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Implications of preferential access to land and clean energy for Sustainable Aviation Fuels

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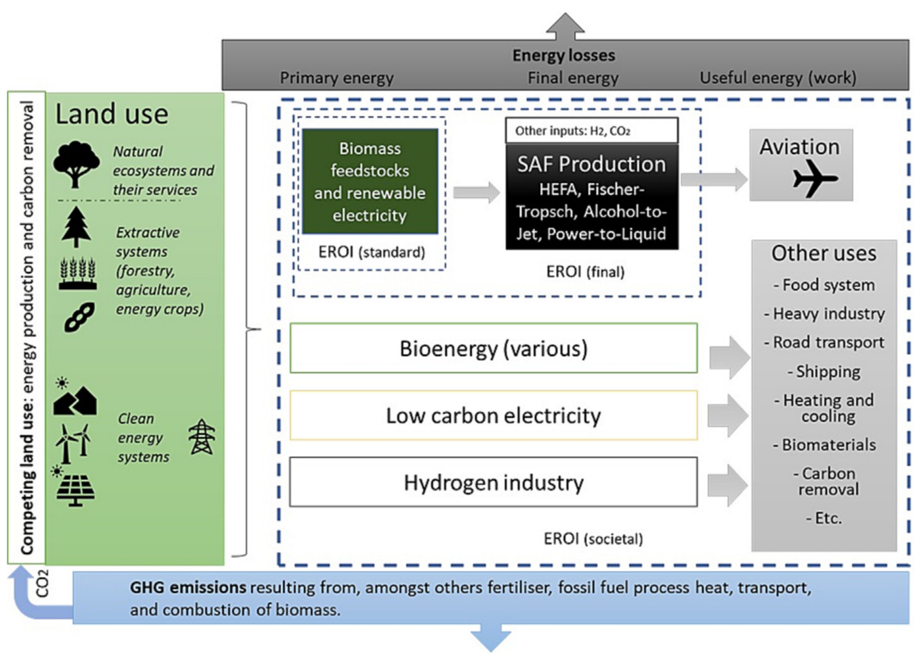
HIGHLIGHTS

- 12 aviation decarbonisation roadmaps rely on Sustainable Aviation Fuels (SAF).
- Bio-SAF would consume 30 % of sustainably available biomass in 2050.
- SAF production is energy intensive with a risk of clean energy displacement.
- All SAF emits CO_2 emissions and re-sequestration can take decades.
- Permanent removals of CO_2 are potentially inhibited by SAF.

GRAPHICAL ABSTRACT



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ABSTRACT

Aviation is highly dependent on liquid fossil fuel, and the production of 'sustainable aviation fuels' (SAF) is being proposed as a solution to removing the fossil carbon component, especially for long-haul flights. An analysis of 12 aviation roadmaps for net zero 2050 reveals heavy reliance on biogenic SAF in the medium-term and synthetic e-kerosene in the longer term. Realising these roadmaps could require 9 % of global renewable electricity and 30 % of sustainably available biomass in 2050, with significant energy 'losses'. The continued use of hydrocarbon fuel in the roadmaps generates 1.35 $GtCO_2$ in 2050, of which 30 % are still from fossil fuel. The net carbon savings from the 70 % depend on the direct and indirect life cycle emissions of producing SAF. Additional effects that are omitted in most roadmaps relate to decadal time lags in re-sequestering biocarbon in the case of forest biomass and the impact of non-CO_2 emissions. Both

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require greater scrutiny in fully understanding the climate impact of SAF substitution. The scaling up of SAF to not only maintain but grow global aviation is problematic as it competes for land needed for nature-based carbon removal, clean energy that could more effectively decarbonise other sectors, and captured CO_2 to be stored permanently. As such, SAF production undermines global goals of limiting warming to 1.5 °C; a conflict that is neither recognised in the roadmaps nor in the public debate.

1. Introduction

The world is experiencing the impacts from 1.1 °C global warming above pre-industrial levels, and "as the climate continues to warm, the observed changes in the probability and/or magnitude of some extreme weather events will continue as the human influences on these events increase" (IPCC, 2021 [SPM B2.2 C3.3; Chapter 11 FAQ11.3]). Fossil-fuel dependent sectors such as aviation are facing pressure to contribute fairly to the goal of limiting the temperature increase to 1.5 °C. The International Civil Aviation Organization (ICAO, 2022a) has adopted a long-term global aspirational goal (LTAG) for international aviation of net-zero carbon emissions by 2050. Whilst continuing to rely on hydrocarbon aviation fuels, LTAG scenarios provide paths for progressively decreasing greenhouse gas (GHG) emissions intensity through uptake of 'sustainable aviation fuels' (SAF) and liquid hydrogen. But is this strategy feasible? Even if theoretically workable for aviation in isolation, the question arises whether the proposed aviation approach delivers a net climate benefit from a wider-system perspective, given the equally urgent mitigation imperative faced by all sectors? This paper provides a critical assessment of these questions for 'net zero aviation'.

The challenge for aviation is to abate carbon dioxide (CO_2) emissions of over 1 billion tonnes (Gt) in 2019 (the pre-COVID-19 base year), whilst at the same time aiming to grow the sector. The International Air Transport Association (IATA, 2021) expects that business-as-usual emissions associated with 10 billion passengers in 2050 could be over 1.8 $GtCO_2$. The total climate impact of air travel is larger than CO_2 alone due to other emissions, in particular nitrogen oxides (NO_x, where $NO_x = NO_2 + NO$), water vapor and soot (Lee et al., 2020). By convention, the total impact of CO_2 and non-CO_2 emissions is quantified using the metric 'effective radiative forcing' (ERF), whereby a positive ERF implies warming, a negative one cooling of climate. Aviation represents 3.5 % of global ERF or approximately 4 % of the global temperature rise to date (Lee et al., 2020; Klöwer et al., 2021). Historical CO_2 emissions from air travel represent about one third of aviation's present-day ERF, and non-CO_2 emissions make up the remaining two thirds (Lee et al., 2020).

To date, the industry's climate mitigation strategy involved market-based mechanisms including carbon offsetting. However, offsetting does not represent *absolute* emissions reductions (Becken and Mackey, 2017; Allen et al., 2022), nor does it transition airlines away from fossil fuel. There remains potential to reduce emissions through improved aircraft technology and operational efficiency between 1.2 % (Faber et al., 2020) to 2 % per year (MPP, 2022). Step-change technologies such as hydrogen-powered planes – where the hydrogen has been generated using clean energy – and battery-powered short-haul flights will lead to further GHG reductions, albeit at a small scale given the limited contribution of short flights to overall emissions (Langford and Hall, 2020). Importantly, neither batteries nor hydrogen fuel cells will be suitable for long-haul flights (Faber et al., 2020), and liquid hydrogen will likely mean smaller aircraft. The long-haul network will only survive in its current form with liquid hydrocarbon fuels. This fundamental physical reality means that fuel cells and battery technologies play no role in aviation decarbonisation roadmaps for *long-haul* flights. This paper focuses on the 5 % of flights over 4000 km that make up 40 % of fuel used and the feasibility and mitigation efficacy of SAF (Clean Sky 2, 2020).

SAF are liquid kerosene replacements that can be used as a 'drop-in fuel' at a maximum blend of currently 50 %, without major changes in equipment or infrastructure. Broadly, there are three types of SAF, namely biogenic derived from biomass, waste, and fully synthetically manufactured 'e-kerosene'. SAF is generated from various feedstocks, and with the input of energy, combines hydrogen and carbon in ways that result in a lower overall carbon intensity than fossil jet fuel. The current cost of SAF is commercially prohibitive at prices 2.5–10 times higher than fossil jet fuel (Zhou et al., 2022). However, this paper is not concerned with the economic aspects of SAF. Instead, the focus here is on feedstock availability and competition (Perišić et al., 2022), energy losses and displacement (Bergero et al., 2022), net carbon reductions, and broader climate impacts of SAF. The objective is to examine the validity of aviation roadmaps released since 2021 and SAF as a mitigation strategy. The focus is on commercial passenger long-haul aviation. The paper first introduces the framework and approach, followed by an overview of SAF and the roadmaps. Key parameters extracted from the roadmaps help examine energy perspectives, carbon cycle implications, and non-CO_2 warming effects. A concluding discussion summarises aviation's role in global 'net zero' and '1.5°' goals.

