



HAL
open science

Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems

Pimchanok Su-Ungkavatin, L. Tiruta-Barna, Lorie Hamelin

► To cite this version:

Pimchanok Su-Ungkavatin, L. Tiruta-Barna, Lorie Hamelin. Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. *Progress in Energy and Combustion Science*, 2023, 96, pp.101073. 10.1016/j.pecs.2023.101073 . hal-04058085

HAL Id: hal-04058085

<https://hal.inrae.fr/hal-04058085v1>

Submitted on 11 Dec 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

1 **Biofuels, Electrofuels, Electric or Hydrogen?: A review of current and emerging Sustainable Aviation** 2 **Systems**

3 Pimchanok Su-ungkavatin^{1*}, Ligia Tiruta-Barna¹, Lorie Hamelin¹

4 ¹ Toulouse Biotechnology Institute (TBI), INSA, INRAE UMR792, and CNRS UMR5504, Federal University of Toulouse, 135
5 Avenue de Ranguel, F-31077, Toulouse, France

6 * Corresponding author e-mail address: su-ungka@insa-toulouse.fr

7 **Abstract**

8 Climate neutrality is becoming a core long-term competitiveness asset within the aviation industry, as demonstrated
9 by the several innovations and targets set within that sector, prior to and especially after the COVID-19 crisis.
10 Ambitious timelines are set, involving important investment decisions to be taken in a 5-years horizon time. Here, we
11 provide an in-depth review of alternative technologies for sustainable aviation revealed to date, which we classified
12 into four main categories, namely i) biofuels, ii) electrofuels, iii) electric (battery-based), and iv) hydrogen aviation.
13 Nine biofuel and nine electrofuel pathways were reviewed, for which we supply the detailed process flow picturing
14 all input, output, and co-products generated. The market uptake and use of these co-products was also investigated,
15 along with the overall international regulations and targets for future aviation. As most of the inventoried pathways
16 require hydrogen, we further reviewed six existing and emerging carbon-free hydrogen production technologies. Our
17 review also details the five key battery technologies available (lithium-ion, advanced lithium-ion, solid-state battery,
18 lithium-sulfur, lithium-air) for aviation. A semi-quantitative ranking covering environmental-, economic-, and
19 technological performance indicators has been established to guide the selection of promising routes. The possible
20 configuration schemes for electric propulsion systems are documented and classified as: i) battery-based, ii) fuel cell-
21 based and iii) turboelectric configurations. Our review studied these four categories of sustainable aviation systems as
22 modular technologies, yet these still have to be used in a hybridized fashion with conventional fossil-based kerosene.
23 This is among others due to an aromatics content below the standardized requirements for biofuels and electrofuels,
24 to a too low energy storage capacity in the case of batteries, or a sub-optimal gas turbine engine in the case of cryogenic
25 hydrogen. Yet, we found that the latter was the only available option, based on the current and emerging technologies
26 reviewed, for long-range aviation completely decoupled of fossil-based hydrocarbon fuels. The various challenges
27 and opportunities associated with all these technologies are summarized in this study.

28 *Keywords:* Batteries; Environmental performance; Kerosene; Regulatory frameworks; Sustainable Aviation Fuels
29 (SAF); Fuel cells

30 **1. Introduction**

31 With ca. 920 Mt carbon dioxide (CO₂) emissions per year (year 2019; [1]), the global aviation industry (commercial,
32 private and military) represented approximately 2.5% of all-human induced CO₂ emission (37 Gt in 2019; [2]) and
33 accounts for ca. 12% of emissions from all transport sources [3]. Despite growing public concerns on the contribution
34 of the flying industry to climate change [4–7], the aviation traffic was, prior to the COVID-19 outbreak, forecasted to
35 grow 4.3% per annum and the number of passengers to increase by as much as 20 trillion revenue passenger kilometers
36 (RPK) by 2038 [8,9], compensating most gains obtained from years of fuel consumption efficiency improvements
37 (the global amount of fuel burned per passenger dropped by 23% between 2005 and 2017, from 4.4 L per 100 km to
38 3.4 L per 100 km; [10]). The aviation sector itself acknowledges the need of finding sustainable alternatives to fossil
39 fuels. For instance, the International Civil Aviation Organization (ICAO) launched the CORSIA initiative (Carbon
40 Offsetting and Reduction Scheme for International Aviation) in 2016, with the vision to achieve CO₂ emission
41 mitigation for the aviation sector corresponding to a carbon (C) neutral growth by the year 2020 (CNG2020 target). It
42 thereby became the first economic sector to adopt a global, universal, and binding system to control its GHG
43 emissions. In addition, the International Air Transport Association (IATA) and the Air Transport Action Group
44 (ATAG) have set CO₂ emission reduction goals of 50% for 2050 (relative to 2005 levels).

45 The mitigation of the climate impact of aviation is thus the main driver of the present work. Here, we focus on

46 commercial aviation (passengers and cargo), as this represents 88% of the CO₂ emissions from global aviation ([11];
47 military, private, and other flights, e.g. emergency, represent the remaining 12%). Commercial aviation relies
48 essentially on airplanes covered by the European Certification Specification 25 (CS-25) [12] and excludes air taxis
49 [13]. From here onwards, the term “aviation” will thus specifically refer to commercial aviation. Reducing CO₂ (and
50 overall GHG) from aviation may be achieved either by a decreased demand (itself spurred by e.g., shifts in
51 transportation habits), or by technological means (e.g., enhancing fuel consumption efficiency, developing alternative
52 energy sourcing). This study focuses on the latter strategy, i.e. the potential of alternative energy sources to enhance
53 the environmental performance of aviation in comparison to flying on fossil-based kerosene. Four large families of
54 emerging alternative energy sources for fueling future aviation can be highlighted: biofuels, electrofuels (liquid
55 hydrocarbons produced through an electricity input), electricity (battery-based), and hydrogen. These all involve
56 several variants and are here referred to as “sustainable aviation” (SA) systems, though the term sustainability remains
57 to be assessed as later detailed. One commonly used denomination is “sustainable aviation fuels” (SAF), but we
58 refrained from using it for two reasons. First, this term is typically used to represent biofuels (e.g. [14–17]), although
59 the recent ReFuelEU aviation initiative and its regulation proposal have explicitly expanded it to electrofuels (also
60 designated as synthetic fuels) [18–20]. Second, some of the emerging technologies (e.g., batteries) do not fit within
61 the concept of fuel, hence we here propose the more inclusive “sustainable aviation” terminology instead.

62 In the literature, several terminologies are used to designate aviation fuels, such as jet fuels or kerosene. In industry,
63 it is referred to as Jet A or Jet A-1 (among all differences between these, the most notable one relates to their freezing
64 point; Jet A -40°C (233K), Jet A-1 47°C (226K); [21,22]). Through this study, the term kerosene (C₈-C₁₆
65 hydrocarbons) is used to refer to liquid aviation fuels in general, whether these are fossil-based or not. Fossil-free
66 aviation fuels deriving from bio-based feedstock (denoted as bio-kerosene or biofuels; the latter term is used herein)
67 are drawing great interest in achieving GHG emission reduction targets for the aviation industry [23]. Today, biofuels
68 generated from different technology pathways must be certified by the American Society for Testing and Materials
69 International (ASTM) (ASTM D7566 – Standard Specification for Aviation Turbine Fuel Containing Synthesized
70 Hydrocarbons) or equivalent standards (e.g., Standard 90-091 of United Kingdom’s Ministry of Defense; [24]) before
71 it can be used in commercial aircraft. So far, there are only six certified pathways for biofuels, namely the Fischer-
72 Tropsh (FT) process, hydroprocessed esters and fatty acids (HEFA), direct sugar to hydrocarbon (DSHC), alcohol-
73 to-jet (ATJ; with isobutanol or ethanol intermediates), and catalytic hydrothermolysis jet (CHJ). Some of these
74 pathways involve variants (e.g. FT with added aromatics). Here, sugar and syngas fermentation (followed by
75 upgrading of the produced alcohol) are considered separately instead of being aggregated under the umbrella term
76 “ATJ”, as often found in the literature (e.g. [16,25,26]). This is done to reflect the drastically different technologies
77 and overall process flow involved in both cases, among others.

78 Besides biofuels, additional alternative kerosene for fossil-free aviation include electrofuels (sometimes known as
79 synthetic fuels or powerfuels or power-to-liquid). Aviation electrofuels require a source of carbon and hydrogen (H₂)
80 to generate hydrocarbon liquid fuels having properties similar to those of fossil-based kerosene. Hydrogen may be
81 produced via water-splitting technologies including approaches such as water electrolysis [27], thermochemistry [28],
82 or bio-photolysis [29]. Carbon may stem from biomass-free options such as direct capture of carbon dioxide (CO₂)
83 from the atmosphere (typically termed Direct Air Capture, DAC) [30,31]. The carbon source may also arise from
84 biogenic carbon through the use of syngas stemming from biomass gasification. The syngas may also stem from high-
85 temperature co-electrolysis (using water and CO₂ as input, the latter being biomass-derived or not) [32]. Carbon may
86 also stem from CO₂ captured from a point source (industrial process) [33–35]. Liquid fuels are then produced through
87 the FT process [32] or methanol (CH₃OH) synthesis [36,37], although only the former has been certified by ASTM
88 [36,37]. At present, both electrofuels and biofuels can be used as drop-in fuels, i.e. they are, up to a certain blending
89 limit, interchangeable with conventional kerosene, and do not require adaptation of the fuel distribution network or
90 the engine.

91 So far, there are four main categories of alternative kerosene. They include i) Synthetic paraffinic kerosene (SPK)
92 largely composed of normal- and iso-paraffins (e.g., obtained with the FT, HEFA, SuF, SF pathways), ii) Synthetic

93 aromatic kerosene (SAK), primarily consisting of aromatics designed as blend components (e.g. produced in the APR
94 pathway), iii) Synthetic iso-paraffin (SIP) consisting essentially of farnesane ($C_{15}H_{32}$), and iv) Synthetic kerosene (SK)
95 consisting of a composition similar to fossil-based kerosene (e.g. produced in the CHJ pathway; a new SK fuel from
96 this pathway (CHJ-SK) has just been certified in 2020) [16,38]). SPK is however the predominant type of alternative
97 kerosene generated from the currently certified pathways [26].

98 These four types of alternative kerosene are reported to provide cleaner combustion, with reductions of soot; [39,40],
99 particulate matter (PM); [41], and sulfur emissions [42], among others because of the lower aromatic content in the
100 fuel (when not zero). On the other hand, a low aromatic content has the disadvantage to cause shrinkage of some
101 elastomers in the engine seal [43,44]. Reflecting this risk, ASTM D7566 requires a minimum aromatics content of 8%
102 by volume, and as a result alternative fuels have been used as blends with conventional kerosene, up to a certain
103 blending limit varying between 10% (DSHC) and 50% (all other certified processes) of the total fuel volume
104 [17,26,43]. For longer-term solutions, state-of-the-art engines (with novel sealing materials) are being developed to
105 be compatible with unblended aviation biofuels and electrofuels, as tested and announced by aircraft and engine
106 original equipment manufacturers (OEM), namely Airbus [45], Boeing [46], Rolls-Royce [47], Deutsche Aircraft [48].

107 Through this review, electric aviation refers to the use of batteries as energy sourcing to power aircrafts (whether for
108 propulsion, on-board operating systems, or both in a hybridized mode). One challenge this poses is the development
109 of energy-dense batteries as light and compact as possible, which is challenging with today's lithium-ion (Li-ion)
110 battery technology (around 300-400 Wh kg^{-1} ; [49]), relative to Jet A-1 (approx. 12,000 Wh kg^{-1} ; [21]). Lithium-based
111 batteries (with the introduction of novel electrodes/electrolytes such as advanced lithium-ion batteries (Adv. Li-ion),
112 solid-state lithium-ion (SSB), or lithium-sulfur (Li-S)), are foreseen as the most promising approaches for mass
113 sensitive applications like aviation, owing to their higher specific energy density [50,51]. However, these advanced
114 Li-based batteries are still in the early stages of research, and many challenges need to be tackled before their mass
115 production. Current Li-ion batteries have nevertheless been applied as a sole energy source for small aircraft capable
116 of carrying less than 20 passengers per flight missions (e.g. Eviation's Alice aircraft; [52], Bye Aerospace's eFlyers
117 aircraft; [53], Pipistrel's Velis Electro; [54], Heart Aerospace's ES-19; [55]). For larger aircraft, electric aviation
118 requires to be combined with another energy source such as conventional (or alternative) kerosene, an approach
119 commonly known as hybridization [56].

120 Additionally, hydrogen (both gaseous and cryogenic forms) [57,58] is currently researched as an alternative option
121 for use in commercial flights. In the perspective this hydrogen is produced through water-splitting approaches, most
122 of the associated environmental impacts are reported to be related to the type of electricity used [59-61]. Because of
123 the low volumetric energy density of H_2 , the heavy on-board system infrastructure required to accommodate H_2
124 weakens its benefits, as in the case of batteries [62,63]. Moreover, additional external infrastructures are required in
125 both cases, including a charging station for the case of batteries, a H_2 refueling station for hydrogen, while redesigned
126 airframes making the plane lighter or improving its aerodynamic performances are optional. Unlike electric aviation,
127 H_2 systems require a refueling time comparable to conventional (and alternative) kerosene [64].

128 These two approaches (electric and hydrogen) are not associated with CO_2 emissions during the flight. Although the
129 principle of zero tailpipe emissions applies to 100% electric (battery-based) aviation, the pollution occurring during
130 batteries manufacturing (and recycling) is not zero and needs, as for all upstream activities of all other SA approaches,
131 to be addressed as well [65]. Similarly, the emissions generated during the production of H_2 may be important,
132 especially if stemming from conventional steam reforming of natural gas instead of water electrolysis or other carbon-
133 free approaches [61]. Water vapor and nitrogen oxides (NO_x) are tailpipe pollutants from H_2 aviation and are
134 considered as predominant climate forcers [57,66,67]. They are potential precursors, along with soot (emitted with
135 liquid kerosene), for contrail and cirrus cloud formations, depending upon the ambient atmospheric conditions, which
136 in turns affects the amount of heat trapped within the technosphere [63,65,68,69]. The formation of NO_x (also
137 responsible for tropospheric ozone formation) from H_2 combustion is reported to be lower compared to the NO_x
138 emissions from kerosene combustion [57,63].

139 There is, thus, a variety of technical possibilities towards a more sustainable aviation sector, and each involve a variety
140 of options in terms of feedstock. While some options can act as drop-in fuels, others require additional infrastructure,
141 and all options affect the environment (not only climate) in different ways. It thus remains unclear, in the perspective
142 of long-term investment decisions towards tomorrow's aviation, which option leads to the highest overall
143 environmental performance, and even whether some of the options are truly sustainable and environmentally superior
144 to fossil-based kerosene. Clear requirements defining sustainability for aviation do exist, among others through the
145 sustainability criteria elaborated in CORSIA by ICAO [70] and to some extent in the Recast Renewable Energy
146 Directive (RED II [71]) for biofuels, electrofuels as well as (renewable) hydrogen feedstock, although these are not
147 aligned with one another [25]. It should be noted that the former criteria go well beyond the sole GHG reductions,
148 also including criteria on enhancing water quality and availability, or soil health, for example.

149 Nevertheless, to quantify sustainability, Life Cycle Assessment (LCA) is acknowledged as a central tool for
150 environmental management and decision support, in the European Union in particular [72]. Because it can address
151 impacts in a full system perspective, LCA has grown to become one of the key tools for assisting the direction of the
152 so-called "green transition". Yet, to perform such analysis, vital and timely for the case of aviation, the very first step
153 is to have the full overview of the process flow of the alternatives under assessment, including the overview of the
154 types of co-products being generated. It is our claim that such overview is not yet in place for all alternative SA options
155 simultaneously, being one possible reason why no LCA comparing all four-alternative exist at the moment. Although
156 reviews have been published to document the production process, and, to some extent, the sustainability aspects of
157 alternatives to fossil kerosene, these reviews focused mainly on only one of the SA categories distinguished herein.
158 Aviation biofuels have been the most widely reviewed. Notable reviews are the ones of [73,74], where the conversion
159 processes are extensively described, with key technological advances and challenges. In addition to that, economic
160 and environmental aspects of biofuel pathways are comprehensively discussed by [75] and [44]. Similarly, an
161 overview of the state-of-the-art implementation of biofuels within the aviation sector was presented by [76]. Although
162 not as extensively reviewed, the main synthesis pathways for a variety of electrofuels were qualitatively discussed in
163 [77], with regards to the required physical and chemical properties of these fuels when used in airplanes. The studies
164 of [78] as well as [79], albeit not focusing on the aviation sector per se, carried out an economic analysis for a variety
165 of electrofuels documenting several technologies and variations in plant size. However, the electrofuels investigated
166 in these studies can be considered only as intermediates for aviation fuel production. The recent work of [80], on the
167 other hand, represents a notable advance where a general overview of both carbon-free and biofuels options is
168 described. Albeit valuable, the study of Bauen [80] remains largely qualitative and does not detail the technical
169 conversion pathways and processes involved, and completely excludes electrofuels. Moreover, all of the above-
170 mentioned studies, except [44,75], completely overlook the co-products generated along the production process. Yet,
171 these do generate market interactions that in turn are part of the overall economic and environmental performance of
172 these new alternatives, and accordingly must be understood.

173 In the perspective of bridging these gaps, and in the vision of supplying a harmonized comparative background to
174 assess the environmental consequences of current and emerging options for fueling the aviation sector, the present
175 study presents a comprehensive review intending to supply a holistic understanding in the field of sustainable aviation
176 . Concretely, this review intends to gather and discuss information and data relevant and necessary for comparative
177 environmental assessments (in particular LCA) of emerging candidate options for sustainable aviation.

178 The review is organized into thirteen sections. The underlying methodological approach used for the review is first
179 described (section 2). The review starts with detailing the biofuels, electrofuels, electric (battery-based) and hydrogen
180 families and options within each (sections 3, 4, 6, and 7, respectively) as well as the co-products obtained in the liquid
181 fuel pathways (biofuel and electrofuel families) and their potential uses as alternatives to fossil-based products (section
182 5). A semi-quantitative ranking is proposed (section 8), covering environmental, economic, and technological
183 performance indicators, in order to provide a preliminary screening of the environmental performance potential
184 associated with each approach in the near- (2030) and long-term (2050) timescales. In addition to the four dominant
185 SA approaches that are the object of this study, other marginal alternative energy sourcing are reported in section 9.

186 The electric propulsion systems (i.e., those involving electric motors; either battery- or fuel-based) are discussed in
187 section 10. Section 11 discusses the development of regulatory frameworks and legislations related to clean aviation.
188 Finally, sections 12 and 13 address the challenges and prospects for the deployment ofSA, with emphasis on the
189 availability and sustainability of raw materials and the scientific and technological advances needed.

190 **2. Methodological approach**

191 Overall, approximately 600 records, including scientific literature, patents, (company) reports, conference
192 proceedings, and company websites, were extensively screened and reviewed. Efforts were made to ensure that the
193 most recent data from announcements and literature were used. However, in the very process of writing this article,
194 some of these announcements have changed (e.g., the cancellation of the Airbus E-Fan X project in April 2020), and
195 although we strived to keep all the information presented herein up-to-date, it can happen that some will no longer
196 apply following the publication of this article.

197 The scientific literature search was performed through two key search engines, namely Google Scholar and Web of
198 Sciences, while the Google Search engine was used for screening the grey literature. A variety of generic keywords
199 such as “aviation decarbonization,” “alternative aviation fuels,” “sustainable aviation regulation” have first been used,
200 while snowballing strategies [81] were applied to capture additional content. A few variations of the abovementioned
201 keywords have also been used to capture additional records. This procedure was repeated for each specific topic
202 addressed in this review.

