ATKINS
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Alternative Fuels for Sustainable Aviation:

Energy and Infrastructure

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Aviation emissions are hard to abate… but not impossible

As the urgency to eliminate our greenhouse-gas emissions intensifies and many sectors produce and progress credible Net Zero Carbon strategies, the spotlight will increasingly focus on sectors such as aviation, which are the hardest to decarbonise. If aviation continues its current growth trend, it will exceed its 2020-2050 carbon budget target of 22 GtCO2 by 2038 (Institute for Sustainable Futures, 2022). Continuing along this trend with no emissions mitigation will lead to 50 GtCO2 emitted, representing a budget exceedance of 230%.

While it's true that aviation emissions are hard to abate, the technological challenge preventing Net Zero Carbon aviation is widely regarded as feasible to overcome at the aircraft level, with the need to evaluate the wider aviation ecosystem now moving into the spotlight. However, the combination of aircraft and infrastructure change required will result in high costs, complexity, and disruption. Member States at the 41st International Civil Aviation Organisation Assembly, in October 2022, adopted a collective long term aspirational goal of Net Zero carbon emissions by 2050, but to achieve this, it is critical that the direction of travel is set soon, to enable changes to be enacted in time to prevent the sector exceeding its carbon budgets within the next 15 years.

The solution to curbing aviation emissions is the replacement of kerosene, the fossil-based jet fuel, with low carbon alternative fuels. Those under consideration for aviation are:

- Sustainable Aviation Fuel (SAF) – from biological, or solid, waste feedstock.
- eFuel – a synthetic SAF variation.
- Hydrogen
- Batteries

Each of the emerging alternative fuels are at different stages of maturity. Some SAF routes are already in use (in very low volumes), but no large-scale aircraft have been developed for hydrogen or battery power to date.

Low carbon aircraft fuels and technologies are forecast to be available at different times depending on aircraft class so, to achieve emissions' reduction goals, a combination of each alternative will need to be utilised. SAF and eFuel will support the decarbonisation of existing aircraft designs and propulsion systems, with new aircraft designs utilising hydrogen and batteries.

However, anticipating the future fuel mix of aviation requires more than forecasting demand for each type under development. The low carbon energy generation required to produce the fuel must also be factored into the equation, to ensure both that sufficient infrastructure is built to meet aviation demand, and that this infrastructure is in the right locations to match demand for that specific fuel and aircraft class.

Fuelling alternative fuels

Notably, each of the low carbon fuel types has different pathways and routes to production, but they all require a source of low carbon energy to address whole lifecycle, 'source-to-force', emissions. This can be referred to as a generation energy demand.

One of the main challenges is the increase in energy demand required to produce each type of alternative fuel. Whilst existing fossil-based jet fuel results in more energy being released when propelling the aircraft than is required to extract and refine it, more energy generation is required for all other fuel options than is transferred into the propulsion of the aircraft. Batteries prove the most energy efficient pathway, yet batteries alone cannot fuel the aircraft of the near-future. Unlike kerosene, which just needs to be dug up from underground and refined, carbon alternative fuels require extensive processing: for example, hydrogen needs to be generated from the electrolysis of water. eFuel requires this same hydrogen, and then needs to be chemically combined with a source of carbon to produce synthetic hydrocarbons. SAF options follow multiple pathways to chemically extract hydrocarbons from biological or waste sources.

Taking estimated energy efficiencies, a forecast fuel mix, and comparing with the energy demand of flight suggests that, by 2070, up to 44,000 TWh of energy each year will be required to generate the necessary global aircraft fuel demand.

Almost all of this energy will need to be provided as electricity. It is a huge volume: by comparison, global electricity use for 2021 was approximately 27,500 TWh. It's clear that electricity demand will increase as a result of many sectors' decarbonisation pathways, and aviation must be clear in the demand it will have, to support appropriate planning and production development.

With the huge volume of low carbon, sustainable energy required to support the transition and forecast growth rate of aviation, the infrastructure demands for all alternative fuel routes will be substantial. The most effective solution to drive the decarbonisation of aviation will be a mix of all the alternative fuel options, the combination of which will change over time as older aircraft fleets retire, aircraft design evolves, and infrastructure solutions are developed and optimised. Integrated, system-of-systems planning is vitally important to achieve the transition; planning the wider aviation ecosystem must take into account future energy projections, while national governments are key stakeholders and enablers who may provide the up-front investment to enable the necessary changes.

Increasing aviation traffic and CO_2 emissions

If aviation continues along its current growth trajectory without abating emissions, as shown in Figure 1 (using growth estimates from the International Council on Clean Transportation, (ICCT, 2020)), it will reach a 2020-2050 carbon emission budget target of 22 $GtCO_2$ (Institute for Sustainable Futures, 2022), in 2038.

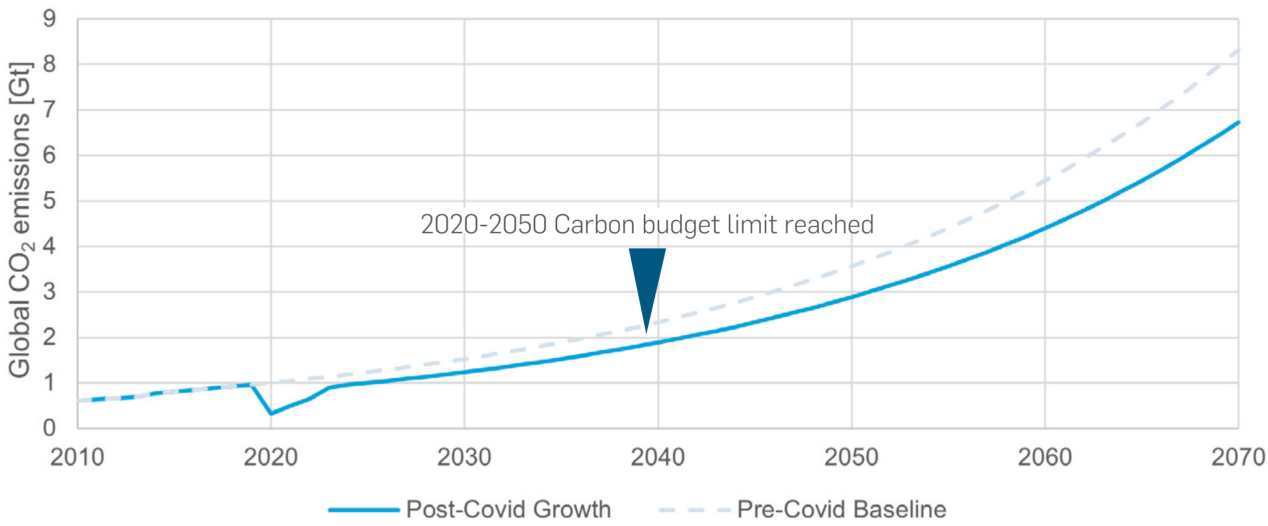

Figure 1: Forecast Global CO_2 aviation emissions considering the effects of the Covid-19 pandemic. Growth forecast taken from ICCT (ICCT, 2020), of 4.3% per annum, applying the consideration of incremental technology and flight operations' improvements.

Figure 2 illustrates the 22 $GtCO_2$ available aviation carbon budget as a proportion of the 402 $GtCO_2$ total carbon budget for the period 2020 to 2050. Also shown are the calculated aviation CO_2 emissions for 2020 to 2050 if growth continues along the trend shown in Figure 1 using fossil fuel. This indicates that aviation is on track to exceed its 2050 carbon budget by 230%, which would form 12% of the total global carbon budget.