2. Method

2.1. Systemic approach

This paper examines aviation decarbonisation roadmaps from a system perspective. Clearly, the societal goal is not to achieve 'net zero' of one single sector, but to maximise our chances of averting catastrophic climate impacts (Kemp et al., 2022). If decarbonising one sector undermines the opportunity of transitioning other parts of the global socio-economic system, then questions need to be asked as to how allocation of scarce resources (here, land and clean energy) should be prioritised. Understanding the consequences of one sector's climate action on the ability to achieve collective mitigation goals is crucial.

We consider resource requirements by aviation from proposed SAF pathways, including those related to biomass, waste and Power-to-Liquid (PtL) e-kerosene. As shown in Fig. 1, harnessing primary energy requires access to the finite resource which is land (noting significant potential for offshore wind generation, IEA, 2019a). This inevitably results in competition with other land uses and ecosystem services, including the increasingly critical function of ecosystems to remove and store carbon. Whilst not explicitly addressed, it should be noted that future changes in climate will affect where (bio)plants can be grown (Freitas et al., 2021). Burning SAF results in emissions of GHG at all stages. These emissions are a combination of 'closed loop' shorter-term biogenic emissions (i.e. reabsorbed by plants over years, decades or centuries, depending on the type of biomass used) and long-term geological carbon cycle emissions (over millennia, including via weathering and ocean sinks) from remaining fossil fuel consumption (Allen et al., 2022; Fankhauser et al., 2022).

A key challenge is to replicate the long-term natural geological processes that produce fossil hydrocarbons. Non-fossil primary energy requires significant processing to be turned into 'final energy' of SAF (Fig. 1) that delivers the 'useful energy' for flying. With energy becoming increasingly valuable due to universally declining ratios of 'energy return to energy invested' (EROI) (Hall et al., 2014), it is necessary to be strategic regarding where to invest primary energy. At each stage of the SAF production process energy is 'lost' as waste heat (second law of thermodynamics). This can be quantified through calculations of $EROI_{standard}$ and $EROI_{final}$ (Ecclesia et al., 2022), whereby $EROI_{standard}$ contrasts the energy content of the primary energy source with the energy required to produce it at the point when it leaves the facility (e.g. oil well head, farmgate) (Hall et al., 2014). $EROI_{final}$ incorporates $EROI_{standard}$ *plus* additional energy inputs required to produce the final energy carrier, such as SAF. In a review

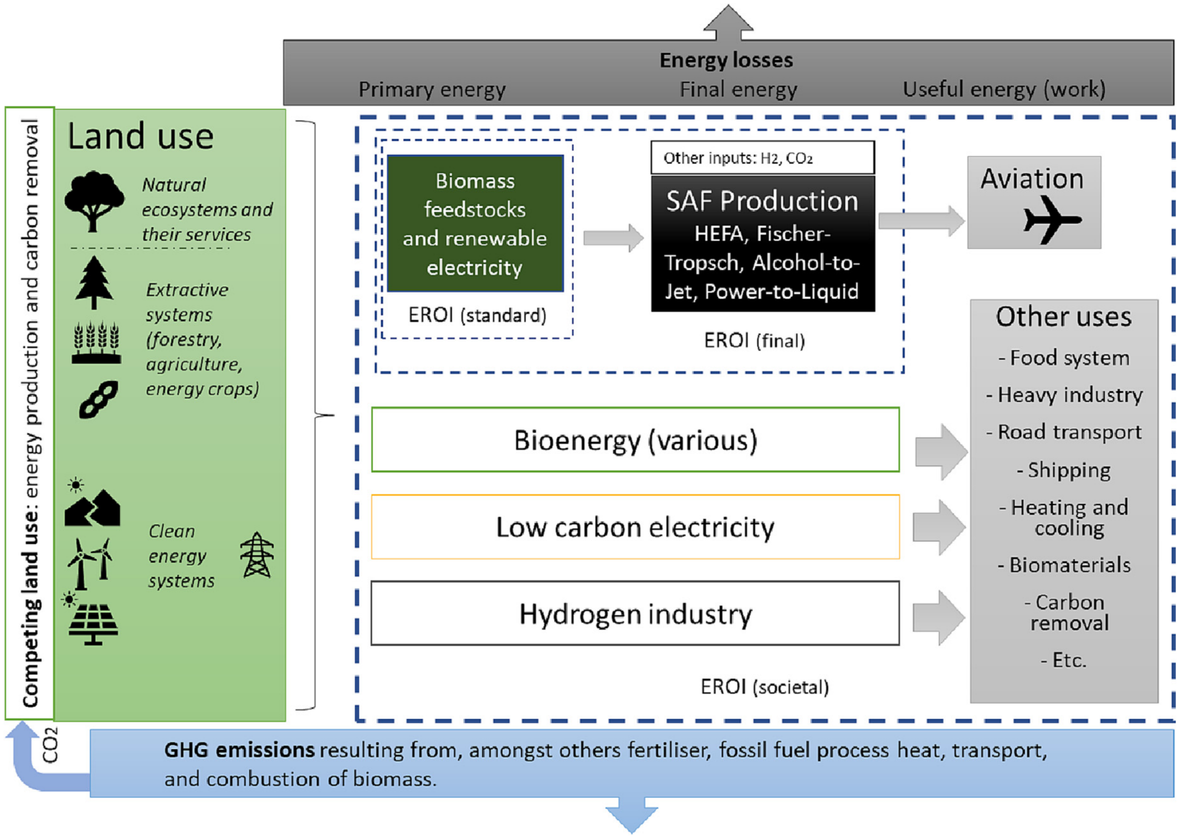

Fig. 1. Energy flows and emissions related to SAF production alongside other users of biomass and low carbon energy in a net zero world. (Source: informed by Ecclesia et al., 2022).

study Hall et al. (2014) reported the greatest $EROI_{standard}$ for hydroelectricity (84, individual studies may arrive at quite different values), followed by coal (>40), and nuclear energy (14). An EROI of <1 is energetically unfavourable.

Whilst there are plenty of potential clean energy sources (solar, wind, tidal, hydro, geothermal), these need to be transformed into useful energy, requiring investment, material inputs and social license. The real-world availability of clean primary energy at present and for the foreseeable future is limited. In terms of achieving global decarbonization, clean energy, just like land, represents a scarce resource. SAF is only one amongst many potential uses. In theory, and if global preferences were known, an optimal $EROI_{societal}$ (Hall et al., 2014) could be derived (Fig. 1).

2.2. Analysis

Twelve roadmaps published by aviation and non-aviation organisations provided data for the analysis of decarbonisation pathways. To establish a common base for comparison across the roadmaps, units were converted to Exajoules (EJ which is 10^{12} MJ), Gigatonnes of CO_2 ($GtCO_2$) and million tonnes fuel (Mt). The energy density of SAF was assumed to be 42.8 GJ/t (Shahriar and Khanal, 2022). No original modelling was undertaken, but instead, the available information was assessed in terms of the implications for the (i) global energy system, (ii) long-term reduction in atmospheric concentrations of CO_2, and iii) non-CO2 atmospheric effects.