203 Moreover, although we strive to explain all key terminology used within the manuscript (e.g., what the notion of
204 electrofuels exactly encompasses), a glossary is provided (SM2) to clarify all terms and acronyms used. Throughout
205 the manuscript, we report the units as supplied in the original references but provide the conversion in units of the
206 International System of Units (SI).

207 **3. Aviation biofuels**

208 Because of their maturity and compatibility with the existing fueling infrastructure, biofuels is the most dominant SA
209 family.

210 Three large biofuel categories are here distinguished according to the feedstock used: carbohydrate-rich,
211 lignocellulosic and oil-based biomass. These will be used within this section to organize the description of each
212 biofuel.

213 Fig. 1 presents, in relation with these three categories, an overview of nine different biofuels pathways for which
214 known investments in terms of capacity have been made.

215 Among the nine pathways covered in Fig. 1, six are already certified by the ASTM D7566. The remaining three are
216 either under the process of certification (APR, IH²; integrated hydrolysis and hydroconversion) or under
217 development (HDCJ pathway). Some pathways are well developed, documented, and applied in large-scale production
218 (pilot/demonstration plants), while some, such as the CHJ and IH² pathways, are less extensively documented. These
219 are briefly described herein, and additional insights on, e.g., the biofuels properties, blending ratios, or the leading
220 industrial producers to date are available in supplementary material 1 (SM1) (Tables S1-S2).

221 Low readiness level emerging pathways are disregarded from this section because they are scarcely documented,
222 including the one described by e.g. [82], where volatile fatty acids (VFAs) from anaerobic digestion of residual
223 biomass are processed for catalytic upgrading to kerosene-ranged paraffins [82]. It also includes the emerging
224 methanol-based pathway to produce kerosene described in e.g. [83].

225 **3.1 Biofuel pathways involving carbohydrate-rich feedstock**

226 This category comprises three pathways (Fig. 1). They greatly rely upon carbohydrate-rich feedstock such as
227 sugarcane, sorghum, maize dextrose, maize, etc., but can also be used with less dense carbohydrate sources such as
228 molasses. Simple mechanical pretreatment for particle size reduction (milling, chopping, grinding, etc.) may be

229 performed for sugar-rich feedstock (e.g., sugarcane, maize, fodder beet). For lignocellulosic-rich feedstock (e.g.,
230 straw, woody crops, and/or residues), mechanical pretreatment is followed by delignification. In this step, the lignin
231 fraction is typically separated from cellulose and hemicellulose by alkaline deacetylation, followed by vacuum
232 filtration [75,84]. The remaining lignin may be utilized in various applications, such as the generation of heat and
233 electricity or the production of syngas (through gasification) for liquid fuel production [85,86]. The cellulose and
234 hemicellulose fractions are further processed with enzymatic or acid hydrolysis approaches to recover C₅ and C₆
235 sugars. As a result, a hydrolysate is produced and further used as input for the pathways described in this section,
236 namely the aqueous phase reforming (APR), DSHC, and SuF pathways.

237 3.1.1 Aqueous phase reforming (APR)

238 In this pathway, the generated hydrolysate (Fig. 2) first undergoes a purification and concentration process. In this
239 step, numerous techniques may be applied, for instance, alkaline solvents for ash and residual lignin removal and
240 filtration for insoluble solid residues removal [74,85]. Depending on the initial feedstock characteristics, the sugar-
241 rich hydrolysate produced in the concentration step undergoes an hydrotreating process to convert sugars and organic
242 acids through hydrogenation (forming polyhydric alcohols) and/or hydrogenolysis (forming shorter-chain
243 compounds) [86,87]. Oxygen is then removed from the obtained molecules through two successive steps: the APR
244 followed by a condensation process.

245 In the APR process, the aqueous phase is reacted in the presence of a catalyst under a large variety of operating
246 conditions. A temperature range of 175–300°C (448-573K) and pressure range of 10-90 bar (1-9 MPa) are necessary
247 [86] when catalysts such as Cu, Re, Ni, Fe, Co, Ru, Pd, Rh, or Pt are used [85]. Examples of specific operating
248 conditions reported in the literature are summarized in SM1. The reactions happening within this process strongly
249 depend upon the specific configuration and typically include dehydrogenation of alcohols, hydrogenation of
250 carbonyls, deoxygenation, hydrogenolysis and cyclization. As a result of this step, the water-soluble oxygenated
251 compounds are converted into a liquid mixture (APR liquid), which is a complex mixture of hydrocarbons and
252 undesired oxygenated hydrocarbons (e.g. alcohols, aldehydes, ketones). These may be separated at this stage or fed
253 directly to the subsequent condensation step [87] as illustrated in Fig. 2. A gas phase rich in H₂, CO₂, CO and light
254 alkanes is also produced (Fig. 2), which can be directly used for heat and power production [84], among other uses.
255 Alternatively, the H₂ produced in the gas stream could be separated and recirculated to the process [84,88], prior to
256 burning the light alkanes (C₁-C₄) for heat and electricity [84,85,88]. The exact mixture of both gas and liquid output
257 is rather difficult to predict given the complex mixture of hydrocarbons and oxygenated hydrocarbons involved [89].

258 Through condensation reactions, the liquid mixture from the APR process is upgraded to longer-chain hydrocarbons.
259 For example, base condensation is applied for the production of gasoline and kerosene. The liquid condensate may,
260 prior to distillation, undergo hydrotreating according to the desired hydrocarbon fuels output. The resulting products
261 are polyhydric alcohols or shorter-chain compounds depending on the hydrotreating approaches used. Dehydration of
262 alcohols into alkanes and oligomerization (using solid phosphoric acid or zeolite as catalyst) is used for kerosene
263 production [86]. Hydrogenation and/or isomerization might also be required to ensure conformity with the specific
264 market requirements (e.g. the mandatory ASTM D1655 for aviation fuel blends to be used in commercial aviation)
265 [85]. As illustrated in Fig. 2, these processes can be combined in different configurations and with different operating
266 conditions to fit with the desired final product. Finally, the generated products are subsequently condensed and
267 distilled to produce the desired aviation fuels, here as hydrodeoxygenation synthetic aromatic kerosene (HDO-SAK)
268 or hydrodeoxygenation synthetic kerosene (cycloparaffin-rich fuel) (HDO-SK), along with hydrocarbons co-products
269 including naphtha, and diesel [84,86]. Currently, both HDO-SK and HDO-SAK are under consideration for ASTM
270 certification [90].

271 3.1.2 Direct sugar to hydrocarbon (DSHC)

272 The DSHC pathway allows to produce aviation biofuels without an alcohol intermediate (Fig. 3). The sugars derived
273 from the biomass feedstock input are converted to C₁₅H₂₄ (denoted as isoprenoid farnesene) through fermentation,
274 subsequently hydrogenated to farnesane (C₁₅H₃₂), which can be used as aviation fuel [91,92]. The joint venture

275 between Amyris and Total is the main global developer of the DSHC pathway with carbohydrate-rich feedstock such
276 as maize, sugar beet, sugarcane [93]. These companies engineered microorganisms capable of fermenting both C₅ and
277 C₆ sugars [94,95]. Accordingly, lignocellulosic-rich substrates can also be used as a feedstock in this pathway.
278 Additional examples of industrial partnerships developed to produce aviation biofuels via the DSHC pathway are
279 described in SM1.

280 The fermentation process with the engineered yeasts takes place at operating temperatures of 30-34°C (303-304K)
281 [94]. A liquid/solid centrifugation process separates the yeast cells and fermentation broth. The supernatant, consisting
282 of farnesene oil, farnesene emulsion and fermentation broth, is collected for further purification. Within the
283 purification process, the collected supernatant is heated in the de-emulsification unit (65-70°C; 338-343K) with the
284 addition of surfactant and is transferred to liquid/liquid centrifugation in order to separate the oil and aqueous phases
285 [94]. The distillation stage separates the contaminants into a heavy fraction containing triglyceride, monoglyceride
286 and salts, and a light fraction of the distilled farnesene. Distilled farnesene then undergoes hydrogenation in the
287 presence of catalysts such as Ni, Pd, Ru, Pt, Mo, Zn, etc. [96]. The purification step may be combined with
288 hydroprocessing in downstream operations for achieving high recovery efficiency (97% reported) [94] (not shown in
289 Fig. 3). The farnesane produced can be used as diesel fuel for terrestrial transport or as aviation kerosene, although
290 the former tends to be preferred due to the low blending ratio allowed for the kerosene obtained from this pathway
291 (10% by volume; Table S1). Alternatively, the farnesene can be chemically converted to produce a variety of products
292 including fragrances, flavors, cosmetics, lubricants, etc. The co-products derived from the separation and purification
293 step (Fig. 3) are reported to be used in anaerobic digestion for biogas production [95], where the biogas is subsequently
294 led to a steam methane reforming (SMR) process in order to produce part of the hydrogen needed for the hydrogenation
295 step.

296 3.1.3 Sugar fermentation with alcohol upgrading (SuF)

297 This pathway is based upon the fermentation of the hydrolysate derived from carbohydrate-rich biomass (e.g.
298 molasses, sugarcane, sweet sorghum, sugar beets, food waste, inedible fodder maize) or lignocellulosic-based biomass
299 (e.g. cereal or rice straw) to produce alcohols [97–99]. The generated alcohol, typically ethanol or isobutanol
300 [100,101], is then further upgraded to aviation biofuel through a series of four key processes (Fig. 4) described below
301 (fermentation generating an ethanol or isobutanol intermediate, dehydration, oligomerization, hydrogenation). Both
302 alcohol intermediates are certified by ASTM [16]. The solid residue (often referred to as distiller grains) not converted
303 to alcohol is generally dried and sold as a protein-rich ingredient for animal feed [102–104]. This pathway is often
304 aggregated with the SF pathway (3.2.1.1) under the umbrella of “alcohol-to-jet (ATJ)”, and the biofuels production
305 with those pathways are referred to as ATJ-SPK.

306 In the fermentation step of SuF, bacteria, in particular Clostridia and a modified strain of *E. coli*, are commonly used
307 for isobutanol production through the acetone-butanol-ethanol (ABE) fermentation process [105], albeit other
308 microorganisms are also possible in the presence of yeast *S. cerevisiae* [106] or engineered yeast (details in SM1). For
309 ethanol, *S. cerevisiae* yeasts are typically used [107]. Fermentation temperatures from 20°C (293K) to 95°C (368K)
310 are reported, depending upon the microorganisms used [102,106,108,109]. After the fermentation, the broth
311 containing the desired alcohols, microorganisms and other organic compounds is separated into an alcoholic fraction
312 and distiller grains (by e.g. membrane separations, distillation, solid/liquid separation, etc.) [102]. The alcohol
313 obtained from the fermentation stage will typically not be pure but consists of a mixture of C₂-C₆ alcohols including
314 ethanol, propanol, butanol, isobutanol and pentanol [102].

315 In the case of the isobutanol intermediate pathway, the produced isobutanol is typically converted into isobutenes in
316 the presence of dehydration catalysts such as inorganic strong acids, metal oxides, zeolites, acidic resins, etc. at
317 operating temperatures ranging from 250-350°C (523-623K) [98,110] (dehydration stage; Fig. 4). Isobutene
318 monomers are oligomerized in the presence of acid- or metal-based catalysts, which results in a liquid mixture of
319 longer chains alkenes (C₁₀-C₁₆) and shorter chains (C₄-C₈) ones (oligomerization stage; Fig. 4). Shorter chains alkenes
320 are separated and recycled to the oligomerization unit [98]. The heavier olefin fractions (C₁₀-C₁₆) are then fed to the

321 hydrogenation process (Fig. 4) [111]. The hydrogenated hydrocarbons are distilled into distinct fractions, namely the
322 ATJ-SPK along with an isooctane co-product [44]. A variation has been proposed where the heavier olefin fractions
323 are, prior to hydrogenation and fractionation, enriched in aromatics (C₈-C₁₆; content of ca. 20 vol.% [38]) in order to
324 get a fuel without blending limits, leading to the production of so-called synthetic kerosene with aromatics [26]. This
325 is promoted by among others Byogy and Swedish Biofuels and is under ASTM certification process [90,112].
326 However, at the light of the available information [113,114], it remains unclear whether the upstream part of this
327 process involves direct biomass fermentation as described herein, or the fermentation of gasified biomass (i.e. syngas),
328 which is further described in section 3.2.1.1. Additional details on the SuF process are presented in SM1. The process
329 with the ethanol intermediate is similar; oxygen is removed via a catalytic dehydration process, producing ethylene,
330 then turned into linear or non-linear (branched) α -olefins through a catalytic oligomerization process, in turn
331 hydrogenated to produce paraffins (C₉-C₁₆ alkanes) [115].

332 **3.2 Pathways handling residual and lignocellulosic biomass feedstock**

333 Some pathways can be considered as specifically targeting residual (often lignocellulosic) biomasses such as primary
334 forestry residues, crop residues, municipal solid waste (MSW), etc., although these can also technically be used in the
335 previously described biofuels pathways if subjected to pre-treatments. These low-value residues have attracted
336 tremendous attention due to their potential to avoid the competition with food production [116], and their potential
337 important bio-physical availability [117–119]. The pathways described herein use thermochemical conversion
338 processes to convert lignocellulosic biomasses into kerosene. The vision is whether to first convert residual biomasses
339 to gas, and then convert this gas into liquid fuels through so-called Gas-to-Liquid (GtL) processes, or to convert the
340 biomass into a bio-oil to be further processed to kerosene.

341 *3.2.1 Biomass-to-gas via gasification: a prerequisite to several biofuels and electrofuels pathways*

342 Gasification and anaerobic digestion are the two most known technologies to convert biomasses into gas. While the
343 former targets biomasses with dry matter content of at least 65%, the latter is typically considered for wet biomasses
344 (dry matter content below 30%) [120]. The exact amount of carbon from the biomass that will convert to gas, as well
345 as the gas composition itself, will heavily depend upon the technology, process conditions and biomass composition.
346 Anaerobic digestion can be expected to convert ca. 60% of the biomass carbon into biogas [121] while gasification is
347 expected to convert at least 75% of the carbon into syngas [122]. The present review will, based on the reviewed
348 pathways, only focus on gasification, as none consider anaerobic digestion (for kerosene production).

349 Prior to gasification, biomass must be pretreated into fine particles (80-100 μ m) by mechanical techniques (including
350 chopping, grinding) in order to enhance the efficiency of moisture removal, which in turn facilitates the biomass
351 conversion to syngas [123–125]. Gasification typically occurs at temperatures of 600-1,000°C (873-1,273K) or even
352 higher with controlled amount of oxidizing agent such as air, steam, oxygen, their mixture or supercritical water [123–
353 125]. Supplying the appropriate amount of oxidizer is an important parameter for a high syngas production and for
354 limiting the amount of by-products generation (e.g. char) [124]. During the gasification process, carbonaceous
355 materials are transformed through several reactions including drying, pyrolysis (PL), combustion and reduction of
356 feedstock to produce syngas, water vapor, tar, and a solid co-product denoted as char [126].

357 Syngas, based on the experimental data compiled by [122] for fixed bed gasifiers, is a gaseous mixture of H₂ (10-
358 20%), CO (15-23%), CO₂ (8-18%), CH₄ (1-4%) and N₂ (42-60%). Syngas impurities are composed of tar particles,
359 nitrogenous compounds (NH₃, HCN), sulfur compounds (H₂S, COS, CS₂), hydrogen halides (HCl, HF), and trace
360 metals (Na, K) [127]. Hence, syngas needs to be further conditioned to reform tar contaminants, and remove particulate
361 matters and acid gases prior to utilization in downstream gas-to-liquid processes (Figs. 5 and 6). Depending on the
362 gas-to-liquid process to be used, additional steps to adjust for the H₂/CO ratio of the cleaned syngas may be required.
363 While it could be avoided entirely for the SF pathway, the FT typically requires adjusting the H₂/CO ratio to ~2.0 to
364 avoid methane formation. In addition, syngas must be strictly purified from acid gas and ash to avoid catalyst
365 deactivation during the FT step as well as downstream corrosion [124]. Details on gasification and syngas conditioning
366 and cleanup processes are presented in SM1.

367 3.2.1.1 Gas-to-liquid: Syngas fermentation and alcohol upgrading (SF)

368 The syngas deriving from waste gases from industrial processes and/or gasified biomass can be converted into various
369 intermediate products (e.g. alcohols, organic acids) through fermentation process (Fig. 5) after cleanup/conditioning
370 as above described. Different microorganisms can be used to obtain a panel of co-products [128]. Typically, the
371 objective is to convert syngas into ethanol, which is subsequently upgraded into kerosene.

372 Microorganisms such as acetogenic *Clostridium* spp. convert syngas into several intermediates including ethanol, 2,3-
373 butanediol (2,3-BDO), and acetic acid [109,129,130]. Optimum fermentation conditions intensively depend upon the
374 microorganisms used [131], however, pressures higher than ambient pressure are preferred for enhancing the syngas
375 transfer between the gas and the liquid phase [132]. After the fermentation, the broth including co-products and
376 microbial biomass is fractionated through several processes depending on the co-products formed. For example,
377 distillation is typically used for ethanol recovery [130], while simulated moving bed chromatography may be used for
378 2,3-BDO recovery [133].

379 The fermentation residue, comprising microbial biomass and other organic fractions (also known as distillation
380 grains), is filtered [134]. The filtered liquid stream, consisting of soluble nutrient mixtures, can be further recycled
381 back to the fermentation reactor while the filtrated insoluble sludge is typically sent to anaerobic digestion. The
382 resulting biogas can be used for internal steam and power generation [130,133].

383 Ethanol may be upgraded to kerosene through a variety of processes. First, ethanol is converted to ethylene in the
384 presence of catalysts such as γ -alumina (Al_2O_3), transition metal oxides, or zeolites at operating temperatures of 320-
385 500°C (593-773K) [135]. Oligomerization then converts the produced ethylene to linear long-chain olefins at
386 operating temperatures of 100-300°C (373-573K), also in the presence of catalysts [136]. Nickel complexes are
387 commonly used as catalysts for industrial ethylene oligomerization (e.g. used in the Shell Higher Olefin Process;
388 SHOP) [136,137]. Aluminum-based catalysts (tri-ethyl-aluminum) generate, through the Gulf and Ethyl process,
389 linear α -olefins and by-products (alkanes and branched α -olefins) [137].

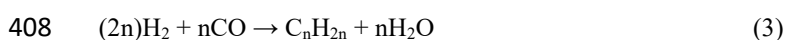
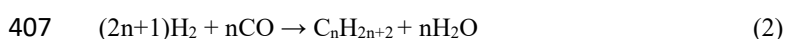
390 The longer-chain olefins generated are afterwards hydrogenated into alkanes. Copper, zinc chromite or sulfide are
391 utilized as catalysts for high-pressure hydrogenation with temperature ranges of 150 and 200°C (423 and 473K) and
392 under a pressure of 200-350 bar (20-35 MPa) [137]. Hydrogenated hydrocarbons are further distilled to recover the
393 C_8 - C_{16} fraction known as ATJ-SPK. In addition, naphtha and diesel can be obtained as co-products [133].

394 The SF pathway, when deriving from lignocellulosic biomass, has an overall reported energy efficiency of 57%, while
395 the FT pathway has an overall reported energy efficiency of 45% [138].

396 The fermentation pathway provides numerous advantages such as operating conditions near the ambient temperature
397 and pressure [139]. However, the main challenge with the SF pathway is the low solubility of syngas in the
398 fermentation medium, which limits the mass transfer to the liquid phase, in turns resulting in the generation of
399 untargeted (or less desired) products [140,141].

