbers are installed on ships to capture a portion of emissions. At the time of the announcement, only a few of the largest refineries globally had the infrastructure capable of producing compliant fuels. Given that the timeframe between announcement and introduction of the cap had not allowed for the construction of new facilities, global refineries have been forced to upgrade their process plants to be able to produce compliant fuels in time for 2020.

Even with these upgrades, there are fears that supply will be insufficient in meeting demand and that fuels purchased from different suppliers will not be compatible when mixed. Uncertainty is believed to be continuing as the market attempts to achieve equilibrium.[102]

While key aviation sector advisory bodies may have an important role to play in delivering expectations around appropriate blending quotas, to be most effective, it is expected that these mandates be imposed by Federal and State Governments. Governing entities will typically have the resources to enforce, track and then report on the performance of fuel providers. This framework may also help ensure some level of consistency in blending fuel quotas between jurisdictions and prevent extensive market distortion.

Enforcing blending requirements on oil refineries is also likely to result in the most efficient outcomes. This is primarily because the largest airlines have an international footprint and will not always use all fuel carried, making it more difficult to report on usage and for local governments to regulate. Further, regulation requiring manufacturers to prioritize kerosene fractions over other products that may have a higher value in certain markets may be critical in ensuring price stability and the availability of supply.

99 International Council on Clean Transport (ICCT) (2019) *Opportunities and risks for continued biofuel expansion in Brazil*. ICCT

100 Morgera E, Kulovesi K, Gobena A (2009) *Case Studies on bioenergy policy and law: options for sustainability*. FAO

101 ExxonMobil (2017) *What Does IMO's 0.50% Sulfur Cap Decision Mean for the Bunker Supply Chain?* ExxonMobil

102 Gelder A (2019) *Uncertainty Shrouds IMO 2020's Impact*. Forbes

Taxation and subsidies

The aforementioned schemes are unlikely to solve the issue of increased cost and cost pass-through that stems from the use of electrofuels. Therefore, other policy mechanisms that may be considered by governments to stimulate the uptake of electrofuels include tax credits and subsidies. Although this approach runs contrary to the 'polluter pays' principle and promotes questions over whether the taxpayer should subsidize the cost of flying, at least in the initial stages of development it is necessary for building the economies of scale without creating resentment within the industry. Such incentives would be similar to those currently supporting the use of electric vehicles wherein the subsidy is reduced as their capital and operating costs continue to decrease.

Without undertaking an extensive analysis of various taxation measures, at a high level, tax regimes (e.g. value-added tax (VAT), ticket taxes, kerosene taxes) which differ by state, are typically administered through the imposition of a levy on all passengers leaving an origin on a commercial airline. This levy is generally embedded within a ticket price, meaning that the airline is then responsible for collecting the tax and paying it back to the government. Airlines generally retain the discretion to decide how much of that tax to pass on to the consumer.[103]

An applicable taxation subsidy program could involve a reduced tax levy for flights using sustainable aviation fuels (or in some cases a restoration of a tax levy for flights using conventional jet fuel). 'Contracts for difference', which have been used successfully in the electricity sector, would see the government responsible for absorbing the premium associated with the use of electrofuels over jet fuel.

Modal shift

Within the EU, increasing taxation on jet fuel and aviation is being employed as a mechanism to encourage use of other less emissions-intensive means of transport such as rail. For instance, in April 2020, the German government will impose an aviation climate tax which will see the cost of both domestic and international flights rise by approximately 28%. The tax raised will be used to subsidize rail ticket prices.[104]

While the degree to which this reduces demand remains unclear, such initiatives are only likely to be effective for low-speed rail at distances less than 600km (due to travel times and customer preference for flying beyond this distance). In the EU, such distances account for less than 7% of total flights and many of these flight routes do not have sufficient rail infrastructure in place.[105]

Offset programs

Carbon offset programs have long been recognized as a more immediate solution to achieving emissions abatement within the aviation sector given the technological and economic barriers associated with use of SAF.

The most important scheme currently in place is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) adopted by ICAO. The Pilot Phase (2021 – 2023) and First Phase (2024-2026) of the program are voluntary, before becoming mandatory thereafter.[106] The exact offset programs that are eligible for purchase are currently being assessed by the ICAO Technical Advisory Body (TAB).[107] CORSIA also plan to set out criteria for eligible lower carbon jet fuels that when used, will reduce the number of offsets required for purchase. Fuels that may be excluded include those derived from feedstocks that are deemed unsustainable.[108]

Countries captured under the mandatory condition include those whose share of international activities, measured in revenue tonne-kilometres (RTKs),[109] were either above 0.5% of total RTKs in 2018 or are in the list of countries that make up the top 90% of RTKs. This list excludes countries classified under the UN's Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs) unless they volunteer to participate.

However, by continuing to promote abatement projects in other sectors via lower cost offset programs, these schemes divert investment from longer-term emissions reduction within the aviation sector, particularly as they relate to alternative fuels. A mechanism by which this challenge may be overcome is by aligning the offset credit value with the cost premium of electrofuels over conventional jet fuel.[110]

103 CE Delft (2018) *A study on aviation ticket taxes*. Transport & Environment

104 Parkin B, Philip S, Delfs A (2019) *Germany Targets Discount Fliers in Move to Raise Air Ticket Tax*. Bloomberg News

105 Murphy et al. (2018) *Roadmap to decarbonisation of the aviation sector.* Transport & Environment

106 ICAO (2019) *What is CORSIA and how does it work?* Available at https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx

107 ICAO (2019) *Technical Advisory Body.* Available at https://www.icao.int/environmental-protection/CORSIA/Pages/TAB.aspx

108 Timperley J (2019) *Corsia: The UN's plan to 'offset' growth in aviation emissions after 2020.* CarbonBrief

109 A revenue tonne-kilometre is generated when a metric tonne of revenue load is carried one kilometre. This includes freight and passengers.

110 Global Alliance Powerfuels (2019) *Powerfuels in Aviation.* German Energy Agency – Dena

Regulatory approval of new fuels

All new synthetically derived jet fuels will be subject to rigorous testing prior to approval for use, ensuring that they meet all the operating requirements of conventional jet fuel. This is critical not just for combustion, but also for other uses of the fuel including cooling, hydraulics and as a lubricant.

Before undergoing the ASTM D7566 certification process, a fuel must be subject to a four-tiered testing protocol known as ASTM D4054. The approval process includes:[111]

- Tier 1 – Specifying the new fuel
- Tier 2 – Establishing fit for purpose
- Tier 3 – Testing components
- Tier 4 – Testing engine and auxiliary power unit

To supplement the ASTM standard, which does not provide guidance on handling synthetic fuels, global entities such as IATA and the Joint Inspection Group (JIG) (set up voluntarily by oil suppliers) provide further guidance on 'best practice' standards. This adds another level of cost and complexity for those looking to introduce new fuels into the market.[112]

The current certification process is expensive and time consuming, taking between 3-5 years and costing in the order of $10-15m. This is particularly challenging for start-up companies looking to ramp up development of a synthetic fuel,[113] where much of the cost stems from access to equipment such as demonstrator engines and the volume of fuel required to meet the D4054 testing requirements. Efforts to address this issue have recently been made via the introduction of the 'Fast Track Annex' which allows for reduced approval time if the fuel has conventional hydrocarbon compositions. Blending concentrations are limited to 10% when this approval method is used.[114]

Thus without compromising the integrity of the certification process and the need for use of fuels with robust operating properties, there are a number of measures that might be taken to reduce the regulatory burden and help streamline cost and resource requirements. These measures are currently being progressed through the National Jet Fuels Combustion Program (NJFCP), FAA's Aviation Sustainability Center (ASCENT), the D4054 Clearinghouse and the JETSCREEN program under development in the EU.

ASCENT is a cost-sharing program established by the FAA with academia and industry to research alternative jet fuels and the impact of aviation on the environment. It is a coalition of 16 leading US research universities, over 60 private sector stakeholders and several federal agencies.[115] ASCENT has a comprehensive portfolio of research projects to meet environmental and energy goals to reduce noise, improve air quality and reduce climate impacts around airports and in the sky. Their portfolio also examines methods for SAF production at scale and oversees the D4054 Clearinghouse.

NJFCP's mission is to help "streamline the current ASTM fuel approval process". Tiers 3 and 4 of the ground fuel qualification process is the primary cost driver and makes up most of the NJFCP's efforts. This is due to the cost of the fuel quantities required and uncertainty among engine OEMs regarding the effects of new fuels on combustor operability. The NJPCP proposes to develop generic fuel composition and chemistry evaluation methodologies as well as standardize rig and lab tests. They also seek to drive collaboration between OEMs, universities and federal agencies.[116]

D4054 Clearinghouse[117] was established by the FAA under the ASCENT program to guide candidate fuel producers through the OEM review process. The clearinghouse aims to increase the efficiency of the ASTM process for fuel producers and expert reviewers by supporting coordinated testing, evaluation and review of alternative fuels.

JETSCREEN will provide fuel producers, air framers and aero-engine and fuel system OEMs with tools to streamline the approval process, assess the compatibility of fuel compositions with fuel and combustion systems, as well as quantify value add and optimize fuel formulation to maximize environmental potential.[118]

111 ASCENT (2019) *ASCENT – The Aviation Sustainability Center*. Available at https://ascent.aero/

112 Commercial Aviation Alternative Fuels Initiative (CAAFI) (2018) *Initial Results of Alternative Fuel Effects on Combustor Performance: Lean Blowout and Ignition*. CAAFI

113 ASCENT (2018) *ASTM D4054 Clearinghouse Guide*. Available at https://s3.wp.wsu.edu/uploads/sites/192/2018/03/clearinhouse.pdf

114 JETSCREEN (2019) Available at https://www.jetscreen-h2020.eu/

115 US Department Of Energy (DOE) (2017) Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps. DOE

116 Bullerdiek N, Buse J, Kaltschmitt M, Pechstein J (2019) *Regulatory Requirements for Production, Blending, Logistics, Storage, Aircraft Refuelling, Sustainability Certification and Accounting of Sustainable Aviation Fuels* (SAF). https://elib.dlr.de/130946/2/demo-spk-recommendation-paper.pdf

117 US Department of Energy (DOE) (2017) Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps. DOE

118 IATA (2019) *IATA Sustainable Aviation Fuel Symposium.* https://www.iata.org/contentassets/8dc7f9f4c38247ae8f007998295a37d5/safs2019-day1.pdf

4.2.4 RD&D investment priorities

End-to-end demonstration

While each of the discrete technologies supporting electrofuel synthesis will require ongoing RD&D investment (discussed in the following subsections), the commercial demonstration and integration of these elements across the full value chain will be of equal importance. This is currently the focus in Europe, with key players such as Sunfire (high-temperature electrolysis), Climeworks (DAC) and Ineratec (FT) successfully demonstrating the integrated production of jet fuel within the lab and now looking towards commercial scale-up.

Case study: Sunfire

Industry leader Sunfire has recently announced that a commercial demonstration plant to produce Blue Crude, which is comparable to crude oil, will be in operation in Norway in 2020. Paired with DAC technology from Climeworks, the plant is expected to produce 8,000t of Blue Crude per year via FT, which will be refined to supply cars, trucks and aircraft.[119]

Another recent collaboration is providing Total, a major French energy company, with a SOE solution for an RD&D project that explores utilizing its CO_2 emissions and waste heat from a refinery to produce green methanol and hydrogen.

Hydrogen/syngas production

Solid oxide electrolysis and co-electrolysis

As mentioned in Section 4.2.1, solid oxide electrolyzers (TRL 6-7)[120] use thermal energy from heat (700-800°C) in combination with electrical energy to synthesize hydrogen from steam. Due to the high temperatures involved, RD&D is required to improve the durability of electrolyzer materials to extend the system life. Further research is also needed to refine the integration and optimization of heat transfer within these systems in order to improve overall economics. Once mature, based on modelling undertaken in this report, a 100MW solid oxide electrolyzer could produce hydrogen at a cost $0.88/lbs ($1.95/kg) due to the efficiencies gained.

High-temperature electrolysis also allows for the addition of CO_2 to the input stream to directly produce syngas (TRL 6-7). This is critical to achieving cost improvements for jet fuel production via FT as it removes the need for the RWGS reaction. Further research is required to develop cathodes with improved performance and stability across the large temperature ranges of SOE.[121]

Electrochemical CO_2 reduction

A low-temperature alternative to co-electrolysis is the electrochemical reduction of CO_2 to CO (TRL 3-5)[122] combined with a hydrogen source to produce syngas. Whereas RWGS operates at 400°C, and SOE at 800°C, electrochemical reduction can be performed at ambient temperatures and be driven by renewable energy. Challenges remain in achieving economical efficiencies. This is due to the high activation barrier of the reaction and the occurrence of side reactions that result in a variety of products formed (i.e. low CO selectivity). To overcome these difficulties and improve efficiencies, development of electrocatalysts is a priority, with materials like carbon nanomaterials showing promise.[123]

Direct reduction of CO_2 and H_2O can also be utilized to produce methanol through various processes such as photocatalysis (TRL 2-4)[124], electrochemistry (TRL 1)[124] or a combination of both. A major challenge for this process is the selection and application of electrocatalysts to drive the reaction efficiently, again due to the high activation energy required and tendency for side reactions to occur. The development of metal organic framework (MOF) electrocatalysts with superior efficiencies, stability and conductivity are reported to have shown encouraging results.[125]

119 Sunfire (2017) *First commercial plant for the production of blue crude planned in Norway*. Available at https://www.sunfire.de/en/company/news/detail/first-commercial-plant-for-the-production-of-blue-crude-planned-in-norway

120 Charnock S, Temminghoff M, Srinivasan V, Burke N, Munnings C, Hartley P (2019) *Hydrogen Research, Development and Demonstration: Technical Repository,* CSIRO

121 Zhang A, Song Y, Wang G, Bao X (2017) *Co-electrolysis of CO2 and H2O in high-temperature solid oxide electrolysis cells: Recent advance in cathodes*. Journal of Energy Chemistry

122 Jarvis S, Samsatli S (2018) *Technologies and infrastructures underpinning future CO2 value chains: A comprehensive review and comparative analysis*. Renewable and Sustainable Energy Reviews

123 Zheng T, Jiang K, Wang H (2018) *Recent Advances in Electrochemical CO2-to-CO Conversion on Heterogeneous Catalysts*. Advanced Materials

124 Charnock S, Temminghoff M, Srinivasan V, Burke N, Munnings C, Hartley P (2019) *Hydrogen Research, Development and Demonstration: Technical Repository,* CSIRO

125 Al-Rowaili F, Jamal A, Shammakh M, Rana A (2018) *A Review on Recent Advances for Electrochemical Reduction of Carbon Dioxide to Methanol Using Metal–Organic Framework (MOF) and Non-MOF Catalysts: Challenges and Future Prospects*. ACS Sustainable Chemistry & Engineering

Photoelectrochemical direct synthesis

An emerging area of research involves removing the need to supply electricity to the reaction, relying entirely on sunlight and catalysts to produce syngas directly from aqueous CO_2 and water (TRL 2-3).[126] Further research will be required to integrate cheaper catalyst materials and improve efficiency levels in order to reduce overall system costs. Effort is needed to scale up the system from the laboratory scale and optimize solar irradiance.

Hydrogen storage

Underground caverns present as one of the more favorable options for large-scale storage, wherein hydrogen gas is compressed and injected via wells into subsurface formations. The options for subsurface storage include salt caverns (which are excavated and shaped by injecting fresh water into existing rock salt formations), depleted gas or oil fields, and saline aquifers. The hydrogen is then extracted from the formation via the wells.

While salt caverns provide the most mature option for subsurface storage due to the small pore sizes of their surfaces (TRL 8), their availability is highly dependent on the local geography. Depleted gas fields or saline aquifers (TRL 5) may be more readily available, but are more challenging due to the larger pore size of the rock and presence of contaminants.

High-concentration CO_2 capture

New membrane development[127]

Membranes (TRL 5)[128] are likely to remain more suitable to high concentration CO_2 streams because of a requirement for higher partial pressures. Although relatively new, they show promise compared to other solutions due to their continuous operation, compactness, energy efficiency, ease of operation and flexibility in being retrofitted to existing industrial processes.

Membrane RD&D is needed to develop robust materials that can operate in harsh conditions associated with flue gas streams. At present, support equipment (e.g. compression and cooling units) is required to maintain, stabilize and protect the membrane, which increases capital costs.