Drawing on literature, we compile estimates on energy availability in 2050 to provide context for aviation's energy requirements. Further, published EROI values help to establish the magnitude of energy losses involved in SAF production. This is relevant to capture ‘opportunity costs’ of prioritising SAF. The carbon analysis compares Life Cycle Analysis (LCA) values for different SAF feedstock, alongside estimates of emissions from land use change and time lag effects of CO_2-sequestration in biomass. The effects of SAF usage on atmospheric chemistry and physics are summarised using the latest scientific evidence in this field. Environmental impacts such as water use and pollution, and geographic and socio-economic aspects of SAF deployment are not considered.

There are several limitations to the analysis presented in this paper. First, research on SAF technology and (commercial) production in itself is at an early stage and there are many knowledge gaps in relation to the energy and carbon intensities of different feedstocks and processes, especially when considering different geographic context. Predictions of energy systems to 2050 also carry uncertainties, and assumptions differ vastly across different models, for example for total available (sustainable) biomass. The analysis presented here had to draw on diverse sources in an attempt to generate a coherent picture of the *broad* parameters that determine the landscape within which SAF production is expected to expand significantly. This paper is about capturing the fundamental challenges associated with SAF.

3. SAF roadmaps

3.1. Overview of SAF

Several states and organisations have put forward SAF production targets. The European Commission (2021) envisage that by 2030 aviation fuel in Europe should contain 5 % of SAF, with a sub-target of 0.7 % being e-kerosene. These increase to 32 % of SAF by 2040 and 63 % by 2050. By then, the minimum share of e-kerosene should be 28 %. The task is significant: the current availability of 140 million litres of SAF represents <0.1 % of global aviation fuel consumption (IRENA, 2021). To expand from the planned 7.9 billion litres in 2025 that deliver 0.27 Exajoules (EJ), to reach a supply of 15.5 EJ in 2050 (IATA, 2021), 57-fold growth is necessary. An estimated 300 to 400 production plants are needed to just reach the 2030 volumes (MPP, 2022). At present, there are eight plants in progress.

Table 1
Overview of roadmaps (detail in Supplement 1).

Publication	Description	GHG in 2050	SAF contribution in 2050	Residual in 2050
Destination 2050 (van der Sman et al., 2021)	Supported by five European air transport associations.	Unmitigated: 0.293 GtCO2. Hydrogen on intra-European routes.	32 Mt. of SAF (13 Mt. biogenic) (83 % of jet fuel burn in Europe).	Annual 0.022 $GtCO_2$ (6 Mt. of fossil fuel).
Fly Green (Airlines for America, 2021)	Industry statement promoting innovation and government support.	Pledged 'net zero'.	'2 billion gallons in the US' by 2030 (ca. 6 Mt)	
DEPA 2050 (German Aerospace Center, 2021)	The 'Development Pathways for Aviation up to 2050' analyses air transport technologies using two scenarios.	Conservative: 1.81 $GtCO_2$ and 11.8 MtNOx; Progressive: 0.580 GtCO2 and 10 MtNOx. Hybrid aircraft in the progressive scenario.	Conservative: 230 Mt. of SAF (30–50 % of fuel). Progressive: 405 Mt. (70–90 %).	Fossil fuel of 100–345 Mt.
Net Zero Emissions (IEA, 2021)	Global energy roadmap with details about aviation in the Net Zero Emissions (NZE) scenario.	Mitigated 0.21 $GtCO_2$ in 2050. Reductions from behaviour change, small savings from electric and hybrid aircraft.	Aviation needs 14 EJ, total SAF is 245 Mt. (45 % bio-SAF and 33 % e-kerosene).	Remove 70 $MtCO_2$ from 3 EJ of fossil jet fuel.
Reaching Zero with Renew-ables (IRENA, 2021)	Assessment of SAF prospects in the context of IRENA's 1.5 °C path.	Unmitigated 1.2–1.9 $GtCO_2$. Annual efficiency improvement target is 2 %.	200 billion litre/year 'biojet fuel' (i.e. 160 Mt).	CORSIA.
Net zero by 2050 (AAPA, 2021)	Industry pledge of net zero emissions in 2050 by Asia Pacific airlines.	1.5 % fuel efficiency improvement and SAF deployment.	Asia Pacific region will need 40 % of global SAF to replace fossil fuel.	CORSIA.
Fly Net Zero (IATA, 2021)	IATA resolution to achieve net-zero carbon emissions by 2050.	Unmitigated: 1.8 $GtCO_2$. Potential for new propulsion.	359 Mt. of SAF, abating 65 % of emissions.	CCS (11 %) and offsets (8 %) of the 1.8 $GtCO_2$.
Waypoint 2050 (ATAG, 2021)	Waypoint presents three scenarios for emissions reductions.	Unmitigated: 2 $GtCO_2$.	380 Mt. of SAF in S1; 445 Mt. in S2; 330 Mt. in S3 (53–71 % of fuel); 41–55 % of bio-SAF.	6–8 % of BAU offset.
The role of Sustainable Aviation Fuels (Malina et al., 2022)	World Bank report on SAF progress using three scenarios.	Unmitigated: 0.69–2.11 $GtCO_2$.	Three scenarios: 108 Mt. of SAF, 216 Mt., and 331 Mt. (23–72 % of fuel).	
LTAG (ICAO, 2022a)	CAEP developed three integrated scenarios, modelled to 2070.	Unmitigated: 0.203 (IS3), 0.495 (IS2) or 0.954 (IS1) $GtCO_2$. Emissions 21–68 % lower than baseline. Small role for hydrogen.	Appendix M5 specifies three fuel scenarios of 164, 414 and 523 Mt. SAF (29.2–100 % of fuel). (Global fuel use)	Residual emissions from fossil jet fuel.
Vision 2050 (ICCT, Graver et al., 2022)	A global aviation decarbonisation roadmap with three scenarios.	Mitigated in Breakthrough scenario: 0.07 $GtCO_2$ remaining. Hydrogen and electric aircraft contribute to reductions.	Action: 220 Mt. of SAF; Transformation: 250 Mt.; Breakthrough: 315 Mt. (50–100 %).	Removal for all scenarios required for 1.5° goal.
Making Net-Zero Aviation Possible (MPP, 2022)	For aviation sector decision makers to decarbonise the industry.	Unmitigated: 2.9 $GtCO_2$. Demand reductions could reduce SAF by 10–15 %. Hydrogen aircraft in the Optimistic scenario.	SAF volume between 300 and 370 Mt. for PRU and ORE scenarios.	0.12–0.14 Gt CO_2 to be offset.

The immediate increase in SAF production will come from biomass. First generation (1G) feedstocks, such as corn, oil palm, soy or sugarcane, have been linked to increases in the cost of food and a range of adverse environmental impacts (Doliente et al., 2020; Perišić et al., 2022). The focus has therefore shifted to second generation (2G) sources, such as feedstocks containing lignocelluloses. These are often by-products from agriculture or forestry. Using woody biomass is problematic from a carbon cycle perspective and this will be explored further below. 2G biomass also includes energy crops such as jatropha, willow or switchgrass, as well as used cooking oil, municipal solid waste, and waste products from palm oil production. Both Palm Fatty Acid Distillate (PFAD) and Palm Oil Mill Effluent (POME) have attracted interest as carbon sources in biofuel production (Yeoh and Goh, 2022). Third generation (3G) fuels based on algae are not covered in the examined roadmaps.