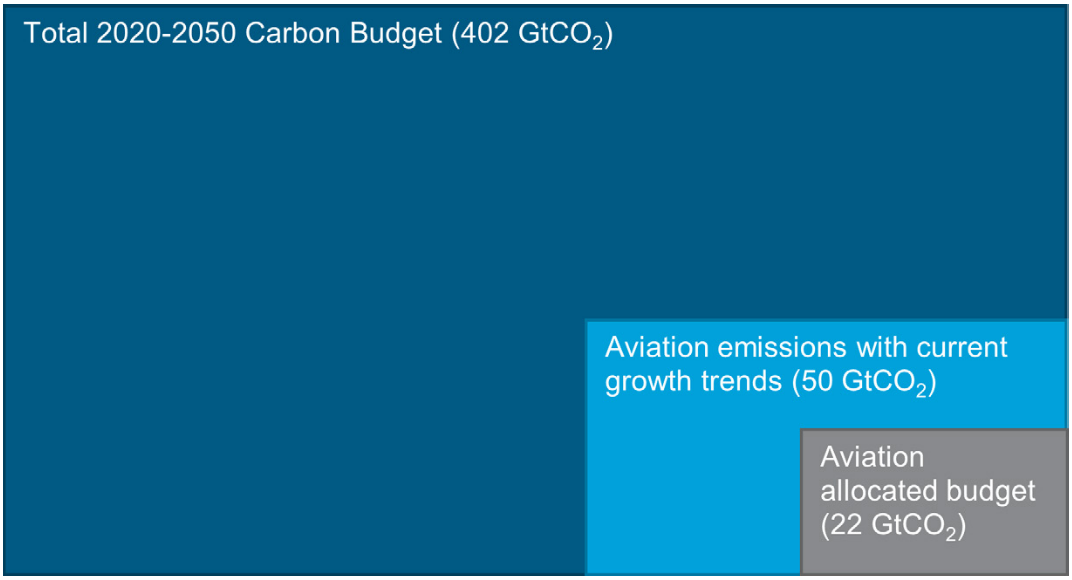

Figure 2: 2020-2050 Carbon budget, showing aviation allocation (both from Institute for Sustainable Futures, (Institute for Sustainable Futures, 2022), and unconstrained growth forecast, calculated from ICCT, (ICCT, 2020))

What is the solution?

So, what could the path to decarbonisation look like? At the aircraft level, the technological challenges preventing Net Zero Carbon aviation are widely regarded as feasible to overcome. However, more attention is now needed to evaluate the options of the wider aviation ecosystem, while the combination of aircraft and infrastructure change required will result in high costs, complexity, and disruption. There are also several other sustainability considerations involved in this transition which could introduce further challenges or constraints. Utilising a range of technologies, at an ecosystem level, will therefore be essential in enabling aviation to grow in a sustainable manner.

There are various routes to decarbonise aviation, with many at different stages of planning, development, implementation, and scale. They are all based on the use of alternative fuels, and they have different challenges, opportunities, and development timelines (Atkins, 2020)). As outlined above, the available low carbon alternative fuels under consideration for aviation are:

- Sustainable Aviation Fuel (SAF) – this hydrocarbon fuel is developed from biological or waste material by a variety of different processes.
- eFuel – a variation of SAF that is completely artificially synthesised from a source of carbon (for example, direct air capture of CO_2 is considered here) and hydrogen (green hydrogen is considered here).
- Hydrogen – stored in the aircraft as a liquid fuel with energy extracted via either combustion or fuel cells (green hydrogen is considered here).
- Batteries – implemented as seen in the automotive industry, but with a clear recognition that further development will be required to achieve power densities sufficient to meet the aviation sector's needs.

To achieve emissions' reduction goals a combination of each of these alternatives will need to be utilised. SAF and eFuel will support the decarbonisation of existing aircraft designs and propulsion systems, with new aircraft designs utilising hydrogen and battery energy.

Beyond 2050 – as fossil-based jet fuel is phased out completely – energy, resource availability, cost and aircraft development considerations are likely to see a reduction in demand for SAF and eFuel and an increase in demand for hydrogen and battery electric options.

Low carbon aircraft fuels and technologies are due to be available at different times depending on aircraft class. This is closely related to airline operating models and the basic flight physics associated with the aircraft payload and range. Aircraft can be assigned into one of three different classes:

- Regional – this covers all fixed wing aircraft up to approximately 100 passengers over 1000 nm range.
- Narrowbody – aircraft ranging from 120 to 200 passengers with ranges up to 5000 nm (e.g. Airbus A320 and Boeing 737 families).
- Widebody – long haul aircraft with 220 to 400 passengers and ranges greater than 5000 nm (e.g. Airbus A350, Boeing 787 and 777).

Separating the global CO_2 emissions data by aircraft class provides the view in Figure 3, showing that the bulk of CO_2 emissions come from the larger, longer range, aircraft.

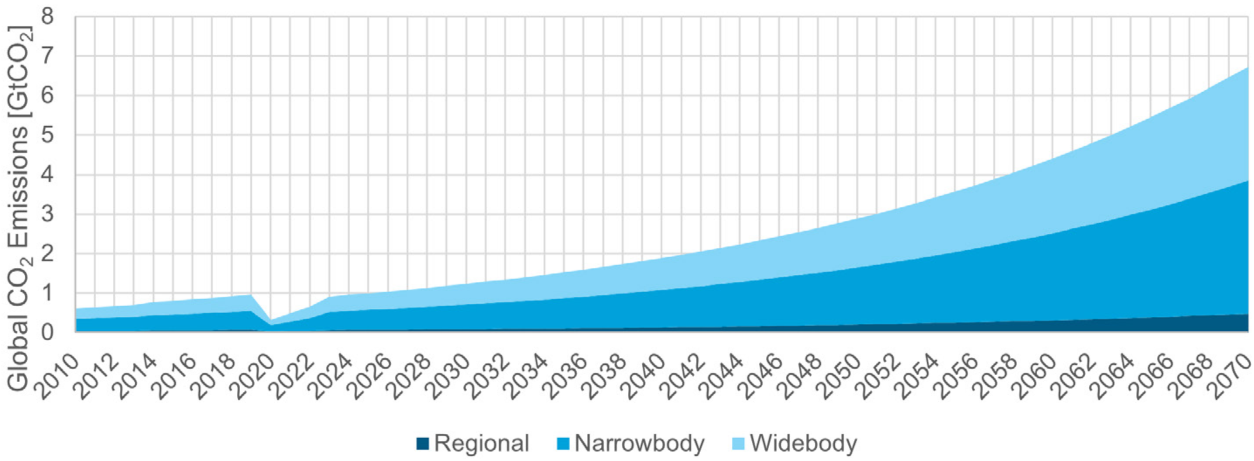

Figure 3: Forecast Global CO_2 emissions split by aircraft class (ICCT, 2020)

A Net Zero aircraft fleet

To achieve a Net Zero aircraft fleet for 2050 whilst maintaining emissions below a 22 $GtCO_2$ budget limit, the following technology-based targets and assumptions are used:

- SAF produces 16% of the equivalent CO_2 emissions to fossil fuel (Airports Council International and ATI, 2022), which we expect will reduce to zero emissions by 2050 as the industrial generation processes for this fuel type are decarbonised.
- Zero fossil fuel in use by 2050 as an aviation fuel or to power their production.
- Narrowbody hydrogen aircraft to be available from 2035, as forecast by Airbus and their ZeroE programme, (Airbus, 2022).
- Widebody hydrogen aircraft to be available from 2050, informed by extension of the ATI FlyZero conclusions (ATI FlyZero, 2022), and an optimistic outlook on in-service availability.
- Sufficient green hydrogen available to support all aircraft demand.
- Growing availability of battery powered aircraft, particularly in the regional category, but also entering the narrowbody class from 2050.
- Enough SAF and eFuel being available to support the 2050 carbon budget target where this cannot be met by hydrogen or battery aircraft technology.
- eFuel, hydrogen and battery powered flight are a zero CO_2 solution, which implies sufficient zero carbon energy is available to generate these fuels.