Other membrane challenges include developing a solution to plasticization, wherein continued exposure to CO_2 causes the membrane to swell and change shape. This increases its permeability which allows other undesired gases to pass through. Investment is also needed to improve chemical and thermal stress resistance.

Direct air capture

Metal organic frameworks (MOFs)

MOFs offer another alternative for direct capture of CO_2 from the air. MOFs are a crystalline porous material constructed from metallic units with organic linkers containing some of the highest surface areas of any material. The technology has been demonstrated for direct air capture and shown to be able to capture 13.2lb/day (6kg/day) of CO_2 (TRL 7). For comparison, Climeworks offers DAC modules (TRL 9) that capture 308lb/day (140kg/day).[129] An advantage of this technology is the ability to regenerate at a lower temperature (i.e. 80°C), thereby reducing the energy requirements of the system. However, due to a complex and 'batch' production method, scaling up production is the primary challenge currently.

Amines

Amines have been widely used in high concentration CO_2 but still face a number of challenges with respect to DAC. Further RD&D is required to manage evaporative losses, contactor costs and reduce energy use for materials regeneration.

Use of amines can also be enhanced through the addition of other compounds and chemicals such as 'hydrogels' which increase the contact surface area between the gas and the amine by using low cost readily available materials (TRL 3-4). Key areas for further development include improvements in the optimization of the hydrogel size, shape and swelling media which are all needed to maximize absorbency and reduce costs.[130]

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126 Andrei V, Reuillard B, Reisner E (2019) *Bias-free solar syngas production by integrating a molecular cobalt catalyst with perovskite–BiVO4 tandems*. Nature Materials

127 Norahim N, Yaisanga P, Faungnawakij K, Charinpanitkul T, Klaysom C (2018) *Recent Membrane Developments for CO2 Separation and Capture*. Chemical Engineering & Technology

128 He X (2018) *The Latest Development on Membrane Materials and Processes for Post-combustion CO2 Capture: A Review*. SF Journal of Material and Chemical Engineering

129 Viebahn P, Scholz A, Zelt O (2019) *The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis*. Energies

130 Xu X, Heath C, Pejcic B, Wood C (2018) *CO2 capture by amine infused hydrogels (AIHS).* Journal of Materials Chemistry

Electrofuel synthesis

Process intensification

Process intensification (PI) aims to improve mature fuel synthesis processes by optimizing existing methods. This may involve combining separate processes or miniaturizing reactors which can improve mass and heat transfer, reaction kinetics, yields and selectivity. Developments in PI can lead to reduced process complexity and plant footprint which lowers capital and operating costs.[131]

Microreactors, or microchannel reactors, are an example of process intensification that can enable novel processing routes and process flexibility. Microreactor technology aims to reduce the reliance on scale to deliver positive economics by enabling a more modular, decentralized production process. Microchannels provide a confined space for chemical reactions to occur which can increase energy efficiency, safety, reliability and provide a finer degree of process control as well as heat and mass transfer.[132] Microreactors have also demonstrated significantly higher fuel yields when compared to conventional reactors and are able to use milder conditions due to the higher surface areas achieved.[133] Scale-up issues exist, with the distribution of catalysts and heat transfer optimization requiring further attention. Current modules can produce 50 to 2,000bpd.

VTT Group in Finland has demonstrated a mobile synthesis unit as part of the SOLETAIR project. The modular unit includes a small-scale reverse water gas shift reactor that feeds syngas into a microscale Fischer-Tropsch reactor developed by Ineratec. Initial pilot studies have demonstrated gasoline production rates of 80L per day (TRL 6)[134] with more a broader range of products and larger quantities expected as the project advances. This small-scale system option could be utilized at remote airports.

Fischer Tropsch improvements

Despite being a commercial fuel synthesis method, improvements can still be found within the FT process. Developments in product selectivity and yields via pre-treating and alterations in catalyst compositions will be important in improving project economics. A recent study employing a zeolite supported cobalt catalyst was able to yield jet fuel selectivity of 72% (by mass).[135]

Co-feeding provides another means by which the traditional Fischer-Tropsch synthesis can be improved. This involves the addition of molecules other than syngas combined with various catalysts to alter final product fractions. These additives could be water or organic molecules such as 1-olefins which show a high selectivity to jet fuel type hydrocarbons and minimize CO_2 by-products.[136]

Concentrated solar fuels

Using mirrors, sunlight can be concentrated on a receiver to produce extremely high temperatures and facilitate chemical reactions. With the aid of metal oxides, which are not consumed, water and carbon dioxide can be split to produce syngas to be used as an input for further fuel synthesis.

As an example, the SOLAR-JET program, which included agencies such as DLR and Shell, formed in 2011 in an effort to utilize concentrated solar to produce kerosene (TRL 4). 3-fold increases in efficiency would be required before the process is cost-competitive which would lead to the production of 20,000L (126bbl) of kerosene per day from a system spanning 1km^2 (0.39mi^2).[137]

Summary and prioritization

To progress RD&D efforts in a coordinated manner, Figure 15 considers each of the themes summarized in this section according to their level of priority in developing the electrofuels industry further. TRLs have also been included here to reflect the level of effort still required to commercialize each of the underpinning technologies.

131 US Department of Energy (DOE) (2015) *Quadrennial Technology Review 2015: Process Intensification.* DOE

132 Almeida L, Sanz O, D'olhaberriague J, Yunes S, Montes M (2012) *Microchannel reactor for Fischer–Tropsch synthesis: Adaptation of a commercial unit for testing microchannel blocks*. Fuel

133 Hafeez S, Manos G, Al-Salem SM, Aristoemou E, Constantinou A (2018) *Liquid fuel synthesis in microreactors.* Reaction Chemistry & Engineering

134 Mortensen A, Wenzel H, Rasmussen K, Justesen S, Wormslev E, Porsgaard M () *Nordic GTL – a pre-feasibility study on sustainable aviation fuel from biogas, hydrogen and CO2*. SDU, NIRAS, NISA

135 Li J, He Y, Tan L, Zhang P, Peng X, Oruganti A, Yang G, Abe H, Wang Y, Tsubaki N (2018) *Integrated tuneable synthesis of liquid fuels via Fischer–Tropsch technology*. Nature catalysis

136 Li J, Yang G, Yoneyama Y, Vitidsant T, Tsubaki N (2016) *Jet fuel synthesis via Fischer–Tropsch synthesis with varied 1-olefins as additives using Co/ZrO2–SiO2 bimodal catalyst*. Fuel

137 Sigler D (2018) *Earth, Air, Water and Jet Fire*. Sustainable Skies

Given the maturity of several key discrete technologies, commercial demonstration projects that de-risk the end-to-end value chain form a critical next stage in industry development. As the industry matures, more investment should be targeted towards higher TRL solid oxide electrolysis and DAC as a means of improving project economics and increasing the flexibility of production plant location. Large-scale underground hydrogen storage may also form a key component of production at scale but is location specific.

Other more direct pathways to electrofuels such as electrochemical CO_2 reduction have a number of obstacles to overcome and a longer development timeline. They are therefore more likely to comprise the next wave of technology development once the industry progresses further.

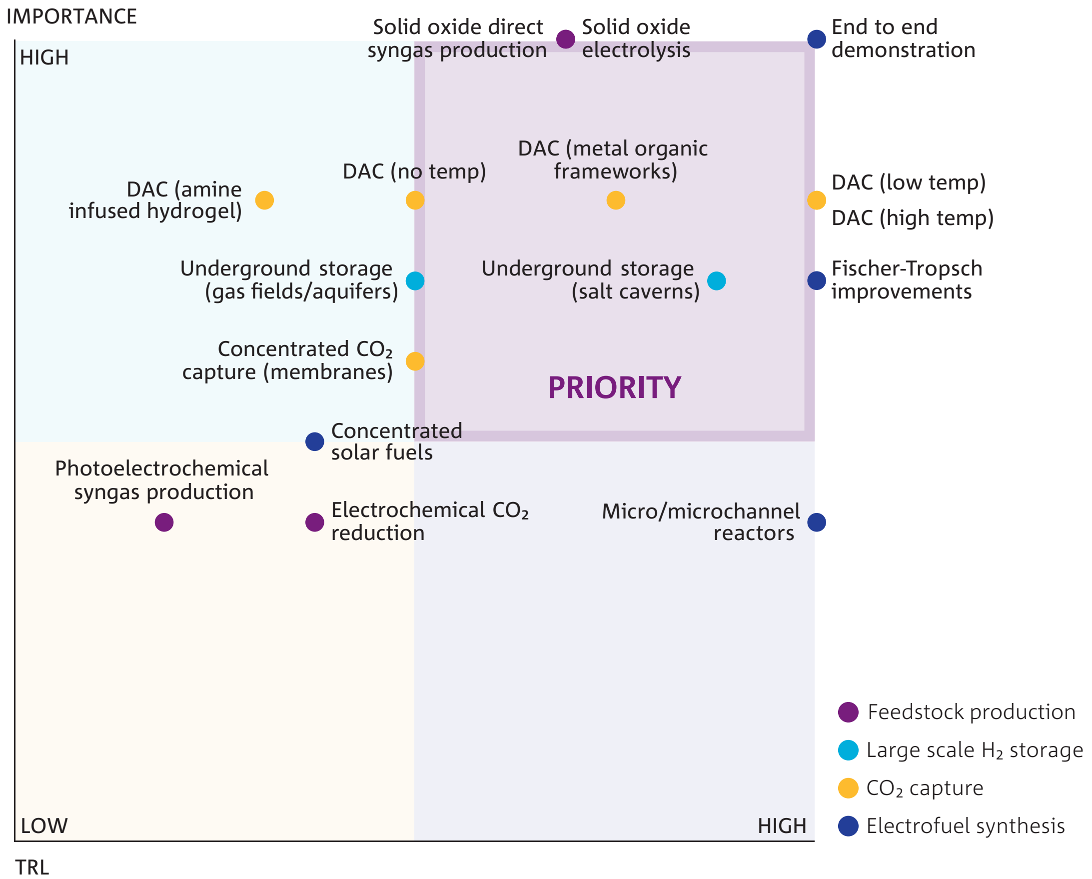

Figure 15. Prioritization of RD&D measures for electrofuels

4.2.5 Social license

Given that utilization of electrofuels requires no extensive changes to existing fuel type and aviation infrastructure, it is unlikely to face the same social license challenges as use of pure hydrogen. Rather, it is more likely that use of a sustainable aviation fuel would be welcomed by both airlines and customers alike.

However, given that electrofuel use will continue to involve high concentrations of jet fuel that generate both CO_2 and other environmentally harmful pollutants, the overall process may not be satisfactory for more interested industry stakeholders. This is particularly the case given the lead time required to produce meaningful electrofuel blending rates. The social license challenge may be furthered if combined with noticeably higher cost pass-through to consumers.

The transition to electrofuels may also be met with some resistance from within the broader hydrogen and electricity sectors. This is due to the considerable renewable energy, hydrogen resources and infrastructure that would be dedicated to an industry where less meaningful levels of abatement could be achieved as compared with other forms of transport and stationary power.

A detailed assessment of these effects will be required to ensure that the development of electrofuels is accepted across the various stakeholder groups. Communication on the part of governments, airlines and refineries regarding the levels of use for different resources as well as transparency over cost and environmental impact will play a critical role in industry scale-up.

Lastly, particularly in the early development stages of the industry, it is important for manufacturers of electrofuels to allow ongoing access to plant output and quality data to ensure that aviation fuel regulators continue to gain comfort over the synthesis process and quality of outputs.

4.2.6 Modelling summary

Figure 16 summarizes the base case (limited by a 100MW PEM electrolyzer) and best case (based on a 50% blending rate at a 10,000bpd refinery) for both the FT and MeOH pathways to electrofuels. For the best case, costs are in the order of 1.25 to 2.5 times the expected jet fuel price (~$125/bbl[138] between 2040 and 2050) depending on the fuel synthesis method used. CRI 6, which would require electrofuels to be cost competitive with conventional jet fuel is therefore unlikely to occur without the right policy framework in place.

Given the extensive lead time required to achieve such blending concentrations (i.e. after 2040), significant developments in both DAC and SOE are expected and have been incorporated into the best-case scenario. Although use of DAC increases the cost of CO_2 capture, there is a net reduction in cost for both electrofuel pathways that is driven primarily by increases in scale and use of SOE. For FT, SOE displaces the cost of hydrogen due to it enabling the direct production of syngas.

While challenging, a 90% capacity factor has also been maintained in the best case primarily due to the continuous operating requirements of the electrofuel synthesis process as well as the requirement for solid-oxide electrolyzers to maintain a high operating temperature. This will require a focus on the more dispatchable low emissions technologies already considered. For this reason, large scale hydrogen storage costs which are typically in the order of 5c/lb (13c/kgH_2)[139], have not been included as part of this techno-economic assessment.

Note that 50% blending rates in a 10,000bpd refinery will require solid oxide electrolyzers in the order of 726MW for MeOH and 1,956MW for FT. All supporting assumptions are detailed in Appendix A.

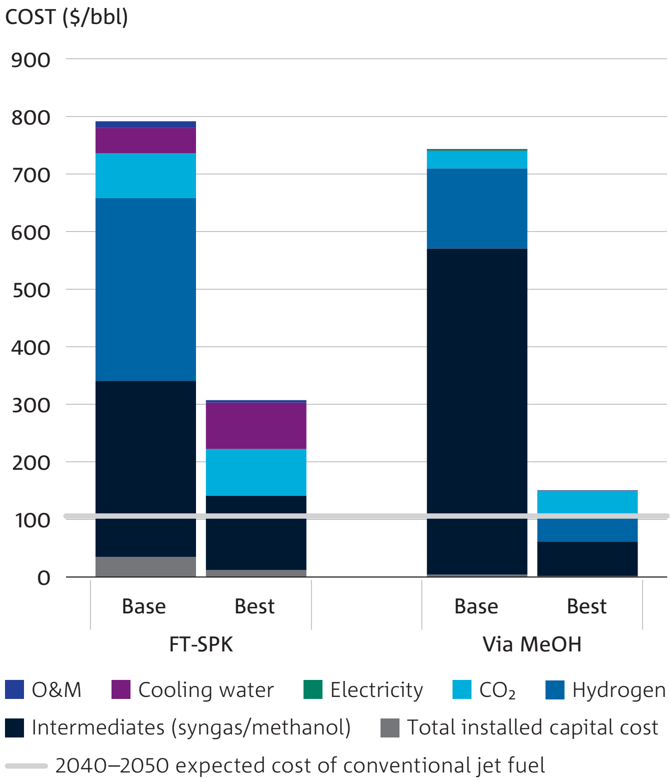

Figure 16. Summary of best and base-case results for electrofuel production using FT and MeOH

138 As per Annual Energy Outlook 2019 available at https://www.eia.gov/outlooks/aeo/

139 Refer to storage costs in *National Hydrogen Roadmap*, CSIRO

5 Emerging infrastructure

Although significant CO_2 emissions abatement can be achieved via the uptake of 'drop-in' electrofuels, ongoing use is likely to continue to involve high concentrations of jet fuel. Therefore, it may be reasonable to expect that increasingly stringent environmental regulations could force a complete move away from kerosene closer to 2050.

The potential for hydrogen and other hydrogen augmented fuels to facilitate this transition is therefore the focus of this section. Acknowledging the intricate nature of aircraft and supporting infrastructure as well as the long lead times to development, this section focuses on the RD&D priorities relating to universal rules within commercial aviation, namely safety, environment (including noise) as well as economics of travel (e.g. weight, fuel use, time of refueling). Hydrogen specific RD&D requirements are also explored in this section.

5.1 Fuel cells for non-propulsion applications

5.1.1 Applications

On-aircraft use of fuel cells may present as one of the nearer term applications for hydrogen in aviation. This is because they have the potential to be incorporated onto jet aircraft without developing materially new plane designs. Electricity generated via fuel cells can be used for auxiliary power (i.e. Auxiliary Power Units or APUs) and aircraft taxiing, as well as other on-board equipment as part of the broader transition to 'more electric architecture' explored further below.

Auxiliary Power Units

APUs are typically used to power on-board electrical equipment while on-ground, allowing the aircraft to operate independently of GSE. They are also used to start primary jet engines, provide air for heating and cooling, and as a back-up electricity source if a primary generator goes offline during flight. APUs consist of a small turbine engine located at the rear of the fuselage that generates electrical energy and compressed air via the combustion of jet fuel.