Most approved conversion paths for production of alternative fuels in commercial aviation are variations of hydro-processed esters and fatty acids (HEFA), Fischer-Tropsch (FT), and Alcohol-to-Jet (AtJ) processes (producing synthesized paraffin kerosene (SPK)), and the (less advanced) Synthetic Iso-Paraffins (SIP) pathway converting sugars into a hydrocarbon ($C_{14}H_{32}$) (Pavlenko and Searle, 2021). HEFA is most mature commercially (e.g. Neste), but the FOGs (fats, oils, and grease) feedstock only delivers a fraction of required volumes (Heinberg and Fridley, 2016). Moreover, the HEFA process requires hydrogen for 'hydrotreatment', which presently comes from fossil fuels. Globally, <0.1 % of hydrogen production is from electrolysis powered by clean energy (IEA, 2019b) and is therefore 'green hydrogen'. The newer FT and AtJ pathways allow conversion of more diverse feedstocks into SAF. Aemetis, for example, has signed major SAF agreements with airlines using orchard residues in California. In the UK, LanzaTech is processing ethanol feedstock made from steel mill waste gases to produce SAF. The PtL path does not require biomass, but clean electricity for electrolysis of water to produce (green) hydrogen, and CO_2 to create e-kerosene in a FT process via methanation or methanol synthesis (Zhou et al., 2022). This process is essentially the reverse of combustion. The PTL process for e-fuels is still at the development stage with the first industrial pilot plant opened in 2021 in Germany.

3.2. Pathways to 2050

Table 1 summarises the roadmaps and reports (more detail in Supplement 1). The inconsistency presents analytical challenges. Not all roadmaps contain baseline data, nor measurable goals for 2050. Some present quantitative data on CO_2 emissions, others express changes in the form of percentage reduction relative to business-as-usual (BAU). Except for the German Aerospace Center (2021), non-CO_2 emissions are not quantified, despite their significant contribution to warming. Passenger volume is recognised as a key driver, but only few roadmaps explore the possibility of relative demand reductions. For example, the International Energy Agency's (2021) Net Zero Emissions (NZE) scenario models a reduction in flights by 12 % between 2020 and 2050. Some roadmaps include (limited) GHG savings for short- to medium-haul flights from hydrogen-powered aircraft (ATAG, 2021).

The share of SAF relative to all fuel will grow significantly. IATA's (2021) milestones are 5 % in 2030, 39 % in 2040 and 65 % in 2005. The ICCT Breakthrough scenario and both Mission Possible Partnership scenarios model 100 % SAF by mid-century. Absolute SAF volumes in 2050 range from 245 Mt. (IEA, 2021) to 370 Mt. (MPP, 2022) (Fig. 2), with a shift from biogenic SAF to e-kerosene towards 2050. Some roadmaps provide information on fossil jet fuel volumes, most prominently the conservative IS1 by ICAO's Committee on Aviation Environmental Protection (CAEP) where jet fuel makes up 71 % of all fuel in 2050. The provided fuel volumes of both SAF and fossil fuel in 2050 can be converted into CO_2 emissions from combustion (Fig. 2 insert), showing that mid-century emissions will be around 1.35 $GtCO_2$. Of these, the data indicate that 0.4 Gt (30 %) are from fossil fuel. The carbon cycle of the 0.95 Gt from SAF combustion will be discussed further below.

Several roadmaps flag that 'residual emissions' need to be offset, presumably by purchasing carbon credits through current governmental and

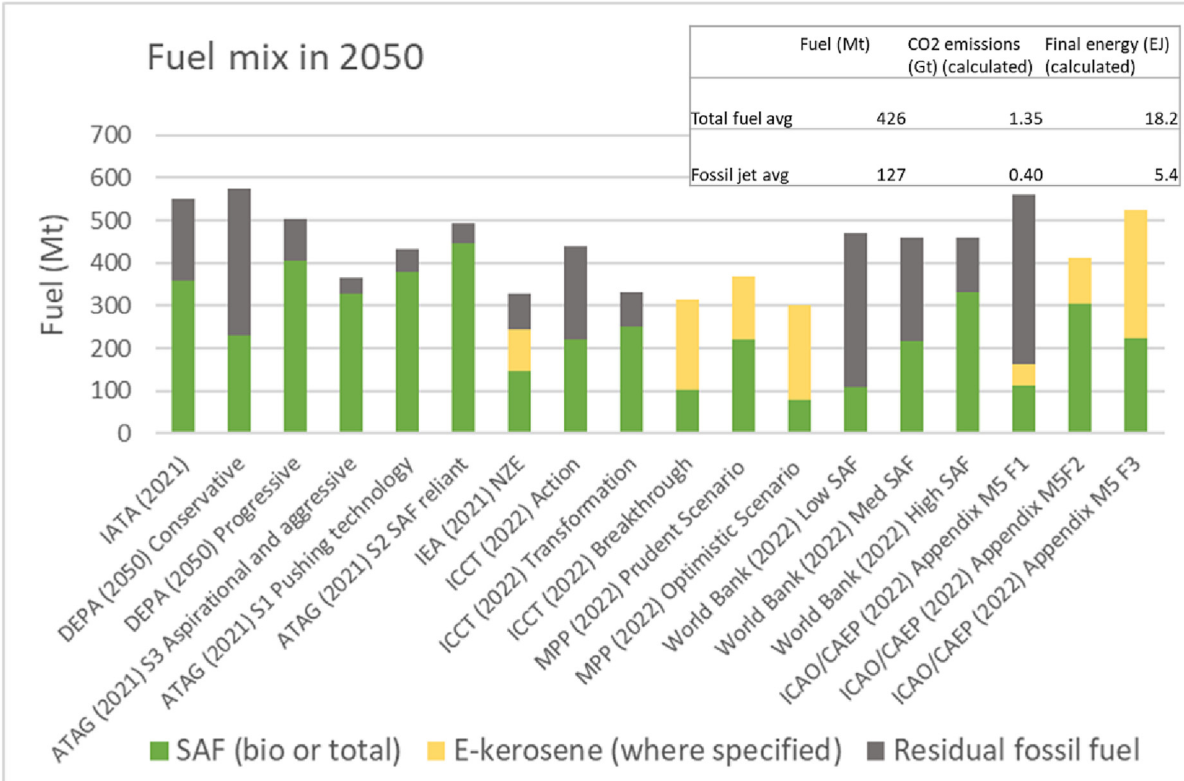

Fig. 2. Fuel volumes (SAF and fossil) for roadmaps where data were available. Average volume, derived CO_2 emissions (3.16 tCO_2 per tonne of fuel) and final energy demand presented in the insert.

voluntary markets and/or the new mechanism being implemented under Article 6 of the Paris Agreement. Some also refer to carbon removal through yet-to-be developed (at scale) Direct Air Carbon Capture and Storage (DACCS) technology.

4. Assessment of SAF as a mitigation option

4.1. Availability of SAF inputs

The biomass and clean energy requirements of SAF production necessitate a perspective on the availability of these resources beyond aviation. The 2019 global primary energy supply of 612 EJ was dominated by fossil fuels (84.3 %). It delivered final energy of 435 EJ (IEA, 2021), the difference being losses from the conversion. Predicting energy demand for 2050 depends on many parameters including the extent to which fossil fuels can be replaced by direct electricity use (e.g. electric cars) so as to minimise losses. Socio-Economic Pathways provided by the IPCC (2022) show final energy demand between 410 EJ (C1 scenario) and 696 EJ (C8). Several organisations have estimated that final energy demand that is in line with 'net zero 2050 goals' would be around 344 EJ (IEA, 2021) and 356 to 493 EJ (ETC, 2021).

Ultimately, the 2050 energy system relies on two energy sources, namely clean electricity and biomass (Fig. 1). Estimates for electricity generation in 2050 range from 224 EJ from renewable sources plus 20 EJ from nuclear (IEA, 2021, Table A.3) to 469 EJ estimated by the Energy Transition Commission (2021). In 2019, total supply of renewable plus nuclear electricity was 36 EJ, meaning that substantial investment is required to grow the clean electricity sector by about a factor of 10 (range 7–13 from the above studies). Second, biomass will become more important. ETC (2021) and UK Committee on Climate Change (2018) both assume robust sustainability criteria that will limit total availability mid-century around 40–60 EJ. In contrast, IEA's (2021) NZE scenario foresees 102 EJ bioenergy annually from 2050, similar to IPCC's (2022) lower emissions scenarios and ETC's 'maximum potential' of 120 EJ (i.e. demanding lower meat consumption and increased agricultural productivity). Five aviation roadmaps provide figures for bio-energy which are in the above ballpark, except for the World Bank (Malina et al., 2022) who assume 41–510 EJ.