400 3.2.1.2 Gas-to-Liquid: Fischer-Tropsch (FT) process

401 The FT technology has been extensively used for the production of synthetic liquid fuels and chemicals (e.g. diesel;
402 [21]; kerosene; [142,143]; naphtha; [144]). FT consists of a series of catalytic processes (Fig. 6) which convert purified
403 syngas (mostly composed of H_2 and CO) into liquid fuels. During the FT synthesis, the purified syngas is passed over
404 catalysts in specific process conditions to form a variety of hydrocarbons (ranging from gases to waxes) following
405 three main reactions [145]:



409 The hydrocarbon product composition is strongly influenced by the operating temperature, pressure, syngas
410 composition, and used catalyst [44,147–150]. The FT process can be categorized into high temperature (HTFT) and
411 low temperature (LTFT). Gasoline, solvent oil and olefins as shorter-hydrocarbon compounds can be generated
412 through HTFT process with operating temperatures of 310-340°C (583-613K). LTFT will typically involve operating
413 temperature of 210-260°C (483-533K) and generate an hydrocarbon mixture consisting of ca. 50% solid wax, the
414 remaining consisting of a liquid phase containing aromatics and cycloparaffins [143]. The wax can later be processed
415 to produce naphtha, kerosene and diesel, among others [124,150]. It should be noted that the wax is sometimes defined
416 as C₂₀ [151], C₂₁ [152], C₂₂ [153] or C₂₃ [143] and heavier fractions. Common catalysts used are transition metals like
417 Fe, Co, Ni and Ru. Fe and Co are widely used catalysts, with distinct selectivity. For example, Fe-based LTFT
418 generates higher olefins concentration as Co-based LTFT, but with lower hydrocarbon conversion and more CO₂
419 production. Cobalt-based catalyst is often preferred for GtL FT due to its high activity and selectivity to linear paraffins
420 [44,154–156].

421 There are three fractions generated from the FT process: gaseous, liquid and wax phases. The gaseous phase represents
422 unconverted syngas and contains CO, H₂, CO₂, and potentially N₂. It can either be fractionated for H₂ recovery or be
423 recycled back to the FT unit in order to maximize kerosene yield [154], while a fraction (ca. 10% of the syngas) will
424 end as off-gas (Fig. 6). The liquid hydrocarbons from FT undergo an hydrotreating process including deoxygenation,
425 decarboxylation and decarbonylation in the presence of supported base metal- or supported noble metal- catalysts
426 [142]. Additional hydrogenation may be applied for transforming olefins and residual oxygenated molecules into
427 saturated hydrocarbons. Wax (C₂₀₋₂₃₊) produced in the FT unit are transformed to smaller molecules by hydrocracking
428 followed by isomerization into branched hydrocarbons. Obtained hydrocarbons with different lengths are distilled to
429 produce naphtha, kerosene, diesel and lubricants [108,143,157].

430 This technology allows the use of lignin deriving from lignocellulosic biomass as primary feedstock for bio-based
431 kerosene production (SPK). The SPK derived from the FT process, denoted as FT-SPK, consists of a high proportion
432 of n- and iso-paraffins with a maximum of 15% by weight of cycloparaffins resulting in a high cetane number, high
433 specific energy, and high thermal stability. FT-SPK provides a high quality kerosene in the absence of sulfur, nitrogen,
434 and other impurities [43,87]. FT-SPK with the addition of aromatics (denoted as SPK/A) is another FT-SPK variation,
435 certified in 2015 [26]. This variant is here considered within the overall umbrella of FT-SPK.

436 3.2.2 Hydrotreated depolymerized cellulosic jet (HDCJ)

437 Residual biomass can be converted into liquid fuels via a pyrolysis (PL) process, denoted as HDCJ-PL, or via
438 hydrothermal liquefaction (HTL) for wet substrates, denoted as HDCJ-HTL (Figs. 1 and 7). Oily feedstock (e.g. waste
439 cooking oil) can also be used directly (i.e. straight to the separation/upgrading process of Fig. 7).

440 The PL process converts dry biomass into bio-oil, gases, and biochar, the proportion and composition depending on
441 the process conditions and the nature of the feedstock [158]. Biomass feedstock, finely ground (< 5 mm), is dried to
442 achieve less than 10% moisture content by weight, often seen as mandatory for the PL process, especially in the
443 perspective of quality bio-oil production intended for use as a transport fuel [159–161]. Fast PL is conducted at
444 relatively high temperatures (450-550°C; 723-823K) and ambient pressure with short residence time of the gas phase
445 (typically less than 2s) [162]. Fast PL is proposed for maximizing the production of liquid hydrocarbons (bio-oil)
446 while lower temperatures PL mainly produce a solid product known as biochar [163]. In the HTL process, residual
447 biomass reacts with water at temperature ranging from 200-450°C (473-723K) and pressures of 50-280 bar (5-28
448 MPa) [164] with or without a catalyst. This process is suitable for the conversion of relatively wet biomasses (5-35%
449 dry matter content) into bio-crude oil; drying pretreatment processes are therefore not necessary [162,164–167].
450 During the HTL process, bio-oil is produced through multiple reactions such as hydrolysis, dehydration,
451 decarboxylation, condensation, cyclisation or, polymerization. The produced bio-oil contains lower oxygen (in
452 oxygenated compounds) and moisture content with higher heating value in comparison to the PL bio-oil [92,168,169].
453 Moreover, PL bio-oil has higher acidity and weaker thermal stability relative to the HTL bio-oil [169]; therefore it
454 requires more extensive upgrading processes. More details about the HDCJ processes and examples of industrial

455 developments can be retrieved in SM1. During the upgrading process of the bio-oil to kerosene (Fig. 7), distillation,
456 centrifugation and extraction are preliminary processes for the fractionation of the bio-oil into a gaseous phase, a
457 liquid bio-crude oil phase (the main output), an aqueous phase and solid residue (e.g. tar). Subsequently, other
458 upgrading processes are performed, for example, emulsification, catalytic cracking and/or, steam reforming [170].
459 The liquid bio-crude oil phase is further refined by hydrotreating to increase its alkane composition, by reduction of
460 heteroatom-containing molecules and by hydrogenation of unsaturated molecules. Hydrotreated hydrocarbons are
461 distilled into liquid fuels including naphtha, kerosene and diesel.

462 3.2.3 Integrated hydrolysis and hydroconversion (IH²)

463 The integrated hydrolysis and hydroconversion (IH²) pathway is characterized by a series of thermochemical
464 processes, enabling the conversion of lignocellulosic biomass into hydrocarbon fuels, namely gasoline, kerosene, and
465 diesel ranged hydrocarbons [171]. Four key processes are involved: pretreatment, hydrolysis, hydroconversion,
466 and steam reforming (also known as hydrogen manufacturing unit) [171] (Fig. 8).

467 Lignocellulosic biomass is first passed to the pretreatment unit (including size reduction and drying). Pretreated
468 biomass is sent to the catalytic hydrolysis, operated at temperatures of 350-450°C (623-723K), where it is reacted
469 with hydrogen at an incoming pressure of 20-35 bar (2-3.5 MPa) in the presence of a catalyst. As a result, it is
470 converted to deoxygenated vapors along with light gases vapors (C₁-C₃ hydrocarbons, and CO), and char [172,173].
471 This process minimizes the undesirable properties of standard pyrolysis bio-oil, namely a high acid number, low
472 heating value, high oxygen content, low liquid fuels yields, etc., by adding hydrogen to the pyrolysis process [172].
473 Char is continuously removed by cyclones, followed by a hot filter [172]. Light gases are further converted to
474 hydrogen (to be reused in the process) through a steam reformer [26,174]. Char, on the other hand, is passed to the
475 hydroconversion reactor. It operates at temperatures 340-400°C (613-673K), at essentially the same pressure as the
476 hydrolysis, with a catalyst that induces hydrodeoxygenation and hydrogenation to take place [174,175]. Within
477 this unit, deoxygenated vapors are converted to hydrocarbon vapors (of gasoline, diesel, kerosene) through a
478 hydrotreating processes (e.g. hydrodeoxygenation, hydrogenation). They are subsequently recovered through
479 condensation (e.g. via a distillation column) to liquid hydrocarbon fuels [172,175].

480 Currently, this pathway is going through the ASTM certification process [26,90]. IH² could be a blending component
481 owing to its high aromatic content (up to 92 vol.% when from woody biomass; [174]), which is above the maximum
482 limit for aviation kerosene (25 vol.%) [38]. They can be additionally added to SPK (low/lacking aromatics) [174].

483 3.3 Pathways involving oil feedstock

484 Oil feedstock may be derived from many sources, for example, non-edible oil crops (e.g. camelina, jatropha, carinata,
485 pongamia, pennycress) or oleochemical wastes (e.g. waste cooking oils; WCO, waste animal fats, greases stemming
486 from municipal waste facilities). Crops are converted to oil through several processes such as, mechanical processes
487 (e.g. chopping, pressing, chipping), chemical extraction with solvent and/or enzymatic methods [176].

488 3.3.1 Hydroprocessed esters and fatty acids (HEFA)

489 Triglycerides containing saturated and/or unsaturated fatty acids can be converted to liquid hydrocarbons (naphtha,
490 kerosene, diesel) by hydroprocessing under various conditions [161,177,178], as illustrated in Fig. 9. In the literature,
491 this is typically referred to as hydroprocessed esters and fatty acids (HEFA) when related to terrestrial biofuels
492 production, and as hydroprocessed renewable jet (HRJ) when related to aviation fuels. In term of process pathway,
493 these terminologies are here considered as equivalent.

494 Waste fats and oils with different degrees of unsaturation are firstly hydrogenated to saturate the double bonds leading
495 to the production of propane along with free fatty acids. The hydrogenated fatty acids are subsequently converted into
496 straight chain hydrocarbons through hydrotreating processes including deoxygenation, decarboxylation and
497 decarbonylation with the formation of H₂O, CO₂ and CO, respectively [73,75,179]. Subsequently, the hydrocarbons
498 produced are transformed by isomerization and hydrocracking reactions. Isomerization converts straight chain
499 hydrocarbons into highly branched alkanes exhibiting a low freezing point, a desired property as a blending

500 component. Long chain hydrocarbons are broken through an hydrocracking process to desirable carbon length
501 compounds (e.g. in the range of C₈ to C₁₆ aviation kerosene) [180]. The product is distilled into naphtha, kerosene and
502 diesel [181,182].

503 Several parameters have an impact on product generation during the HEFA process, for instance, the type of catalyst
504 used, the fatty acids profile of the feedstock used and the operating conditions [181,183,184]. A variety of research
505 and industrial experiments resulting in the production of aviation biofuels with the HEFA pathway under various
506 conditions are summarized in SM1.

507 The HEFA pathway is considered as a relatively mature technology at commercial scale. However, the availability
508 and the cost of the sustainable oleochemical feedstock, in particular if waste-based (as in e.g., [185,186]) or relying
509 on limited marginal lands (e.g., [187–190]) to grow the feedstock, may become a limiting factor in the perspective of
510 increased biofuels demand in the future. The HEFA pathway with the variant of using third-generation feedstock (e.g.
511 oils stemming from microalgae *Botryococcus braunii*, denoted as Bb oil) has been recently certified (ASTM approved
512 for 10% maximum blend in 2020) [191]. This pathway produces biofuels known as hydroprocessed hydrocarbons
513 HEFA-SPK (HH HEFA-SPK).

514 High freeze point HEFA-SK (HFP HEFA-SK, also known as HEFA+) is another variation of already certified HEFA,
515 nearing final ASTM approval [90,112]. The production cost is expected to be reduced as involving lower requirements
516 for the upgrading process (e.g. isomerization) relative to HEFA-SPK [26]. This is among others due to the longer
517 length of the molecule chain, varying from C₁₅ to C₁₈ [26,192,193]

518 3.3.2 Catalytic hydrothermolysis jet (CHJ)

519 The CHJ pathway, similarly to the HTL process, is based on high temperature water chemistry (hydrothermal
520 processes), converting oil-based feedstock into a mixture of straight, branched and cyclic hydrocarbons as shown in
521 Fig. 10. The process is composed of four steps including hydrothermal pre-conditioning, catalytic hydrothermolysis
522 (CH), upgrading through hydrotreatment and products fractionation.

523 During the pre-conditioning stage, the oil-based material is cracked resulting in the production of free fatty acids with
524 the removal of heteroatoms (S, N, metals, etc.) in the presence of steam and catalyst under operating temperatures of
525 150-300°C (423-573K) and pressures of 5-50 bar (0.5-5 MPa) [194]. These generated fatty acids are converted in a
526 CH unit at elevated temperature (240-450°C; 513-723K) and pressure (15-250 bar; 1.5-25 MPa) [194]. Within the CH
527 unit, numerous reactions take place including cracking, hydrolysis, decarboxylation, isomerization, and cyclization to
528 produce a mixture of paraffin and cyclic hydrocarbons. In a nutshell, the outputs of the CH unit consist of an organic
529 phase and an aqueous phase. The aqueous phase is composed mostly of low molecular weight carboxylic acids (C₂-
530 C₅), glycerol, and some of small polar molecules [194]. They are transformed through decarboxylation and
531 dehydration into alkene products. These intermediates could be upgraded to aviation biofuels through alcohol recovery
532 stage (oligomerization, hydrogenation and distillation) as described above. The organic phase, referred to as CHJ bio-
533 crude, is further decarboxylated, hydrogenated, and finally distilled into several product fractions including naphtha,
534 kerosene (denoted as catalytic hydrothermolysis jet-synthesized kerosene; CHJ-SK) and diesel [195].

535 Aviation biofuels obtained with this process contain high density aromatics, iso-paraffins and cycloparaffins
536 [194,196]. Additional details on the CHJ pathway and its industrial developments are presented in SM1.

537 4. Aviation liquid electrofuels

538 Electrofuels (power-to-liquid) allow, pushed to its extreme, to decouple the production of kerosene from the demand
539 of biomass, relying on water-based hydrogen (H₂), and atmospheric CO₂ [19,197]. Through hydrogen produced from
540 water electrolysis, electrofuels involve the storage of electrical energy within chemical bonds in the form of liquid
541 fuels, these providing more energy density and lower aircraft mass, compared to emerging electric (battery) aviation
542 and hydrogen aviation.

543 Clear climate benefits have been documented when renewable sources of energy (whether electricity or heat) are
544 employed to produce the required H₂ [186–188; SM2].

545 *4.1 Hydrogen supply*

546 There are several pathways to produce hydrogen with different resources, e.g. from fossil fuel resources through steam
547 reforming and/or partial oxidation, from non-fossil resources through biomass gasification or fermentation, and from
548 water-splitting technologies [201–205]. Today, around one-third of global hydrogen supply is obtained as a by-product
549 from industrial processes, (e.g. chlorine production from electrolysis of brine; [206–208]). Here, the focus is on
550 hydrogen production decoupled from a carbon source, and as the main product driving the production process.

551 Water is a promising resource generating growing interest for hydrogen production. Several pathways are possible,
552 such as electrochemistry (including water electrolysis and photo electrolysis) [209,210], thermochemistry [211], or
553 biological water-splitting such as bio-photolysis [29,204] as summarized in Fig. 12. The latter, along with photo-
554 electrolysis, have however not been considered any further herein, being still in early development stages.

555 Water electrolysis, in particular if powered with fluctuating power in excess of demand, has attracted growing attention
556 as a process to generate so-called green hydrogen [203,212]. There are different water electrolysis technologies
557 available such as alkaline electrolysis [213], proton/polymer exchange membrane (PEM) electrolysis [214], or solid
558 oxide electrolysis (SOE) [215,216] (details on these technologies are presented in SM1). However, these technologies
559 remain relatively expensive, and their profitability is bound to low renewable energy prices [58,62]. Alkaline
560 electrolysis, for example, provides two to four times the production cost of the conventional steam reforming of natural
561 gas [62,217,218], as further detailed in SM1.

562 *4.2 Carbon sourcing*

563 Carbon sources include (i) biomass (undergoing gasification), (ii) fossil or biogenic carbon stemming from industrial
564 activities captured at a point source (e.g. biofuel/bioethanol production, waste gases from steel production and cement
565 industry, from biogas upgrading process, mine gases, etc.; here denoted as point source CO₂) and (iii) atmospheric
566 carbon captured by DAC (Fig. 11) [130,197]. As DAC, point source carbon also requires a capture process, as further
567 described in SM1. It should be noted that biomass here also acts as source of H₂.

568 There are two major technical approaches for DAC. One is based on the absorption of CO₂ using low-toxicity solvents
569 such as water (through a scrubbing process) and alkaline aqueous solutions (NaOH, Ca (OH)₂ KOH) with a CO₂ strong
570 affinity. In addition to water and alkaline solutions, amino acid salts, ammonia, polyglycol ether and ionic liquids can
571 also be used as solvent for CO₂ extraction [219]. The solvent-based technology is mature and is already applied in
572 large-scale plant, however, the solvent regeneration is a high energy-consuming process. The second approach utilizes
573 an alkaline carbonate bonded to a mesoporous solid support in which the sorbents can be easily regenerated. The most
574 promising technology is the use of supported amine materials; this solid sorbent-based approach revealed higher
575 sorption performance with higher capacities and selectivity, and lower heating requirement compared to the liquid
576 sorbent-based method [31,220]. However, the tradeoff is the high operational expenditure resulting from sorbent
577 degradation [220].

578 On the other hand, capturing technologies for industrial point sources are already well addressed and deployed (details
579 in SM1). CO₂ concentrations vary greatly according to the origin of the point source, ranging from 15-30 vol.% for
580 the cement industry, to up to 90-100 vol.% for natural gas processing [221,222]. The capture cost is around ten times
581 less than the DAC technology cost, and is mainly associated to the cost of energy needed [30,78,221,223].

582 *4.3 Liquid hydrocarbon synthesis*

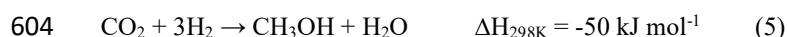
583 In this step, hydrogen is combined with CO₂ to produce syngas. This happens with a reverse water gas shift reaction
584 (i.e. reaction (6) below, from right to left) in the direct electrolysis pathway (Fig. 11a) or through a co-electrolysis
585 process where water thermal splitting and reverse water gas shift reactions jointly occur, thereby converting steam
586 and CO₂ into syngas [224] (Fig. 11b). This is in particular possible with high temperature electrolysis using SOE (600-

587 1,000°C; 873-1,273K) [224]. Co-electrolysis provides high conversion and energy efficiencies utilizing the industrial
588 waste heat derived from other industrial processes such as the FT synthesis [75,216]. The reverse water gas shift
589 reaction implies operating conditions of varying from ca. 300–800°C (573-1,073K) depending on the use of a catalyst
590 (typically copper-based; [225–228]) as well as the operating conditions (e.g., syngas compositions; [228]).

591 As shown in (Fig. 11c), a third option is to thermochemically combine H₂ (from H₂O) and CO₂ for syngas production
592 through the direct use of concentrated solar radiation as energy source. Nuclear and geothermal resources are also
593 possible [229]. Here, the H₂O and CO₂ conversion into syngas is carried out by multi-step thermochemical cycles such
594 as cerium-chlorine, copper-chlorine, sulfur-iodine, iron-chlorine, etc. [202,229–231]. This was demonstrated in the
595 SOLARJET project [202], with a 4 kW solar reactor prototype. The upscaling of this solar thermochemical reactor
596 (50 kW) is being performed within the SUN-to-LIQUID project [205,232], where syngas is to be produced from
597 concentrated solar energy.

598 To produce liquid fuels, the syngas is further used in either the FT or methanol synthesis process, as depicted in Figs.
599 11a-c (and Table S3). For the FT route, the syngas-to-kerosene conversion is exactly as described for biofuels (Fig. 6).