With the primary purpose of the APU being to provide electrical (and some heat) energy, it is necessary to consider the potential for a hydrogen fuel cell system to replace the existing turbine engine. While detailed analysis regarding weight distribution, safety and operability would be required to determine the preferred positioning, a potential placement for the fuel cell is illustrated in Figure 17.

Taxiing

Post pushback (which is assisted by 'push-back tugs') the taxi-in and taxi-out phases of flight rely on jet engines operating at low power settings. In this phase, engines operate with poor fuel efficiency and produce considerable emissions in local and nearby areas.[140] Taxiing time and distance can often be extended due to congestion at major airports, where in Europe for example, it can comprise 10-30% of total flight time.[140]

One potential solution is the extended use of push-back tugs, effectively making them responsible for the whole of the taxiing cycle. Previously trialed systems include the TaxiBot which is a semi-automated system that connects with the nose wheel of the plane and is subsequently controlled by the pilot. While these solutions are likely to be important in the near term, they also come with a range of issues including added congestion, additional capex and maintenance requirements for airports as well as increasing delays in the movement of aircraft.

One alternative is to use electric drive systems for aircraft taxiing (also known as an 'electric green taxiing system'). This involves the addition of electric motors in the wheels of landing gear[140], allowing the taxiing phase to be driven by the APU as opposed to aircraft engines. A version of this upgrade was trialed in a Honeywell and Safran joint venture in 2013.[141]

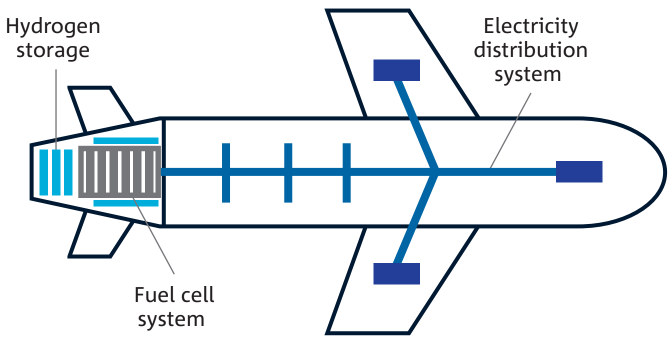

Figure 17. Potential integration of fuel cell APU into aircraft fuselage

140 Guo R, Zhang Y, Wang Q (2013) *Comparison of emerging ground propulsion systems for electrified aircraft taxi operations*. Transportation Research

141 Carey B (2013) *Honeywell, Safran Demo Electric Taxiing System For Airlines.* Available at https://www.ainonline.com/aviation-news/air-transport/2013-06-18/honeywell-safran-demo-electric-taxiing-system-airlines

While the addition of electric drive systems would add to the plane weight, they can result in a more efficient use of fuel. For instance, ground movement of the aircraft is likely to be more efficient because it does not require use of main engine throttles.[142] Importantly, fuel cell-powered APUs (described above) can be used to power these taxiing systems. However, for both this and the Taxibot option, start-up of jet engines just prior to take-off creates a number of operational and safety challenges that would need to be overcome.

Other electrical equipment

Existing aircraft rely on engine generated pneumatic bleed air (pressurized gas), hydraulic (pressurized liquid) and mechanical equipment to operate functions such as landing gear and flight controls. However, as part of a move to more electric architecture, such operating equipment is continuing to be electrified, as seen with the partial electrification of flight control actuators in Boeing's 787 Dreamliner.

Although these electrical systems tend to be heavier, as observed in relation to electric taxiing systems, more efficient use of fuel can translate into a net weight benefit.[143] Increased levels of electrification may also lend favorably to greater use of fuel cells which can provide a more reliable and efficient power source.

5.1.2 Technology options

Fuel cells

At present, there are several available hydrogen fuel cell technologies with varying levels of maturity.[144] Those most suited to non-propulsion applications on aircraft are likely to include PEM (PEMFC), solid oxide (SOFC) and direct methanol fuel cells (DMFC). The potential for each is summarized in Table 12.

Table 12. Likely fuel cells technologies for on-platform non-propulsion applications

FUEL CELL	DESCRIPTION	TRL	SPECIFIC POWER, KW/LB (KW/KG)	ON-PLATFORM APPLICABILITY
PEMFC	Hydrogen is catalytically split into protons which permeate through the membrane from the anode to the cathode to create an electrical current	9	0.7 (1.6[145])	• Low temperature of operation, quick start-up times compared to other FCs, high efficiency, low noise and vibration • Highest specific energy/power
SOFC	A fuel cell that uses a solid oxide or ceramic electrolyte and high temperatures (up to 1000°C) negating the need for a catalyst	6	0.5 (~1[146])	• More efficient but requires the use of waste heat • TRL 6 for transport (9 for stationary applications) • Better for hydrocarbon input • Typically larger and require more operating parts when compared with PEMFC • Poor thermal cyclability which makes it harder for mobile applications
DMFC[147]	Instead of being reformed to release hydrogen, methanol is fed directly to the fuel cell anode. The fuel cell runs at operating temperatures of 50-120°C	9	0.05 (0.1[148])	• DMFCs suffer from low efficiency and are most likely to be used for small portable applications • Poor power density

142 Ganev E (2017) *Electric Drives for Electric Green Taxiing Systems: Examining and Evaluating the Electric Drive System*, Institute of Electrical and Electronics Engineers

143 Schallert C, Pfeiffer A, Bals J (2006) *Generator power optimisation for a more-electric aircraft by use of a virtual iron bird*. DLR

145 Kadyk T, Winnefeld C, Hanke-Rauschenbach R, Krewer U (2018) *Analysis and Design of Fuel Cell Systems for Aviation*. Energies

146 Hussain A, Wachsman E (2018) *Liquids-to-Power Using Low-Temperature Solid Oxide Fuel Cells*. Energy Technology.

147 Joghee P, Malik J, Plylypenko S, O'Hayre R (2015) *A review on direct methanol fuel cells – in the perspective of energy and sustainability*. Energy Sustainability

148 Sgroi M, Zedde F, Barbera O, Stassi A, Sebastian D, Lufrano F, Baglio V, Arico A, Bonde J, Schuster M (2016) *Cost Analysis of Direct Methanol Fuel Cell Stacks for Mass Production*. Energies

Notably, PEMFCs are the most widely deployed technology for ground transport applications and are therefore continuing to benefit from increasing cross-sector investment and improvements that can be leveraged by the aviation industry. Despite slightly longer start-up times, PEMFCs can cycle in the same way as existing APU turbines. These delays can also be overcome by running the fuel cell at low loads during flight and pairing with batteries (discussed further in Section 5.1.7).

Storage

The same hydrogen storage technologies discussed in Section 3.1.2 are applicable in the context of on-aircraft hydrogen storage. As distinct from on-airport hydrogen storage however, considerations relating to weight and volumetric density are of greater importance. The respective volumetric and gravimetric densities for each of the storage technologies are illustrated in Figure 18. Note that gravimetric densities are measured in weight percentage of hydrogen (H_2wt%) which depicts the total weight of hydrogen as a percentage of overall tank weight.

Each of the storage technologies require tanks made from different materials that will have varying weight burdens that need to be considered. For storage of pure hydrogen, there is an additional weight burden (as compared with other carriers) due to the degree of insulation and pressurization required (i.e. compressed hydrogen at 700bar therefore has a relatively low gravimetric density of 5 H_2wt%).

While kerosene has a 15 H_2wt%, it requires the use of a reformer to extract hydrogen from the fuel for subsequent use in a PEMFC, which adds to the overall system weight. The same is true of other carriers such as methanol and ammonia where the required processors could decrease the current power density of the fuel cell system by up to a factor of 2.[153]

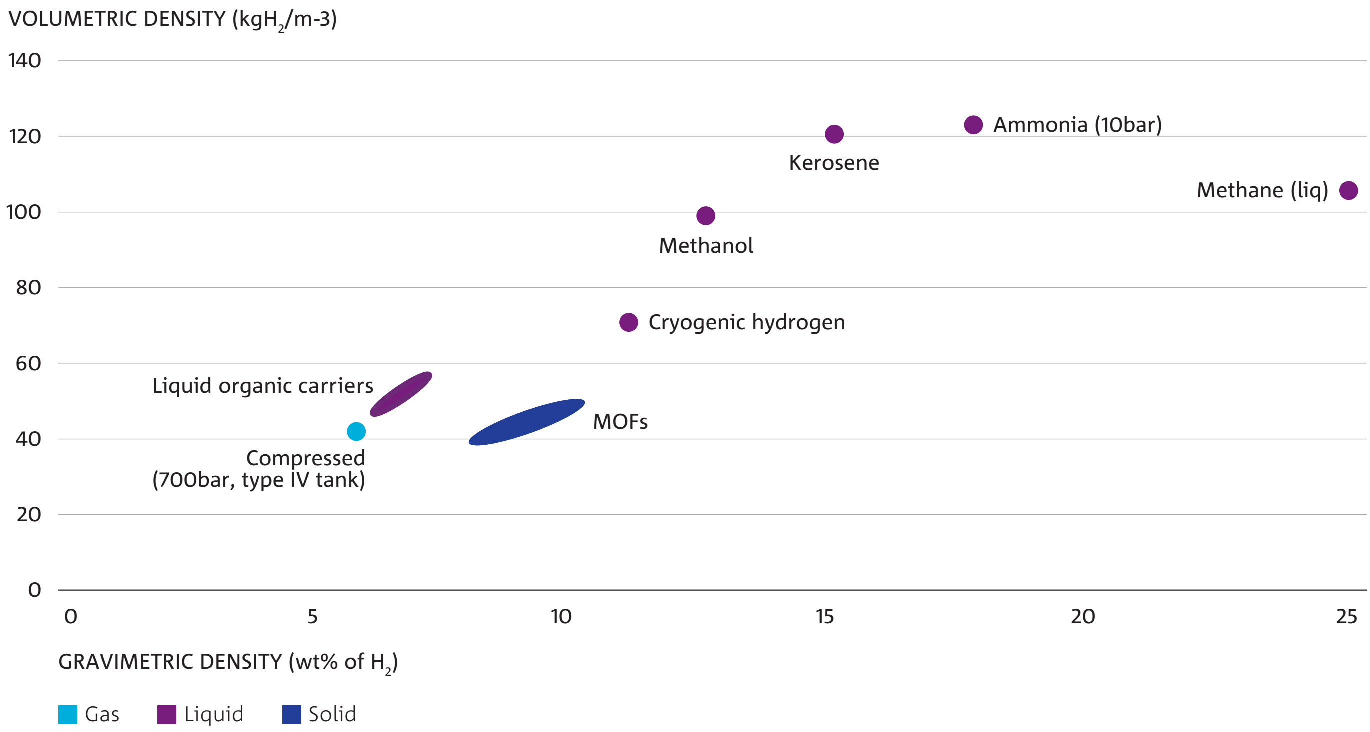

Figure 18. Volumetric and gravimetric densities of hydrogen storage[149,150,151,152]

149 Rivard E, Trudeau M, Zaghib K (2019) *Hydrogen storage for mobility: A review.* Materials

150 Jet fuel is comprised of a range of hydrocarbons, with chains ranging from C_8 to C_{16}, as an average, $C_{12}H_{26}$ was chosen to calculate %wt of H_2

151 Note that the wt% of cryogenic hydrogen is different to that proposed in Rivard 2019 given that it is sized for a vehicle in the relevant reference. Aircraft storage will be considerably greater and therefore have a more favourable wt%

152 Aakko-Saksa P, Cook C, Kiviaho J, Repo T (2018) *Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion.* Journal of Power Sources

153 Fuel processors have power densities ranging from 0.20 to 0.82kW/lb (0.45 to 1.8kW/kg)

Hydrogen tanks pressurized at 700bar are commonplace in ground transport today, with the latest fuel cell vehicles holding a single carbon fiber reinforced composite tank that can store 9-13lb (4-6kg) of gaseous hydrogen. However, storage of cryogenic hydrogen is comparatively less mature and has significant technical challenges relating to maintaining required temperatures and reducing hydrogen boil-off (or vaporization) which leads to fuel losses. Spherical tanks made of a range of alternating materials such as glass fiber, metal layers and foam insulation are most effective in reducing surface to air ratios and consequently the inward transfer of heat through the tank wall.[154] While the weight burden of pressurized hydrogen is approximately twice that of cryogenic hydrogen for the equivalent volume, the process of liquefying is more capital and energy-intensive which adds to the overall cost of fuel.

Chemical carriers such as liquid organic carriers (e.g. toluene) and MOFs require recycling of the carrier molecule and would therefore add a 'dead weight' to be carried for the full flight duration.

5.1.3 Economics of use

Excluding capital costs, consideration of hydrogen fuel cells for non-propulsion applications will generally center around a trade-off between fuel cost, demand and weight. While ongoing detailed analysis into these trade-offs using sophisticated design tools will be required, some of the general concepts are introduced below.

Using a Boeing 737 as an example, current APU systems weigh in the order of ˜2,400lb (1,088kg) which includes fuel supporting 6 hours of runtime. An equivalent fuel cell system with a compressed hydrogen tank at 700bar using current specific energies would weigh over double that amount (˜6,000lb or 2,700kg). This increase in weight stems primarily from the compressed storage (Type IV generation) hydrogen tank.

Minor improvements may be realized when the same APU system is used for the purposes of taxiing. If total average taxiing times are in the order of 40min (30min for taxi-out and 10 minutes for taxi-in),[155] hydrogen (including additional tank weight) adds ˜90lb (40kg). In contrast, existing systems would require 960lb (436kg) of jet fuel to meet the same taxiing requirements. However, the addition of electric taxiing systems adds another ˜880lb (400kg) which again undermines improvements in the weight of fuel.

Thus, while use of compression at 700bar obviates the need for liquefaction, it adds a significant burden in terms of weight and volume required (200ft^3 or 5.5m^3) which increases jet fuel requirements and thus worsens round trip economics. Some improvements can be realized via use of cryogenic hydrogen (which weighs 60% of compression at 700bar to meet the same hydrogen demand). However, this is likely to force a more involved redesign of aircraft (discussed further in Section 5.2.3) and higher operating costs.

Use of fuel cells for non-propulsion applications may therefore make more sense once hydrogen is introduced for propulsion. Alternatively, they may be used to demonstrate use of cryogenic hydrogen storage on-board aircraft prior to the roll-out of hydrogen combustion engines.

The use of fuel cells on-aircraft also provides an opportunity to harvest water as a by-product that can then be used for other in-flight applications such as restrooms and air humidification, thereby reducing water storage requirements and associated weight.

5.1.4 Environment

Local emissions and pollutants from aircraft are fast becoming an issue of growing concern at major airports. For example, studies recently undertaken at Los Angeles Airport (LAX) show detection of particle pollutants such as nitrogen oxides (NOx) at concentrations 4-fold normal levels 6.2mi (10km) downwind from the airport.[156]

Although use of hydrogen fuel cell systems for APU and taxiing would significantly reduce aircraft ground emissions, local pollution and noise, it will likely result in a net increase in round-trip aircraft emissions due to the additional weight and consequent increase in jet fuel consumed. In the more immediate term, this finding promotes the use of hydrogen powered GSE (i.e. GPUs and tugs) while the aircraft is on-ground.

This theme applies to the further roll out of more electric architecture supported by a fuel cell system, wherein as long as any increase in weight that stems from use does not result in increased fuel demand, emissions reductions can be achieved.

154 Rondinelli S, Sabatini R, Gardi A (2014) *Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation.* Engineers Australia Convention

155 Assumptions found in https://www.bts.gov/archive/publications/special_reports_and_issue_briefs/special_report/2008_008/entire

156 Hudda N, Gould T, Hartin K, Larson T, Fruin S (2014) *Emissions from an International Airport Increase Particle Number Concentrations 4-fold at 10 km Downwind*. Environmental Science & Technology

5.1.5 Safety

Use and handling of compressed and cryogenic hydrogen on-board aircraft would introduce a new series of safety risks to be managed. These are summarized in Table 13.