Using these assumptions and targets, factors for fuel use shown in Figure 4 emerge as split by aircraft class.

It's important to consider that, as technology develops, different fuel mixes could prove optimal. Battery technology could see a breakthrough in power density, leading to this mode becoming available for larger aircraft classes earlier. The capacity to generate eFuel at higher volumes could reduce the need for SAF sourced from waste products. Breakthroughs in aircraft technology supporting hydrogen powered flight could accelerate the roll-out of hydrogen into widebody aircraft.

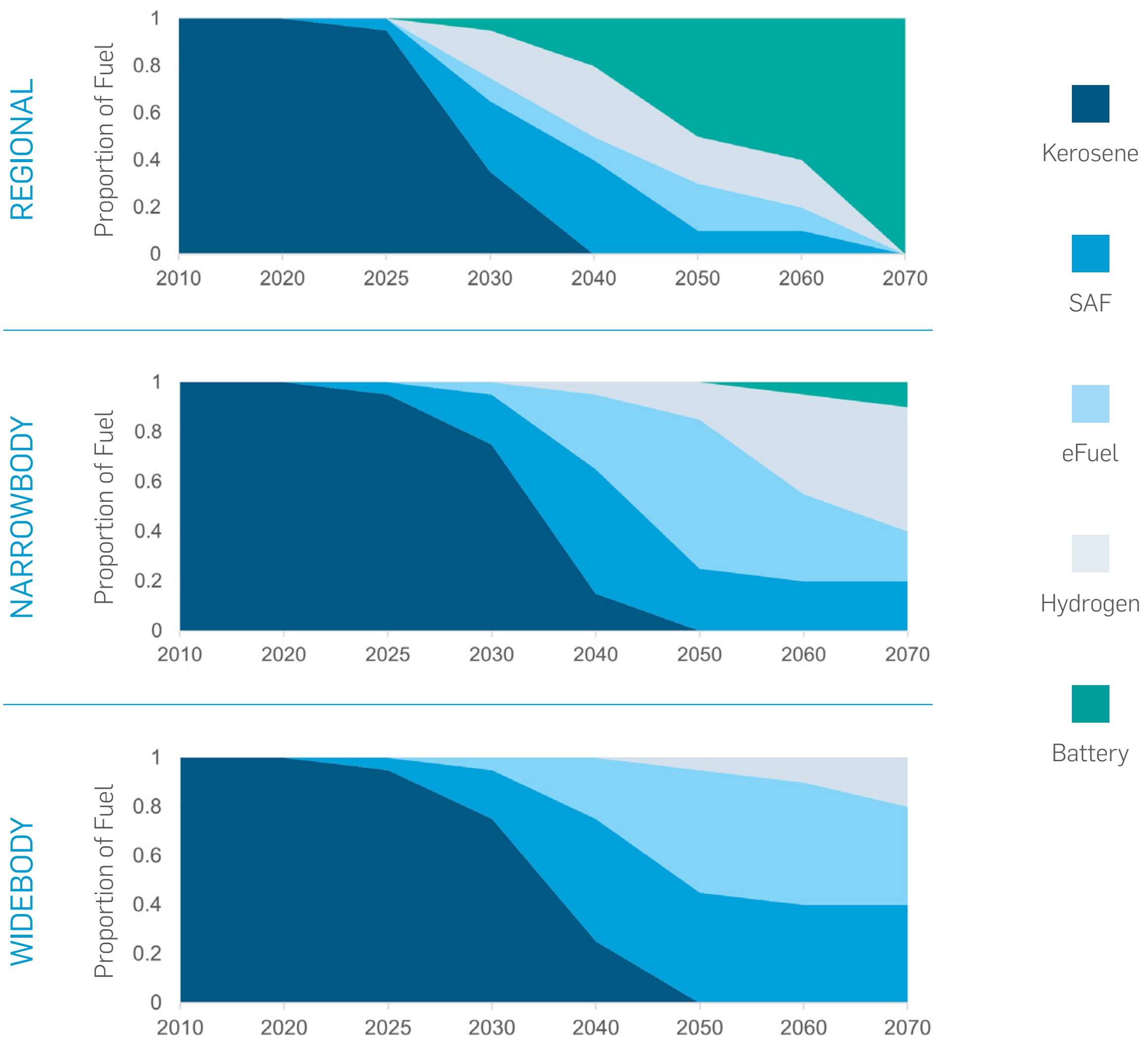

Figure 4: Low carbon, and kerosene, fuel proportion estimates

The resulting forecast annual CO_2 emissions following from these factors are shown in Figure 5.

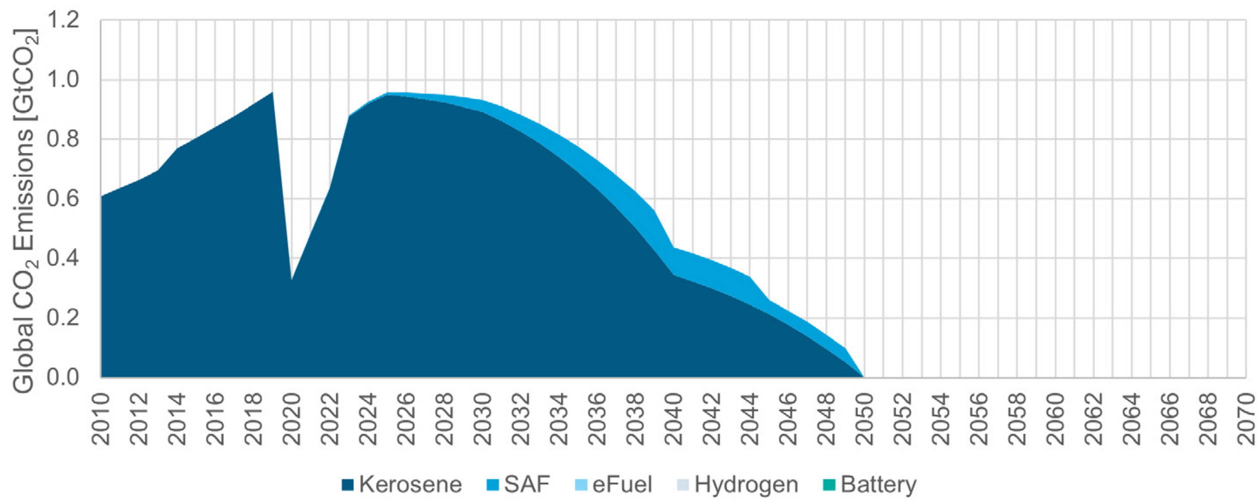

Figure 5: Global CO_2 emissions under a scenario that aims to meet the 2020-2050 Carbon Budget

The scenario shown in Figure 5 would lead to 19 $GtCO_2$ released between 2020 and 2050, within the carbon budget. To achieve this, SAF and eFuel will need to supply approximately 25% of aviation fuel demand by 2030, growing to around 90% by 2050, shown in Figure 6 by flight energy demand.