600 In the methanol route, syngas is converted at temperatures of 150-300°C (423-573K) and under pressures in the range
601 of 10-100 bar (1-10 MPa) in the presence of copper-based catalysts (e.g. Cu/ZnO) [233]. The hydrogenation of
602 CO/CO₂ can be described by the following reactions [234]:



605 The water gas shift reaction occurs simultaneously according to the following reaction [234]:



607 Subsequently, the methanol is condensed and separated by distillation. It can then be processed to the desired
608 chemicals and fuels [233,234]. This conversion and upgrading of methanol to desired fuels and chemicals comprises
609 several processes depending on the preferred target product. For instance, methanol may be used for olefin synthesis
610 (an alkene intermediate to produce kerosene) via di-methyl ether, oligomerization and hydrotreating [37,233,235].
611 The methanol generated from syngas could also serve for the production of gasoline (denoted as methanol-to-
612 gasoline), as currently done in commercial plants, for example ExxonMobil [236]. However, no aviation electrofuels
613 have yet been produced via the methanol pathway [37]. On the other hand, FT-SPK has already been tested, and
614 approved by ASTM D7566 as a blending constituent. To the best of our knowledge, the first electrofuel industrial
615 plant (Power-to-Liquid for the production of e-kerosene) was officially opened at the beginning of October 2021 in
616 Werlte (Emsland, Germany) [237]. The Lufthansa Group announced, in October 2021, purchases of at least 25,000 L
617 (ca. 25 m³) annually over the next five years [238].

618 5. Co-products generation in liquid fuels production pathways (biofuels and electrofuels)

619 The technologies previously described (sections 3 and 4, Figs. 2-11) generate, besides the desired fuels, multiple co-
620 products, no matter which route is used. As such, biofuel/electrofuel production pathways are to be seen as refineries
621 rather than mere kerosene suppliers (Table S2). Their co-products include liquid fuels (other than kerosene),
622 chemicals, animal feed, etc. and their generation depends on the specific technologies and operating conditions being
623 used within a given conversion route as illustrated in Table 1. In some cases, it may also depend upon market
624 conditions, where the production chain can flexibly be adjusted towards enhanced production of the most valuable
625 product. These co-products represent an additional market or value generation opportunity for the production plant.
626 These co-products are here grouped in three major categories: chemicals, liquid fuels, and other products.

627 5.1 Chemicals

628 Various chemical compounds are generated as co-products during production processes. Those that have been reported
629 by biofuel producers are detailed here.

630 *5.1.1 Propane*

631 Propane (C₃H₈) is formed as a co-product in the FT and HEFA pathway (Figs. 6 and 9, respectively). Propane is used
632 in a variety of applications, for instance as a fuel for commercial boilers, camping stoves, heating animal houses (e.g.
633 piglet nursery) in livestock production, etc. It can also be used as refrigerant [239,240]. Propane is generally
634 pressurized and stored as liquid in storage vessels or tanks. Due to its high energy density and high quality combustion
635 characteristics, propane is also used as alternative vehicle fuel for internal combustion engine [241,242]. Propane is
636 categorized as one of the bulk components of liquefied petroleum gas (LPG) in combination with other gases such as
637 butane, isobutene, isopentane. Currently, propane is typically generated as a co-product of natural gas processing and
638 petroleum refinery [137]. The cost of propane thus corresponds with fossil fuels resources. The global propane market
639 has been estimated to reach \$84 billion (with 200 million tonnes in its production) by 2030 [243].

640 *5.1.2 Naphtha*

641 Naphtha is a mixture of liquid hydrocarbons comprising carbon compounds ranging from C₅-C₉ [244]. Naphtha is the
642 main combustible component of both gasoline and kerosene. It has a great potential for diverse industrial purposes
643 including plastic production or its use as a cleaning extraction or dilution agent [245,246]. Naphtha is traditionally
644 generated as a co-product in fractional distillation processes from the petrochemical industry, including the production
645 of (fossil-based) kerosene for aviation fuel. The market price of naphtha is thus closely tight to the price of crude oil
646 [247].

647 Biofuel pathways involve the production of naphtha as a co-product (including FT, HDCJ, and HEFA; Figs. 6, 7, and
648 9, respectively). It can be recirculated within the process, for instance in the FT pathway it can be fed into the partial
649 oxidation unit and reformed as syngas feedstock to produce a greater amount of aviation fuel [248]. Additional
650 examples of such bio-based naphtha use are described in SM1.

651 *5.1.3 2,3-Butanediol (optional)*

652 2,3-BDO (C₄H₁₀O₂) is a bulk commodity chemical. It is seen as a promising fuel additive or gasoline blendstock for
653 enhancing the octane number [249]. 2,3-BDO is readily convertible to butadiene, butane, methyl-ethyl ketone (MEK)
654 which could be used as intermediates in a variety of product manufactures. In particular, MEK is used in several
655 applications such as solvents in surface coating, printing inks, dewaxing agent, liquid fuel additive, indirect food
656 additive for adhesives and polymers [250]. According to [249,251,252], 2,3-BDO will reach a global market around
657 \$220 million by the year 2027.

658 2,3-BDO is usually produced on the industrial scale by conventional chemical (or synthetic) methods [253,254]. In
659 the production of aviation biofuel, 2,3-BDO is involved in the SF pathway (Fig. 5). It is not directly generated (hence
660 the optional label above), but can be recovered providing adjustments to the product separation step prior to ethanol
661 production, if favorable market conditions makes it desirable [249]. For recovery, the fermentation broth including
662 liquid mixture or a mixed alcohol stream containing 2,3-BDO would be processed with separation techniques such as
663 fractional distillation, evaporation, pervaporation, adsorption [249]. For instance, LanzaTech has patented the
664 production of 2,3-BDO from CO-rich industrial waste gases (from the steel industry) by fermentation (Table S2).
665 Their commercial ethanol/2,3-BDO production plant has a production capacity of 30-50 million gallons (ca. 0.11-0.19
666 million m³) and costed \$75-125 million. In partnership with Orochem Technologies (USA), LanzaTech seeks to
667 economically convert its 2,3-BDO into MEK or 1,3-butadiene through thermocatalytic processes [249].

668 *5.1.4 Isobutene (optional)*

669 Isobutene (C₄H₈) may be optionally recovered in the SuF pathway. It is produced after dehydration of alcohols, just
670 prior the oligomerization process (Fig. 4). If the market conditions are favorable to isobutene, a choice could be made
671 to stop the process after the dehydration process for a certain proportion of the stream, and not continue further to
672 kerosene production. Isobutene production thus implies less bio-based kerosene production; hence its “optional” label.

673 Isobutene is used as a building block in the manufacturing of several industrial products namely fuel additive, butyl
674 rubber, plastic and lubricants, domestic gas, chemicals and cosmetics, etc. Isobutene can be reacted with methanol
675 leading to methyl tert-butyl ether (MTBE) or with ethanol leading to the production of the gasoline additive ethyl tert-
676 butyl ether (ETBE), used as an anti-knocking agent for the automotive industry [255]. The isobutene polymerization
677 generates butyl rubber that can be used as precursor in several products such as window seals, bottle stoppers,
678 protective gloves, etc. Isobutene is also one of the main constituents of LPG. Moreover, isooctane (a gasoline
679 blendstock) could be generated by dimerization of isobutene [255].

680 Currently, isobutene as a key chemical building block, is massively obtained from petrochemical sources. Being a
681 major precursor in various industrial applications with continuous demand, its market is worth \$25 billion with 15
682 million tonnes produced annually and used as cosmetic ingredients and specialty fuels [256].

683 **5.2 Liquid fuels**

684 *5.2.1 Isooctane*

685 Isooctane is a co-product produced in the SuF pathway (Fig. 4), during the oligomerization/hydrogenation steps.
686 Isooctane represents a large share of gasoline composition and has properties (e.g. high energy content, high antiknock
687 quality) that make it suitable as a blending component for the production of premium-grade fuels [257]. Isooctane is
688 typically produced through the dimerization of isobutene and isopentene generated as by-products from steam
689 cracking of naphtha and light gas oil in refineries, dimer separation and hydrogenation in conventional industrial
690 processes [257]. Isooctane is further used as a feedstock to produce gasoline, in a process where it is blended with
691 naphtha [258].

692 The major market for the isooctane co-product generated in the production of aviation biofuels appears to be its use
693 as drop-in blending component for the automotive industry, with a global market reaching \$99 billion in 2019 [259].
694 Yet, new markets are also emerging. For instance, high purity solvents or specialty fuels used for racing and classic
695 cars [260].

696 *5.2.2 Gasoline*

697 Gasoline is a refined product of petroleum consisting of hydrocarbon mixtures, additives and blending agents. The
698 gasoline composition strongly depends on various parameters such as the crude oil sources, the refinery process
699 available and product specification defined by octane rating [261]. Gasoline may be generated in particular in the SuF
700 (Fig. 4) and FT (Figs. 6 and 11) pathways. In the latter, gasoline is not directly produced as a co-product, but can be
701 produced from the isooctane generated as explained above. Similarly, gasoline (C_5 - C_{12} hydrocarbon ranged; [262])
702 can also be produced from the APR, FT, and CHJ pathways (Figs. 2, 6, 10, respectively); it is not directly visible in
703 the figures, but is captured within the naphtha fraction. The fraction generated strongly depends upon the operating
704 conditions, which in turn can, to some extent, be adjusted according to the market value of bio-based kerosene, diesel
705 and gasoline. For instance, in the production of aviation biofuel through LTFT process, the proportions of gasoline
706 observed correspond to approximately 10-15% of product distillation output [263]. Additional information about
707 renewable gasoline is described in SM1.

708 *5.2.3 Diesel*

709 Diesel is a key fuel powering compression ignition engine. As for gasoline, it is derived from petroleum refining, and
710 its exact composition is influenced by market demands and prices.

711 Diesel with carbon distribution ranging C_{10} - C_{20} is produced in aviation biofuel pathways such as SF, FT (Figs. 2, 5,
712 and 7-10) and in considerable volumes. It is optionally produced in the SF pathway, derived from ethanol upgrading
713 processes. Furthermore, diesel is also generated as the co-product from the FT process where the volume produced is
714 also depended upon the operating conditions [263]. The main market for the diesel co-product appears to be as a

715 renewable fuel for terrestrial transport as reflected by several recent examples of purchasing agreements and
 716 collaboration deals detailed in SM1.

717 5.3 Others

718 5.3.1 Waxes

719 Waxes are generated as a co-product in the FT pathway (Figs. 6 and 11). They consist primarily of straight chain
 720 alkanes (C₂₀₋₂₃₊) which are typically not used in fuel refinery due to their physical properties with i.e. high melting
 721 point, low viscosity and hardness. During the LTFT route, the heavy fraction of the FT syncrude accounts for 20-30%
 722 weight of total hydrocarbons. The molecular mass of the wax fraction generated is higher relative to the wax produced
 723 in the HTFT process [263]. These wax fractions can be cracked into lower molecular weight compounds appropriate
 724 for use as liquid fuels or may be sold as precursor of a variety of products. These heavy alkanes have a high potential
 725 commercial value due to their competitive prices and versatility in both industrial and medical applications including
 726 petroleum jellies, lithium grease, engine oil, industrial gear oil, industrial cleaners, adhesives, etc. [264]. Examples of
 727 wax purchase agreements are listed in SM1.

728 5.3.2 High-protein animal feed

729 An animal feed co-product is generated in the SuF pathway (Fig. 4), where the protein-rich solid residues derived
 730 from the fermentation broth can be further processed. Upon drying, these are often referred to as distiller dried grains,
 731 and typically have a high concentration of crude protein with an amino acid profile suitable for animal feed [265]. Ten
 732 pounds (around 4.5 kg) of animal feed can be produced from one gallon (ca. 0.0038 m³) of aviation biofuel [266]. As
 733 in the case of the distiller dried grains co-generated with bio-based alcohol (e.g. ethanol) production, the access to the
 734 feed market is real and already in place [267].

735 **Table 1** Summary of the co-products generated in the various liquid biofuels production pathways for aviation

Co-product	Conversion pathways	Production status	Market uptake and Displacement	Co-product ratio ^a (kg MJ ⁻¹ kerosene) (% mass) ^b
Chemicals				
Propane	FT HEFA	Generated from triglyceride hydrogenation	<ul style="list-style-type: none"> • One of the main LPG constituents • Used as fuel in numerous applications (e.g. commercial boiler, burner, etc.) • Displaces fossil-based propane from petrochemical sources (natural gas processing, crude oil refinery) 	0.0003 ^{1,12} (1.1%) 0.004 ^{2,3} (9.7%)
Naphtha	FT HDCJ HEFA	Generated along with aviation biofuel (final production step)	<ul style="list-style-type: none"> • Gasoline blending component • Precursors for plastics manufacturing • Can be recycled in the FT unit to produce additional aviation fuel • Displaces fossil-based naphtha from petrochemical sources 	0.0004 ^{1,12} (1.3%) 0.019 ⁴ (27.0%) 0.005 ^{2,3} (12.5%)
2,3-butanediol (2,3-BDO)	SF	Generated along with ethanol, may be recovered through a separation process before the ethanol production (optional)	<ul style="list-style-type: none"> • Conversion to various precursors namely MEK, 1,3-butadiene, etc. • Displaces 2,3-BDO from chemical engineering (or synthetic) methods 	0.013 ⁵ (if they are recovered from the fermentation process) (33.0%)
Isobutene	SuF	Derived from isobutanol, which can be further processed the dehydration (optional)	<ul style="list-style-type: none"> • Precursor for numerous products such as butyl rubber, plastics, isooctane, etc. • One of the main LPG constituents • Dimerization for isooctane production • Polymerization in butyl rubber production • Displaces isobutene from petrochemical sources 	Unclear, because isobutene is an intermediate that can either be processed (fully or partly) to kerosene or not depending on the market context (flexible production)

Liquid fuels				
Isooctane	SuF	<ul style="list-style-type: none"> Generated along with aviation biofuel (final production step) 	<ul style="list-style-type: none"> (Premium-grade) gasoline production Displaces fossil-based isooctane from petrochemical sources 	0.002 ^{6,7} (7.5%)
Gasoline	APR	<ul style="list-style-type: none"> Derived from isobutanol in the SuF process, which can be further upgraded to isooctane (optional) Generated along with aviation fuel (final production step) 	<ul style="list-style-type: none"> Transportation fuel Displaces fossil-based gasoline derived from petrochemical source 	0.003 ⁸ (8.0%)
	FT			0.004 ^{a,1,12} (14.7%)
	IH ²			0.086 ⁹ (72.2%)
	CHJ			0.016 ¹⁰ (28.1%)
Diesel	APR	<ul style="list-style-type: none"> Generated along with aviation fuel from APR, FT and HEFA processes Derived from isobutanol in the SuF process, which can be further upgraded to diesel (optional) 	<ul style="list-style-type: none"> Transportation fuel Displaces fossil-based diesel derived from petrochemical sources 	0.012 ⁸ (32.0%)
	SF			0.003 ⁵ (8.7%)
	HDCJ			0.028 ⁴ (40.1%)
	HEFA			0.009 ^{2,3} (21.1%)
	IH ²			0.010 ⁹ (8.3%)
CHJ	0.018 ¹⁰ (31.0%)			
Others				
Waxes	FT	<ul style="list-style-type: none"> Generate along with aviation biofuel (final production step) 	<ul style="list-style-type: none"> Raw materials for various products such as petroleum jellies, adhesive, etc. Displaces petrochemical-based waxes 	0.001 ^{1,12} (2.9%)
High-protein animal feed	SuF	<ul style="list-style-type: none"> Derived from fermentation residues and may require further processing such as evaporation/drying 	<ul style="list-style-type: none"> High protein and nutrient concentrations derived from dried distiller grains Displaces marginal carbohydrate, protein and lipid sources (maize, soybean meals and palm oil) in animal feed 	0.037 ¹¹ (59.4%)

736 **Note.** ^a Co-product ratios presented are extracted from the available literature in which the operating conditions intend to maximize kerosene
737 production. This could not be done for the advanced IH² process, which is currently essentially used for gasoline production as demonstrated in the
738 study of [174]. ^b The mass (%) of the co-products are provided in parenthesis. This includes the % (mass) out of all products (including kerosene):
739 therefore the total is lower than 100%. The calculation procedure can be retrieved in SM2. The considered lower heating value (LHV) of kerosene
740 is 43.0 MJ kg⁻¹.

741 **References:** ¹ [143]; ² [268]; ³ [269]; ⁴ [270]; ⁵ [133]; ⁶ [271]; ⁷ [272]; ⁸ [273]; ⁹ [174]; ¹⁰ [274]; ¹¹ [266]; ¹² [275]

742 6. Electric (battery-based) aviation

743 Batteries can serve as the energy sourcing for either propulsion (as further explained in section 10.1) or non-propulsion
744 systems (overall electricity within the aircraft). The latter is often referred to as the “more electric” architecture, and
745 is applied in aircraft to power services such as the flight control system and cabin environmental control system, or
746 the auxiliary power unit (APU) [49,276,277]. “More electric” architectures were implemented in the Airbus A350 and
747 Boeing 787 [51,276].

748 Albeit battery is one of the most promising energy sourcing (for propulsion) in terms of climate impacts (further
749 discussed in section 8), there are several limitations to overcome for a widespread implementation within aviation.
750 First, they cover essentially short-haul flights due to the limited energy storage capacity. Table 2 details the emerging
751 lithium-based battery technologies for aviation applications [277]. The present lithium-ion batteries (Li-ion) have a
752 maximum specific energy of 400 Wh kg⁻¹ (1.44 MJ kg⁻¹) [49,278], which is relatively low in comparison with
753 conventional kerosene, having a specific energy density of ca. 12,000 Wh kg⁻¹ (43.2 MJ kg⁻¹). This introduces a crucial
754 mass penalty factor to consider [277,279,280], and affects the final supplied service (e.g. reduction of the number of
755 seats and thus passengers carried, a lower distance travelled; [56,279]).

756 To overcome this challenge, different innovations are in place. The main focus has been on the use of different
757 materials for the cathode/anode, and on the use of different electrolytes (Table 2). This has led to the development of
758 high performance batteries including advanced lithium metal/silicon anode (Adv. Li-ion) [49], solid-state electrolyte
759 battery (SSB) [278,281], lithium-sulfur (Li-S) [282,283] and lithium-air (Li-air) batteries [284,285]. Moreover, nickel-
760 rich NCM (Nickel-Cobalt-Manganese)-811 cathodes [49,286], alternative anode material to graphite (e.g. silicon,

761 lithium metal) [287], approximate solid-state electrolytes in SSB [49], prevention of polysulfide shuttle effects in Li-
762 S batteries [288,289] and improvement of moisture sensitivity in Li-air batteries [285,290] are additional avenues
763 being investigated.

764 Other advances for batteries have been introduced, for instance with systems based on sodium, magnesium, zinc, and
765 aluminum [291], albeit, still in the early stage of research and development. These can be potential candidates to
766 substitute the lithium, cobalt, natural graphite, silicon metals used as the major materials for the electrodes (defined
767 as EU critical raw materials; CRM [292]) [293]

768 Another concern applying to battery electric aviation relates to safety, among other associated with overheating of the
769 battery, which can cause failure of thermal runaway, known to be a key cause of undesired incidents [294,295]. For
770 example, the fire incident of the Boeing 787 Dreamliner in 2013 was reported to be due to the failure of the Li-ion
771 batteries, powering the aircraft APU [296]. Therefore, the development of high-performance, long-lived batteries with
772 thermal stability is one of the numerous technological challenges to be solved before broad deployment [286].

773 One other important issue relates to the charging time of batteries and the possibility to recycle them after their limited
774 lifetime (>1,000 cycles for current Li-ion batteries; [49]). The battery swapping station model, where batteries are not
775 charged but replaced by charged batteries during the turnaround phase of the plane, is one option that has been
776 considered to overcome the charging time issue [297,298], however, this option implies high investment costs because
777 of the great number of batteries involved.

778 Although battery recycling has advantages over the use of virgin metals (e.g., need for less energy for extraction
779 operations, avoid emissions from batteries disposal) [299], several challenges remain to be alleviated, related to a
780 variety of factors. The efficiencies of the collection and dismantling methods (e.g., difficulties in the dissociating used
781 graphite from others) and the appropriate recycling technologies (e.g., for the developing sustainable methods, for
782 high purity requirements such as 99.9% carbon purity for the graphite; [300]) are some examples [299,301,302].