However, in a number of ways, hydrogen presents a potentially safer option due to the rigidity of pressurized and cryogenic storage tanks and the tendency for the gas to dissipate quickly in the event that it is ruptured. Note that this would require the tanks to be incorporated into aircraft in a way that allows hydrogen to escape should a rupturing event occur. Further, the heat and intensity of hydrogen-fueled fires are typically smaller than for kerosene[157] (i.e. heat radiation of a hydrogen flame is only 10% of a kerosene flame which makes it easier to contain.)[158]

Aircraft certification

An overview of the current process for new aircraft design approval is outlined in Appendix B. This process is intended to support the addition of discrete upgrades and significant effort is therefore likely to be required on the part of regulators to develop a certification process for materially new airframe designs and systems (e.g. to accommodate hydrogen for both propulsion and non-propulsion applications).

Currently, there are ongoing efforts to develop a regulatory framework for fuel cells used for propulsion (discussed further in Section 5.2.1). This work may also be leveraged to support the integration of fuel cells for non-propulsion applications. For instance, in 2008, the European Organisation for Civil Aviation Equipment (EUROCAE) and SAE International formed a committee to provide design integration and certification guidance for hydrogen fuel cell systems on transport aircraft (i.e. jets with 10 or more seats or propellers with greater than 19 seats). Work by SAE and EUROCAE has led to the development of guidelines for the installation of fuel cell systems (SAE AS6858 – Installation of Fuel Cell Systems in Large Civil Aircraft) and the corresponding safety guidelines (SAE AIR-6464 – Aircraft Fuel Cell Safety Guidelines).[161]

Further, the Energy Supply Device Aviation Rulemaking Committee (ARC) was established in 2015[162] to help inform FAA policy, identify hazards and determine how to incorporate this information into current standards and rules. The outputs from this committee will provide recommendations to the FAA to enable them to develop appropriate airworthiness standards and guidance for fuel cell and hydrogen technologies on transport aircraft.

Table 13. Safety risks for on-platform use of hydrogen[159,160]

RISK	DESCRIPTION
Flammability	Hydrogen gas is highly flammable and has a wide flammability range (4.3 vol% to 75 vol%), requiring very little air to ignite
Leakage	Hydrogen molecules are significantly smaller than other gases and can more easily pass through storage casings which results in increased leakage rates. This risk is compounded by the fact that hydrogen is also difficult to detect due to it being colorless and odorless. Leakage detection devices would be required to alert personnel
Low energy ignition	Hydrogen can mix easily with air and form flammable mixtures that can ignite with minimal energy (0.017MJ)
Embrittlement	Hydrogen can cause stress in materials by permeating the surface. This is seen in the case of steel where cracks may form after continued exposure. Material selection needs to be carefully considered to avoid embrittlement
Exposure	Although not corrosive or poisonous, contact with liquid hydrogen can cause injury. Additionally, in the event of a leak, the inhalation of hydrogen can cause asphyxiation

157 Rondinelli S, Sabatini R, Gardi A (2014) *Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation*. Engineers Australia Convention

158 Schmidtchen U, Behrend E, Pohl H, Rostek N (1998) *Hydrogen aircraft and airport safety.* Renewable and Sustainable Energy Reviews

159 H2 Tools (2019) *Hydrogen Compared with Other Fuels*. Pacific Northwest National Laboratory

160 Crowl D, Jo Y (2007) *The hazards and risks of hydrogen*. Journal of Loss Prevention in the Process Industries

161 Summer S (2017) *Fuel Cell Industry Working Group Update.* Available at https://www.fire.tc.faa.gov/pdf/systems/May17Meeting/Summer-0517-FuelCellIndustryWGUpdates.pdf

162 US Department of Transportation (2015) *Energy Supply Device Aviation Rulemaking Committee.* FAA

5.1.6 Hydrogen specific RD&D

Fuel cells

Improved fuel cell power density

The automotive industry has been the primary user and developer of PEMFCs to date. With significant improvements in power density achieved in recent years,[163] much of the current focus has shifted to improving durability and lowering component costs (e.g. by displacing use of a platinum catalyst with cheaper alternatives).[164]

However, adoption of fuel cells by the aviation sector may see the focus revert back to improving power density. Such improvements are likely to stem from advances in membrane electrode assembly which consists of the membrane stack, catalyst and electrodes. Studies have suggested this could help achieve a power density in the order of 3.6kW/lb (8kW/kg) up from 0.7kW/lb (1.6kW/kg) currently ,[165] and includes development of new lightweight catalysts as well as a change in overall catalyst design.

Further, improvements to bipolar plates, which make up 80% of the weight of a fuel cell stack, could yield significant reductions in overall mass. Currently, these plates utilize graphite-polymer material which could be replaced with metal alternatives coupled with coatings to prevent corrosion and reduce system weight.[165]

On-board storage

If compressed hydrogen is to be used for non-propulsion applications, considerable RD&D is needed to minimize the weight of storage tanks. Type IV composite vessels are currently being utilized to store hydrogen at 700bar in commercial vehicles. These composite vessels consist entirely of carbon fiber, lined with a high-density polymer.

The next wave of composite vessels (Type V and beyond) aim to achieve an H_2wt% above 6.5. To reduce weight, manufacturers are exploring new design techniques that apply the carbon fiber in precise patches around the domed ends of container cylinders, reducing the amount of required material overall.

Other mechanisms include removal of the polymer layer and increasing container volume. However, using the Boeing 737 APU example, realizing a 6.5 H_2wt% would only lead to a reduction of 811lb (367kg) or 15%.

Other RD&D measures will be focused on developing new materials that could support compression at 1,000bar. To progress this technology, research groups are exploring the development of plastic hybrid tanks with improved thermoplastic liner material to reduce permeation at high pressures. This research will also help to resolve issues relating to material degradation and stability through fill cycles, minimize manufacturing flaws and improve understanding of their effect on tank operation.[166]

Further RD&D will be required to enable scaling of production and customization to new specifications such as on-board aircraft.[167] Effort will also be needed to reduce the production cost of carbon fiber which makes up more than 75% of the composite tank component expenditure.[168]

Aircraft design with integrated fuel cells

While exact quantification of the benefits gained is beyond the scope of this report, further improvements in specific energy of fuel cell systems may be realized via integration early in the conceptual design phase. This involves the implementation of a design methodology that seeks to optimize the fuel cell system at the component level as a means of achieving the highest specific energy.[169] Such initiatives are likely to include designing the fuel cell stack components so they can be incorporated into the available space of the aircraft (rather than a retrofitted fuel cell container) and the integration of storage tanks into aircraft structural components.

5.1.7 Comparison with batteries

Depending on the aircraft type and power/energy requirements, battery systems may be viable for non-propulsion applications. As a general rule, greater requirements in terms of specific energy will typically favor the use of fuel cells (i.e. for longer, higher energy consuming flights).

163 Department of Energy (2016) *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan – Section 3.4 Fuel Cells*. DOE

164 Whiston M, Azevedo I, Litster S, Whitefoot K, Samaras C, Whitacre J (2019) *Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles*. Proceedings of the National Academy of Sciences of the United States of America

165 Kadyk T, Winnefeld C, Hanke-Rauschenbach R, Krewer U (2018) *Analysis and design of fuel cell systems for aviation.* Energies

166 FuelCellsWorks (2019) *HYPOS partners work on safe and lightweight high-pressure tanks for storing and transporting green hydrogen.* Available at https://fuelcellsworks.com/news/hypos-partners-work-on-safe-and-lightweight-high-pressure-tanks-for-storing-and-transporting-green-hydrogen/

167 CompositesWorld (2019) *The markets: Pressure vessels (2020)*. Available at https://www.compositesworld.com/articles/the-markets-pressure-vessels

168 Argonne National Laboratory (2010) *Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications.* DOE

169 Guida D, Minutillo M (2016) *Design methodology for a PEM fuel cell power system in a more electrical aircraft*. Applied Energy

When used as the sole power source, issues associated with batteries (when compared to fuel cells) include poorer recharge times while the aircraft is on-ground as well as reduced asset cycle life and consequent replacement requirements. Batteries are however used in conjunction with other power generators on today's aircraft platforms and future hybrid electric systems could be possible using batteries and fuel cells, particularly as a means of managing more rapid changes in power demand.

However, batteries are not devoid of risk and their introduction on platform has required the addition of new safety measures. This includes the need for batteries to be encased in a physical containment structure which adds to the weight of the system.[170]

5.2 Hydrogen for propulsion

Theoretically, jet engines can be designed to combust pure hydrogen (also known in the industry as 'Cryoplanes') as well as hydrogen-augmented fuels for the purposes of propulsion. While use of these fuels has the potential to create significant emissions abatement within the sector, integration in emerging aircraft will have a variety of challenges and trade-offs. Some forms of integration will lend more favorably to incumbent airframes whereas others are likely to be considered as part of more revolutionary step changes in commercial aviation.

Note that technically, hydrogen and hydrogen-augmented fuels also fall under the category of electrofuels. However, this term is not used in this context in order to differentiate from use of 'drop-in' electrofuels discussed in Section 4.

Jet engines explained[171]

The fundamental mechanism of a basic jet engine is to draw in air, compress it, combine it with fuel, ignite that fuel and release the hot gases through the rear of the engine to generate thrust. Modern large aircraft utilize a turbofan jet engine which has a large fan at the front to suck in air. The air is then split into two parts, one-part flows through to the core of the engine, while the second flows through a duct surrounding the core, producing the majority of thrust and helping reduce noise.

The air that passes through the core is progressively compressed via a series of 'compressors' that are attached to a shaft. The highly compressed air is passed through to the combustion chamber where fuel is injected via several nozzles and ignited. This combustion produces hot, expanding gases and the high energy air-flow passes into the turbine, causing the turbine to rotate, driving the compressors and fan at the front. Given that the air released through the rear of the engine is hotter and faster than the air coming through the front, additional thrust is generated which propels the aircraft forward.

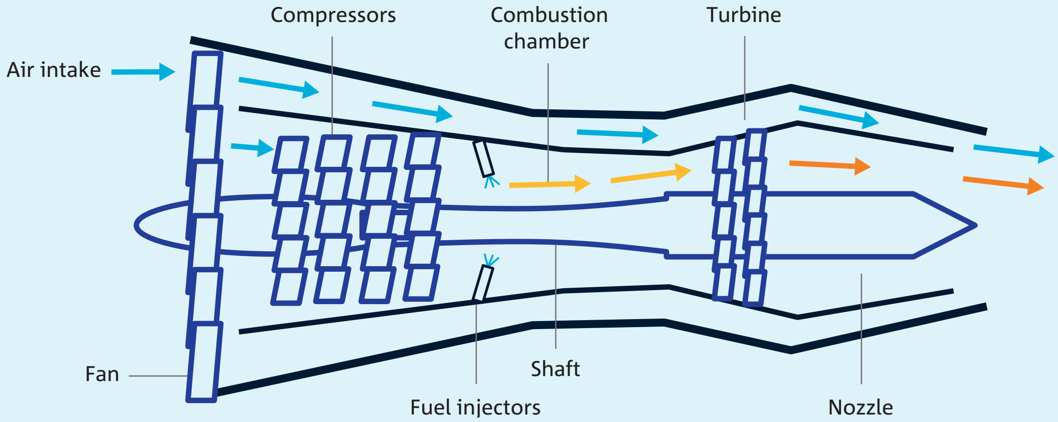

Figure 19. Diagram of a turbofan jet engine

170 Courtin C, Hansman J (2018) *Safety considerations in emerging electric aircraft architectures.* American Institute of Aeronautics and Astronautics

171 NASA (2007) *A NASA guide to engines*. Available at https://er.jsc.nasa.gov/seh/ANASAGUIDETOENGINES[1].pdf

5.2.1 Consideration of fuel cells for propulsion

In addition to the on-aircraft fuel cell applications set out in Section 5.1.2, there is considerable potential for fuel cells for propulsion in propeller aircraft (i.e. turboprops). This is the current focus of companies such as ZeroAvia.

Case study: ZeroAvia

ZeroAvia is developing a zero-emission, hydrogen-fueled electric drivetrain (which also includes a battery for high power requirements). The drivetrain is designed to be installed into existing airframes, targeting aircraft with capacities of 10-20 seats and capable of distances of up to 575mi (925km). The initial models will store hydrogen as compressed gas, with plans to include a liquid hydrogen storage option when safety regulations are implemented, increasing potential ranges to 1000mi (1600km).[172]

ZeroAvia claims that operating costs will be close to half that of fossil fuel-powered aircraft due to reduced fuel costs and maintenance requirements. Prototypes have successfully demonstrated the technology, powering a 6-seat aircraft. The company plans to supply the drivetrain commercially in 2022.[173]

Hydrogen fuel cell systems also lend favorably to vertical take-off and landing (VTOL) taxis which are emerging as a new form of urban aerial transport. Commercial VTOL services are expected to be launched in 2023, and it is estimated that more than 20,000 VTOLs will be flying by 2030. Fuel cells are expected to enable longer range travel than battery-powered alternatives (~75mi/120km and ~31mi/50km respectively) and quick refueling is also possible without risk of lifecycle reductions.[174]

However, use of fuel cells for propulsion is unlikely to be competitive for the heavy payload and long distances achieved by today's larger jet aircraft. Figure 20 illustrates this threshold via consideration of the current fuel cell weights required to achieve the same power output of today's aircraft engines as a percentage of maximum take-off weight. Even with an aggressive power density target of 3.6kW/lb (8kW/kg) already noted in Section 5.1.6, fuel cells would still weigh ~4 times as much as current jet engines for the same power output.

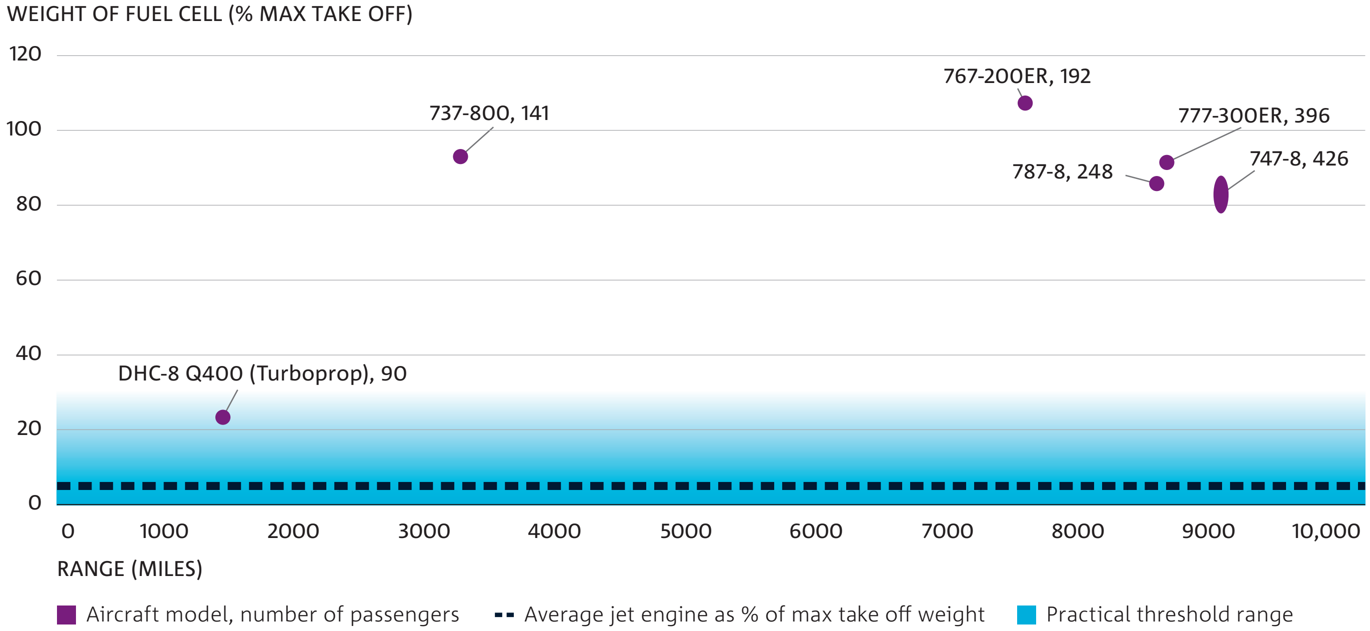

Figure 20. Threshold for use of fuel cell-driven electric planes

172 Moloughney T (2019) *ZeroAvia Bets On Hydrogen For Electric Air Travel*. Inside EVs

173 ZeroAvia (2019) Available at https://www.zeroavia.com/

174 Hydrogen Council (2018) *Hydrogen meets digital.* Available at https://hydrogencouncil.com/wp-content/uploads/2018/10/Hydrogen-Council-Hydrogen-Meets-Digital-2018.pdf

Thus while there is much that can be leveraged from development of fuel cell-powered aircraft as an earlier stage opportunity, given that the focus of this report is on the more emissions-intensive jet engines, the remaining subsections focus on the potential for combustion of hydrogen and hydrogen augmented fuels.