This represents an immediate and rapid increase in the supply of SAF, along with the rapid development and deployment of eFuel generation capability and capacity.

What if we consider the energy generation demand?

Switching to show aviation demand in terms of energy required provides the flight energy demand split by low carbon fuel, as shown in Figure 6, using the assumed factors for the different low carbon fuels.

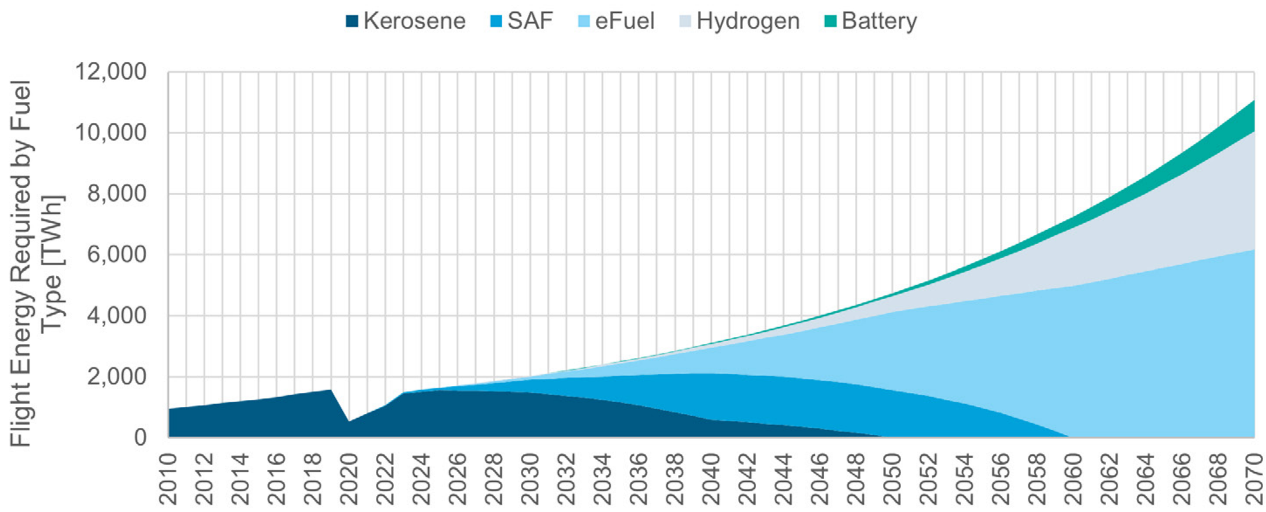

Figure 6: Global aviation flying energy demand split by low carbon fuel source, which has been sourced from previous calculations and explained within an earlier report (Atkins, 2020)

Each of the low carbon fuel types has different pathways and routes to generation, but they all require a source of low carbon energy to address whole lifecycle, 'source-to-force', emissions. This can be referred to as a generation energy demand, which is a function of the energy efficiency of the process. These energy efficiency factors are calculated and shown in Figure 7. For kerosene, you get more energy propelling the aircraft than you start with, because you are just digging up energy rich oil and refining it to create kerosene.

For all other options, more generation energy is required than is transferred into useful work propelling aircraft, because you are starting from more basic, low energy, molecules and needing to process them into higher energy content forms. Batteries prove the most energy efficient pathway, because energy in the form of electricity is stored directly within the battery, without needing any chemical processing (outside of the battery itself).

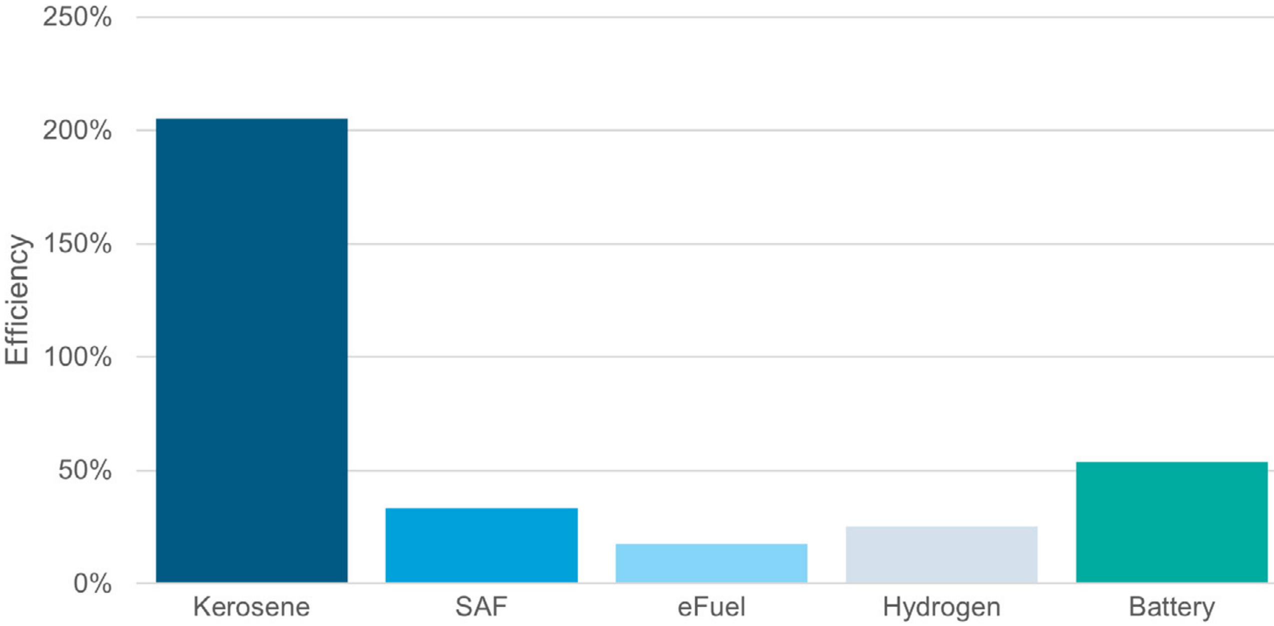

Figure 7: Energy generation efficiency for different fuel types. Where efficiency is greater than 100% for kerosene, more energy is available to power flight than is required to create the fuel.

All these energy efficiency values are reasonable estimates and averages, covering multiple processing pathways where appropriate. There is scope for them to improve over time as effects of scale are realised or new processes are developed – different assumptions on fuel mixes can be evaluated, to see what the effect on energy demand is.

Consequently, due to the varying fuel type efficiencies, and this anticipated potential to scale, we must consider what fuel mixes are used and when, with respect to fuel generation technological advancement.