The aviation final energy demand in 2050 in the roadmaps varies between 15 EJ (IATA, 2021; IEA, 2021) and up to 30 EJ (ATAG, 2021) (see 18 EJ derived in Fig. 2). However, greater amounts of primary energy are required to produce this final energy. ICCT report that the 16 EJ required by aviation in 2050 will demand 28 EJ primary energy (Graver et al., 2022). MPP (2022) specifies that the Prudent scenario will need 12 EJ from biomass plus 21 EJ electricity, whereas the Optimistic Renewable Electricity scenario will use 4 EJ biomass and 34 EJ electricity, directed towards producing e-kerosene. ATAG (2021) estimate at least 20 EJ of biomass requirements. To synthesise the assumptions in the roadmaps, it appears that broadly aviation could require 20 EJ of electricity and 15 EJ from biomass. These would represent 9 % of 224 EJ global (renewable) electricity and 30 % of available 50 EJ biomass, respectively.

Fig. 3 shows potential feedstocks (middle green cells) for SAF, alongside alternative uses of these resources. Clearly, food, municipal and industrial waste volumes will only deliver a fraction (5 EJ in total) of energy. This means that energy crops (5–10 EJ), agricultural (10–12 EJ) and forest residues (10–20 EJ) become crucial. The land use implications are substantial. ETC (2021) suggests that the theoretical production of 50 EJ in 2050 from energy crop biomass would occupy about 280 Mha; the equivalent of 8 % of current agricultural land. Exact land requirements depend on feedstock and climate; for example rapeseed oil (HEFA) generates 48 GJ per hectare per year, compared with sugar cane (AtJ) yielding 120 GJ per hectare per year (German Environment Agency, 2016). Hypothetically, to produce 15 EJ (the estimated total biomass requirements for aviation) from sugar cane would require 125 million hectares of land; larger than the land area of South Africa. For comparison, renewable electricity installations deliver 470–1070 GJ per hectare and year (ibid).

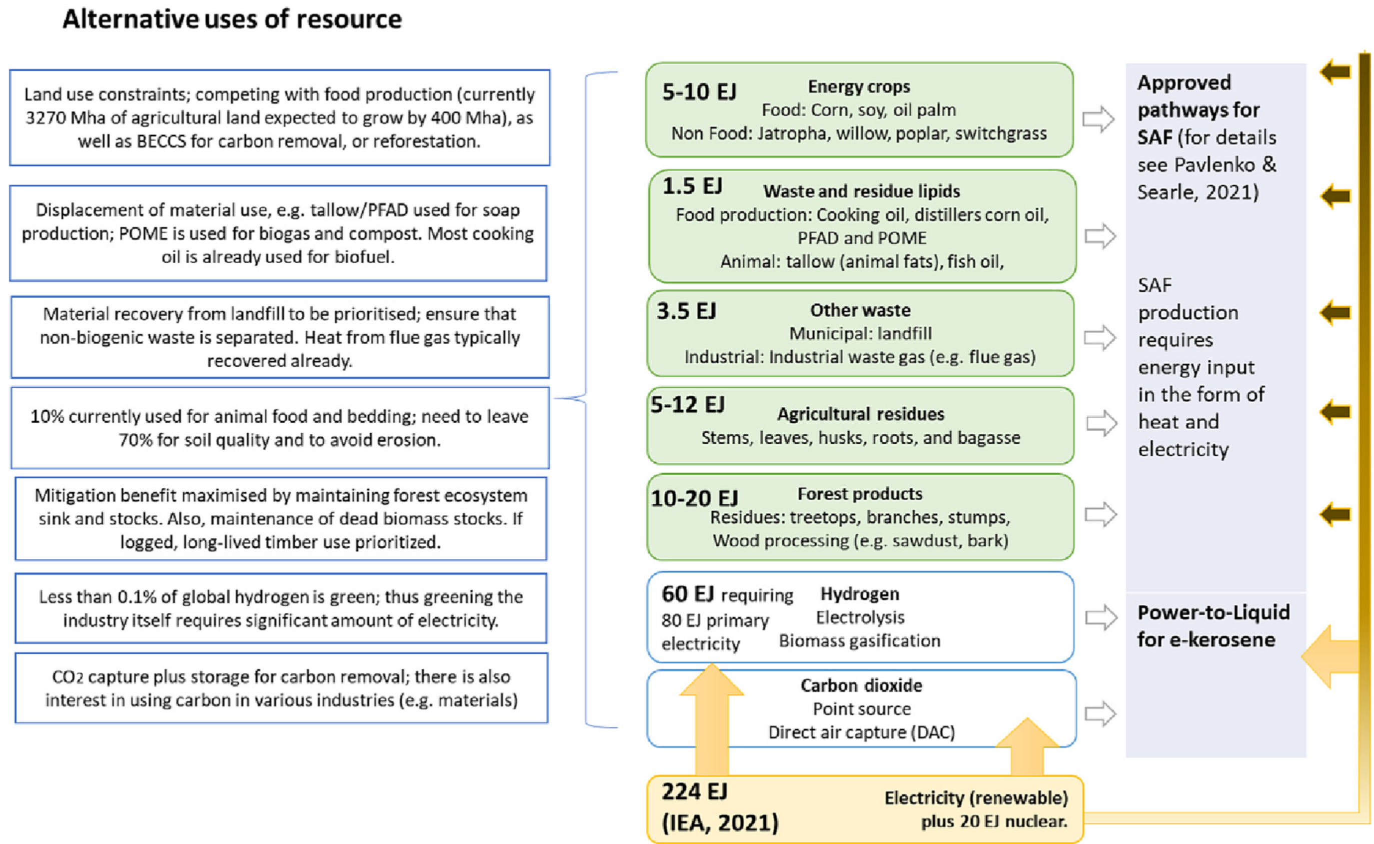

Fig. 3. Biomass and other inputs into SAF, their estimated availability in 2050, and alternative uses.

Hydrogen is required for some biogenic SAF processes as well as for PtL. Again, estimates of how much hydrogen will be available in 2050 vary. We use IEA's (2021) estimate of 60 EJ for Fig. 3. For the MPP (2022) roadmap, which models a need for 11.4–19.2 EJ of hydrogen, this means that aviation would consume up to 32 % of global hydrogen supply. Hydrogen is not a primary energy source but an energy *carrier* and as such the 60 EJ (see IEA, 2021) shown in Fig. 3 is not additional to the 224 EJ renewable electricity assumed by IEA (2021). In addition, for PtL it is necessary to capture CO_2, for example up to 470 Mt. in the ICCT's Breakthrough scenario, demanding significant access to clean energy. Realmonte et al. (2019) provide a range for energy intensity between 5 and 10 GJ/tCO_2 captured.

All inputs bring a risk of displacement. FOGs are already a valuable commodity, including for biodiesel production (ATAG, 2021; IRENA, 2021). Diverting feedstock to SAF could trigger replacement by palm oil, vegetable oil or even fossil fuels. Similarly, there are existing uses of POME such as biogas and electricity generation (Booth, 2018). PFAD and tallow (rendered animal fat) are used in soaps and cosmetics. Industrial flue gases from steel mills are typically already captured for in situ energy recovery, at least in Europe, raising questions around what constitutes a 'waste product' or 'residue' and how emissions should be attributed (Booth, 2018; Pavlenko and Searle, 2021) once a resource is part of a new value chain. *E*-kerosene can lead to displacement when the electricity used in the process is not additional to existing efforts of decarbonising the energy sector (Zhou et al., 2022). The risk of 'energy cannibalism', where "rapid growth of an entire energy producing (or conserving) technology industry creates a need for energy that uses (or cannibalizes) the energy of existing power plants or devices" (Pearce, 2009, p. 1), is explored in the next section.