It is also important to consider the potential impact of fuel cell assisted take off. Given that jet engines are typically sized to accommodate peak demand requirements for the take-off and/or top-of-climb phases of flight, supplementing the thrust source with electric motors could allow for the design of smaller and more efficient jet engines. [175]

5.2.2 Potential fuels

There are several potential hydrogen-augmented fuels to be considered for direct use in jet engines as presented in Table 14. In contrast to the hydrogen storage technologies described in Section 5.1.2, these involve direct combustion of the fuel in question (e.g. combustion of ammonia), as distinct from the release of hydrogen from a carrier molecule.

Table 14. Hydrogen based jet fuels to be considered for commercial aviation

FUEL	DESCRIPTION	(DIS)ADVANTAGES
Hydrogen (H_2)	A colorless and odorless gas that can be combusted in a turbine to generate energy.	+ Water is the primary by-product from combustion + Good specific energy density − Potentially generates increased NOx due to high combustion temperatures
Ammonia (NH_3)	Carbon-free alternative fuel that is colorless and liquid under mild conditions.	+ Extensive infrastructure for production and transport exists − High ignition temperature − Generates NOx on combustion − Lightly pressurized to be a liquid at ambient temperatures − Highly toxic
Methanol (CH_3OH)	A light, volatile, colorless and flammable liquid.	+ Less expensive than ethanol + Flames can be extinguished with water − Burns with a clear flame
Ethanol (C_2H_5OH)	A light, volatile, colorless and flammable liquid. Contains more energy than methanol.	+ Previously used as a fuel − Different interactions with elastomers than kerosene
DME (CH_3OCH_3)	Gas in ambient conditions and liquid at 6 bars of pressure. In its liquid form, DME can be used as a substitute for diesel.	+ History of use in diesel engines due to high octane levels + Low particulate emissions − Different interactions with elastomers than kerosene
Methane or LNG (CH_4)	A gas at ambient conditions, methane can be liquified at -162°C to improve its density. Methane has a long history of powering stationary turbines and can be combusted with hydrogen.	+ Long history of use in turbines + Can utilize existing natural gas infrastructure + Hydrogen rich − Requires cryogenic temperatures for adequate density
n-octane (C_8H_{18})	A colorless liquid with the odor of gasoline.	+ Similar characteristics to jet fuel[176]

175 ICAO Secretariat (2019) *Electric, Hybrid, and Hydrogen Aircraft – State of Play*. ICAO

176 Goldmann A, Sauter W, Oettinger M, Kluge T, Schroder U, Seume J, Friedrichs J, Dinkelacker F (2018) *A Study on Electrofuels in Aviation*. Energies

Use of hydrogen-augmented fuels to date

There is significant precedent regarding the use of hydrogen augmented fuels for jet engines, with a number having been demonstrated in recent decades (illustrated in Figure 21).

Similarly, a number of research efforts have been focused on the development of hydrogen for propulsion, most notably the Cryoplane program from 2000–2002.

> **Liquid hydrogen fueled-aircraft – system analysis (CRYOPLANE)[177]**
>
> The Cryoplane project was funded by the European Union and was conducted by a consortium of 35 partners led by Airbus Deutschland. The research effort aimed to perform a systems analysis of the applicability, safety and environmental compatibility of hydrogen fueled aircraft as well as investigate medium to long-term scenarios for a transition from kerosene to hydrogen. The project produced numerous findings on the viability and requirements of this transition including assessing safety, examining emission profiles, highlighting airworthiness amendments and outlining further RD&D required to develop materials, parts, components and engines for the transition.

Hydrogen blending

Blending of conventional jet fuel with hydrogen is another means by which it can be introduced into aircraft. Recent studies have found the addition of small quantities of hydrogen to kerosene to be effective in improving the overall combustion efficiencies at all levels of engine thrust. For example, simulating a Boeing 777-ER, one study showed that the addition of 5% hydrogen reduced fuel consumption by 8%.[178] Other benefits include a potential reduction in take-off weight due to the superior specific energy of hydrogen (detailed further in Figure 22).

However, the primary challenge relating to hydrogen blending concerns the method in which mixing occurs. This could be achieved via pre-mixing or injection at the point of combustion:

1. **Pre-mixing**: There may be scope to combine hydrogen with jet fuel prior to aircraft loading. The solubility of hydrogen in a liquid fuel is directly proportional to the number of hydrocarbons, the storage temperature and pressure.[179] The primary advantage of this method is the ability to retain a single method of fuel distribution. However, challenges arise in maintaining the mixture in aircraft storage tanks, where at ambient temperature, the mixture separates due to the large density differences between hydrogen and jet fuel. Unless there is a change in storage conditions (i.e. temperature and pressure), the hydrogen will remain in the headspace of the tank while the jet fuel is used.

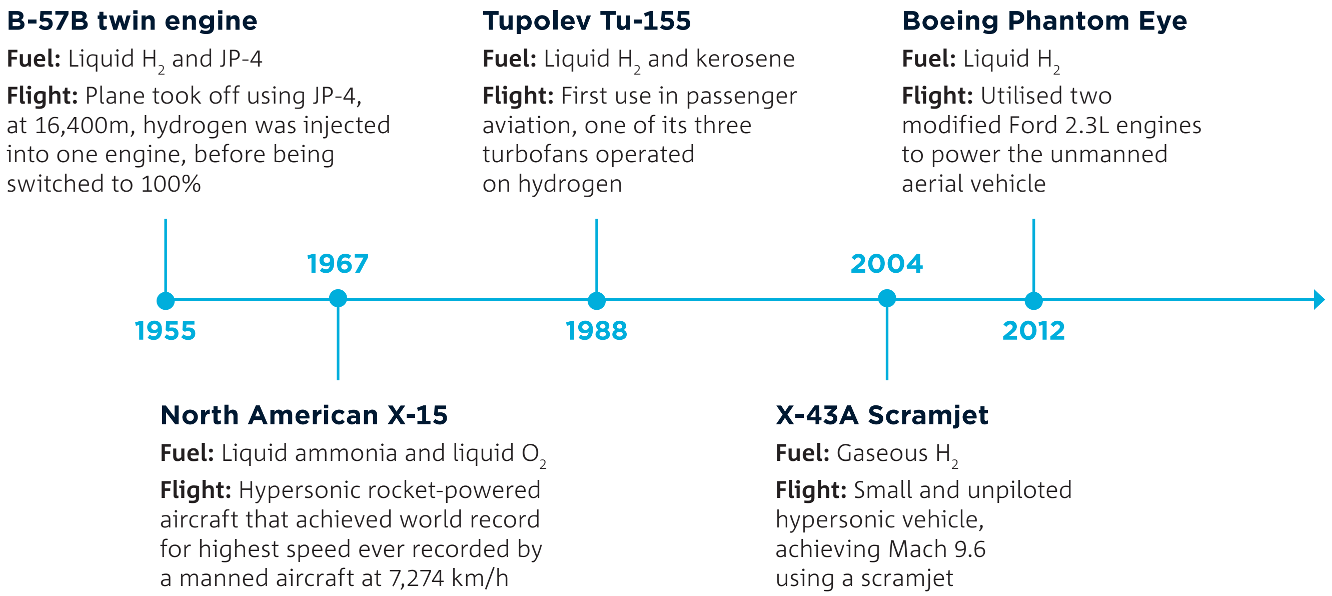

Figure 21. Use of hydrogen-based fuels for jet engines

177 Airbus Deutschalnd et al. (2003) *Liquid Hydrogen Fuelled Aircraft – System Analysis; final technical report*. European Community

178 Juste GL, Benavides E (2008) *Feasibility analysis of hydrogen s additional fuel in aircraft propulsion*. International Journal of Green Energy

179 Riazi M, Roomi A (2007) *A method to predict solubility of hydrogen in hydrocarbons and their mixtures.* Chemical Engineering Science

2. **Hydrogen injection at the point of combustion**: This method would involve the co-injection of gaseous hydrogen into the combustion chamber along with jet fuel. Challenges arise with respect to the required changes in airframe and jet engine design to accommodate hydrogen storage and distribution to the combustor. Part of this challenge could be overcome if there are already on-board hydrogen storage facilities for non-propulsion applications discussed in Section 5.1.

Combustion of hydrogen, even at small quantities (i.e. maximum 5%) also brings a range of safety considerations that would need to be managed via changes in engine specifications. These are considered further in the discussion on jet engines below.

Storage

On-aircraft storage

Figure 22 compares the respective energy densities by volume and by mass of each of the fuels. The former is important in the context of on-platform storage space whereas the latter is necessary in terms of round-trip weight. Both kerosene and lithium batteries have been included as reference points. The impact of use of these fuels on flight economics is then discussed in Section 5.1.3.

On-airport storage

Conventional Jet A is typically stored in large tanks adjacent to the airport, where it is allowed to settle and is subject to final quality testing. The fuel is then transferred to aircraft for refueling via truck or through the use of hydrant systems. Fuels such as methanol and ammonia have the potential to follow a similar supply chain due to the relative ease with which they can be transferred from the storage facility.

The logistical challenge is greater for compressed or cryogenic hydrogen. Major airports are expected to require 1,000s of metric tons of hydrogen per day once there is a meaningful uptake of hydrogen-powered aircraft.[180] At such volumes, it is unlikely that an airport (and adjacent land) would retain the required energy resources to support this level of demand. A potential scenario could therefore involve the import of compressed gaseous hydrogen via pipeline, which adds an implicit storage mechanism, combined with a liquefaction plant on or near the airport. Some studies have suggested that hydrogen could be delivered to aircraft using similar underground hydrant systems with vacuum insulated supply lines.[180]

Jet engines

As discussed in Section 4.2, there are a number of important characteristics of Jet A fuel that when paired with the specific function of jet engines, allow aircraft to operate in their current manner. Therefore, a complete change in the fuel used will trigger a redesign and re-optimization of jet engines. While significant RD&D will be required, some of the overarching themes are discussed below.

Hydrogen augmented fuels

Of the hydrogen augmented fuels listed in Table 13, n-octane would require the least number of modifications to engine and plane design due to its similar operating properties to jet fuel (e.g. flash point, vapor pressure and boiling point). Fuels such as methanol and DME however have significantly different combustion characteristics and are likely to require modifications in engine design. This includes changes to the combustion chamber to ensure flame stabilization and to turbines which may require redesign to mitigate the effects of different combustion rates, flame speeds and temperatures.[181]

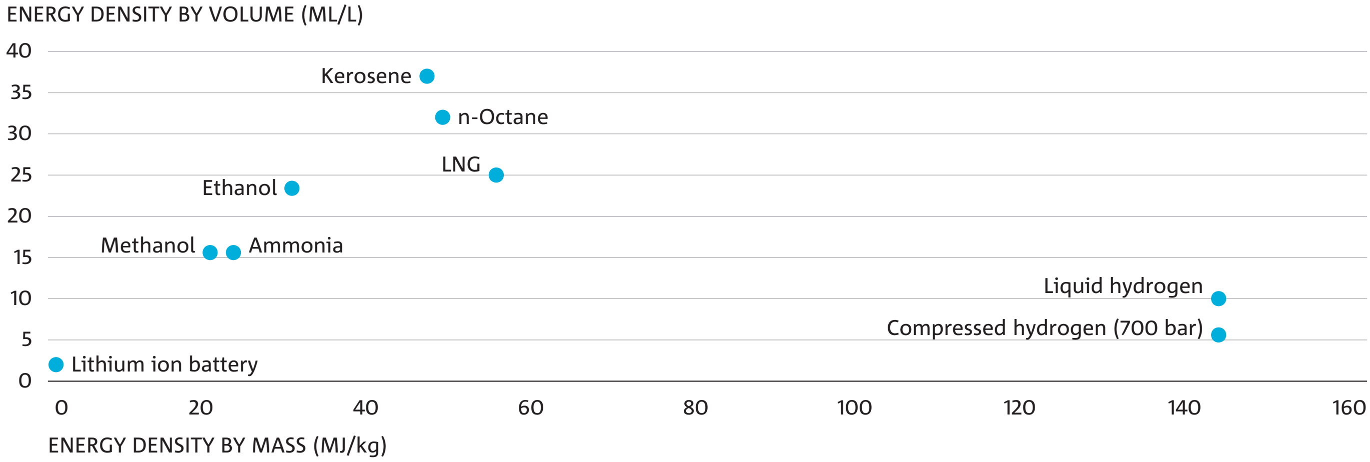

Figure 22. Energy densities for combustion for hydrogen-based fuels

180 Peschka W (1992) *Liquid hydrogen, fuel of the future*, Springer-Verlag Wien New York

181 Goldmann A, Sauter W, Oettinger M, Kluge T, Schroder U, Seume J, Friedrichs J, Dinkelacker F (2018) *A study on electrofuels in aviation*. Energies

For oxygenated hydrocarbon fuels (e.g. methanol, ethanol and DME), suitable seals on tanks and distribution systems would need to be used, as these have significantly different interactions with elastomers than kerosene. Fuel additives including lubricants, anti-static agents, antioxidants and corrosion inhibitors would also be required. However, given that these components are added to kerosene currently, this would not result in a significant departure from current practice, requiring only a reformulation specific to the fuel in use.

Hydrogen

Gaseous hydrogen has a wide ignition range and therefore only minor modifications to the engine combustion chamber may be necessary.[182] Rather, and particularly in the case of cryogenic hydrogen, extensive changes will be required to support equipment such as pumps, supply pipes and control valves. A heat exchanger will also be required to vaporize liquid hydrogen before entering the combustion chamber.[182]

As noted in Table 13, metals commonly used in aircraft including aluminum, titanium and steel in particular, are all susceptible to hydrogen embrittlement. Minimization of embrittlement will likely add to the cost and complexity of direct hydrogen use.

Another primary issue relating to use of hydrogen concerns the higher combustion temperatures achieved which promotes the production of NOx (discussed further in Section 5.2.4) and could result in the degradation of other engine components such as the turbine blades. Addressing this problem requires pre-mixing of hydrogen with air (discussed further in Section 5.2.6) to reduce operating temperatures. However, this process increases the risk of premature burning or 'compressor surge' (which is an uncontrolled upstream propagation of the flame) due to the high reactivity of hydrogen with air.[183]

5.2.3 Economics of use

Fuels such as methanol are typically liquids at ambient temperature and therefore may not require an extensive restructuring of aircraft design (e.g. fuel could continue to be stored in the wings). However as shown in Figure 21, these fuels have significantly lower volumetric densities, and with the exception of LNG, reduced densities by mass compared to kerosene. This makes their use less economically competitive as they place limits on long haul travel. The 'well to wheel' efficiencies may also be reduced compared to cryogenic hydrogen (accounting for the energy and cost penalty of liquefaction) due to the need to react it further with CO_2 to produce these higher-order fuels.

Ammonia and DME are both gases at ambient conditions but can be compressed to liquid at relatively low pressures. This improves their specific energy density but may require redesign of on-board storage to allow for these higher pressures. Further, for carbonaceous fuels, combustion still results in the generation of CO_2. This brings into question the motivation for undertaking changes to engine design and infrastructure to accommodate a fuel with a lower energy density and a CO_2 emissions footprint.

In contrast, cryogenic hydrogen has the most favorable energy density by weight of the listed fuels (including kerosene) with no CO_2 emissions generated on combustion. However, with considerably lower volumetric densities than kerosene and the requirement for specialized tanks to maintain high pressures and low temperatures, redesign of existing airframes would be necessary.