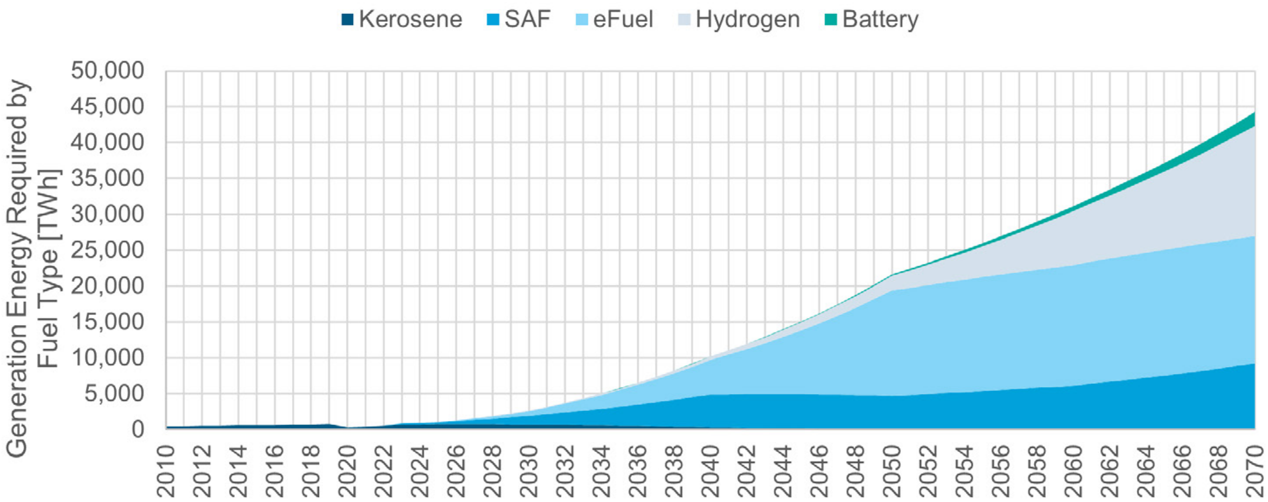

Figure 8: Energy generation capacity required to meet forecast aircraft low carbon fuel demand

Taking estimated energy efficiencies, a forecast fuel mix as above, and comparing with the flight demand energy suggests 44,000 TWh of energy per year, by 2070, is required to generate the necessary global aircraft fuel demand. This demand is shown split by fuel type in Figure 8. Almost all of this energy will need to be provided as electricity and it is a huge volume – a 5,700% increase from current aviation generation requirements (2019 demand estimated as approximately 780 TWh). Global electricity use for 2021 was approximately 27,500 TWh by comparison (Our World in Data, 2022).

To help put this volume of energy into context, a new, large-scale 3.2 GW nuclear station can be expected to generate 25 TWh of electricity per year[1]. One thousand, eight hundred of these stations would be required to meet the global demand for energy just for aviation predicted in Figure 8.

The approach used can be further demonstrated by considering the extreme positions.

The delicate balance of fuel mix will have a significant impact on the volume of energy required to power the aviation industry's future demand: for example, a maximum energy demand scenario arises from the use of 100% eFuel, which would require 63,000 TWh of energy generation by 2070 and is operationally feasible, if enough energy were available to power its production.

Whilst a minimum energy generation demand scenario of 20,000 TWh could be created by using 100% batteries – yet the limitations of battery technology means this is highly unlikely to be feasible in that timeframe.

This model can be applied to any geographic region, or specific airport, to determine energy supply infrastructure requirements. By inputting the flight demand for a region, and adding in any changes to fuel mix, we can understand the generation energy requirement and identify the relative need for SAF, hydrogen, eFuels, etc. It is this level of scenario modelling that will be required by regions, governments, airports and the wider industry, as we create masterplans for the infrastructure and ecosystems that will enable the future of sustainable aviation.

[1] *Based on Hinkley Point C new nuclear power station under construction in the United Kingdom*

Scenarios and sensitivity

To assess the robustness of the scenario shown, which could be considered a reasonable case, the contribution of each alternative fuel type to the energy demands of the different aircraft classes can be varied. In each case the reduction to Net Zero carbon by 2050 is maintained through the total phase-out of kerosene.

Low generation energy scenario

In this scenario, the use of eFuel is minimised and replaced with SAF options and increasing hydrogen and battery powered options. This takes an optimistic view of the development of battery energy density and roll-out of this into suitable aircraft designs, combined with acceleration of hydrogen aircraft design along with green hydrogen supply infrastructure availability to match.

As a proportional mix by aircraft class, Figure 9 shows the outcome, with Figure 10 providing the overall flight energy demand split by alternative fuel source.

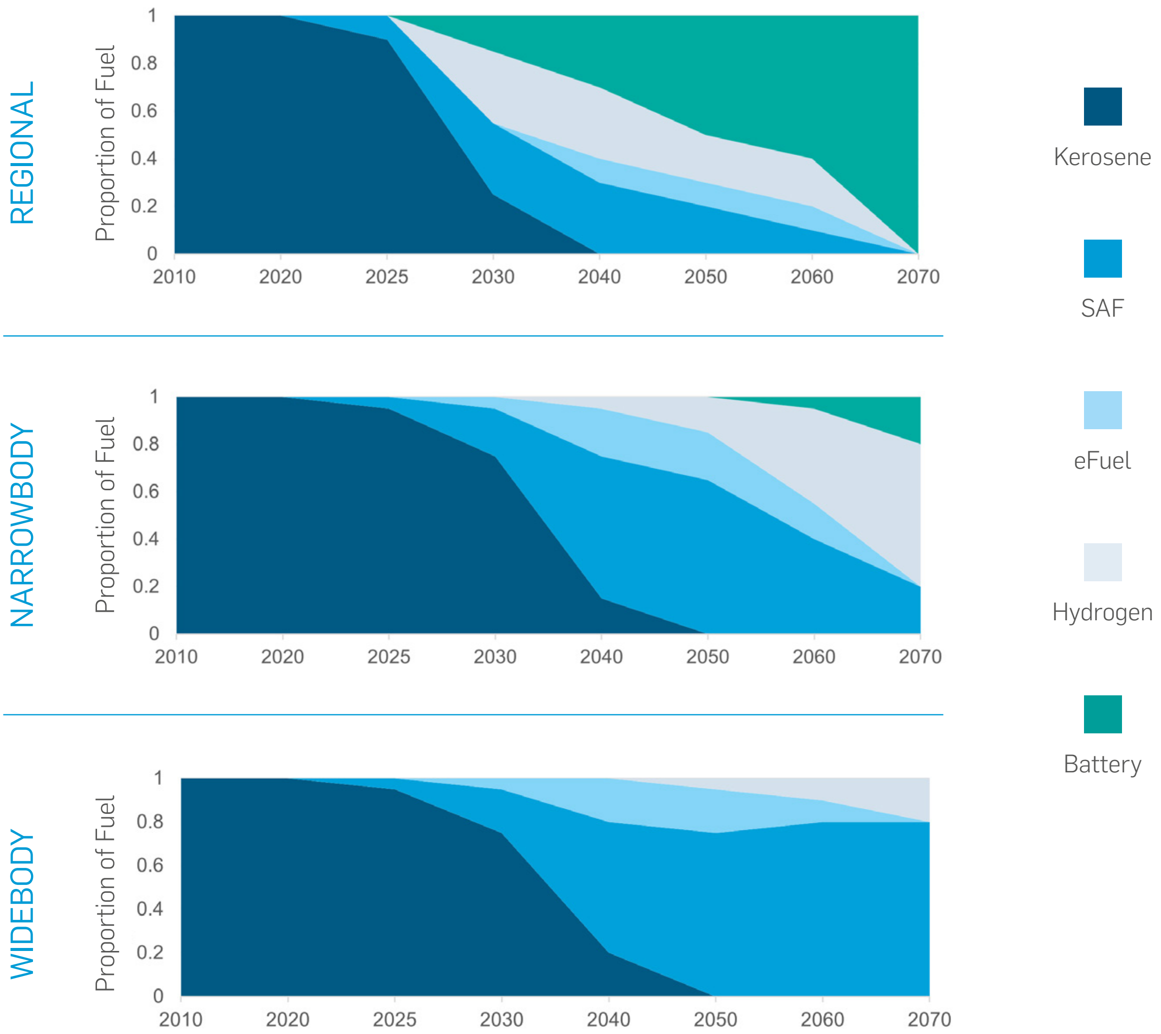

Figure 9: Low carbon, and kerosene, fuel proportion estimates – low energy demand scenario