783 **Table 2** Battery technology outlook for aviation

784

785

786

787

788

789

790

791

792

793

794

795

796

797

798

799

800

801

802

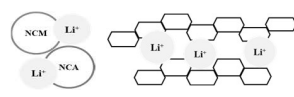
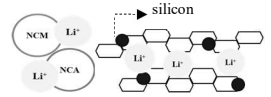
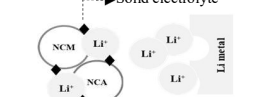
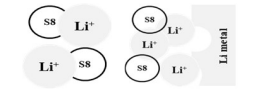
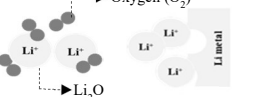
803

804

805

806

807

	Lithium-ion (Li-ion)	Advanced Li-ion	Solid-state battery	Lithium-sulfur (Li-S)	Lithium-air (Li-air)	
						
Battery cell chemistry	Cathode (+) Lithium metal oxide such as LFP, LMO, Li-NMC Li-NCA ³	Lithium metal oxide with Ni-rich fraction (e.g. Li-NMC811) ^{4,5,6}	Lithium metal oxide With Ni-rich fraction (e.g. Li-NMC811) ^{4,5,6}	Sulfur Graphene Acetylene black ^{6,7,8}	Porous carbon (e.g. carbon nanotube) ¹⁰	
	Anode (-) Graphite (with silicon)	Lithium metal or Silicon ^{5,11}	Graphite Silicon ³	Lithium metal Graphite ^{5,12}	Lithium metal ^{5,12,13}	
	Electrolyte Organic liquid (e.g. lithium salt-LiPF ₆) ³	Organic liquid (e.g. lithium salt-LiPF ₆) ³	Inorganic solid (e.g. Li ₁₀ SnP ₂ S ₁₂) Organic solid (e.g. polycarbonate) ⁵	Organic liquid (e.g. LiN(SO ₂ CF ₃) ₂) ^{3,5}	Organic liquid (e.g. LiPF ₆ , LiCO ₄) Aqueous solution (e.g. H ₂ SO ₄) ¹⁰	
	Binder PAA PVDF ^{6,8}	PVDF ^{6,8}	PVDF ⁶	PEI PVP ⁸	PAA ⁸	
	Conductive additive Carbon black ^{3,6}	Carbon black ^{3,6}	Carbon black ^{3,6}	Not specified	Not specified	
Cell properties	Gravimetric (Wh kg ⁻¹) ¹ (MJ kg ⁻¹)	300 ¹⁴ (1.08)	450 ¹⁴ (1.62)	400-500 ¹⁵ (1.44-1.80)	300-400 ¹⁴ (1.08-1.44)	1,350 ⁹ (4.86)
	Volumetric (Wh L ⁻¹) ¹ (MJ L ⁻¹)	700 ¹⁴ (2.52)	1,200 ¹⁴ (4.32)	Not specified	400 ¹⁴ (1.44)	Not specified
	Life-time (cycle) ²	1,000-2,000 ¹⁶⁻¹⁷	1,000 ¹⁸	500 ¹⁵ -1,000 ¹⁴	100 ¹⁴	Not specified
	Nominal cell voltage (V)	3.7 ¹⁴	3.8 (Li-metal anode) ¹⁴	3.8 ¹⁵	2.1 ¹⁴	2.9 ¹⁴
Status	Development status Commercial scale (TRL 9) ^{14,16}	Demonstration scale (TRL 7) ^{14,16}	Technology validation Small-scale prototype (TRL 3-4) ^{14,16}	Small-scale prototype (TRL 4) ^{14,16}	Technology concept (TRL 1-2) ^{14,16}	

¹ Energy density is reported at the cell level derived from published papers and reports which were available at the time of writing. The SI unit of energy (MJ) is presented in parenthesis. ² Lifetime of battery is represented for 100% Depth of Discharge (DoD). TRL displayed has been retrieved from the references as indicated in the table.

Sources: ³[299]; ⁴[303]; ⁵[286]; ⁶[37]; ⁷[304]; ⁸[305]; ⁹[306]; ¹⁰[307]; ¹¹[308]; ¹²[309]; ¹³[310]; ¹⁴[49]; ¹⁵[311]; ¹⁶[278]; ¹⁷[56]; ¹⁸ [312] LFP: Lithium Ferro Phosphate; LMO: Lithium Manganese Oxide; NCA: Nickel-Cobalt-Aluminum; NMC: Nickel-Manganese-Cobalt; PAA: Polyacrylic acid; PEI: Polyethyleneimine; PVDF: Polyvinylidene fluoride; PVP: Polyvinyl pyrrolidone; TRL: Technology Readiness Level.

808 7. Hydrogen aviation

809 The energy density of hydrogen, in terms of energy-to-weight ratio (MJ kg^{-1}) is three-fold that of conventional
810 kerosene, rendering it suitable for longer flights in large planes supporting high payload capacity. Despite being
811 lighter, hydrogen, in its cryogenic liquid form, has an energy-to-volume ratio (MJ L^{-1}) four-fold lower than fossil
812 kerosene, which implies obvious storage challenges [313]. The different pathways for hydrogen production through
813 water-splitting technologies are presented in Fig. 12.

814 Cryogenic hydrogen (referred as liquid hydrogen; LH_2) requires cryogenic storage (-253°C ; 20K) to maintain
815 hydrogen in a liquid form [314]. This is due to hydrogen's high specific volume at standard atmospheric pressure and
816 temperature.

817 Hydrogen propulsion system have been demonstrated whether in combustion mode or fuel cell mode (the latter is
818 detailed in section 10.2.1). The Russian manufacturer Tupolev manufactured, in 1989, the first hydrogen aircraft using
819 both gaseous H_2 (from an LH_2 tank), and liquefied natural gas (LNG) fuel in a gas turbine engine to propel the Tupolev
820 155 (Tu-155) [315]. The direct use of H_2 in gas turbines and piston engines generally involve that LH_2 is pumped from
821 the tank to a heat exchanger, where LH_2 is heated to gaseous form prior to being injected into the combustion chamber
822 of the engine [316]. The A380 MSN1 is an additional undertaking demonstrator to be powered by the H_2 combustion
823 mode, which is expected to fly by 2026 [317]. Those require, besides the gas turbine with modified components (such
824 as combustion chamber, fuel injector), a cryogenic tank with insulation system, additional on-board infrastructure
825 such as high-pressure pumps, and a heat exchanger suitable to H_2 combustion characteristics (e.g., a tendency to
826 flashback, a high flame temperature) [62,313,316,318], although scarcely detailed. Hydrogen turbine engines with
827 low- NO_x emissions are already expected as the next improvement of this technology [58,62,63]. Boeing Phantom Eye
828 is another example of an unmanned drone powered by hydrogen combustion in piston engines [319]. Other hydrogen
829 aircraft, and projects can be retrieved in SM1.

830 Cryogenic LH_2 has a propensity to leak due to hydrogen's high boil-off rate and small size molecule. Because of this,
831 the use of H_2 raises important concerns about safety, and involves stringent procedures and requirements with regards
832 to safety regulation certification, at airports, production and storage sites, transportation, distribution as well as for the
833 aircraft operation, to avoid and control these leakages in case of occurrence [58,313,320]. It is even suggested to build
834 airports where only H_2 would be used for all airport vehicles used for ground operations [321]. Despite this, H_2 has
835 some advantages safety-wise, over conventional kerosene, such as lower flammability (more H_2 leak than kerosene
836 leak is required prior to fire hazards, among others due H_2 rapid dispersion in air), and a higher auto-ignition
837 temperature (550°C ; 823K for H_2 versus 300°C ; 573K for conventional kerosene), leading to a lower risk of
838 spontaneous ignition of the fuel [320–322].

839 The key challenge of hydrogen as aviation fuel relates to the mass penalty induced by the onboard storage system.
840 The mass penalty derived from the H_2 storage system is, at current technological state, reported to be twice as much
841 as the conventional aviation fuel-based APU, when the compressed H_2 system is applied [58,63].

842 A light cryogenic storage tank with cooling system advancement is necessary for tackling this challenge [62]. On top
843 of this, the fuselage may need a further redesign to accommodate the cryogenic hydrogen tank. The Airbus ZEROe
844 project for instance announced the use of a blended wing body (BWB), as one type of aircraft allowing to efficiently
845 accommodate hydrogen [323].

846 8. Semi-quantitative comparison and prioritization in the perspective of environmental mitigation

847 The strengths, challenges and prospects of the four SA families studied herein are summarized in Fig. 13. At the light
848 of Fig. 13, it however remains unclear which pathways are the most promising from a technical, economic and
849 environmental point of view.

850 To this end, a semi-quantitative multi-criteria decision matrix has been established to enable a relative prioritization
851 of the various types of SA approaches elaborated to this point (Table 3), inspired by the approach used in [324]. It is
852 meant as a tool to pre-screen the global performance, and is by no means intended to replace state-of-the art

853 quantitative assessment. It proposes three performance criteria (Table 3) seen as key for sustainable aviation:
854 technology status, market prospects, and environmental performance, reflecting that short- and longer-term
855 environmental mitigation are deeply intertwined with broader market considerations. For each of these critical criteria,
856 sub-criteria were elaborated, to which a score (from 0 to 3) is given, on the basis of quantitative or qualitative
857 descriptions (Table 3). The tool is distinctively applied on two timescales: near-term future (~2030) and long-term
858 (~2050). These 10-20 years' time scopes are used as judged representative to reflect the time elapsed between two
859 generations of technologies [325]. Several supporting references, including literature, scientific papers, patents,
860 industrial/research organization reports, announcements, were accessed to assign scores for all criteria, and all
861 pathways. This is thoroughly documented in SM2.

862 Figure 14 summarizes, for all pathways considered herein, the score obtained for some of the key quantitative
863 performance indicators of Table 3, namely fossil fuel reduction, GHG reduction and technology readiness level (TRL),
864 distinguished according to the time scope. Accordingly, 11 groups of pathways can be distinguished (Fig 14).
865 Pathways of group (1) are, according to the criteria selected in Fig. 14, the most promising, implying zero fossil fuels
866 requirement and high (>60%) GHG reductions expected in comparison to fossil kerosene. It involves hydrogen
867 (produced with alkaline or PEM electrolysis) as well as one biofuel and electrofuel pathway. The former is highlighted
868 as particularly interesting due to its higher TRL. On the other hand, pathways of group (11), involving Li-ion and
869 Advanced Li-ion batteries used in hybridized mode (i.e. used for propulsion) are shown as the least interesting,
870 involving a high fossil fuels share and less than 40% expected GHG reductions.

871 Despite useful, Figure 14 does not allow to reflect all criteria, especially the qualitative ones, of Table 3. In a second
872 stage, the Analytical Hierarchy Process (AHP) protocol proposed by [326] has therefore been used to assign weights
873 to the different sub-criteria through the application of weighting factors between 0 and 1 to each sub-criteria, the total
874 being 1 (Table 3). This is of course subjective, but the vision, for the screening exercise to be useful, is to supply a
875 weight choice that is transparently argued (SM2). For instance, here, the sub-criteria "requirement of fossil fuels" is
876 the one with the highest weight for both the short- and long-term, keeping a maximum of fossil carbon in the ground
877 being seen as a key driver for the development of SA at the first place. Final weighted scores are calculated by
878 multiplying the weighting factors by the sub-criteria assigned scores, as detailed in SM2. The resulting final weighted
879 scores are presented in Figs. 15 and 16, for near- and long-term, respectively, with a breakdown per sub-criteria.

880 As a result (Figs. 15-16), the most promising biofuels technologies uncovered for the near-term (Fig. 15) are HEFA
881 (oleochemical wastes) and BGFT (biomass gasification and the FT process, with residual lignocellulosic biomass),
882 significantly standing out from the other biofuel technologies. This result for (waste-derived) HEFA is explained by
883 two key advantages of this pathway in comparison to the other options addressed: it benefits from existing capacity
884 and it is not directly requiring additional arable land demand. For BGFT (based on lignocellulosic biomass), this
885 decoupling from additional land demand is also important, along with its expected lower well-to-wake GHG emissions
886 ([327,328]; SM2). Based on available literature, a well-to-wake reduction of GHG emissions of 91% was considered
887 for BGFT (in comparison to fossil fuels), which is much higher than for all other biofuels (SM2). Yet, this result is to
888 be considered with caution, as essentially reflecting methodological choices attributing GHG credits to energy-dense
889 co-products. For electrofuels, only one technology stands out, namely FT using H₂ from alkaline water electrolysis
890 and carbon from DAC (irrespective of the exact DAC technology), due to its expected lower well-to-wake GHG
891 emissions. For electric (battery-based) systems, current technology for lithium-ion battery is highlighted with a higher
892 weighted score, essentially benefiting from its greater maturity. For H₂ systems, alkaline water electrolysis
893 significantly stands out from the other H₂ production technologies assessed, benefiting from its greater existing
894 capacity (and the weight assigned to this criterion in the near-term).

895 For the long-term (Fig. 16), the results are similar for electrofuels, and biofuels, except that here, the BGFT
896 lignocellulosic biomass clearly stands out from all other biofuels, essentially because of its expected lower well-to-
897 wake GHG advantage, weighted higher for the long-term (SM2). This explanation also applies for the electrofuels
898 result. The alkaline water electrolysis is again shown as the most interesting technology for H₂ production, but the
899 difference with other technologies is less pronounced than in the short-term. For electric (battery), however, the

900 lithium-air battery is highlighted as the most interesting technology due to its anticipated higher energy density (see
901 Table 2) and hence ability to carry more passengers with a longer distance traveled [56] or to the use less fossil
902 kerosene supplement in a hybrid mode. Higher weights are put on these sub-criteria, namely the requirement of fossil
903 fuel, GHG emissions reduction, in comparison to the short-term.

904

905 **Table 3** Semi-quantitative criteria for prioritizing sustainable aviation approaches^a

Overall criteria	Weight (0-1) ^b		Sub-criteria	Score				Comments
	2030	2050		0	1	2	3	
Technology current status	0.19	0.25	Requirement of fossil fuels	100% fossil fuel required	> 50% fossil fuel required	≤ 50% fossil fuel required	Not required or Required for takeoff only	Based on known standards for aviation (e.g. ASTM D7566, etc.)
	0.12	n/c	Technology readiness level (TRL)	0-2	3-4	5-7	8-9	The general principles used for TRL assessment can be retrieved in SM2.
	0.12	n/c	Existing capacity ($\times 10^9$ MJ y ⁻¹)	<1	1.00-4.99	5.00-9.99	> 10	Current production capacity
	0.01	0.02	Energy density (MJ kg ⁻¹)	<20	20-30	31-40	> 40	43 MJ kg ⁻¹ is considered as a default value for conventional kerosene [143]. The ranges proposed herein are based on this.
Market prospects	0.03	0.04	Commodity co-products (with offsetting production costs) (€ kg ⁻¹)	< 0.10	0.10-0.49	0.50-1.0	> 1.0	The average jet fuel price in 2020 was around 0.60 € kg ⁻¹ [329]. We also consider that aviation kerosene has a fuel density of 0.785 kg L ⁻¹ [143].
	0.08	0.06	Passenger carrying capacity (seat)	Not for carrying passenger	1-50	51-100	> 100	Electric battery aviation is evaluated based on [56,325]. Hydrogen aircraft are evaluated based on [63].
	0.08	0.06	Flight range (km)	<500	500-2,000	2,001-5,000	> 5,000	Electric battery aviation is evaluated based on [56,330]. Hydrogen aircraft are evaluated based on [63].
	0.04	0.03	Cost competitiveness in low-fossil carbons future (€cent MJ ⁻¹)	>5.00	3.01-5.00	1.31-3.00	<1.30	Conventional jet fuel price 1.30 €cent MJ ⁻¹ [329].
Environmental performance	0.12	0.17	GHG emission reduction in comparison to fossil kerosene, as reported by studies	<40%	40-60%	60-80%	>80%	The Well-to-Wake GHG emission of conventional jet fuel is considered to be 87.5 gCO ₂ -e MJ ⁻¹ [331].
	0.02	0.08	Energy demand to produce the fuel (MJ MJ ⁻¹ fuel produced or battery)	> 10.0	5.01-10.0	2.0-5.0	< 1.99	
	0.12	0.17	Land requirement	Growing crops with a high impact on the food/feed competition	High share of residual biomass (wastes), but crops may be involved	Biomass share overall low, and from residual resources only	No biomass needed	Relates to feedstock sourcing only
	0.05	0.12	Sustainable availability of feedstock	Highly limited availability Feedstock otherwise used for food and feed	Limited availability: Feedstock otherwise not used for food/feed (Non-edible crops)	Limited availability but independent from land (e.g. residual, waste) included in the EC critical raw materials (CRMs) list 2020 [292]	Abundant availability (e.g. solar energy, CO ₂ from the air)	
	0.02	0.01	Water demand (L H ₂ O MJ ⁻¹ fuel produced or battery)	>100	50.01-99.99	10.01-50	< 10	Considering the overall water requirement during their production stage.
	1.00	1.00						

906
907

^an/c: not considered. The reference data and rationale used for the scores attributed herein are further detailed in SM2; ^b The weight of each sub-criteria has been calculated through the Analytical Hierarchy Process (AHP) as described in [326]

908 **9. Other emerging energy sourcing for aviation not considered herein**

909 *9.1 Liquefied natural gas (LNG) based aviation*

910 The use of LNG (i.e. liquefied methane) as a fuel is highly researched and discussed for the maritime sector
911 ([332,333]), and to some extent the aviation sector (e.g. Savion aerospace; [334]), though it is still very marginal. One
912 driver for the development of this technology is the price of fuels; low natural gas price relative to fossil kerosene may
913 favor the LNG. It is further suggested that LNG aviation fuels could reduce CO₂ tailpipe emissions of approximately
914 20-25% relative to conventional kerosene, for the same energy content [313,335]. Although LNG is presently derived
915 from natural gas, it could stem from biomethane generated through anaerobic digestion [121], biomass gasification
916 [336], or power-to-methane routes decoupled from biomass [337]. It also has a gravimetric energy density slightly
917 higher than conventional kerosene (around 48-54 MJ kg⁻¹) [335,336].

918 LNG for aviation, however, still involve a number of challenges. First, it implies, as for LH₂, cryogenic form (-162°C;
919 111K), and thus a certain mass penalty [313,338,339]. It also implies infrastructure not already in place (e.g. refueling
920 system, LNG storage tanks, liquefaction facilities) [335,338]. Importantly, eventual leakages of LNG is another factor
921 to be considered, as methane has a global warming potential (GWP₁₀₀) around 28 times the one of CO₂ [340].

922 As LH₂, LNG is compatible with whether combustion mode or fuel cell mode [341]. The former has been show-cased
923 in gas turbines (e.g., TU-155 aircraft [315]) as well as within the Advanced Hybrid Engines for Aircraft Development
924 (AHEAD) project [342]. The combustion mode implies that modification and/or change in propulsion systems are
925 required, including engines, injectors and heat exchangers, able to use this fuel [343,344]. The fuel cell mode has been
926 showcased in a solid oxide fuel cell (SOFC) within the Subsonic Ultra Green Aircraft Research (SUGAR) project
927 [341]. To make it viable on long-range aircraft, additional research on advanced materials for fuel cells is however
928 needed [341].

929 *9.2 Ammonia based aviation*

930 The use of liquefied ammonia (NH₃) for aviation has been discussed and considered within some research and
931 industrial communities [345,346]. For instance, ammonia-powered aircraft are being developed within the Zero-
932 carbon Ammonia-Powered Turboelectric propulsion project (ZAPturbo) [347]. In comparison to LH₂, it involves
933 lower mass penalties owing to the superior density of liquid ammonia (730 kg m⁻³; [343]). Ammonia requires
934 refrigeration to -33°C (240K) under atmospheric pressure, this implies prior refrigeration when on ground, and is
935 maintained by the outside temperature during cruise altitude (at ca. 8-12 km; [348,349]) through heat exchanger
936 systems [346]. Refrigerated ammonia can be stored in the wings like in the case of conventional kerosene [350].