Airframe design

The requirement for special purpose tanks raises the question of optimal placement within an aircraft. Studies have compared the benefits of 'integral' (inside the fuselage) and 'non-integral' (outside the fuselage) and shown that positioning the tanks above the passenger cabin but inside the fuselage is the best way to reduce drag, maintain structural integrity and ensure an even distribution of weight.[184]

182 Dagget D, Hendricks R, Walther R, Corporan E (2006) *Alternate Fuels for use in Commercial Aircraft*. Boeing Company
183 Dahl G, Suttrop F (1998) *Engine control and low-NOx combustion for hydrogen fuelled aircraft gas turbines*. International Journal of Hydrogen Energy
184 Rondinelli S, Sabatini R, Gardi A (2014) *Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation*. Engineers Australia Convention

For cryogenic storage, special purpose spherical tanks are likely to add a significant weight burden to aircraft, with one study suggesting there would be an increase in the operating empty weight (OEW) of up to 13%. Take-off weight however would be 5% lighter than kerosene equivalents due to hydrogen being a lighter fuel. Use of cryogenic hydrogen is therefore potentially more favorable for longer-range flights (i.e. greater than 3000mi/5,000km) where higher quantities of fuel can be stored without as significant a weight penalty.[185]

Blended-wing-body

Challenges that arise in relation to the volumetric energy density of hydrogen may provoke a move away from conventional aircraft designs to a model that can accommodate larger fuel storage tanks. This includes the development of 'blended wing body' designs which resemble a flying wing as shown in Figure 23. Despite extensive engineering challenges that would need to be overcome to support this design, some of the potential advantages include higher aerodynamic efficiency, reduced drag (10-20%) and noise, wing weight reduction and engine integration.[186] Importantly for cryogenic hydrogen, the cargo and passenger load are distributed across a wider fuselage, increasing the volumetric capacity of the aircraft.[187]

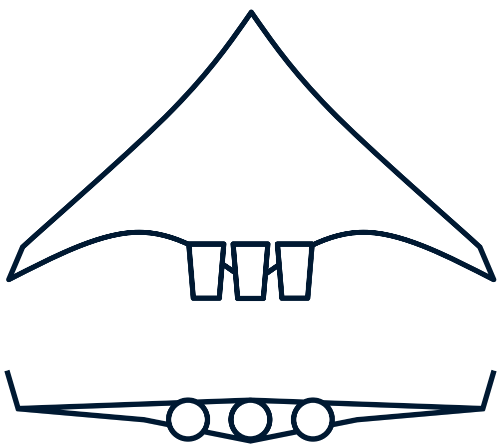

Figure 23. Blended wing body aircraft design

Rocket engines (Synergistic Air-Breathing Rocket Engine)

Whereas jet engines take in air from the atmosphere, rocket engines (or 'Scramjets') carry their own oxidizer (i.e. oxygen) which is combined with fuel and combusted to produce thrust. This system enables rocket engines to operate in space and to achieve higher speeds than jet engines which are restricted by the need to compress oxygen from air and therefore can only reach speeds up to approximately Mach 3. [188]

Rocket engines are expected to play a role in a potential overhaul of long-distance commercial aviation, with hydrogen shaping as a promising fuel. For example, with funding from the European Space Agency and the UK government, private company Reaction Engines are developing a SABRE or Synergistic Air-Breathing Rocket Engine.

Case study: Synergistic Air-Breathing Rocket Engine

The SABRE is a hybrid engine that works in two modes. For speeds up to Mach 5.4, the rocket takes in air from the atmosphere where it is compressed and cooled from 1000°C to -150°C using onboard liquid hydrogen. The compressed air is then combined with liquid hydrogen in the rocket combustion chamber and ignited to produce thrust. After achieving Mach 5.4, the inlet cone is shut off, creating a closed cycle rocket engine, burning liquid hydrogen with liquid oxygen instead of atmospheric oxygen to potentially produce speeds of Mach 25.

The SABRE could be used to take payloads to space or be utilized in commercial flight, with advertised speeds reducing the travel time between Brussels and Sydney to just over 4 hours with no CO_2 emissions. Due to the hybrid engine, SABRE could help to reduce the amount of oxidizer required, significantly lowering the costs of aerospace travel. Although discrete parts have been tested independently, the overall system has yet to be demonstrated.[188]

185 Dagget D, Hendricks R, Walther R (2006) *Alternative Fuels and Their Potential Impact on Aviation.* NASA

186 Chen Z, Zhang M, Chen Y, Sang W, Tan Z, Li D, Zhang B (2019) *Assessment on critical technologies for conceptual design of blended-wing-body civil aircraft.* Chinese Journal of Aeronautics

187 NASA (2017) *Past Projects: X-48B Blended Wing Body.* Available https://www.nasa.gov/centers/dryden/research/X-48B/index.html

188 Reaction Engines (2019) *SABRE: Synergetic Air-Breathing Rocket Engine.* Available at https://www.reactionengines.co.uk/sabre

Hydrogen demand and cost

The quantities of hydrogen needed to support the aviation sector are anticipated to be of the same order of magnitude as that required for electrofuel production determined in Section 4.2.2. Figure 24 shows the quantities of hydrogen required to support some of the most travelled flight paths globally.

As hydrogen-fueled aircraft are rolled out, hydrogen production could be gradually diverted away from the production of synthetic fuels. Such quantities would have the same observed impact on price, with the cost of hydrogen likely to be in the order of $0.53/lb ($1.16/kg). While cryogenic hydrogen is likely to be cheaper on a dollar per gigajoule basis than the observed 'best case' for electrofuels, more work is required to determine the expected additional cost of liquefaction of hydrogen over the coming decades.

Refueling infrastructure requirements

Extended periods in which an aircraft is on-ground have an adverse impact on airline business models with cost estimates ranging from $11-30/min.[190] This is expected to become increasingly challenging as passenger numbers grow. Turn-around times, particularly when it comes to refueling, are therefore critical.

To facilitate turn around requirements, current hydrant systems can dispense fuel at 1,050gal/min (4,000L/min)[191], filling a Boeing 787's 33,550gal (127,000L) fuel tank in just over 30 minutes. The challenge is likely to be significantly greater for cryogenic hydrogen refueling due to its low fuel density and flow rates (as compared with jet fuel). Maintaining the required temperatures and pressures between the ground supply system and aircraft tanks to reduce boil-off also presents a significant challenge. Some studies have suggested that turn-around times of 1-hour for larger jets could be achieved.[192]

Progressive infrastructure roll-out

One of the luxuries enjoyed by the commercial aviation sector is the ability to travel to any airport in the knowledge that jet fuel of a specified and suitable standard will be available. This adds another layer of complexity to the potential for any change in aircraft design and jet fuel use.

Given the safety challenges and need to improve overall stakeholder acceptance, hydrogen-fueled planes may be first employed specifically for freight, as opposed to passenger transport, to allow for scale-up of aircraft and training of pilots. For passenger routes, the initial focus should be on building infrastructure to support the most popular flight paths, with gradual expansion as the industry matures.

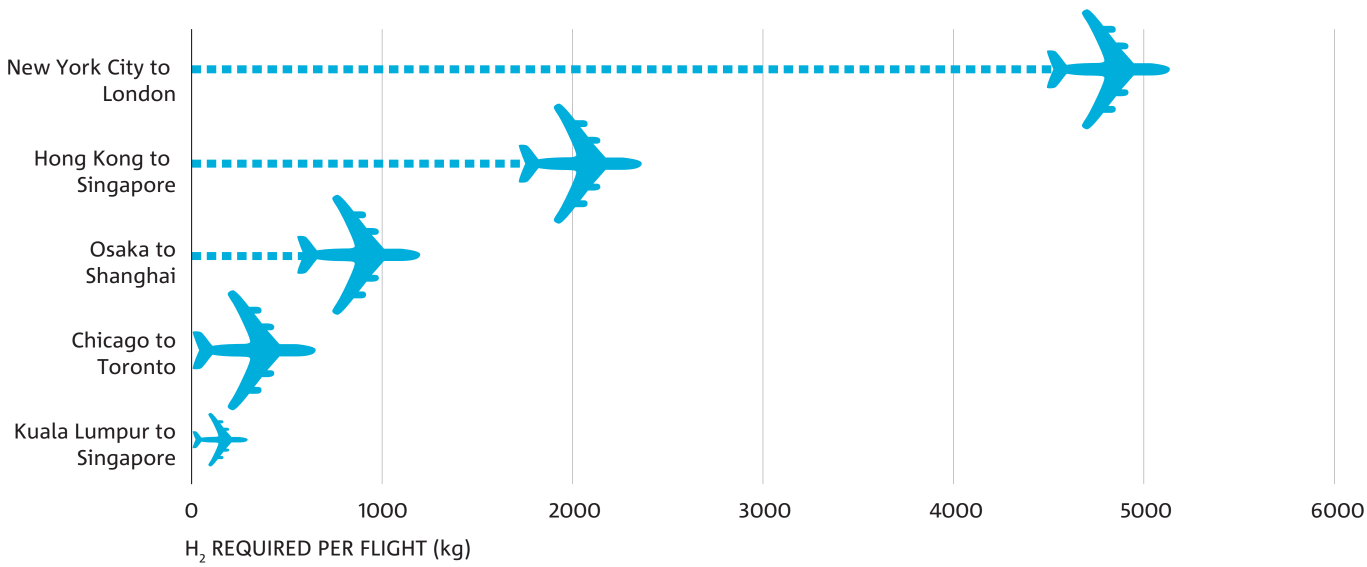

Figure 24. Quantities of hydrogen required for most travelled flight paths[189]

189 Assumed energy utilisation equivalence between Jet A and hydrogen aircraft based on Brewer G, Morris R, Lange R, Moore J (1975) *Summary report: Study of the application of hydrogen fuel to long-range subsonic transport aircraft*. Lockheed

190 Ferguson J, Kara A, Hoffman K, Sherry L (2011) *Estimating domestic US airline cost of delay based on European model*. Transportation Research

191 Airport Suppliers (2020) *Refuel International*. Available at https://www.airport-suppliers.com/supplier/refuel-international/

192 Dagget D, Hendricks R, Walther R (2006) *Alternative Fuels and Their Potential Impact on Aviation*. NASA

5.2.4 Environment

Emissions and particulates

As mentioned in Section 5.2.3, hydrogen augmented fuels such as methanol and DME contain carbon and will emit CO_2 upon combustion.

For non-carbon fuels such as ammonia and hydrogen, the primary emissions component from combustion (along with water in the exhaust) are nitrous oxides (NOx). Even when there is no nitrogen in the fuel, NOx are formed via the reaction of oxygen and nitrogen in the air at high temperatures caused by combustion of the fuel. This can be mitigated via use of Lean-Direct Injection and Micro-Mixing (discussed further in Section 5.2.6) which aim to reduce the size of flames, improve mixing and in turn, minimize NOx.[193] That said, a significant amount of effort is required to determine the overall GHG impacts of combustion of pure hydrogen, including the production of contrails.

Contrails

Contrails are thin cloud streams that may be observed trailing jet aircraft when cruising at high altitudes. As water vapor is released from the combustion of fuel, it meets the cold atmosphere and freezes around particles that are also expelled from the engine or particles present in the air. Contrails affect the temperature structure of the atmosphere by interfering with the flow of radiation from the sun and radiation reflected from the Earth.[194] Unlike CO_2, contrails have an immediate effect on radiation, but their duration is much shorter, lasting only minutes to hours.

Due to the absence of soot particles released from the combustion of hydrogen, there are fewer sites for water vapor to bind to and form contrails as compared with conventional jet engines. This could result in optically thinner contrails and thus lower radiative forcing. However, since the combustion of hydrogen produces 2.6 times more water vapor compared to jet A, contrails will form under warmer conditions (i.e. both regional and altitude). The net benefit of hydrogen fueled airplanes for contrails is therefore highly uncertain and further studies are needed.

Noise

In a direct comparison of hydrogen with kerosene engines of similar size, certain studies have shown minimal difference in noise levels.[195] However, as hydrogen planes are likely to have a lighter take-off weight than jet fuel equivalents, it has been suggested they may require smaller engines which will lead to reduced levels of noise.[196] Reductions in engine size and noise could also be assisted through the development of fuel cell assisted take-off.

5.2.5 Safety

Hydrogen and hydrogen-augmented fuels have different risk profiles when it comes to on-aircraft safety. For hydrogen in particular, due to the differences in fuel properties and the changes to airframe required, a new regulatory framework will be needed to govern handling and use. The basis for these regulatory frameworks have been discussed to some extent in Section 4.2.3 (ASTM certification requirements), 5.1.5 (aircraft design certification) and 5.1.5 (safety considerations for hydrogen in non-propulsion applications).

Several other safety issues arise specifically relating to refueling. The large flammability range (4.3 vol% to 75 vol% in air) of hydrogen, combined with its low ignition energy means that leakage could have serious consequences if an explosive atmosphere is formed (i.e. above 4.3 vol%). Leakage detection is more difficult in this context because odorants cannot be added to hydrogen in its cryogenic form. Complex hydrant systems that mitigate the risk of leakage would therefore need to be developed.

193 Rondinelli S, Sabatini R, Gardi A (2014) *Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation*. Engineers Australia Convention
194 Karcher B (2018) *Formation and radiative forcing of contrail cirrus*. Nature Communications
195 Brewer G, Morris R, Lange R, Moore J (1975) *Summary report: Study of the application of hydrogen fuel to long-range subsonic transport aircraft.* NASA
196 Brewer G (1982) *The prospects for liquid hydrogen fuelled aircraft*. International Journal of Hydrogen Energy

5.2.6 Hydrogen specific RD&D

Liquefaction and refueling

Liquefaction of hydrogen is an energy-intensive process and considerable RD&D is therefore required to improve process efficiencies. To produce cryogenic hydrogen, the direction in which hydrogen atoms spin needs to be altered. This process is the most challenging component of liquefaction, requiring complicated cooling processes, catalysts and large amounts of energy.[197] Identifying innovative and low-cost catalysts beyond the current use of hydrous ferric oxide can assist with increasing the efficiency of the process.[198] There is also a need for new and optimized design concepts for more efficient kinetic management, including various precooling, cooling and compression methods utilizing a range of refrigerants and heat exchangers.[199]

NASA and its affiliates have undertaken significant work in recent decades on the design and development of cryogenic hydrogen refueling infrastructure. This includes diagnostic solutions to identify faults when they occur and appropriate safety systems like venting and drainage.[200] Such expertise could be leveraged and applied to a cryogenic refueling system design for commercial aircraft.

Lean direct injection and micro-mixing

One method of reducing the NOx impacts of aviation is lean direct injection (LDI), which is a lean-front-end combustion concept. This means the combustor operates with a higher concentration of air than needed and all the combustor air, except that used for cooling, enters through the combustor dome.

LDI requires optimally mixed fuel and air before burning to eliminate hot spots that produce NOx. This optimization can be assessed using advanced diagnostic systems to computationally and experimentally explore new injection designs like micro mixing distributions.[201] These techniques will allow experimentation with various operating conditions like fuel ratios, pressure and combustion control.[202] Multiple versions of LDI technology exist, with varying associated levels of maturity (e.g. TRL 7 for Rolls Royce LDI and TRL 5 for multipoint injection LDI).[203]

On-board liquid storage

Minimizing or utilizing hydrogen boil-off is one of the primary challenges associated with cryogenic storage. Boil-off recovery is a potential solution wherein the hydrogen that evaporates is captured by the system and utilized by the fuel cell or engine on-board.[204]

The choice of insulation material selection, as well as its configuration, will also play a significant role in reducing boil-off. Optimizing this configuration with respect to the parameters of the aircraft (including available space and mass) will be essential. Variables that need testing and optimization include tank volume, tank structure, tank-wall material, insulation, thermal modelling and pressure changes. All these elements require computational analysis and experimentation to test for the ideal configuration.[205]

Space agencies and their affiliates have made significant progress in the last few decades in reducing cryogenic tank weight in order to minimize launch mass. Moving away from aluminum-lithium tanks, NASA/Boeing have tested composite Cryotanks and hope to achieve 30% weight reduction with cost savings of 25%.[206] The additional challenge however is to ensure these lighter-weight materials also reduce heat transfer.[207]

197 Charnock S, Temminghoff M, Srinivasan V, Burke N, Munnings C, Hartley P (2019) *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO

198 Ainscough C, Leachman J (2017) *Improved hydrogen liquefaction through Heisenberg Vortex separation of para and ortho-hydrogen*. Available at https://www.hydrogen.energy.gov/pdfs/review17/pd130_ainscough_2017_o.pdf

199 Yin L, Ju Y (2019) *Review on the design and optimization of hydrogen liquefaction processes*. Frontiers in Energy

200 Daigle M, Foygel M, Smelyanskiy V (2014) *Model-based Diagnostics for Propellant Loading Systems.* IEEE Aerospace Conference Proceedings

201 Ren X, Sung C, Mongia (2018) *On Lean Direct Injection Research*. Green Energy and Technology

202 Tacina K, Chang C, He Z (2014) *A second generation swirl-venturi lean direct injection combustion concept*. American Institute of Aeronautics and Astronautics

203 Liu Y, Sun X, Sethi V, Nalianda D, Li Y, Wang L (2017) *Review of modern low emissions combustion technologies for aero gas turbine engines*. Progress in Aerospace Sciences

204 Petitpas G (2018) *Boil-off losses along LH2 pathway*. Lawrence Livermore National Laboratory

205 Winnefeld C, Kadyk T, Bensmann B, Krewer U, Hanke-Rauschenbach (2018) *Modelling and Designing Cryogenic Hydrogen Tanks for Future Aircraft Applications*

206 NASA (2013) *Composite Cryotank Technologies & Demonstration*. Available at https://gameon.nasa.gov/gcd/files/2015/11/FS_CCTD_factsheet.pdf

207 Zheng H, Zeng X, Zhang J, Sun H (2018) *The Application of Carbon Fiber Composites in Cryotank*, Solidification. DOI: 10.5772/intechopen.7312

6 Synthesis

Figure 25 illustrates the potential aviation sector CO_2 emissions abatement (against the industry 2050 target) that could be achieved through the incorporation of hydrogen-based technologies. A summary of the investment priorities and consequent rates of uptake are set out below.