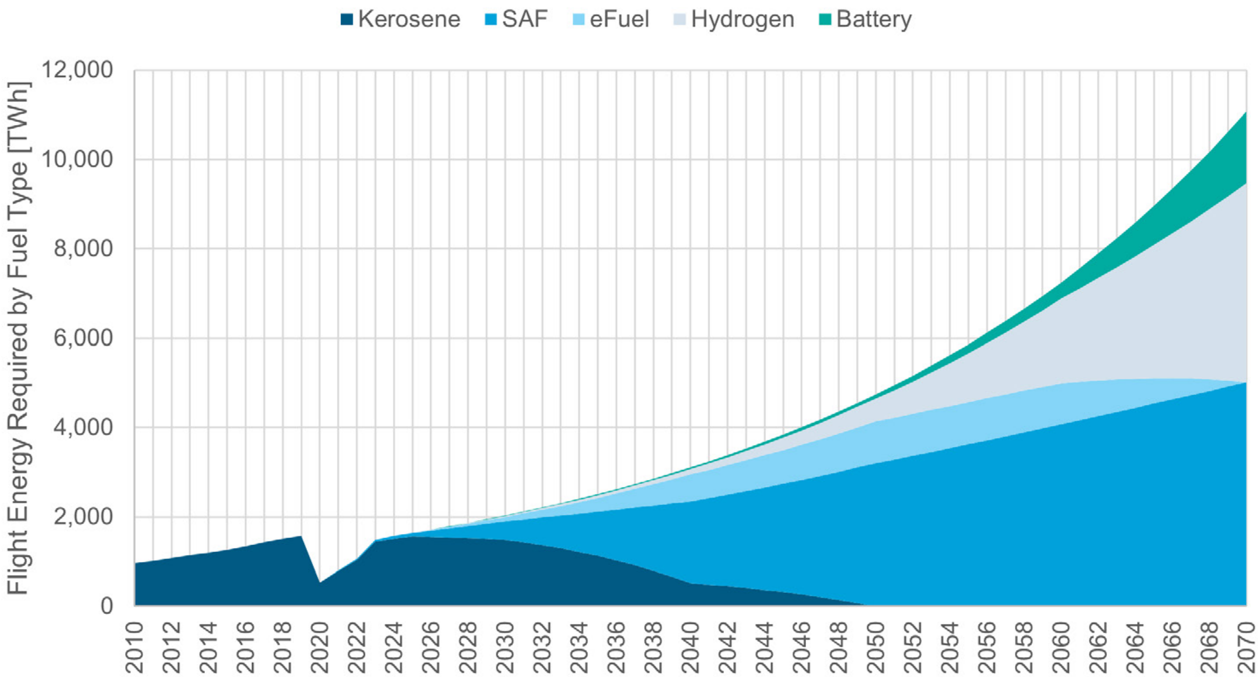

Figure 10: Global aviation flying energy demand split by low carbon fuel source, low energy scenario

As seen in Figure 10, when compared to the already presented reasonable case in Figure 6, the volume of SAF and hydrogen is noticeably increased with a corresponding drop in demand for energy intensive eFuel.

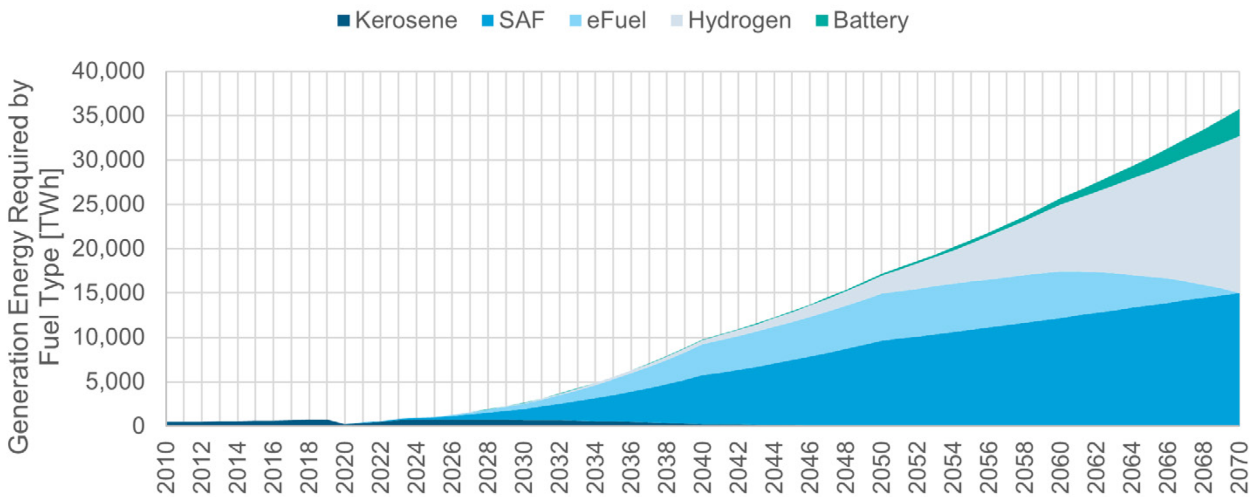

Figure 11: Energy generation capacity required to meet forecast aircraft low carbon fuel demand – low energy scenario

Figure 11 shows the generation energy demand for the low energy scenario, with a total requirement of 35,700 TWh.

High generation energy scenario

In this scenario a more pessimistic view on the availability of battery power and hydrogen is taken, combined with sufficient volumes of energy intensive eFuel production to meet any shortfall in availability of other types of fuel.

As a proportional mix by aircraft class, Figure 12 shows the outcome, with Figure 13 providing the overall flight energy demand split by alternative fuel source.