4.2. Energy losses

Energy 'losses' of SAF production occur at multiple stages. Determining EROIs is therefore complex. Trivedi et al. (2015), for example distinguish whether the 'energy invested' in the denominator is fossil fuel-based or inclusive of all energy. The former reveals the extent to which SAF relies on fossil fuel (i.e. 'are we better off'), whereas the latter can help determine opportunity costs of other forms of energy embodied in SAF. For our purpose, we consider all energy required to produce the primary energy sources for SAF (Fig. 1) captured as $EROI_{standard}$. Discussions on whether 'waste' feedstock should be attributed some of the 'energy invested' of the primary product are inconclusive; hence we focus on biogenic SAF and e-kerosene. Once, transport, processing and distribution are included, $EROI_{final}$ can be calculated. For comparison the $EROI_{standard}$ of oil is about 20 (Hall et al., 2014), and the $EROI_{final}$ of fossil jet fuel is 5.8 (Trivedi et al., 2015).

$EROI_{standard}$ for bioenergy varies vastly with one of the higher values being 3 to 4 for sugar cane but others being <1 (Chiriboga et al., 2020; Heinberg and Fridley, 2016). Trivedi et al. (2015) show that the stage of 'fuel conversion' (i.e. processing) into SAF is by far the most energy-intensive, relative to extraction and transportation. Shahriar and Khanal (2022) report process efficiencies (GJ_{output}/GJ_{input}) of between 0.4 and 0.5 for AtJ, 0.71–0.77 for HEFA and 0.91 for FT pathways; that is losing between 60 % and 9 % of energy (figures depend amongst others on how by-products such as heat are attributed). The findings from Trivedi et al. (2015) provide an indication of $EROI_{final}$ for nine types of bio-SAF, ranging from 1.64 for palm oil (HEFA) to 0.36 for sugarcane (AtJ). Overall findings are that biogenic SAF is characterised by unfavourable EROIs.

The EROI of e-kerosene is determined by clean energy technologies and variations of the PtL process such as the source of CO_2, type of process heat, and pathway (methanol or FT). The $EROI_{standard}$ for wind and solar as primary energy is superior to crop production, although it depends on geographic factors and whether energy losses associated with storage facilities are considered. Solar electricity $EROI_{standard}$ ranges from 2 to 3 to 10, and wind could be up to 18 (Hall et al., 2014; Heinberg and Fridley, 2016). Some aviation roadmaps provide useful information on PtL energy requirements and losses. GJ_{output}/GJ_{input} is between 0.5 and

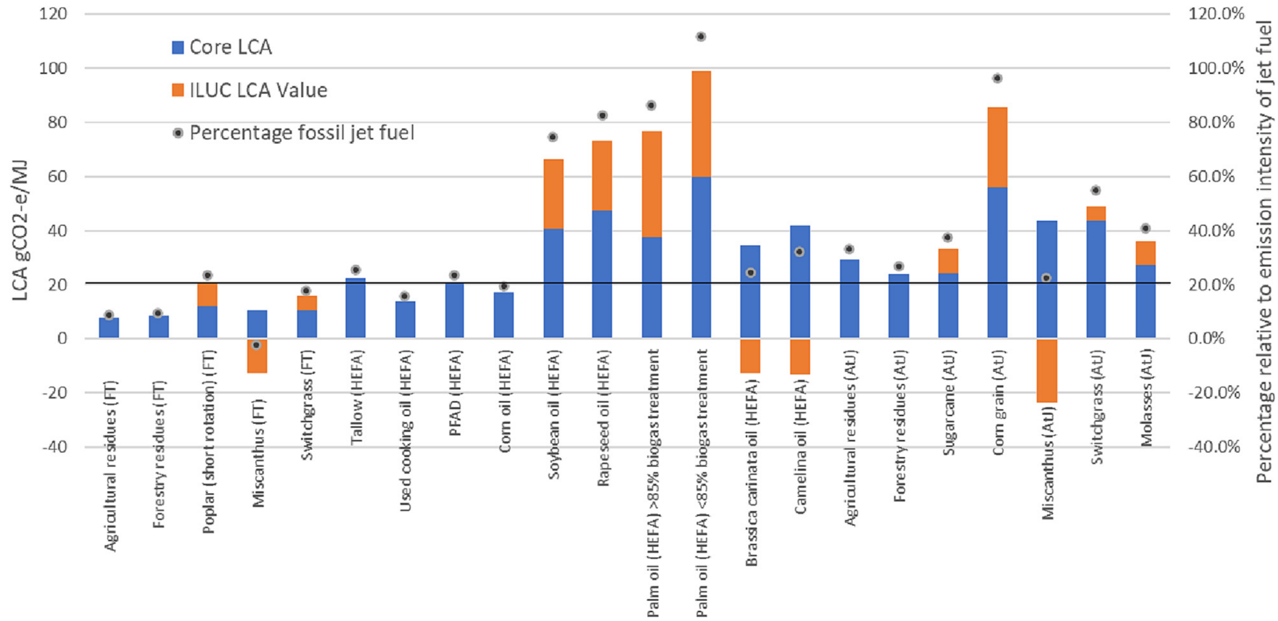

Fig. 4. Core LCA and ILUC values in gCO_2-e/MJ provided by ICAO (2022b) (selection of global default values for key pathways). The black line refers 20 % of fossil fuel emissions on the secondary axis ('80% improvement compared to fossil fuel' assumed in many roadmaps); only six SAF options deliver this value.

0.4 (ICAO, 2022a, Appendix M5), similar to the numbers provided by Zhou et al. (2022) and MPP (2022) (86.4–111.6 GJ required to produce 1 t of e-kerosene, equivalent to efficiencies of 0.5–0.6). The $EROI_{final}$ for e-kerosene mainly depends on the input electricity, of which more than half will be lost due to conversion and distribution which is not yet reflected in the above numbers. As MPP (2022) note, further losses in the order of 70 % occur when e-kerosene is used for propulsion.

SAF energy return to energy invested is a highly relevant measure in a world where (clean) energy is limited. Every unit of biomass or electricity dedicated to SAF is lost to other uses. Consuming electricity to produce e-kerosene represents a major opportunity cost of decarbonising other sectors, including the electricity sector itself. When expressed as CO_2 abatement per MWh of clean electricity, the closure of a coal-fired thermal plant delivers almost 10 times more mitigation benefit than e-kerosene production (Douglas and James, 2022). EROI focuses on energy flows and not carbon. The next section provides an assessment of the carbon implications of SAF usage.

4.3. Net reductions in atmospheric carbon concentrations

The key question is whether SAF use results in net reductions in accumulated atmospheric CO_2 concentrations compared with a fossil fuel usage baseline. First, SAF production induces emissions at various stages. ICAO (2022b, 2022c) provides default Life Cycle Analysis (LCA) emission factors and a methodology that includes: feedstock cultivation; conditioning (e.g., harvesting and collection); feedstock processing and extraction; transportation; SAF conversion processes; transportation/distribution to the blend point; and, finally, fuel combustion. Fig. 4 visualises LCA emissions for different pathways and feedstocks, noting that actual factors – for example in different countries – may deviate substantially (e.g. de German Environment Agency, 2016; de Jong et al., 2017; Doliente et al., 2020; Pavlenko and Searle, 2021).