Note that a detailed LCA of electrofuels has not been undertaken as part of this analysis. However, it has been assumed that clean hydrogen is combined with a waste stream of CO_2 to produce carbon neutral jet fuel. The initial blending rate has been set at 50% in line with the 'best case' assessed in Section 4 and with the maximum rate currently approved under the ASTM for synthetic fuels produced via FT.

Given the significance of jet fuel in terms of sector emissions, it is evident that a blending rate of 50% does not enable the 2050 target to be achieved. While it is accepted that higher blending concentrations are likely to gain approval (in the near future) and that electrofuel production could increase accordingly, the level of infrastructure required to support this demonstrates the importance of other types SAF in achieving industry goals.

6.1 On-airport

Although not a material contributor in terms of sector-wide emissions reduction, on-airport applications provide a more immediate (i.e. ~2025) opportunity to introduce hydrogen into the commercial aviation sector, through the replacement of diesel/gasoline GSE with fuel cell alternatives. While battery powered GSE represent a complementary solution, hydrogen is likely to be a more favorable option for airports with continuous operations given that fuel cell GSE will require significantly less change in behavior (e.g. no need for long charging times and multiple charging points).

One of the primary obstacles associated with roll-out of fuel cell GSE will be achieving an adequate scale of hydrogen production while balancing supply and demand. This is particularly challenging considering the variety of equipment requiring upgrade. In the early stages of development, a reasonable degree of scale can be achieved with a lower risk profile by prioritizing fuel cell powered off-the-shelf technologies such as forklifts, cars, buses and stationary power. Forklifts and stationary power equipment are expected to be commercially competitive with diesel equivalents.

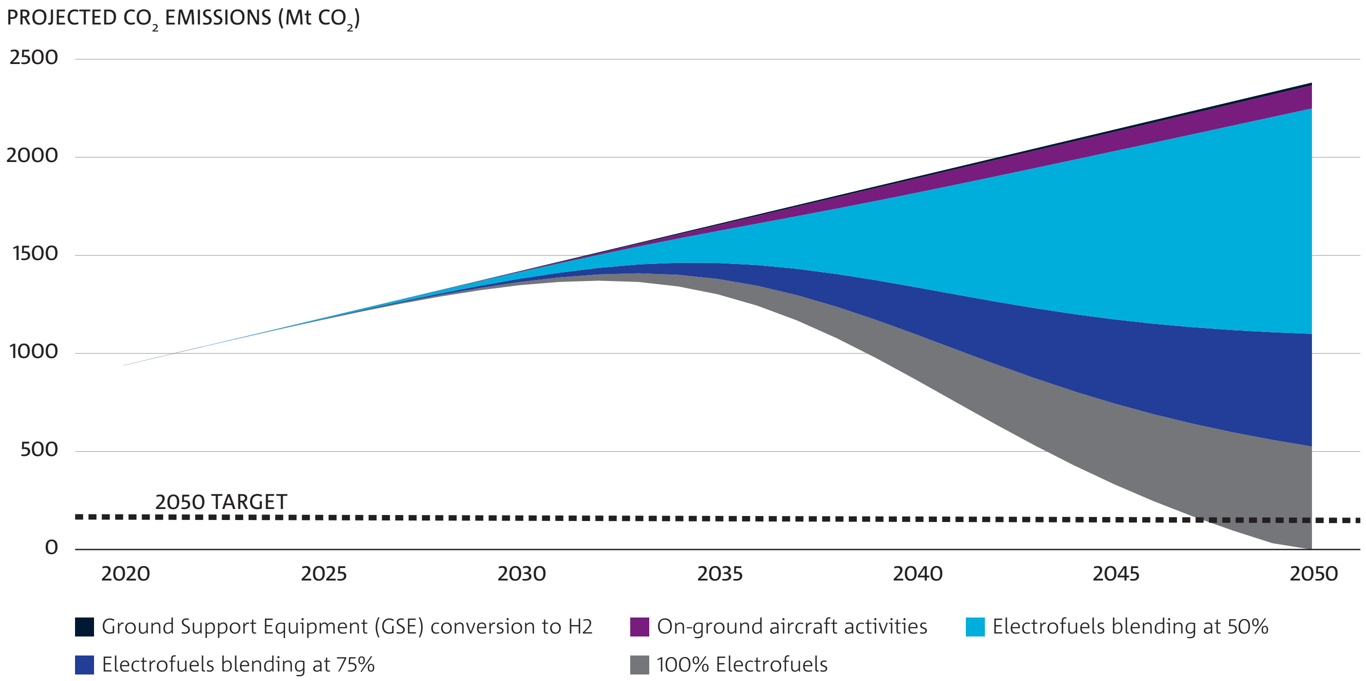

Figure 25. Potential abatement from hydrogen in aviation

Concurrent efforts may then be focused on discrete upgrades to special purpose GSE. With expected reductions in the cost of hydrogen, those GSE with the highest ratio of fuel use to capital cost (e.g. loaders, pushback tugs) will become more economical on a total cost of ownership basis and should be prioritized accordingly.

Despite the longer-term competitiveness of fuel cell options for the most material GSE, the high capital cost associated with asset turnover presents a more immediate challenge. Implementation of policy mechanisms that absorb some of the capital cost and underwrite initial investment risk will be important in facilitating technology uptake. Detailed analysis regarding fleet demand profiles, power requirements and remaining asset life will also be critical in determining the preferred solution for various assets (i.e. retrofit vs purchase of new build systems). This level of analysis will increase the scope for a more coordinated program roll-out.

The challenge associated with complex contractual arrangements between airports, airlines and GSE service providers can be avoided by initially targeting airports with a majority tenant that is responsible for all GSE operations. A more efficient business model would likely see airport operators (via delegation to specialist third parties) assume responsibility for hydrogen production and storage infrastructure. This could allow for an increase in production capacity necessary to service airport adjacent industries such as taxi fleet, buses and freight.

Although hydrogen use within airports is relatively nascent, there is much that can be leveraged in terms of safety standards from other mature transport industries relying on hydrogen. Key aviation sector entities such as IATA will play an important role in developing appropriate Standards, Manuals and Guidelines that can be easily incorporated into a local regulatory framework governing hydrogen use. Combined with transparent demonstration projects and public engagement, this will be critical in helping key stakeholders such as the insurance sector become fully aware of the risks of hydrogen use and in turn, the avoidance of exorbitant premiums.

Given the technological maturity and commercial competitiveness of fuel cell GSE on a total cost of ownership basis, it is expected that implementation of these investment priorities could see the rate of uptake accelerate after 2025, replacing all GSE in or around 2035.

Table 15. On airport investment priorities

COMMERCIAL	POLICY/REGULATORY	RD&D	SOCIAL LICENSE
• Assess whether existing hydrogen production infrastructure is reasonably proximate as part of business case for early-stage demonstration projects • Assess demand profiles, asset life and power requirements of existing GSE fleet • Consider upgrade of 'off-the-shelf' GSE (e.g. forklifts) in the first instance as a means of increasing hydrogen demand with low a lower risk profile • Explore business models for hydrogen production infrastructure including potential for 3rd party operation and opportunities to service adjacent industries • Assess potential for broader industry benefits via use of wastewater on airport and offtakes for oxygen	• Implement a policy mechanism that explicitly promotes the transition to fuel cell GSE by helping absorb risk and cost associated with changeover • Entities such as IATA to develop Standards, Manuals and Guidelines to be incorporated into local frameworks	• Develop a program that assesses benefits of retrofit vs new build purchase of special purpose GSE • Continue to develop effective solutions for GSE retrofit and performance testing • Continue to work with proponents across the hydrogen sector on improvements in electrolysis, refueling systems, system weights and durability	• Develop demonstration projects that highlight safety of hydrogen on airports (e.g. hydrogen buses) • Entities such as IATA to engage broader community on risks and benefits of hydrogen • Continue to educate key stakeholders such as the insurance sector on risks of use

6.2 Existing infrastructure (Electrofuels)

Given the low rate of asset turnover within the aviation sector, use of electrofuels represent one of the primary ways in which meaningful decarbonization can be achieved using hydrogen before 2050 without extensive changes in infrastructure.

While to date there has been no end-to-end commercial demonstration of electrofuel synthesis, there is a strong technology and regulatory base that can be built upon. This includes broader developments within the hydrogen industry such as increasing scale of production via electrolysis, developments in CO_2 capture, and existing approval mechanisms for sustainable aviation fuels under the ASTM.

That said, given the extent of infrastructure required to meet global aviation demand (e.g. thousands of MW of electrolysis), scaling the electrofuel industry will require a coordinated effort on the part of the broader industry (including upstream oil & gas production), governments and research institutions globally.

One of the more effective mechanisms supporting such a coordinated effort could be the implementation of electrofuel blending quotas imposed on jet fuel producers that increase over time, commensurate with industry resources and capacity. Such blending quotas could be determined by key advisory bodies in conjunction with electrofuel manufacturers and then be provided as guidance to governments to enforce on local suppliers. Consistency across jurisdictions will also be important in preventing any market distortion.

The increase in production plant scales that follow higher blending quotas will lead to a natural decrease in cost that is also driven by factors such as renewable energy economies of scale, the industrialization of electrolyzer manufacture and improvements in the capacity and cost of CO_2 capture. Further developments in high-temperature electrolysis due to the availability of waste heat and the opportunity to directly produce syngas will also be critical in achieving significant cost reductions. Additionally, given that synthetic fuels are 1-2% more efficient than conventional jet fuel, overall fuel consumption and consequently emissions are expected to fall (this improvement is reflected in Figure 25).

At larger scales, given the sensitivity of the fuel synthesis process to maintaining a high rate of asset utilization and low electricity price, selection of sites with strong dedicated renewable and dispatchable low emissions energy sources will also be critical. The flexibility required suggests that DAC will be crucial for the long-term viability of the industry and will continue to benefit from cost reductions in mature processes (e.g. calcination) and emerging technologies such as MOFs.

Notwithstanding these developments, synthetic fuels are unlikely to be commercially competitive with conventional jet fuel. While electrofuels start at 8 times (8x) the cost of kerosene and only reach 1.25-2.5x once a 50% blend is achieved, blending at this rate is likely to only occur after 2040 given the lead times required. It is also important to note the higher levels of risk that come with further increases in plant size, particularly when only minimal reductions in cost are achieved when scaling beyond ~3000 bpd.

It is anticipated that as blending quotas continue to increase, so too will the overall cost of jet fuel, resulting in an increased cost pass-through to the consumer. While airlines will likely need to continue to develop new ways to limit this impact on business models (e.g. third party intervention), particularly in the early stages of development, there is likely to be a key role for governments in absorbing some of the premium for electrofuels in order to limit resentment amongst airlines and passengers. In this context, it is also critical that existing aviation offset schemes align carbon credit values with the premium associated with use of electrofuels so as not to divert investment away from their longer-term development.

Implementation of the investment priorities set out in Table 16 could de-risk large-scale electrofuels plants between 2030 and 2035, allowing for subsequent acceleration of uptake. This will require an assessment of global resources and considerable planning to allow for a successful roll-out in the coming decades.

Table 16. Existing infrastructure investment priorities

COMMERCIAL	POLICY/REGULATORY	RD&D	SOCIAL LICENSE
• Investigate achievable electrofuel blending concentrations and provide guidance to governments • Develop joint ventures between electrofuel manufacturers, oil refineries and airlines to secure offtake • Airlines to continue to pursue new business models designed to incentivize consumers to purchase SAF • Identify key global locations with strong energy resources, hydrogen storage and existing oil & gas infrastructure that could accommodate large-scale electrofuels production	• Impose tax concessions and mechanisms that reduce the cost of electrofuels in early stages of development (e.g. contracts for difference) • Fast track approval for alternative fuel synthesis processes such as methanol • Continue to improve mechanisms for certification of alternative synthetic fuel production processes that reduce cost and support an ecosystem of development (e.g. furthering the ASCENT, and D4054 Clearinghouse) • Amend carbon offset schemes so they do not divert investment away from longer term development of electrofuels	• Establish detailed life-cycle-analysis frameworks to better understand emissions abatement achieved through use of electrofuels and other SAF • Develop end-to-end demonstration projects using both mature and emerging technologies • Continue to develop high-temperature electrolysis and co-electrolysis of CO_2 • Continue to develop more mature and emerging forms of DAC technologies including MOFs to reduce energy and capital costs • Continue to improve fuel synthesis technologies and efficiencies via process intensification • Continue to develop large scale underground storage mechanisms	• Continue to educate the public on benefits of use of electrofuels (e.g. carbon neutrality, efficiency) • Consult with technology proponents across the value chain on electricity and hydrogen demand as it aligns to various fuel blending quotas • Electrofuel manufacturers to provide regulators with ongoing access to plant output and quality data

6.3 Emerging infrastructure

Despite the emissions abatement achieved through the uptake of electrofuel blends, the continued roll-out of increasingly stringent environmental regulations could see a potential move away from conventional jet fuel closer to 2050. Given its unique properties, hydrogen could play a key role in facilitating this transition.

Fuel cells for non-propulsion applications

Broader industry moves towards more electric architecture are likely to increase the scope for use of fuel cells on aircraft. Whereas continued electrification of hydraulic and pneumatic systems and their consequent ability to be supported by an on-board fuel cell will require on-going analysis, use of hydrogen-based systems for applications such as auxiliary power and the taxiing phases of flight may present as nearer-term opportunities.

However, incorporating such systems onto jet aircraft is likely to carry a mass penalty that is twice as much as traditional APUs, mostly due to the weight of the storage tank (when hydrogen is compressed at 700bar). While the mass penalty can be reduced using cryogenic hydrogen storage (i.e. 60% of total weight for compressed hydrogen to meet equivalent demand), this will result in higher costs due to the need for liquefaction and extensive changes in airframe design to ensure that the requisite storage temperatures are maintained. Therefore, although use of fuel cell systems would significantly lower local ground emissions, round trip economics and emissions would be worsened due to the higher quantities of jet fuel required to carry the additional aircraft weight.

Reducing overall mass via the introduction of next generation fuel cells and storage tanks are the subject of ongoing RD&D within the hydrogen industry and this could well be accelerated should such investment be prioritized by the aviation sector. This alone however, is unlikely to result in the weight reduction required to compete with incumbent APU systems. Rather, the most significant improvements may be achieved by optimizing the integration of fuel cells early in the conceptual design phase of aircraft.

Given the slow rate of aircraft turnover within the industry and current challenges in reducing the weight of fuel cell systems, it is likely that the focus will be on the further roll-out of external fuel cell GPU systems as well as ‘Taxibots’ in order to decrease ground emissions. While extensive work is required to overcome the safety and operational challenges associated with increased levels of capital equipment on or near runways, it is reasonable to expect that the uptake of such GSE could accelerate after 2030, effectively minimizing ground-based emissions from aircraft by 2045.