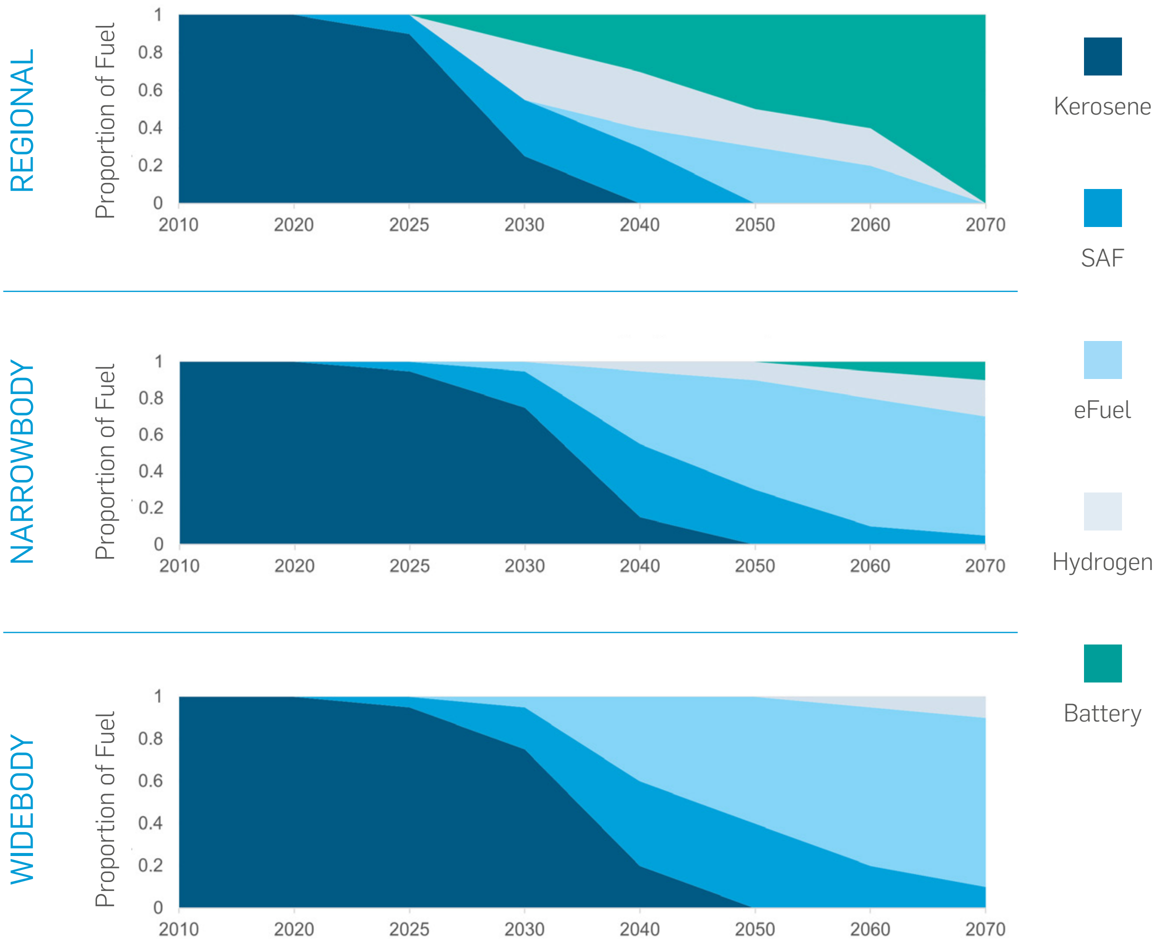

Figure 12: Low carbon, and kerosene, fuel proportion estimates – high energy demand scenario

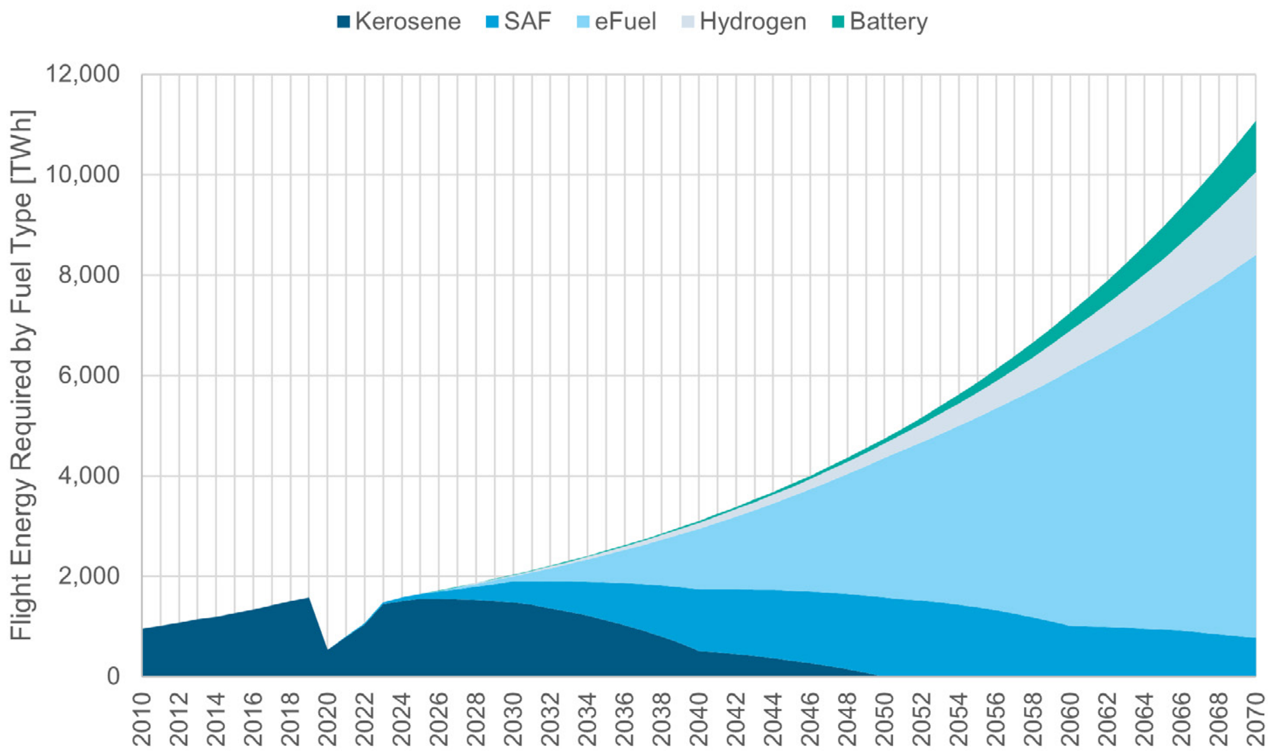

Figure 13: Global aviation flying energy demand split by low carbon fuel source, high energy scenario

As seen in Figure 13, when compared to the already presented reasonable case in Figure 6, the volume of SAF and hydrogen is noticeably reduced with a large shift towards demand for energy intensive eFuel.