Importantly, and in the case of many bio-feedstocks (for a decision tree, see ICAO, 2022c), emissions are incurred due to changes in land use, either directly or indirectly. The induced land use change factors (ILUC) are shown in Fig. 4. ICAO derives these from two global models (GLOBIOM and GTAP-BIO), but uncertainties continue to be considerable (e.g. see Seber et al., 2022). Some SAF options (e.g. most HEFA products) deliver clear mitigation benefits as they only generate about 20 % of the 89 gCO_2/MJ fossil fuel baseline. Moreover, some studies have even identified the potential for negative ILUC values (e.g. Miscanthus, Zhao et al., 2021), when carbon stocks of marginal or abandoned land are improved as a result of biofuel production (e.g. due to soil carbon accumulation). A detailed study of miscanthus and willow extension in Ireland shows, for example, that conversion from arable land generates net benefits, but from pasture it does not (Clarke et al., 2019). However, Fig. 4 reveals that many SAF feedstocks are still associated with high levels of GHG emissions, for example soybean, rapeseed and corn grain. The conversion of high carbon stock peatlands for palm oil production, for example, comes with many decades of 'carbon debt' which negates the benefits of any SAP deployment (Field et al., 2020). Whilst ICAO (2022c) specifies that crop grown on cleared primary forest, wetland or peatland is not CORISA-eligible, it may be difficult to control commercial biomass growers who seek to maximise crop yield.

Whilst ICAO (2022c) does not attribute indirect emissions to waste or residual products, methodologies could change.[1] Tallow, for example, comes from livestock, which inherently is characterised by high GHG emissions (just not assigned to SAF at this stage). Additionally, O'Malley et al. (2021) estimate that displacement of tallow use for animal feed and cosmetic products results in indirect emissions of 32 gCO_2-e/MJ. Adding direct and indirect emissions for tallow results in a carbon intensity of over 50 gCO_2-e/MJ (O'Malley et al., 2021); twice as much as the 22.5 g CO_2-e/MJ in Fig. 4. At the same token, whilst often assumed as zero-carbon, e-kerosene carries embodied emissions, for example 11 to 28 gCO2/MJ of in the case of Germany's electricity infrastructure (German Environment Agency, 2016).

The use of biomass for combustion raises further concerns. By definition, sensu stricto, plant material is not a clean energy source because burning it releases CO_2 emissions and so does not contribute to rapid decarbonization. It can be a source of renewable energy given that plant-growth is an ongoing process, subject to the availability of the required land (see above). This capacity for future plant growth is used to argue the case for bioenergy being carbon neutral. However, the critical factor here is that whilst the emissions from burning biomass are instantaneous, their removals from the atmosphere are not and may take a long time. In other words, there is a lag between when the carbon is emitted and when an equivalent amount is removed from the atmosphere and stored in new

[1] Moretti et al. (2022) demonstrate that applying either attributional or consequential (which takes into account displacement effects) LCA deliver vastly different results for the use of potatoe to produce bio-SAF.

biomass. Forest woody biomass is the most problematic given the multi-decadal to millennial age of trees in some natural ecosystems. If the feedstock is from a 100-year old tree, then the lag time is 100 years.

Furthermore, the net effect on accumulated atmospheric CO_2 of a series of harvest events leads to a permanent increase in atmospheric CO_2 concentration compared to the counterfactual of the forest remaining intact (Holtsmark, 2013). This means, there is always more carbon in the atmosphere so long as we are burning biomass. For bioenergy to reduce atmospheric CO_2 concentrations it would have to be the case that the cumulative emissions are lower than all alternative courses of action that would have happened to the biomass in the absence of burning for energy (e.g. forest protection, Keith et al., 2015). Also, from an ecological perspective, there is no such thing as 'residue' biomass in a forest ecosystem as all biomass, living or dead, is part of the total ecosystem carbon stock (Keith et al., 2021). The assumption made in aviation roadmaps that all biomass is carbon neutral is therefore invalid.

Examining the carbon benefits of using bioenergy requires an understanding of the global carbon cycle, including carbon stocks and flows, and consideration of the size, longevity and stability of the stocks. Biogenic carbon is naturally exchanged between the land (and ocean) and the atmosphere. However, land use, land use change and forestry increase emissions such that these have contributed 30 % of accumulated anthropogenic CO_2 emissions from 1850 to 2000 (Friedlingstein et al., 2022). Protecting forests avoids anthropogenic emissions from this sector and restoring degraded and cleared natural ecosystems could substantially reduce concentrations of CO_2 in the atmosphere (now over 410 ppm, IPCC, 2021), perhaps in the order of 40–70 ppm by 2100 (House et al., 2002). Prioritising land for this purpose should therefore be forefront amongst mitigation portfolios (Mackey et al., 2022). The obvious conflict from expanding energy crops for SAF production was highlighted earlier.

4.4. SAF and aviation's non-CO_2 effects

Non-CO_2 emissions have a significant climate impact with net warming from NO_x (resulting in the production of tropospheric ozone, a GHG, and the destruction of ambient methane and associated effects) and the formation of contrail cirrus. There are also other effects from the emission of sulphur (S) compounds, and the interaction of aerosol particles with both high-level natural cirrus and lower-level warmer liquid water clouds. Whilst hardly covered in the roadmaps, the usage of SAF could potentially alter the balance of these non-CO_2 effects, since they have a slightly different underlying composition to fossil kerosene.

Both bio-SAF and e-kerosene would have near-zero or zero S, whereas it is a natural component of fossil fuels. SAF also have a lower aromatic content, which is estimated to be around 18 % by volume of fossil kerosene (Colket et al., 2008). Presently, a maximum level of 25 % aromatics is set by ASTM, and 8 % is (currently) widely considered to be a minimum for elastomer seals in the aircraft fuel system to remain swollen and leak-proof (Anuar et al., 2021). Aromatics in the fuel play an important role in soot formation, and many measurements at the ground and a few made at cruise altitudes have clearly shown that the use of SAF blends results in lower soot number concentrations per kg fuel (e.g., Schripp et al., 2022). Theoretical work has shown that lower soot numbers should result in fewer and larger ice crystals formed at altitude in cold ice-supersaturated regions (Kärcher and Voigt, 2017; Kärcher, 2018), which has recently been demonstrated from measurements in flight (Voigt et al., 2021; Bräuer et al., 2021). This, in turn, has been modelled to suggest a reduction in ERF from contrail cirrus (Burkhardt et al., 2018; Bier and Burkhardt, 2019); a positive impact of SAF substitution. The modelling of Burkhardt et al. (2018) suggests that an approximate 80 % reduction in ice particles results in a 50 % reduction in RF. However, this is from only one model - another modelling exercise gave conflicting results (Caiazzo et al., 2017), so the usage of SAF as a mitigation approach to contrail cirrus (a very uncertain climate forcing in itself) should be treated with caution. The lower S-content of SAF blend would result in the removal of a small negative forcing.

The results of the above studies outlining potential mitigation of non-CO_2 effects from SAF substitution should be taken as indicative, at best, since there is considerable uncertainty in the basic knowledge of non-CO_2 forcings, and the effects of fuel composition change on forcing. What is far more critical, however, and as shown above, is the level of effectiveness of the SAF in terms of reduced GHG footprint on a LCA basis and displacement emissions.

5. Discussion

5.1. Challenges

Aviation is facing challenges in mitigating its climate impact, and it is likely that aviation emissions in 2050 will contribute over 10 % of unabated CO_2 from all fossil fuels and industrial processes (IEA, 2021). However, the rapidly reducing global budget to limit global warming to 1.5 °C means that we can no longer ignore any 'residual' emissions (Fankhauser et al., 2022). Fossil fuel emissions have a near-permanent impact on atmospheric CO_2 concentrations such that cumulative anthropogenic GHG emissions could only be reversed by active CO_2 removal (Allen et al., 2022). Maximising the removal capacity of natural ecosystems is required to achieve a peaking of emissions by 2025 (IPCC, 2022, SPM C.1).