937 However, most ammonia is currently produced from hydrogen through steam reforming of natural gas, and N₂ is
938 derived from air separation through the energy-intensive Haber-Bosch process [343,351]. Alternatives using
939 renewable H₂ (derived from water electrolysis rather than natural gas; also referred to as the 2nd generation path)
940 [352,353], or electrochemical ammonia synthesis as an alternative to the Haber-Bosch process (electrochemical N₂
941 reduction reaction, NRR, known as the 3rd generation path) [351,353,354] are being developed. However, at present,
942 the production cost of renewable ammonia is roughly twice the price of conventional ammonia. Its production cost is
943 essentially shaped by the price of renewable electricity [355]. In addition, ammonia has a low gravimetric energy
944 density (18.6 MJ kg⁻¹; [343,347]), this means that ammonia-powered aircraft would have a shorter flight range relative
945 to (conventional) kerosene and hydrogen [356], considering a similar payload mass. Moreover, an enhanced use of
946 atmospheric N₂ to produce (additional) ammonia implies an enhanced risk for contributing to excess reactive nitrogen
947 in the environment, known to cause a range of negative environmental, socio-economic, and health consequences
948 [353,357], besides being one of the exceeded planetary boundaries [358].

949 Ammonia per se has a high ignition temperature, and low flow velocity [357,359]. Therefore, a mixture with other
950 reactive molecules (e.g. H₂), has been proposed as one option to improve combustion properties ([353]). In this
951 endeavor, it is proposed to add a cracking unit to the aircraft, where part of the ammonia dissociates into nitrogen and
952 hydrogen, resulting in a mixture of NH₃-H₂-N₂ [347,357]. This feature closely makes it compatible with the current

953 (hydrocarbon-based) gas turbine engines [347,353,357], and is being developed by e.g. Raytheon Technologies
954 Research Center [347] and Reaction Engines Ltd. [345]. Ammonia can also be employed in the fuel cell mode [360],
955 but no showcasing of this has been found. Water vapor, nitrogen, and nitrogen oxides (NO_x) are considered as the
956 only tailpipe emissions of ammonia [356]. To minimize the effects derived from NO_x formation, mitigation
957 technologies such as a low- NO_x combustors have been proposed [347]. Additionally, new materials for storage tanks
958 (in particular for on-board NH_3) are required to safely deal with the corrosive properties of NH_3 [353]. Ammonia's
959 toxicity (inhalation hazards) is another issue to be tackled and would imply mandatory specific training before
960 handling [353,357].

961 *9.3 Solar aviation*

962 Solar energy generates growing attention for aviation [361,362], due to its unlimited availability and envisioned
963 sustainability. Solar-powered aircraft for passenger-carrying purposes however faces many challenges. First, solar
964 panels are limited in their capturing efficiency (around 20%; [363,364]). Even if an increase in efficiency (reaching
965 100%) has been achieved ([362]), the generated power might not be sufficient to deal with the payload a passenger
966 aircraft implies. In addition, because of low efficiency power devices of solar-powered aircraft (e.g., photovoltaic
967 cells, rechargeable batteries; [364]), the maximum speed would not reach beyond 50 miles hr^{-1} (160 km hr^{-1})
968 (commercial aircraft traveling at about 600 miles hr^{-1} ; 965 km hr^{-1}) [362]. The high variability of photon capturing
969 angles is also reported to result in lower power generated (relative to the expected maximum power) [362,364]. Other
970 issues are reported, for instance, the vulnerability of solar panel materials to adverse weather conditions, or the need
971 for large wingspans. Nevertheless, solar power is successfully applied and deployed for unmanned aircraft
972 system/unmanned aerial vehicle (UAS/UAV) as a satellite service (additional detail in SM1).

973 The deployment of solar aviation for carrying passengers therefore appears as an unlikely option till the first half of
974 the century, but it may be considered in hybridization with the other SA systems discussed within the present study.

975 *9.4 Others*

976 Finally, additional initiatives, albeit marginal such as methanol [365,366], and ethanol [367,368] direct use, do exist
977 and have not been covered within this review due to a lack of available documentation about these.

978 **10. Electric propulsion systems for aviation**

979 Electric propulsion (to be distinguished from battery-electric) represents configuration schemes involving an electric
980 motor to supply mechanical power to the aircraft propulsors (which could be propellers or fans) (Fig. 17). These
981 configuration schemes differ with regards to whether they imply or not (i) energy storage from batteries; (ii) a (H_2)
982 gas turbine fueled by H_2 or liquid hydrocarbons and (iii) fuel cells fueled by H_2 or liquid hydrocarbons and supplying
983 electricity to electric motors.

984 Advancing the propulsion efficiency is, after the energy sourcing itself, one key lever considered to improve the overall
985 environmental performance (including noise reduction) of future aviation. Throughout this section (and in Fig. 17),
986 the term propulsor represents devices generating thrust either by a propeller in the turboprop or by fans in the turbofans.
987 It also encompasses the generation of shaft power in the case of turboshaft engines. The term “(H_2) gas turbine”
988 collectively refers to the turboshaft, turboprop, and turbofan engines. Converter refers to the devices converting the
989 voltage of the electrical power source, sometimes denoted as power electronic [276], and considers that one type of
990 converter is an inverter, which converts direct current (DC) to alternating current (AC).

991 To represent the proportion of electric power in total power, two parameters are used [51,56], respectively degree of
992 energy hybridization (H_E) and degree of power hybridization (H_P). H_E and H_P vary from 0 to 1 depending on the
993 conceptual designs [51,369]. H_E is zero when there are no energy storage devices involved (no batteries), and 1 when
994 the power is solely supplied via batteries. H_P is 1 when only electric motors are supplying the required mechanical
995 power, and 0 if no electric motors are involved in supplying the required power.

996 **10.1 Battery-dependent electric propulsion configurations**

997 Electric aircraft relying on batteries have gained substantial interest in recent years. Batteries can serve as the energy
998 sourcing for propulsion either as standalone (“all electric” concept; Fig. 17a) or in combination with other fuels
999 (“hybrid electric” concept; Figs. 17b-c).

1000 The all electric concept is also denoted as “full electric” (e.g. in [370–372]). An all electric configuration (Fig. 17a)
1001 involves that ($H_P=1$) because the propulsor is powered by an electric motor only but also involves that ($H_E=1$) because
1002 it relies solely on batteries without any hydrocarbon-based fuels or H_2 [51].

1003 The concept of “hybrid electric” (Figs. 17b-c) implies, on top of the electric motor, the use of a (H_2) gas turbine fueled
1004 by liquid hydrocarbons or H_2 to generate additional mechanical power. As AC power is required for most of the
1005 electric motors that can be used in aviation, converters are required [373]. The parallel and series hybrid electric
1006 concepts are the two main configurations that have been tested (Figs. 17b-c), however, a series-parallel hybrid scheme
1007 has also been demonstrated (not depicted in Fig. 17) [373,374]. The parallel hybrid electric configuration (Fig. 17b)
1008 involves (H_2) gas turbines and electric motors to generate mechanical power from fuels combustion and batteries,
1009 respectively, [375]. Hence a mechanical transmission (typically gearbox) is required to integrate and control these two
1010 mechanical power sources prior to the propulsor [373,376,377]. In the series hybrid electric configuration, the
1011 generator powered by the (H_2) gas turbine produces electricity for both the electric motor(s) (which is directly linked
1012 to the propulsor; $H_P = 1$), and to charge the battery onboard ($0 < H_E < 1$) [51,371,378] (Fig. 17c).

1013 Several projects have been launched to demonstrate the feasibility of these battery dependent configurations) (Fig.
1014 18). For example, the startup Eviation (Israel) launched Alice, a nine-passenger all electric aircraft with an autonomy
1015 range of 650 miles (1,046 km), expected to be in service by 2024 [379]. The aircraft relies on a battery that can be
1016 fully charged within 70 minutes and is expected to be FAA-certified (FAA: USA Federal Aviation Administration)
1017 by 2024 [379]. However, a fire incident has occurred during the Alice ground test in January 2020 caused by a fault
1018 with a ground-based battery system [380]. The company magniX (Canada) designed and demonstrated a high-power
1019 density electric propulsion system with the world’s first fully electric commercial seaplane, tested on a flight in
1020 December 2019 (6-passenger aircraft; flight range of 1,000 km) [381,382]. In May 2020, magniX together with
1021 Harbour Air successfully tested an all electric powered system carrying up to 9 passengers for a reported flight range
1022 of ca. 160 km (e-Caravan; retrofitted from Ceravan 208) [383,384]. It is announced to be the largest all electric aircraft
1023 with a successful test flight (in the middle of 2020). In Europe, EasyJet and Wright Electric are developing since 2017
1024 an all electric aircraft (186 seats) and announced it will start using electric aircraft to cover short-haul routes by 2030
1025 [385,386]. Additional details on these emerging developments along with specifications on these technologies are
1026 presented in SM1.

1027 **10.2 Electric propulsion independent from batteries**

1028 Electric propulsion configurations independent from the presence of batteries include: Fuel cell electric and
1029 Turboelectric systems.

1030 *10.2.1 Fuel cell electric propulsion (may involve batteries as backup)*

1031 A fuel cell propulsion system could be employed in the mode of all electric (in Fig. 17d), or hybrid electric (electric
1032 motor and (H_2) gas turbine; Figs. 17e-f) [373,387], where hydrocarbon-based fuels or H_2 are converted to electricity
1033 that in turns powers an electric motor involving a modification of the propulsion system [62].

1034 Fuel cells serve as energy converters, not as energy storage as in the case of batteries. Fuel cells can continuously
1035 produce electricity as long as fuels (whether hydrocarbon-based fuels or H_2) are fed to the fuel cell. The existing fuel
1036 cell technologies, for the automobile sector and stationary power applications, include the proton exchange membrane
1037 fuel cells (PEMFC) and SOFC, depending on the electrolyte employed, operating conditions, and fuels compatibility
1038 [387,388]. Fuel cells can be considered for the propulsion system in aviation, providing an increase in their specific
1039 power (targeting 2 kW kg^{-1}) has been achieved [57,63,388]. The electricity produced in excess of what is needed for
1040 propelling the aircraft can additionally be stored in batteries as a backup energy source, not directly involved in the

1041 propulsion system [62] (Figs. 17d-f). Fuel cell propulsion also provide the advantage of short refueling time relative
1042 to batteries with fewer risks of reducing the lifetime [58].

1043 Hydrogen fuel cell designs for aircraft are being developed, for instance by Airbus in ZEROe concepts (hybrid
1044 hydrogen propulsion system). These aircraft are expected to enter service (with a carrying capacity of 100-200
1045 passengers) by 2035 [323]. Furthermore, the first commercial H₂ fuel cell aircraft (with a carrying capacity of 10-20
1046 passengers, and maximal distance traveled up to 555 km), was announced by ZeroAvia to be ready by the year 2024.

1047 Unlike the H₂ combustion in gas engines and piston engines (Fig. 17i) where air is involved in the combustion process
1048 (thus involving nitrogen outputs such as nitrogen oxides; NO_x); the only two by-products from H₂ fuel cell systems
1049 are water vapor and a small amount of heat. This, however, involves non-negligible cooling requirements [58,63].
1050 Additionally, fuel cell propulsion is unlikely to be competitive for heavy payload and long distances, with four times
1051 the mass of current aircraft engines to generate the same power output [58,63].

1052 Various projects have been intensively studied in developing and improving hydrogen fuel cell technologies (Fig. 17),
1053 as detailed in SM1. Hybridization with fuel cell and battery propulsion is another alternative configuration (not
1054 depicted herein) [389].

1055 *10.2.2 Turboelectric propulsion (no batteries)*

1056 Turboelectric propulsion (Figs. 17g and h) is another configuration for electric powertrain systems, and fully relies on
1057 hydrocarbon fuel or H₂ as its energy source. Here, no energy storage (e.g. batteries) is involved [369,370,378]. A (H₂)
1058 gas turbine drives the generator that powers electric motors for thrust or shaft power generation. In the full turboelectric
1059 system (hence, H_E = 0, H_P = 1; Fig. 17g) [51,390], the generic (H₂) gas turbine term denotes a turboshaft engine [391].
1060 In the partial turboelectric concept (Fig. 17h), the generated mechanical power from the (H₂) gas turbine is partially
1061 delivered to the generator ultimately feeding the electric motor(s), and the remaining power is delivered directly to
1062 the other propulsors [51,279,370]. In this case (Fig. 17g), H_E would be zero as there are no energy storage devices
1063 involved, while H_P would be between 0 and 1 because both a (H₂) gas turbine and an electric motor are used to supply
1064 energy to the propulsor. In this particular case, however, a clear standard for attributing the appropriate non-zero and
1065 non-one hybridization value is still missing [51,369].

1066 Albeit the propulsive efficiency of electrically-driven propulsors can improve, the integration of the electric system
1067 introduces mass penalties (although lighter than the all electric configuration as it does not involve batteries) [279,391–
1068 394]. To enhance the overall performance in terms of fuel burnt and mass, this configuration concept has been
1069 integrated with optimized aircraft design, for instance in NASA's STARC-ABL aircraft design (Single-aisle
1070 Turboelectric AiRCraft with an Aft Boundary - Layer propulsors) [394]. This allowed a 12% reduction of fuel burnt
1071 compared to the conventional aircraft concept (conventional kerosene configuration (Fig. 17j) and airframe design)
1072 [394]. The Wright ECO-150R aircraft capable of carrying up to 150 seats (flight range of ~ 3,000 km) initially
1073 demonstrated ca. 44% fuel burn reduction in comparison to the conventional configuration [378]. NASA's N3-X
1074 aircraft is another turboelectric concept with a blended wing body in which electric motors are used to drive several
1075 distributed electric fans, where the effective bypass ratio (BPR) is increased while reducing the fan pressure ratio
1076 [393]. It demonstrated to provide ca. 63% energy and 90% NO_x reductions [395]. This architecture has been proposed
1077 as the upcoming technology to meet environmental goals [370,396], where hydrocarbon-based fuels
1078 (biofuels/electrofuels) or H₂ can be used instead of fossil kerosene.

1079 Other projects on electric propulsion systems are demonstrated in Fig. 18 and can be further retrieved in SM1.

1080 **11. Regulatory frameworks/ Sustainability policies**

1081 Policy and regulatory frameworks are often pinpointed as essential to encourage the deployment of SA, and to ensure
1082 this deployment is sustainable [397–399]. Alternative fuels for aviation have been considered in numerous
1083 launched/ongoing regulatory framework and sustainable policy initiatives. These essentially apply to liquid biofuels
1084 and to some extent electrofuels, owing to their technological maturity. As of today, the use of biofuels nevertheless

1085 remains minimal, with less than 1% of total aviation fuel demand [25,400,401] (electrofuels are not yet widely
1086 available for commercial use).

1087 A handful of frameworks/policies have also been paying attention to other emerging alternatives to power aircraft,
1088 including electric (battery) aviation and hydrogen (H₂) systems. The regulatory context on alternatives implemented
1089 at the point of writing is summarized herein, with a greater focus on schemes affecting the EU countries.

1090 *11.1 European Union's sustainable & smart mobility strategy*

1091 The EU's sustainable & smart mobility strategy (part of the EU Green Deal) has been adopted by the European
1092 Commission on December 9th, 2020. Being a strategy, it is not binding, but it aims to ensure that the EU's transport
1093 systems are able to achieve the climate targets for 2030, and the 2050 climate neutrality [25], and describes the
1094 Commission's current vision to reach these goals. A package of milestones for all transport modes are proposed,
1095 covering also the aviation sector [402]. For instance, the production and deployment of biofuels and electrofuels
1096 (labelled as SAF in the strategy) are highly encouraged at Union airports to reduce aircraft's emissions in line with
1097 the ReFuelEU Aviation proposal (section 11.5). Alternative propulsion technologies powered by electricity or
1098 hydrogen are also required to achieve zero (carbon-) emissions. Other measures, such as improving the air traffic
1099 management (ATM) efficiency, developing an environmental label program, and revising the EU Emission Trading
1100 Scheme (EU ETS) with respect to aviation (section 11.4) are also mentioned [403].

1101 *11.2 'Fit for 55' package*

1102 The European Commission has proposed, as announced in the European Green Deal communication [403], to increase
1103 the 2030 GHG emission reduction target (at overall EU level) from 40% to 55%, relative to 1990 levels. To this end,
1104 the European climate-, energy- and transport-related legislation is being revised under the so-called Fit for 55 package
1105 [404], being a set of proposals to align the EU legislation with the new target. The most relevant points of this package
1106 for aviation include: i) the amendment to the Renewable Energy Directive II (RED II) (section 11.3); ii) the revision
1107 of the EU ETS (section 11.4), ii) the ReFuel EU Aviation proposal (section 11.5), and iii) the revision of the Energy
1108 Taxation Directive (section 11.6).

1109 *11.3 EU Renewable Energy Directive (RED)*

1110 The EU Renewable Energy Directive (RED) adopted in 2009 established an overall policy framework for the
1111 production and promotion of energy from renewable sources. It is a binding regulation for EU Member States. The
1112 RED requires all EU countries to ensure a share of at least 10% of final energy consumed in transportation stems from
1113 renewable sources by 2020 [405]. The RED (or RED I) target, however, does not fully include the aviation sector, by
1114 limiting, in the calculation of the gross final energy consumed by a Member State, the aviation share to maximum of
1115 6.18% (4.12% in the specific case of Malta and Cyprus).

1116 The RED was further amended with the Directive 2015/1513 to, among others, recognize the opportunity offered by
1117 biofuels/electrofuels to enhance the consumption of fuels not derived from fossil resources within the aviation sector.
1118 This translated in the so-called 'voluntary opt-in' [406]. The Member States could implement this opt-in differently:
1119 in form of a certificate system for fuel suppliers, or as a tax exemption for reaching the 10% of final energy
1120 consumption from renewable sources by 2020 [407].

1121 The revised RED for the period 2021-2030, denoted as RED II, requires a minimum share of 14% of final energy
1122 consumption in transport sector to be derived from renewable energy by 2030, and is set as an obligation for fuel
1123 suppliers [71]. It also sets additional sustainability criteria, namely requirements associated to specific GHG emission
1124 savings, specific shares of advanced fuels to incorporate (in 2022, 2025, 2030), criteria for feedstock sourced from
1125 forest biomass (e.g., harvesting with legal permits, maintaining soil quality and biodiversity during the harvesting
1126 process), and the consideration of indirect land use changes (ILUC) to limit the use of high ILUC-risk feedstock from
1127 land with high carbon stocks [71,408,409], among others. The new directive further introduces a slight incentive for
1128 using non-food biomass for aviation and maritime fuels production through a multiplication factor of 1.2 (of their

1129 energy content) in the calculation of renewable energy not stemming from feedstock intended for food and feed
1130 consumption. As the original RED, RED II has no specific target for the aviation sector.

1131 Key provisions affecting the aviation sector have been suggested in an amendment to RED II proposed by the
1132 Commission in July 2021 [410]. This includes a reduction of the minimum share of advanced fuels for 2025 and 2030,
1133 and the introduction of a new sub-category of renewable fuel, namely renewable fuels of non-biological origin
1134 (RFNBOs; including electrofuels, renewable hydrogen, renewable electricity). Besides the minimal share of advanced
1135 fuels to be supplied to the overall transport sector, the amendment proposes to also ensure a minimal share of 2.6% of
1136 RFNBO by 2030.

1137 *11.4 EU Emission Trading System (EU ETS)*

1138 The EU ETS is one of the EU's policy instrument to mitigate climate change [411], used to implement the current
1139 40% GHG emission reduction target for 2030. It is a mandatory cap-and-trade system and covers approximately 40%
1140 of total EU GHG emissions from industrial activities, including the aviation and maritime sectors. The EU ETS aims
1141 at achieving economy-wide emission reduction targets through tradable allowances putting a price on carbon
1142 emissions.