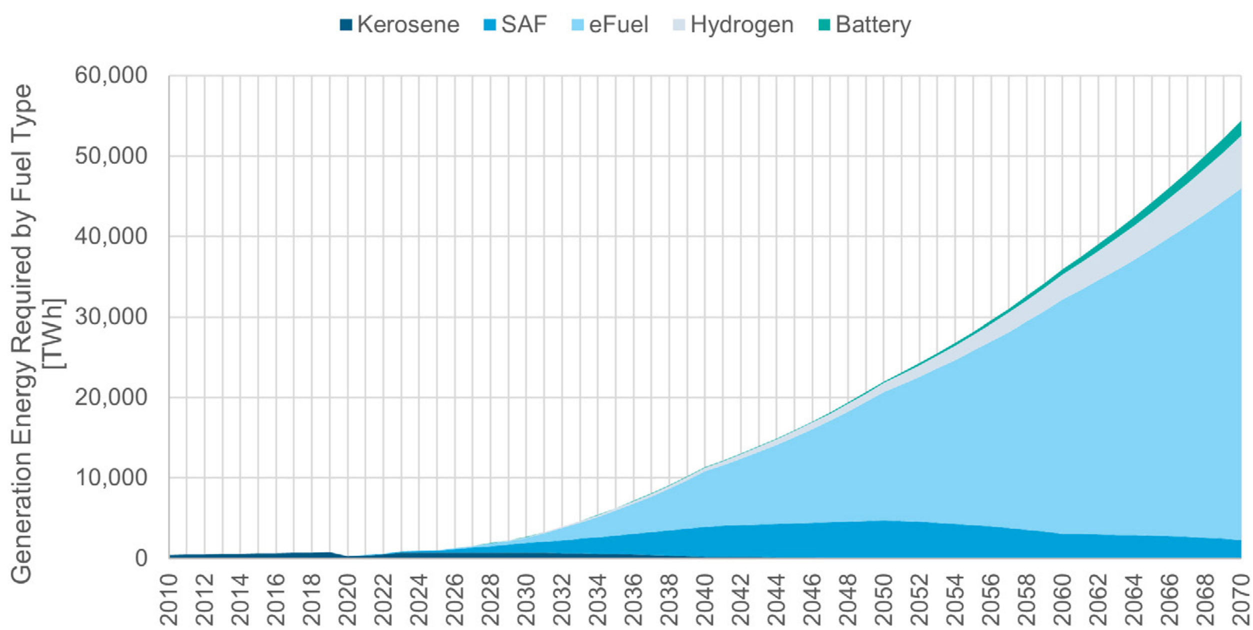

Figure 14: Energy generation capacity required to meet forecast aircraft low carbon fuel demand – high energy scenario

Figure 14 shows the generation energy demand for the low energy scenario, with a total requirement of 54,400 TWh.

Energy demand sensitivity to different alternative fuel mixes

The table provides a summary of the sensitivity analysis resulting from the different scenarios: to help illustrate the impact on energy infrastructure that would result in each case, we have included the difference in the number of 3.2GW nuclear power stations that would be required to meet the energy demand in each scenario, from the reference of 2,400 stations in the "reasonable" scenario.

This represents an example of how the approach presented in this paper can be used to inform aviation decarbonisation strategies. By adjusting the alternative fuel mix, the resulting system of systems level implications for energy generation can quickly be identified and compared to available resources, or planned developments. Where shortfalls, or gaps, are identified, the alternative fuels mix, or energy generation plans can be iterated to reach achievable Net Zero solutions.

Scenario	Generation Energy Demand 2070	Variation	Change in number of stations needed*
Low Energy	35,700 TWh per year	~20% decrease	370 fewer
Global aircraft fuel demand by 2070	44,000 TWh per year	Reference	Reference (1,800)
High Energy	54,400 TWh per year	~20% increase	380 more

**Of course, the future electricity generation mix supporting carbon alternative fuels will be a mixture of clean energy generation approaches, including renewables and nuclear. This will also change depending on regional and geographical variations in energy generation.*

Implications of this level of flight energy demand

The most effective solutions to the decarbonisation of aviation are to implement and develop all the low carbon pathways discussed. Over the next 50 years that will result in a mixed fleet of aircraft being powered by a new mix of carbon alternative fuels, rather than the reliance on any one individual fuel. This approach will support mitigation of delays in any single technology approach and recognises the need to stay within an aviation carbon budget.

The mix of alternative fuels creates infrastructure challenges around the generation of sufficient energy to produce these fuels, their transportation, and the means used to get the fuel to airports, to store it, and to deliver it to aircraft safely and economically. The scale of change needed is substantial, and complexity will increase over the system currently in operation for a single fuel type.

Because of the potentially divergent situation, and the uncertainty around technical details, an integrated planning approach – which brings together aircraft technology, airport operations and layout, alternative fuel generation and energy generation – is required, in a system-of-systems approach.

A fundamental consideration is the replacement of energy provided by fossil fuels with a low carbon, sustainable source. Ultimately this is an energy transition process that will result in a fuel that is suitable to be carried by the aircraft. As all energy transition processes result in losses, the understanding of how much energy is required for the different fuel routes is important when designing the system; while understanding the constraints geographies present to doing this will influence related export and import strategies at the national level.

Limitations on the ability to provide sufficient clean energy, fuel feedstock or aircraft could require demand control, to ensure fossil fuel aviation is phased out in accordance with wider Net Zero targets and aviation carbon budgets are supported.

The volume of energy required is also largely influenced by the alternative fuel route being followed. The lowest overall energy requirement is that of batteries, however technology limitations with power density prevent this being a solution that will be suitable for most aircraft classes out to 2070.

SAF obtained from waste sources and hydrogen are the next lowest. SAF relies on suitable quantities of available feedstock material. The availability of such material will dictate whether sufficient volumes of this fuel source can be created locally to use, and hence import/export considerations. SAF generation also interacts with other sustainability considerations to a greater extent than the other alternative fuel options.

Hydrogen comes with the benefit of an abundant source of feedstock material, available almost universally around the globe, in water. There are additional difficulties if the water is sourced directly from the sea, increasing the generation energy required, but this abundance of source material is a strong factor behind the support of a so-called hydrogen economy.

Synthetic eFuel tops the list with its requirement for a source of carbon, typically proposed to be obtained via direct air capture or from seawater, which then needs to be combined with hydrogen in a further energy intensive process.

With any of the alternative fuel options being discussed, their availability is very uncertain. Overall, these options are more expensive than kerosene (some significantly so), with high initial investment costs, and aren't predicted to be price competitive for a while. As a result, many targets for increased adoption of the SAF options which are already operational have been set and missed (Possible, 2022). Producing the quantities suggested, as required here, will be a substantial challenge across many industry areas. The intent is to be clear about the volume required if aviation is to achieve Net Zero carbon by 2050. Many similar roadmaps maintain kerosene as a fuel beyond 2050 because they include limited availability of alternative fuels as a constraint based on current production trends and estimates.

Key stakeholders to support this energy transition will be governments and their response will be influenced by their relationship with their national decarbonisation strategies. The changes required are extremely challenging, contain a level of technical uncertainty and are expensive, so are unlikely to be met through reliance on private industry alone. By understanding the fuel mix and energy demands for sustainable aviation, governments can use these to inform their policy-making and actions – whether introducing carbon taxes, green fuel subsidies or grants for development. The social and economic benefits from aviation are likely to be sufficient to support the massive investment required.

Conclusion

What the results of this paper show is the massive amount of sustainable energy and fuel production infrastructure required to support a Net Zero carbon aviation sector which continues to forecast growth of around 5% per year. An alternative approach to relying purely on technological innovation is to limit the demand for flying, which is also recommended by the UK Climate Change Committee (Climate Change Committee, 2022). It would be incumbent on governments to do this, and, if required, a fair and balanced global approach would be essential.

The most effective solution to drive the decarbonisation of aviation will be a mix of all the alternative fuel options, the combination of which will change over time. Integrated, system-of-systems planning is vitally important to achieve the transition; planning the wider aviation ecosystem must take into account future energy projections, while national governments are key stakeholders and enablers who may provide the up-front investment to enable the necessary changes.

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James Domone is a Principal Engineer at Atkins, a member of the SNC-Lavalin Group, working within the Aerospace and Defence market. He has supported numerous aerospace clients through his career, including Airbus and Rolls-Royce, on both commercial and military platforms, working on structural and propulsion systems. James has played a leading role at Atkins in developing knowledge and capabilities around improving the sustainability or aircraft with objective of achieving Net Zero operations.

Shaping the future of flight

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