Against this precarious backdrop and given the physical constraints on land and clean energy, the amount of SAF required to support aviation growth (mostly unchallenged, see Becken and Carmignani, 2020) lacks critical and systemic assessment of feedstocks. Airlines have adopted a strategy that is dependent upon rapid and sustainable expansion of SAF because it is the only technical solution to maintaining long-haul flights. Whilst technologically feasible as evidenced in a small number of (pilot) plants, the production of SAF *at scale* and the simultaneous minimisation of unintended consequences (including for the Sustainable Development Goals) have yet to be demonstrated (Faber et al., 2020). A major constraint is that it is not only aviation but the whole global energy system – still largely dependent on fossil fuel – that needs to decarbonise within the next decade or two.

Large-scale use of bioenergy depends on access to what is a shrinking area of usable land (given sea level rise, increasing population, climate impacts on productive land, forest protection, and biodiversity goals) and, at the same time, increased demand for biological materials in emerging bio-economies (Perišić et al., 2022). The analysis here revealed that the production of bio-SAF is energetically costly with $EROI_{final}$ values of around 1. Research shows that human exploitation of energy should deliver overall EROIs of ideally 15 (but at least 3) to support human activity and flourishing (Heinberg and Fridley, 2016; Singh and Colosi, 2021). In addition to high energy costs, SAF consumption itself continues to be associated with (sometimes high) emissions of CO_2. The industry assumption that SAF emissions will be 80 % lower than fossil jet fuel rests on a small number of feedstock, incidentally the ones that are not yet deployed industrially or limited in volume. Regardless, the combustion of biomass is emissive (Keith et al., 2021) and suffers from time lags in (re)sequestration of carbon. However, despite well documented evidence, the published roadmaps propose forest 'residues' as one of the key scalable feedstocks for SAF production.

Recognising the limitations of bio-SAF, aviation roadmaps foresee a shift to e-kerosene in the coming 20 years. However, whilst the $EROI_{final}$ of e-kerosene is more favourable than bio-SAF, the metric does not reveal the large opportunity cost of providing potentially 9 % of all renewable electricity to aviation. The low GHG abatement value of e-kerosene represents a massive challenge. It remains to be seen what place e-kerosene has in the future of an energy system where "renewable power should be directed to displacing fossil fuel generation before powering processes where the majority of electricity is wasted" (Douglas and James, 2022, p. 19). It is also worth noting that all forms of SAF contribute to non-CO_2 warming (with high uncertainties), increasing the overall climate impact of aviation relative to other sectors.

To advance SAF, considerable public sector subsidies (Heinberg and Fridley, 2016) and "aggressive government policies" (Graver et al., 2022,

p. 27) are needed. Governments are already supporting SAF through investment into research and pilot plants, policy instruments such as blend-in mandates, targets and tax credits (Shahriar and Khanal, 2022). Given the economic and political investments required, the question is whether SAF really reduces atmospheric concentrations of CO_2 compared with a business-as-usual case of fossil fuel usage. In other words: is it a worthwhile climate action? This paper provided insights into some of the trade-offs and risks, including competition over land and scarce clean energy, and the answer will differ for different countries.

5.2. Net zero is not the endpoint

The concept of 'net zero' has effectively captured the public's and institutions' imaginations (Rogelj et al., 2021). From a scientific perspective, net zero CO_2 emissions refers to the condition in which anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals over a specified period (IPCC, 2021: Glossary). Given that there is a near linear relationship between cumulative CO_2 emissions and temperature (IPCC, 2021), "… limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other GHG emissions" (Figure SPM.10, section D.1, IPCC, 2021). Until net zero emissions can be achieved globally, every tonne of accumulated CO_2 emissions adds to global warming. Importantly, the current land sector sink is largely a function of emissions from prior land use (~15 % of anthropogenic CO_2 emissions from ~1800–2019, Gasser et al., 2020). And, the ocean sink capacity declines with the proportion of CO_2 removed declining as atmospheric concentrations increase (IPCC, 2021, WGI SPM Figure SPM.7).

IPCC WGIII produced 8 'climate category' scenario types (C1–C8, IPCC, 2022, Table 3.1) of which there were 1202 that produced warming estimates. These were represented by 7 major 'Illustrative Mitigation Pathways' (IMPs). Of the scenario categories that limited warming to 1.5 °C (C1; IMPs 'LD', 'Ren', 'SP' – IPCC, 2022, Fig. 3.6), net zero CO_2 emissions were achieved (median) in 2050, but all IMPs for C1 required negative emissions in the second half of the century (see IPCC, 2022 SPM Table SPM.2), with a central value of −220 Gt cumulative CO_2. In two of these IMPs, (Ren, SP) heavy reliance is assumed for negative emissions on BECCS (see IPCC, 2022, Fig. 3.7), and LUC (predominant in IMP-LD).

The limitations of natural sinks explain why IPCC pathways (and aviation roadmaps) invoke Carbon Capture and Storage (CCS) technologies that in simulation modelling can remove ongoing residual emissions once all feasible decarbonisation strategies have been deployed. Relying on these removal strategies is high risk, thermodynamically costly and societally untested (Allen et al., 2022; Rogelj et al., 2021). Bioenergy with carbon capture and storage (BECCS) does not yet exist at any scale and is a controversial mechanism amongst others because it maintains high-carbon economies (especially when captured carbon is re-used as is the case for SAF, Palmer and Carton, 2021). Clearly, land dedicated to long-lived ecosystem carbon sinks is a superior mitigation strategy compared to its use for bioenergy and should be prioritised where possible (Mackey et al., 2022). So, the message that 'net zero is not enough for 1.5 °C' is a critical one in the SAF debate. SAF production competes for land area dedicated to nature-based removal, but it also competes – in the case of e-kerosene – with all forms of carbon capture and *storage*. Both biogenic and PtL-derived SAF are designed with the purpose of combustion thereby releasing GHG into the atmosphere. The implications of SAF usage as a counterfactual to i) decarbonisation and ii) permanent carbon removal is widely ignored and rarely acknowledged in aviation roadmaps.

5.3. Concluding remarks

Our critical analysis has brought to the fore a wide range of issues related to SAF that are not sufficiently debated. This recalcitrance stems from the path dependencies that maintain a system's status quo. The science is clear that transformational change is required in all sectors and aviation's continued reliance on fossil fuel (about 30 % of energy needs, even in decarbonisation roadmaps) raises questions. In particular, the desire to maintain long-haul travel, which cannot be served with electric planes, presents major challenges to net zero emissions commitments. We have argued here that large-scale SAF deployment could undermine global climate efforts as aviation mitigation may be a form of energy cannibalism from a system-wide abatement perspective. SAF will clearly play some role in replacing fossil jet fuel but more debate on the notion of 'essential' flights would be useful.

Future aviation roadmaps should consider the challenges presented in this paper, and perhaps undertake similar analyses for battery technologies and hydrogen. Following this, an analysis of the optimum mix of technologies for a minimum viable network should be undertaken. A transparent and science-based roadmap will be needed that specifies clear intermediate goals to 2050, provides sustainability safeguards and proactively manages risks of displacement, adds the effects of non-CO_2 emissions, and articulates mechanisms for addressing residual emissions. Particular attention should be paid to the sustainable availability of land and clean energy, and the competing imperative to invest in negative emission mechanisms that remove carbon from the atmosphere permanently.

CRediT authorship contribution statement

Susanne Becken: Conceptualization, Methodology, Data curation, Writing- Original draft preparation, Vizualisation. Brendan Mackey: Investigation, Resources, Writing – Original and review/edit. David S Lee: Investigation, Resources, Writing – Original and review/edit.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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