1143 Currently, for the aviation sector, the EU ETS covers only CO₂ tailpipe emissions. The flights operated within the
1144 European Economic Area (EEA) as intra-EEA flights (arriving at and departing from EU airports) are presently
1145 accounted in the EU ETS, while flights to and from non-EEA countries are exempted until the end of 2023 [18,412].
1146 Overall, emissions allowances to airline operators covered by the EU ETS, from 2013-2020, are distributed as follows:
1147 82% are granted as free allowances allocated on the basis of airlines' efficiency in transporting passengers and cargo
1148 while 15% are auctioned, for a price reaching ca. €25 for one tonne of CO₂ at the end of 2019 [413] up to about €85
1149 in May 2021 [414]. The remaining 3% are reserved for new entrants (those starting activities after 2010) and fast-
1150 growing airlines (>18% average tonne km annual growth between 2010-2014) [415]. The cap for free allowances is
1151 annually limited to 97% of the average aviation emissions for the years 2004-2006 (approx. 210-220 million tonnes
1152 CO₂) [416,417]. It was further reduced to 95% for 2013-2020. From 2021 onwards, the cap is to be decreased by an
1153 annual linear reduction factor (LRF) of 2.2% [418,419]. For CO₂ emissions exceeding the cap, the aircraft operators
1154 have to purchase EU emission unit allowances (EUAs) at auction, or from other sectors, leading to additional costs
1155 for the airlines. CO₂ emissions are significantly dependent upon the carried weight, namely the revenue tonne
1156 kilometer (RTK) for cargo flight, the RPK for passenger-carrying flight. The EU allowances are used to fund emission-
1157 saving projects in lower-income countries, such as the development of innovative renewable energy technologies or,
1158 modernization in power sector and energy system [398,420].

1159 The revision proposed for the EU ETS in the framework of the Fit for 55 package includes the following points
1160 relevant for aviation: (i) Free allowance distribution will be phased out progressively from 2024 (by: 25%, 50%, and
1161 75%, in 2024, 2025 and 2026, respectively), for a complete phase-out from 2027 onwards [18]; (ii) Starting 2025, the
1162 application of a LRF of 4.2% (instead of 2.2%) is proposed to meet the more stringent 2030 emission target (revision
1163 proposed by the Fit for 55 package) [237,401,415]; (iii) The allowances will be capped at current level (instead of an
1164 average historical amount); (iv) Flights between the EU's outermost regions and flight to Switzerland and the United
1165 Kingdom (UK) will be included in the EU ETS; (v) International flights (involving CORSIA participating states;
1166 11.10) departing from or arriving at an airport inside the EEA (extra-EEA flight) will be also be integrated [421,422].

1167 Currently, the uptake of SAF can be an incentive for airline operators as this system counts biofuels/electrofuels (to
1168 the extent it complies with the sustainability criteria defined in the RED) as having zero emissions (no allowances
1169 required to be surrendered) [25]. However, this approach is not economically incentivized to encourage the use of
1170 SAF as their prices has remained higher than the CO₂'s price (the price of at least €160 per tonne of CO₂ emissions is
1171 required). This is required to report, of the EU ETS, based on SAF purchasing records [25].

1172 *11.5 The ReFuelEU Aviation proposal*

1173 The ReFuelEU Aviation proposal is a proposal for a regulation to boost the supply and demand for SAF in the EU, by
1174 2050. This proposal has been launched as a part of the ‘Fit for 55’ package, and was released in July 2021 after several
1175 consultation rounds and an impact assessment of the sector [25]. In the context of ReFuelEU, the term SAF specifically
1176 covers RED-compliant (section 11.3) biofuels including advanced biofuels (e.g. agricultural and forestry biomass;
1177 listed in Annex IX Part A of RED II), biofuels produced from feedstock listed in RED II Annex IX, Part B (waste oils
1178 and fats), and electrofuels (equivalent to the term synthetic fuels) [71].

1179 The key highlight of the current proposal version is an obligation for fuel suppliers to ensure that the aviation fuel
1180 made available at EU airports contains a minimum share of SAF (from 2 vol.% in 2023 to 63 vol.% in 2050), including
1181 a minimum share of electrofuels (0.7 vol.% of overall SAF in 2030 to 28 vol.% in 2050) [25]. The European Parliament
1182 has recently endorsed the ReFuel EU proposal, and proposed to raise the SAF share from 63% to 85% by 2050 with
1183 the inclusion of electricity and hydrogen in the overall (sustainable) aviation fuel mix [423].

1184 However, until 2035, fuel suppliers will be allowed to supply this minimum share of SAF to airports through the
1185 trading of SAF certificates obtained by overachievers (suppliers with an excess of SAF) [424]. To mitigate the effects
1186 of tankering (the use, prior to enter the EU, of more fuel than required for the flight in order to reduce the amount of
1187 SAF to be used, and thus save on fuel costs), ReFuelEU proposes a requirement that EU and non-EU airlines, for all
1188 flights departing from the EU, tank at least the whole required amount for their subsequent flight. The proposal also
1189 includes an obligation for EU airports to provide the infrastructure required, including hydrogen refueling, electric
1190 recharging, to reach the above-mentioned SAF supply targets. Additionally, a Sustainable Aviation Fund is proposed
1191 by the Parliament in order to facilitate the establishment of cleaner aviation, including an investment support in
1192 sustainable fuels, and in research on innovative propulsion systems [423].

1193 Non-compliance penalties according to the Commission’s criteria will be proposed by the Member State authorities
1194 and are to be communicated to the Commission by the end of 2023 [424].

1195 *11.6 The Energy Taxation Directive (ETD)*

1196 The Energy Taxation Directive is a European directive in order to support the EU’s climate and energy policy
1197 frameworks through a taxation system of energy products used as motor fuels, heating fuels, and electricity [425,426].

1198 A tax exemption for (conventional) aviation fuels granted by the ETD for intra-EEA flights to be abolished in the
1199 revision of ETD, as part of the ‘Fit for 55’ package. The revised ETD will raise the minimum tax rate for fossil
1200 kerosene for intra-EEA flights: starting at zero from 2023 onwards and to be increased gradually (annual rate of 10%)
1201 over a transition period of ten years, until the rate of €10.75 GJ⁻¹ is reached [425,426].

1202 The revised taxation for aviation fuels proposes to consider energy efficiency and environmental impacts [25].
1203 Therefore, the reduction of tax rates or exemption for SAF as well as renewable hydrogen (i.e., minimum tax rate of
1204 zero) contribute to make these fuels more economically interesting to airlines, relative to fossil jet fuels, and foster
1205 their uptake [25,427]. This strategy would work coherently with the ReFuelEU Aviation proposal to encourage the
1206 necessary investment in SAF production and their deployments. These minimum tax rates would not be applicable for
1207 pleasure flights and business flights [427].

1208 *11.7 EU climate law*

1209 In the framework of the European Green Deal, the EU launched its first proposal for a Climate Law [428]. This law
1210 makes it legally binding for the EU to achieve a balance between GHG emissions and emissions removals (so-called
1211 neutrality) by 2050. The current proposal of the Climate Law covers all GHGs. As it stands now, there are no clear
1212 measures specifically applying to the aviation sector. The updated GHG reduction target (details in section 11.2) along
1213 with the climate neutrality target by 2050 is currently in the process of being enshrined into the EU Climate Law
1214 [415,428]. For aviation, one consequence of the EU Climate Law could be the quicker deployment of DAC
1215 technologies for electrofuels and carbon-free technologies (e.g. batteries, hydrogen), on the premise that decarbonized
1216 renewable energy can be used.

1217 *11.8 The European Advanced Biofuels Flightpath Initiative (EABFI)*

1218 The EABFI was launched in 2011 as a partnership between the European Commission and major European
1219 stakeholders including airlines and biofuel producers. The objective is to promote the commercialization of biofuels
1220 in terms of production, storage and distribution in an endeavor to support the European Commission’s ambition to
1221 reach energy security [429]. Concretely, this translates in the objective of reaching 2 million tonnes of biofuel
1222 consumption per annum by 2020 through the construction of advanced biofuels production plants in Europe. The
1223 EABFI is a shared and voluntary commitment to promote the biofuel deployment through appropriate financial
1224 mechanisms [429]. However, its 2020 goal has not been met. The EABFI is working on an updated roadmap towards
1225 2030 [429,430].

1226 *11.9 The French sustainable aviation targets as an example of national initiative*

1227 France was one of the first country to announce the ambition of making its aviation industry “the cleanest in the
1228 world”.

1229 At the end of 2017, France planned to facilitate the production, distribution and deployment for aviation biofuels,
1230 corresponding to a “Commitment to Green Growth” with five industrial partnerships including Air France, Airbus,
1231 Safran, Total and Suez Environment [431]. The intention, as stated in the French “National Low Carbon Strategy” of
1232 March 2019 is the deployment of 2% and 5% biofuels of the expected gross demand of the aviation fuel in 2025 and
1233 2030, respectively [432]. Accordingly, aviation biofuels should be produced from resources listed in Annex IX of the
1234 EU RED II [71]. The HEFA from WCO, being a mature technology, is the pathway that received the most focus. By
1235 2050, it is intended that alternative liquid fuels from other advanced pathways (both aviation biofuels and electrofuels)
1236 substitute 50% of conventional kerosene [432].

1237 In addition, in early 2020, French government officials announced a 15 billion euros recovery plan for the aeronautical
1238 industry, including 1.5 billion euros aid to support research and development into cleaner aviation technologies, for
1239 instance, the improvement of engine efficiency with a 30% reduction in fuel consumption for the early 2030s, relative
1240 to the current engine, or the development of carbon-emission free aircraft whether electric or hydrogen powered by
1241 2035 [433–435]. Investments to transit towards electric and hydrogen aviation have been announced, along with
1242 investments in the advancement of biofuel/electrofuel production pathways in order to reduce GHG emissions [433].

1243 *11.10 Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*

1244 The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was launched in 2016 by ICAO
1245 in the endeavor of meeting international goals in terms of GHG mitigation. The aviation industry organizations
1246 including IATA and ATAG have set goals of CO₂ emission reductions by 50% in 2050 (relative to 2005 level). It
1247 covers all states that are ICAO members. CORSIA aims to offset the emission from international aviation that is not
1248 covered under the Paris Agreement. The aircraft operators with emissions greater than 10,000 tonnes CO₂ from the
1249 use of aircraft with a maximum certified take-off mass greater than 5,700 kg need to prepare emission monitoring
1250 plans and emission reports for all their international flights on an annual basis, from 1 January 2019.

1251 The total CO₂ emissions of each operator are required to calculate in order to demonstrate the offsetting requirements
1252 [436,437]. The aircraft operators will then be required to purchase emission units labelled as “carbon offsets” from
1253 the Aviation Carbon Exchange (ACE), in order to offset the CO₂ emissions exceeding the defined baseline [438].
1254 These carbon offsets are credits in certified projects that reduce carbon emissions.

1255 Aircraft technology development, operational improvement and deployment of biofuels can be used to achieve their
1256 CO₂ offsetting requirements. The sustainability criteria for alternative aviation fuels has been developed under
1257 CORSIA Eligible Fuels, which will support the maximum use of biofuels and long-term investment in their
1258 productions [439].

1259 ICAO’s CORSIA is being implemented since 2019. The compensation phase thus begins in 2021. This market-based
1260 measure encouraged the airlines and other aircraft operators to use SAF. CORSIA SAF are defined in CORSIA

1261 Eligible Fuels [70] (SAF in CORSIA corresponds to biofuels in this review). The objective of CORSIA is to reach
 1262 carbon neutral growth onwards in the aviation sector, in an endeavor to stabilize the net CO₂ emissions from
 1263 international aviation [70]. CORSIA is composed of three implementation phases: the pilot phase (2021-2023), a first
 1264 phase (2024-2026) and a second phase (2027-2035). Year 2019 is considered as the baseline emissions for the pilot
 1265 phase instead of the first proposed baseline of average 2019-2020 due to the pandemic's impact on the international
 1266 aviation emissions. The baseline for the first-phase is still under discussion [421,440]. During the pilot and first phases,
 1267 the offsetting requirements will be applicable for ICAO member states that have volunteered to participate in the
 1268 scheme. A total of 81 states have officially participated in the pilot phase, representing approximately 76% of
 1269 international aviation activities in terms of RTK [398]. The second phase is legally binding for all ICAO member
 1270 states, with the exception of least developed countries and, states with small share of international traffic (less than
 1271 0.5% of air traffic), unless they volunteer to participate.

1272 ICAO has launched a detailed requirement for the monitoring, reporting and verification (MRV) of emissions for the
 1273 CORSIA scheme [439]. It proposes default life cycle assessment (LCA) emission values for five (biomass-based)
 1274 certified production pathways, these being backed up by a detailed methodological study [439]. However, the
 1275 calculated default life cycle emission for what CORSIA defines as lower carbon aviation fuels (here referred as
 1276 electrofuels) and the latest certified CHJ pathway have not been announced at the time of writing.

1277 12. Challenges for Sustainable Aviation (SA) systems

1278 Some challenges for the use of the SA approaches detailed in this review, in the future low GHG emissions, are
 1279 summarized in Fig. 13 and discussed below.

1280 12.1 Availability of sustainable biomass feedstock

1281 In the perspective of a sustainable transition towards GHG neutral economies, the procurement of sustainable
 1282 feedstock not inducing additional arable land demand is a key concern when it comes to biofuels [441], including for
 1283 aviation biofuels [330,398]. In this context, residual biomasses generated increased attention as they can be decoupled
 1284 from the need for additional arable land (e.g. [119,442,443]). Residual biomasses have the potential to feed the future
 1285 low fossil carbon aviation, and several examples have been documented and even show-cased (Table 4). Numerous
 1286 aviation biofuel producers such as LanzaTech or Neste have adapted their technologies to flexibly incorporate residual
 1287 biomasses (Table S2).

1288 **Table 4** Documented examples of residual biomasses used in the production of aviation fuels

Feedstock	Residues/wastes	Conversion pathway	Comments	References
Carbohydrate	Molasses	SuF	• Co-product from sugar production, albeit already sold as an ingredient for the feed industry	[97]
	Food waste	SuF	• Organic waste from food processing industries, restaurants, and household	[99,266]
	MSW ¹	FT, IH ²	• Organic portion of household waste	[156,174]
	Anaerobic sludge (digestate)	HDCJ	• Digestate from anaerobic digesters • The digestate is used as an input for bio-crude oil production by HTL ¹ , subsequently upgraded to kerosene	[165]
	Algae biomass	HDCJ	• Grown in wastewater • For bio-crude oil production by HTL, subsequently upgraded to kerosene	[444]
	Swine manure	HDCJ	• For bio-crude oil production by fast pyrolysis, subsequently upgraded to kerosene	[159]
Lignocellulose	Forestry waste	SuF, IH ² FT	• Pretreatment requirement • Gasification and syngas conditioning requirements	[98,157,174,266]
	Wheat/rice straw	SuF DSHC	• Pretreatment requirement • Pretreatment and hydrolysis requirements	[266,445]

	Maize stover	SF, FT DSHC APR	<ul style="list-style-type: none"> • Gasification and syngas conditioning requirements • Pretreatment and hydrolysis requirements • Pretreatment and hydrolysis requirement 	[91,132,446]
	Woody chips	SF, FT DSHC APR	<ul style="list-style-type: none"> • Gasification and syngas conditioning requirements • Pretreatment and hydrolysis requirement • Pretreatment and hydrolysis requirement 	[95,132,447]
	Bagasse	SF, DSHC	<ul style="list-style-type: none"> • Gasification and syngas conditioning requirements • Pretreatment and hydrolysis requirements 	[95,130]
	Eucalyptus tips	FT	<ul style="list-style-type: none"> • Gasification and syngas conditioning requirements 	[147]
	Wood sawdust	HDCJ	<ul style="list-style-type: none"> • For bio-crude oil production by HTL, subsequently upgraded to kerosene 	[168]
	Maize stalk	HDCJ	<ul style="list-style-type: none"> • Pretreatment requirement • For bio-crude oil production by HTL, subsequently upgraded to kerosene 	[166]
	Straw stalk	HDCJ	<ul style="list-style-type: none"> • For bio-crude oil production by fast pyrolysis, subsequently upgraded to kerosene 	[448]
Oil/Fat	Waste cooking oil (WCO)	HEFA CHJ	<ul style="list-style-type: none"> • Collected from restaurants, food processing industries 	[196,449,450]
	Non-edible sunflower oil	HEFA	<ul style="list-style-type: none"> • Extracted from sunflower residual wastes 	[184]
	Tall oil pitch	HEFA	<ul style="list-style-type: none"> • Residue from the distillation of tall oil 	[248]
	Animal fats	HEFA	<ul style="list-style-type: none"> • Slaughterhouse waste 	[248]
	Palm fatty acid distillate	HEFA	<ul style="list-style-type: none"> • Co-product of palm oil production 	[248]
	Brown grease	CHJ	<ul style="list-style-type: none"> • Derived from grease trap waste 	[196]

1289 **Note.** ¹ MSW: Municipal Solid Waste; HTL: Hydrothermal liquefaction

1290 A key question remains whether the residual biomass potential is large enough to supply the demand. We estimated,
1291 on the basis of the ICAO projections [451], for 2045, a global aviation fuel demand of 16.73 EJ y⁻¹ (ca. 390 Mt
1292 kerosene y⁻¹). In comparison, it was 7.62 EJ y⁻¹ in 2019 (details in SM2). In the hypothetical case that this future
1293 demand should be fully supplied by a biofuel pathway (i.e. disregarding the ASTM D7566 standard on aromatics), we
1294 evaluated, considering the FT-SPK pathway as a technology capable to process most residual biomasses, that at least
1295 46 EJ y⁻¹ of biomass feedstock is required (assuming 0.183 kg biomass (dry matter) MJ⁻¹ FT-SPK and 15 GJ t⁻¹
1296 biomass; details in SM2). This alone represents ca. 23% of the global residual biomass potential (being at maximum
1297 ca. 200 EJ y⁻¹ based on the meta-study of [117]). Yet, the transition towards GHG neutral economies implies other
1298 demands for this limited potential. One example is the plastic sector; based on a forecasted demand of 1,124 Mt
1299 plastics for 2050 from [452], and considering a biomass:bioplastic ratio of 1.26 [453], a rough biomass demand of ca.
1300 20 EJ y⁻¹ can be derived if future plastics are to be bio-based (details in SM1). Similarly, supplying 100% bio-based
1301 maritime fuels would, considering the 2050 projected demand of 9.50 EJ y⁻¹ [332,333], also require at least 20 EJ
1302 biomass y⁻¹ (estimation based on supplying 9.50 EJ y⁻¹ with 100% bio-based LNG, itself deriving from the anaerobic
1303 digestion of straw biomass; details in SM1). This rough yet illustrative back of the envelope estimation of the
1304 productions illustrates the eventual pressure on the residual biomass potential, where only 3 demands already
1305 mobilizes ca. half of the potential.

1306 Further, while some biofuel pathways (e.g., the FT and IH²) can use most types of residual biomasses, other pathways
1307 are less flexible, such as the HEFA pathway requiring oil feedstock. At present, aviation biofuels are mainly obtained
1308 from the HEFA pathway [248]. This pathway has the advantage of having a greater energy yield in comparison to
1309 other biofuels pathways (an overall energy efficiency of ca. 75% for HEFA in comparison to 40% for FT-SPK;
1310 [44,454]). The current production capacity of HEFA is reaching ca. 100,000 tonnes SPK y⁻¹ (0.1 Mt SPK y⁻¹) (in 2019;
1311 reported by Neste) derives from dedicated oilseed crops and a variety of oil/fat residues [248]. One question is to
1312 which extent this new capacity will be based upon waste feedstock versus dedicated oilseed crops. Moreover, basing
1313 new investment strategies upon food waste poses the risk of rebound effects encouraging whether the generation of
1314 waste, or inducing unforeseen additional demand for the most competitive oil feedstock (often identified as palm oil,
1315 e.g. [443]) if no waste oil can be supplied. Globally, the potential of waste fats, oils, and greases has been estimated

1316 to ca. 1 EJ y⁻¹ [455]. The current 100,000 tonnes HEFA-SPK y⁻¹ capacity mobilizes ca. 0.02 EJ waste oil and fat. For
1317 illustration purposes, supplying the 2045 aviation demand of 16.73 EJ y⁻¹ by 100% HEFA-SPK would require 77.41
1318 EJ waste oil and fats (details in SM1). Despite being an unrealistic scenario, it illustrates that the current potential
1319 could only supply 1% of the future demand. On the other hand, competing bioeconomy sectors (e.g. bio-based
1320 polypropylene; [456]) also aspire to use these fat waste resources.