Table 17. RD&D priorities for non-propulsion applications

ECONOMICS OF USE	SAFETY	ENVIRONMENT	HYDROGEN SPECIFIC RD&D
• Develop fuel cell GPUs and continue demonstration of Taxibot systems to understand the impact on apron traffic • Adapt further investigation of more electric architecture to include the role of fuel cells in meeting electricity demand on aircraft • Explore ancillary benefits of fuel cell use on aircraft such as water harvesting • Develop airframe concepts that optimize fuel cell integration at the component level in order to improve system weight	• Extend existing regulatory framework supporting use of hydrogen fuel cells in the turboprop market for non-propulsion applications in jet aircraft • Develop mechanisms to test aircraft engines just prior to take-off if not being used during taxiing. • Provide ongoing stakeholder consultation demonstrating safety risks and benefits of hydrogen over jet fuel	• Undertake detailed analysis on local emissions, pollution and noise reductions achieved via electrification of APU and taxiing using either on-board or GSE fuel cells	• Continue to improve fuel cell power densities via developments in membrane electrode assembly and use of different materials for bipolar plates • Continue to progress Type V composite compressed storage tanks as well as scaling of production

Hydrogen for propulsion

There is significant potential for hydrogen fuel cells to disrupt the current turboprop market (i.e. shorter haul flights up to 1,000mi/1600km and 100 passengers). However, given the limitations on the power density of fuel cell systems, they are unlikely to compete in relation to long-distance flights with higher payloads that rely on use of traditional jet engines.

Although use of hydrogen-based fuels such as ammonia and methanol (i.e. non-drop in electrofuels) are likely to require fewer changes to airframe and engine design, when compared to kerosene, these fuels have a poor energy density by volume and with the exception of LNG, poorer energy densities by mass. This can limit their competitiveness in long haul travel. For the carbonaceous fuels, poorer energy densities, combined with CO_2 emissions upon combustion, bring into question the motivation for changing existing infrastructure to accommodate non-drop-in fuels, particularly when minimal gains are expected in the overall production cost (when compared to drop-in electrofuels).

In contrast, cryogenic hydrogen has a superior energy density by mass compared with kerosene and produces no CO_2 emissions upon combustion. However, challenges arise with respect to its poor volumetric density. This obstacle may encourage a move away from conventional aircraft designs to models such as the blended-wing-body which show promise in improved aerodynamic efficiency and can accommodate larger volumes of fuel.

To facilitate development of hydrogen aircraft, a considerable amount of research is required in the immediate term regarding changes in engine design and on-aircraft infrastructure such as light-weight cryogenic storage tanks, supply pumps and heat exchangers. Emerging fuel mixing methods such as lean-direct injection will also be required to manage engine temperatures and minimize NOx levels. Further, given its unique risk profile, hydrogen use on aircraft will require a new supporting regulatory framework leveraging existing fuel and aircraft certification standards.

Significant uptake of hydrogen aircraft at major airports is unlikely to occur prior to 2050 and therefore has not been included in the emissions abatement curve in Figure 25. However, once this level of uptake occurs, it will require hydrogen volumes in the order of thousands of tons per day. In this context, hydrogen production infrastructure supporting the electrofuels industry could be gradually diverted towards an increasing demand for hydrogen fueled aircraft. A potential scenario could involve the distribution of hydrogen via pipeline to airport with onsite liquefaction facilities.

While it is possible for hydrogen to be supplied to aircraft via hydrant systems (as per current refueling models), significant RD&D is required to ensure safe and efficient refueling times by simultaneously increasing flow rates and preventing hydrogen leakage and boil-off. This infrastructure model could be rolled out strategically, initially by targeting airports that support the most popular flight paths with gradual expansion thereafter.

Table 18. RD&D priorities for propulsion applications

ECONOMICS OF USE	SAFETY	ENVIRONMENT	HYDROGEN RD&D
• Continue to develop emerging airframe designs such as blended-wing-body with a view to accommodating cryogenic hydrogen storage • Pursue development of efficient cryogenic hydrogen refueling systems with reduced impact on flight turnaround times • Develop a long-term strategy for the divergence of large-scale hydrogen production infrastructure from electrofuels to hydrogen aircraft • Continue to pursue hydrogen as a fuel in development of hybrid air-breathing rocket engines • Target infrastructure development at airports supporting most popular flight paths	• Develop new regulatory frameworks supporting hydrogen-based jet engines, handling and new airframe designs • Develop hydrant refueling systems that minimize leakage of hydrogen and include mechanisms to measure the concentration of hydrogen in proximate areas	• Continue to assess the warming effect of enhanced levels of water vapor from hydrogen engines and broader impact of contrails on climate • Continue development of lean-direct injection methods to reduce NOx levels from combustion of hydrogen • Continue studies on the potential for reduced noise levels and smaller engine designs	• Continue to develop and test engines capable of combusting 100% hydrogen as well as supporting pumps and heat exchangers • Develop low cost catalysts designed to improve the efficiency of hydrogen liquefaction • Develop cryogenic storage tanks that reduce overall weight but minimize heat transfer • Increase understanding of mechanisms relating to hydrogen boil-off as a means of limiting fuel losses • Explore use of fuel cells in meeting power densities for fuel cell assisted take-off

7 Appendices

Appendix A: Modelling assumptions

Emissions abatement curve

Assumptions supporting the emissions abatement curve are set out in the table below.

Fuel projection	Based on Boeing Commercial Outlook growth rate RPKs to 2037 and extended to 2050
Fuel efficiency	Improvements in efficiency of 1% per annum to 2050 Additional 1% efficiency for combustion of electrofuels as opposed to jet fuel
Emissions from GSE	Based on Boeing Commercial Outlook growth rate RPKs to 2037 and extended to 2050
Ground emissions from aircraft	Assumed 5% of total jet fuel consumed attributed to on ground aircraft emissions from APU and taxiing
Technology uptake curves	Assumed rates of uptake acceleration based on analysis undertaken in this report

GSE Modelling assumptions

GSE diesel usage

The Airport Cooperative Research Program (ACRP) undertook a survey of ground support equipment (GSE) at 12 US airports in 2011.[208] They were able to use this data to develop a relationship between the number of airport operations and the quantity of GSE per airport, and to then extend this to all airports in the US. They detailed the type and amount of each GSE and estimated the fuel use of the fleets per airport. They also obtained data from GSE manufacturers and were able to estimate the engine sizes, load factors, hours of operation and emissions from different types of GSE. From this data, we were able to determine the major pieces of GSE and the majority users of diesel.

Levelized cost of transport

LCOT is a metric suitable for comparing various vehicle types and has been calculated for existing diesel/gasoline GSE vehicles and their hydrogen equivalents. The LCOT factors in the depreciation of the hours of operation per year into the total hours of use over the total 10-year period. The LCOT equation is shown below:

$$LCOT = \frac{\sum_{t=1}^{T} \frac{(CAPEX_t + OPEX_t + F_t)}{(1+d)^t}}{\sum_{t=1}^{T} \frac{H}{(1+d)^t}}$$

Where *CAPEX*t and *OPEX*t refer to the capital and operating expenditures respectively ($); *F*t refers to the fuel cost ($) during an annual period *t*; *H* refers to the hours of operation within a year; *d* is the discount rate and *T* is the time period examined (years). The annual operational and maintenance expenditures (*OPEX*t*)* are assumed to be fixed. The levelized cost determines the total (in this case hourly) expense to operate a vehicle, and hence the revenue required to cover this cost.

208 National Academies of Sciences, 2012, Airport Ground Support Equipment (GSE): Emission Reduction Strategies, Inventory, and Tutorial, US

FUEL TYPE	ENGINE POWER, KW	LOAD FACTOR	ANNUAL USE, HOURS	FUEL CONSUMPTION, GALLONS OF DIESEL OR KG OF H_2	CO_2 EMISSIONS, KG/YEAR	CAPEX, $	OPEX, $	LCOT, $/HOUR
Baggage/cargo tractors								
Diesel	53	0.6	1,500	3,958	40,414	40,000	4,560	17.17
Hydrogen	22	0.6	1,500	1,248	0	65,000	2,928	9.42
Cars/pickups/SUVs Vans								
Diesel	3	1,722	6.2	486	4,966	36,000	599	4.11
Gasoline	3.5	1,722	6.2	594	5,219	37,520	599	4.34
Hydrogen	120	1,722	6.2	184	0	58,300	103	4.60
Belt loaders								
Diesel	53	0.5	1300	2,859	29,187	150,000	4,560	26.89
Hydrogen	53	0.5	1300	1,870	0	202,265	2,928	26.00
Aircraft tug/tractors								
Diesel	460*	0.8	641	19,599	200,106	500,000	4,560	229.55
Hydrogen	368[209]	0.8	641	10,256	0	706,465	2,928	190.41
De-icing trucks								
Diesel	196*	1	500	8,146	83,167	485,471	1,520	190.77
Hydrogen	196a	1	500	5,329	0	687,094	976	205.52
Generators and ground power units								
Diesel	90*	0.8	1,630	9,569	97,705	70,000	4,560	32.80
Hydrogen	90*	0.8	1,630	6,261	0	156,744	2,928	25.90
Forklifts								
Diesel	41	0.3	976	998	10,185	25,000	1,500	8.92
Hydrogen	40	0.3	976	641	0	30,000	2,800	8.69
LPG	45	0.3	976	2,323	13,199	20,000	1,500	12.18
Air Conditioners/Heaters								
Diesel	300	0.8	976	12,012	122,645	100,000	4,560	81.95
Hydrogen	300	0.8	976	7.859	0	153,139	4,650	58.74

209 Based on a 368 kW fuel cell, a 30 kg H2 tank and a 1.6 kWh Li-ion battery for regenerative braking

Existing infrastructure (electrofuels)

PEM electrolyzer[210]

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity	MW	100.00	2,891.74
Electricity price	c/kWh	3.00	1.50
Capacity factor	%	90.00	90.00
Efficiency	kWh/kg	45.00	45.00
Direct capex	$/kW	689.21	450.00
LCOH	**$/lb ($/kg)**	**1.00 (2.20)**	**0.53 (1.16)**

Solid oxide electrolyzer[211,212]

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity	MW	100.00	726.29
Electricity price	c/kWh	3.00	1.50
Capacity factor	%	90.00	94.00
Efficiency	kWh/kg	33.33	33.33
Direct capex	$/kw	449.53	171.25
LCOH	**$/lb ($/kg)**	**0.88 (1.95)**	**0.33 (0.73)**

Concentrated CO_2 stream[213,214]

- Captured at cement kiln using amine adsorption technology (based on jet fuel production via FT using RWGS)

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity	t/day	408.06	11,088.15
Capture rate	%	90.00	90.00
Electricity price	c/kWh	3.00	1.50
Direct capex	$/kg CO_2/day	52.94	17.03
Operating cost *less* electricity	$/t$CO_2$	43.14	29.43
Capacity factor	%	91.30	91.30
LCOCO_2	**$/lb ($/kg)**	**0.03 (0.07)**	**0.02 (0.04)**

210 Informed by *National Hydrogen Roadmap*, CSIRO

211 Fu Q, Mabilat C, Zahid M, Brisse A, Gautier L (2010) *Syngas production via high-temperature steam/CO2 co-electrolysis: an economic assessment.* Energy & Environmental Science

212 Becker W, Brau R, Penev M, Melaina M (2012) *Production of Fischer–Tropsch liquid fuels from high temperature solid oxide co-electrolysis units*. Energy

213 Voldsund M (2019) *Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation*. Energies

214 Gardarsdottir S et al. (2019) *Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis.* Energies

Direct air capture[215]

- Based on CO_2 capture using solution-based absorption and calcination (based on jet fuel production via FT using RWGS)
- Natural gas not material; may become a key cost driver if substituted with another heat source

VARIABLE	UNIT	BASE CASE	BEST CASE
Capacity	t/day	408.06	11,088.15
Electricity price	c/kWh	3.00	1.50
Direct capex	$/kg CO_2/day	4,062.93	37.04
Non-fuel operating costs	$/kg	0.09	0.06
$LCOCO_2$	**$/lb ($/kg)**	**0.80 (1.76)**	**0.04 (0.10)**

Fischer-Tropsch pathway to synthetic electrofuels

Optimized refinery design recovers ˜60% SPK

Base case

- High concentration CO_2 capture
- PEM electrolysis (limited by 100MW) and RWGS

Best case

- Direct air CO_2 capture
- Utilizes solid oxide electrolysis (SOE)

VARIABLE	UNIT	BASE CASE (WITH PEM)	BEST CASE (WITH SOE)
Capacity	FT bbl per day	232.09	5,000.00
Electricity price	c/kWh	3.00	1.50
Capacity factor	%	90.00	90
Direct capex	$/FT kg/day	604.21	224.92
LCOFT	**$ per bbl**	**791.63**	**307.30**

Methanol (MeOH) pathway to synthetic electrofuels

Base case

- High concentration CO_2 capture
- Scale limited by 100MW PEM Electrolyzer

Best case

- Direct air CO_2 capture
- Utilizing solid oxide electrolyzers

VARIABLE	UNIT	BASE CASE (WITH PEM)	BEST CASE (WITH SOE)
Capacity	FT bbl per day	488.20	5,000.00
Electricity price	c/kWh	3.00	1.50
Capacity factor	%	90.00	90.00
Direct capex	$/FT kg/day	66.76	35.92
LCOMeOH	**$ per bbl**	**743.34**	**150.61**

215 Keith D, Holmes G, Angelo D, Heidel K (2018) *A Process for Capturing CO2 from the Atmosphere*. Joule

Appendix B: Further technical information

New aircraft certification process

New aircraft designs need to pass several stages to attain approval. The following outlines these stages at a high level[216] based on the procedures set out by the European Union Aviation Safety Agency (EASA)[217] and the FAA[218].

Technical overview and certification basis: Product designer presents the project to the relevant primary certificating authority (PCA), e.g. EASA in Europe and FAA in the US. The certification team and the set of rules (Certification Basis) are established.

Certification program: The PCA and designer define and agree on the means to demonstrate compliance of the product with every requirement of the Certification Basis and the level of regulatory involvement is established.

Compliance demonstration: The designer must demonstrate compliance of the aircraft with the regulatory requirements for each element, e.g. systems, airframe and engines. This is demonstrated to the PCA through analysis combined with ground and flight testing.

Technical closure and Type certificate issue: Once technically satisfied with the compliance demonstration, the PCA will close the investigation and issue a Type certificate for that specific product type. This primary certificate is issued by the authority of application and subsequently recognized by other authorities under a shared Bilateral Aviation Safety Agreement.

The process is lengthy and potentially subject to many delays which increases cost. The process for the original Boeing 787 Dreamliner took 8 years from application and involved certification of components such as composite wing structures and battery systems. During testing it completed 4,645 flight hours and required more than 200,000 hours in FAA expert time.[219]
It follows that greater departures from conventional tube and wing designs with kerosene-based engines are likely to result in more extensive certification processes with significantly higher cost.

216 Skybrary (2019) *Certification of Aircraft, Design and Production*. Available at https://www.skybrary.aero/index.php/Certification_of_Aircraft,_Design_and_Production#

217 EASA (2019) *Certification Procedures*. Available at https://www.easa.europa.eu/document-library/certification-procedures

218 FAA (2019) *Design approvals*. Available at https://www.faa.gov/aircraft/air_cert/design_approvals/

219 Shankara P (2018) *Certifiably cheaper*. Aerospace Testing International. Available at https://www.aerospacetestinginternational.com/online-magazines/in-this-issue-showcase-2019.html

Appendix C: Stakeholder consultation list

EXTERNAL ORGANIZATIONS
ADME fuels
Australian Government Department of Defence: Science and Technology (DST)
Australian Government Department of Environment
Ballard
Carbon Engineering
Cerulogy
Climeworks
Commercial Aviation Alternative Fuels Initiative (CAAFI)
Coregas
E4Tech
Federal Aviation Administration (FAA)
Fortescue Metals Group (FMG)
Future Fuels CRC
General Electric (GE)
H2H Energy
Heider Refinery
Hyundai
ITM Power
Kawasaki Heavy Industries (KHI)
Lanzatech
Melbourne Airport
Qantas
RMIT
Shell
Siemens
Sunfire
Toyota
Transport & Environment
University of Melbourne
Western Sydney Airport
ZeroAvia

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Dr. David Harris
Dr. Patrick Hartley
Prof. Matthew Hill
Mr. Chris Knight
Dr. Daniel Liang
Dr. Seng Lim
Mr. Robbie McNaughton
Dr. Christopher Munnings
Dr. Jim Patel
Dr. Daniel Roberts
Dr. Valerie Sage
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