1321 *12.2 Uncertain deployment of DAC*

1322 Liquid fuel pathways (biofuels, electrofuels) have the advantage of not requiring heavy infrastructure changes in
1323 comparison to the other options discussed in this review. These imply two sources of carbon: biomass and captured-
1324 C, either from the atmosphere through DAC or from industrial point sources. While the former and the latter are
1325 limited, the potential of DAC is theoretically very large, to the extent the technology is deployed.

1326 There are currently 15 DAC plants operating worldwide, capturing more than 9,000 tonnes CO₂ y⁻¹ (0.009 Mt CO₂ y⁻¹) [30,223]. To produce 16.73 EJ (2045 demand) of electrofuels (FT pathway), approximately 1,200 Mt CO₂ captured
1327 would be needed, based on the stoichiometry described in the FT reaction (details in SM2). Keith et al. [30] provide
1328 the design and engineering costs for a plausible advanced DAC plant to be implemented at industrial scale, capturing
1329 1 Mt CO₂ y⁻¹ when operated at full capacity. Taking the plant of Keith et al. as a basis, it implies that ca. 1,200 DAC
1330 plants would need to operate to supply the carbon needed for future aviation demand by biomass-free FT electrofuels.
1331 Yet, the costs of DAC [457] are often pinpointed as a barrier for massive deployment [458,459], along with
1332 uncertainties on the markets for CO₂ to ensure a revenue offsetting the costs of capture. Keith et al. [30] report, for
1333 the 1 Mt CO₂ y⁻¹ industrial plant they describe, current levelized costs ranging from US\$ 94-232 t⁻¹ CO₂ (range
1334 reflecting different technology choices), while other studies report that levelized costs below €50 t⁻¹ CO₂ are achievable
1335 by mid-century [460,461]. For comparison, the first commercial-scale DAC plant built in 2017 (with storage of the
1336 captured carbon) costed US\$ 600 t⁻¹ CO₂, foreseen to decrease to US\$ 200 t⁻¹ CO₂ as additional plants are built [462].
1337 It is further argued that DAC costs are minor when reported to a country gross domestic product (GDP) [463], or to
1338 global GDP (an emergency massive DAC deployment would imply an investment of 1.2-1.9% global annual GDP;
1339 [464]).
1340

1341 Nevertheless, DAC technologies are improving and maturing, reflecting among others their vital role in stabilizing
1342 warming at 1.5°C above pre-industrial levels [465–467]. On-going reported improvements include new contactors
1343 and tower designs [457,468], optimized operating conditions (e.g. kinetics stability, process stability; [468]), new
1344 materials development (e.g. composites of potassium carbonate and γ -Al₂O₃; [457], amine-oxide hybrid materials;
1345 [469]), or alternative regeneration processes (e.g. electrochemistry; [470]).

1346 Assuming a favorable techno-economic environment, the potential of DAC is theoretically unlimited. Potentials up to
1347 40 Gt CO₂ y⁻¹ (40,000 Mt CO₂ y⁻¹) by the end of the century have been reported [471] for global warming mitigation,
1348 albeit the meta-study of Fuss et al. [462] suggests a potential limited to 0.5-5 Gt CO₂ y⁻¹ (500-5,000 Mt CO₂ y⁻¹). For
1349 comparison, the global annual CO₂ fossil emissions were ca. 36 Gt CO₂ (36,000 Mt CO₂) in 2019 [472].

1350 However, it must be highlighted that the driver for DAC is the perspective of inducing so-called negative emissions,
1351 i.e., a net long-term sequestration (or removal) of atmospheric CO₂. The use of the captured CO₂ for fuels, as proposed
1352 for aviation electrofuels, is therefore deriving the technology from its original purpose.

1353 *12.3 Need for sustainable hydrogen*

1354 All pathways described herein involve hydrogen, with the exception of electric (battery-based) SA, unless part of a
1355 hybridized system involving a share of hydrogen fuel or liquid biofuels or electrofuels. Hydrogen is used whether for
1356 hydrogenation of aviation biofuels (Figs. 2-10), electrofuels (Fig. 11), as well as for fossil-based kerosene production,
1357 although more H₂ is used for biofuels than fossil kerosene (3 to 75-fold more, depending on the pathway; [473]). Yet,
1358 some alternatives will require significantly more H₂, namely electrofuels and LH₂ pathways.

1359 Electrofuels, in particular, require H₂ for the reverse water gas shift reaction, where 12 moles of CO₂ are reacted with
1360 12 moles of H₂ to produce 12 moles of CO (Eq. 3 and its adjustment in SM1). This CO is then reacted with another

1361 25 moles of H₂ in order to generate for 1 mole of C₁₂H₂₆ fuel via the FT process. This involves that approximately 169
1362 Mt H₂ is required to produce 16.73 EJ (2045 demand) with this pathway (details in SM2), involving 1,520 Mt of water
1363 (equivalent to 1.52 billion m³). This clearly exceeds the current capacity of H₂ produced by water electrolysis (around
1364 2% global H₂ production), which amounts to 1.4 Mt H₂ y⁻¹ [473]. Furthermore, the amount of water needed is not
1365 negligible either, representing ca. 10% of Australia's freshwater withdrawals (ca. 15.95 billion m³ in the year 2017;
1366 [474]). This also applies for electricity, as detailed in 12.4.

1367 Albeit not discussed in this study, hydrogen can also stem from biomass-based hydrocarbons through a gasification
1368 process, a process that can also be applied to fossil resources (e.g. coal) [475]. This, however, implies an additional
1369 demand for limited biomass and land resources as discussed in 12.1. Renewable H₂ can also be produced through
1370 biogas/biomethane reformation (instead of natural gas) [63], which again implies increasing the pressure on biomass
1371 residues to produce the biogas.

1372 Hydrogen fuels (LH₂), on the other hand, are not dependent upon a carbon intermediate, and therefore require slightly
1373 less hydrogen when reported by MJ of fuel (details in SM2).

1374 *12.4 Need for sustainable electricity*

1375 Several of the emerging pathways presented in this review involve important electricity requirements, in particular for
1376 electrofuels. Electricity consumption for DAC alone may need between 0.23 and 0.37 kWh kg⁻¹ CO₂ captured (0.83
1377 and 1.33 MJ kg⁻¹ CO₂ captured) [30,31,476]. Water electrolysis, on the other hand, requires 30-80 kWh kg⁻¹ H₂ (around
1378 110-290 MJ kg⁻¹ H₂) (Table S4), depending on the technologies. To produce the 16.73 EJ demand in 2045 with current
1379 technologies for electrofuels, an estimated range of 5,900-10,000 TWh electricity (ca. 21-36 EJ) is needed (i.e. 0.55-
1380 0.74 kWh electricity MJ⁻¹ electrofuel produced; 1.81-2.66 MJ MJ⁻¹ electrofuel produced), depending on the DAC and
1381 electrolysis technology considered (detailed calculations in SM2). This illustrates, for electricity alone, that 25%-
1382 140% more energy is required compared to what is obtained from the produced electrofuel, which only makes sense
1383 in the perspective of harnessing the full potential of fluctuating decarbonized energy sources. Independently of the
1384 electrolysis-DAC technological combination selected, water electrolysis always represents ca. 90% of the
1385 consumption; the electricity consumption for DAC thus appears negligible in comparison.

1386 The 0.55-0.74 kWh MJ⁻¹ electrofuel derived herein lies in the wide range of estimates found in the literature (0.59-
1387 1.00 kWh MJ⁻¹ electrofuel; 2.12-3.60 MJ MJ⁻¹ electrofuel, details in SM2). It should also be highlighted that 5,900-
1388 10,000 TWh electricity y⁻¹ (21-36 EJ electricity y⁻¹), i.e. the electricity requirement to produce 16.73 EJ electrofuels,
1389 is not a negligible quantity. To put it into perspective, the global electricity consumption in 2019 was about 23,000
1390 TWh (ca. 82.8 EJ) [477]. In other words, the equivalent of 25%-43% of today's global electricity consumption would
1391 be required to supply the electricity needed just for producing the H₂ necessary for a demand of 16.73 EJ of electrofuels
1392 per year. Similarly, supplying 16.73 EJ of fuels with LH₂ would require only ca. 5,500-9,000 TWh electricity (20-32
1393 EJ electricity), including the liquefaction requirements for ground storage (details in SM1 and SM2). It should be
1394 highlighted that in both cases, the lower end of interval is due to the use of SOE technology, based on high-temperature
1395 water splitting rather than electricity. This technology requires, per unit of H₂ produced, ca. 40% less electricity than
1396 alkaline electrolysis, but 40% more heat (SM2).

1397 *12.5 Limits of current quantification methods for environmental impacts*

1398 To compare the different emerging technologies covered in this study, it must be ensured that the same service is
1399 supplied (the amounts of passengers and freight transported over a given distance and time). These may require
1400 different number of aircraft (e.g. smaller electric planes), type of aircraft (e.g. to accommodate onboard hydrogen
1401 storage systems [57]); infrastructure (e.g. charging), blending with fossil kerosene, etc. Current comparative studies
1402 assessing the environmental impacts of alternative fuels often only compare impacts per MJ fuel (e.g. [478-480]),
1403 which cannot be applied for SA that are not purely based upon liquid fuels. Further, the requirements for blending
1404 with fossil kerosene are typically completely ignored (e.g. [478,479,481]).

1405 Another key issue is the evaluation of the global warming potential related to the non-CO₂ emissions generated during
1406 propulsion. Pollutants such as NO_x and particulate matter (including black carbon) serve as precursors for contrail
1407 formation, an important climate forcer [68,348]. These are generally ignored in current life cycle assessment studies
1408 (e.g., [115,327,482]). Yet, Lee et al. [348] illustrated that the greatest share of cumulative radiative forcing from global
1409 aviation between 2000 and 2018 is due to these non-CO₂ effects, and in particular on the radiative forcing effect of
1410 NO_x, and to a smaller extent to the aviation induced cloudiness (including cirrus induced by condensation contrails).
1411 In the perspective of life cycle assessments, this implies two issues. First, there is a need to quantify these emissions,
1412 and second to translate these into warming effect (and eventual other environmental impacts), often through
1413 characterization factors.

1414 To date, the most robust method available for the former is to use emission factors relating to the amount of fuel use
1415 (e.g., in g of pollutant per g of fuel burnt), which can be found in the literature for all substances including contrails
1416 [348,483–485]. Yet, non-CO₂ emissions are not necessarily due to the fuel itself, and are also highly dependent upon
1417 the location where they are emitted. Emissions of NO_x, for instance, can be considered as independent from the fuel
1418 chemical composition [486], stemming from the nitrogen in the air. Similarly, aviation induced cloudiness is highly
1419 influenced by the water vapor saturation of the air where the emission takes place, and by the aerosols (e.g., sulfate,
1420 soot) emitted during combustion.

1421 Moreover, there is no consensus on the characterization factors to use to translate NO_x, induced cloudiness, water
1422 vapor, black carbon and sulfate to a warming effect. Although recent studies tend to refer to the factors proposed by
1423 Lee et al. [348], the differences in proposed factors are really large. For aircraft NO_x for example, the effect will
1424 depend not only on the emission altitude but also on the latitude as discussed by Fuglestedt et al. [483]. A GWP₁₀₀
1425 between -2.1 to 71 can be obtained following the modeling approach. Köhler et al. [487] proposed a GWP₁₀₀ of 75 at
1426 the global scale with important variations according to the region of emission. Other methods have also been proposed
1427 to translate these non-CO₂ substances into a warming effect, such as the global temperature change potential (GTP),
1428 a measure of the temperature change (rather than heat absorbed) over a given time period due to the emission of a gas,
1429 in comparison to CO₂ [483,488,489]. Step-change emission approaches (e.g., GWP*, Combined GTP; CGTP) [340]
1430 which are applied to a change in emission rate rather than a change in emission amount (as for GWP and GTP) [490],
1431 should also be highlighted as existing alternative approaches.

1432 Accounting for non-CO₂ climate forcers will impact the hydrogen-based SA approaches. The hydrogen used in H₂
1433 internal combustion engines or fuel cells, can generate approximately 2.6 times more water emissions relative to
1434 conventional kerosene [58,491]. Lee et al. [348] proposed a GWP₁₀₀ of 0.06 for water vapor. Despite useful, this may
1435 however not entirely reflect the exact effect that massively deploying hydrogen aviation would have on the radiative
1436 equilibrium of water vapor in the low stratosphere [492].

1437 Finally, reductions of soot and particulate matter (PM) have been reported for alternative liquid fuels, in particular
1438 biofuels (e.g., HEFA-SPK, FT-SPK) [39,40,486]. This reduction could be explained by the low levels of aromatic
1439 content in biofuels [40,486,493]. Some studies, however, consider these differences as negligible (e.g., [327]), while
1440 others shed light on the high level of uncertainty still existing regarding these measurements in test rig [486,494]. It
1441 thus remains unclear whether biofuels (and electrofuels) really induce a reduction in particulate matters, and the
1442 magnitude such reduction could have.

1443 *12.6 Other impacts*

1444 Noise is another impact of aviation especially for residential developments around airports. Novel propulsion systems
1445 including battery-electric and hydrogen aviation are foreseen to mitigate and minimize noise impact [58,495,496],
1446 facilitating their use in densely populated areas [330,496]. The electric propulsion system, magniX eBeaver aircraft,
1447 for instance, has been reported to reduce the average noise level by about 22% (~66 dBA) relative to standard Beaver
1448 with piston engines (~85 dBA) [497].

1449 Electric (battery) and H₂ aviation will induce the need for additional infrastructure, among other to charge batteries or
1450 store hydrogen. The recharging time, which is mainly dependent upon the charging point (e.g. power outlet capacity)
1451 and the battery capacity, is one key challenge of electric aviation to meet desired flight turnaround times.

1452 Similarly, hydrogen refueling stations should be developed with important flow rates to maintain flight turnaround
1453 times and prevent hydrogen boil-off issues [58,63]. According to [387], onsite hydrogen production (through water
1454 electrolysis) may be possible in a foreseeable future to produce the needed hydrogen on-demand. Cryogenic storage
1455 (whether on ground or onboard), which implies the storage of liquefied hydrogen below -253°C (20K) in a double-
1456 walled vessel with vacuum insulation [57], implies the need for reliable components including valves, and pumps
1457 allowing to ensure these cryogenic conditions as well as safety requirements [498].

1458 **13. Prospects for Sustainable Aviation (SA) systems**

1459 Despite the potential of the four large SA approaches described herein, there are a number of issues to be addressed
1460 prior to broad adoption. This section provides the prospects of their applications for sustainable aviation in the
1461 upcoming future. Other sustainable routes are also discussed.

1462 *13.1 Future aspects for unblended biofuels/electrofuels*

1463 All pathways documented in this study require blending with fossil carbon with exception of hydrogen aviation and
1464 100% electric concepts (either 100% battery as shown in Fig. 17a, or hybrid LH₂ or fuel cell with battery, as in Figs.
1465 17b to 17d). The prospects for alternative hydrocarbon-based fuels (biofuels/electrofuels) is summarized herein.

1466 One of the key limiting factors of liquid fuels free of fossil carbon is their low fuel density (below ASTM's minimum
1467 specific requirement of 775 kg m⁻³ [499]) and their low (<8%) aromatics content [44,500], which shrinks engine seals.
1468 The latter effect is notably observed with the commonly used nitrile rubber material [499,501]. To overcome this, a
1469 certain research focus has been placed on the development of new sealing materials preventing leakages [499,502].

1470 The use of 100% alternative liquid fuels is also being investigated through the possibility of combining SAK with
1471 HEFA-SPK [503]. SAK is produced through the APR pathway (Fig. 2) by converting oxygenated compounds to
1472 aromatics in the presence of heterogeneous catalysts such as the aluminosilicate zeolite ZSM-5 [504], a pathway
1473 currently under the ASTM approval process [26].

1474 Besides aromatics, cycloparaffins (e.g. cyclohexane, cyclooctane), at a concentration above 30 vol.%, have been
1475 shown to supply suitable volume swelling properties [505,506]. They provide increased fuel density, similar to the
1476 function of aromatics. Furthermore, they have high gravimetric heat of combustion with the respect to aromatics,
1477 resulting in reduction of particulate matter emissions from fuels containing aromatics [21,506]. These compounds,
1478 that could be blended in the fuel, have been produced through multiple pathways and from numerous renewable
1479 feedstock, for instance through hydrodeoxygenation of lignocellulosic biomass [507,508]. This approach can be
1480 introduced as near-term solution for current aircraft, before new engines capable of handling unblended SPK are
1481 widely available.

1482 Another investigated solution is, as earlier reported, the development of alternative fuels identical to conventional
1483 kerosene (synthetic kerosene; SK) that could be used without blending. This includes the recently certified CHJ-SK
1484 (in February 2020; Fig. 10), as well as some biofuels currently under certification (e.g. ATJ-SK from the SuF pathway,
1485 HEFA⁺) [26,38]. It is important to note that there is currently no guideline for blending more than one alternative fuel
1486 with conventional kerosene (or several alternative fuels without conventional kerosene) within the same hydrant
1487 system [509].

1488 Finally, new engine generations capable of using low aromatic fuels may be another solution. For example, the
1489 D328neo aircraft manufactured by Deutsche Aircraft Inc. has been publicized in September 2021, to be compatible
1490 with unblended alternative fuels by the use of new sealants, surface protection measures, and materials. It is a sub 50
1491 seater regional commuter expected to start its test flight in 2024 and to enter into service by the end of 2025 [48,510].

1492 *13.2 Electric propulsion development*

1493 Motors and generators are key elements for parallel hybrid electric and turboelectric configurations [388] (Fig. 17),
1494 with additional converters in the case of electric configurations, whether from battery or fuel cell. Further research for
1495 the high power-to-weight ratio of electric components is essential to be able to fit with the aircraft weight and volume
1496 constraints [390]. A thermal management system, in particular the removal of the generated waste heat, is another key
1497 challenge for further research [388]. Alongside, certification standards must be developed to assure the safety and use
1498 of batteries (or fuel cells).

1499 High power density fuel cells need to be developed to attain the power requested in propulsion system, and to improve
1500 the weight and volume constraints in commercial aircraft. Current power density of fuel cells is ca. 0.75 kW kg^{-1} ,
1501 whereas 2 kW kg^{-1} would be required for commercial aircraft [57,63,387].

1502 Another key development is the optimization of the aircraft configuration, in order to optimally integrate the electrical
1503 propulsion system and batteries into the aircraft [277], which in turn is dependent on the electric propulsion
1504 configuration (Fig. 17). This is also studied in combination with alternative design approaches to improve the overall
1505 propulsion efficiency (e.g. boundary layer ingestion, wingtip propulsors, BWB aircraft) [511].

1506 *13.3 Further improvement of hydrogen aviation*

1507 Albeit hydrogen can be used as standalone fuel, the integration of either fuel cells or hydrogen combustion engines
1508 (whether gas turbines or piston engines) in airplanes remains an engineering challenge. Among others, novel airframes
1509 such as the BWB design may present the advantage of having extra volume to accommodate onboard LH_2 storage
1510 systems [58,63,313]. In addition to engine developments, airframe designs are required for accommodating cryogenic
1511 hydrogen storage, which is beyond the current aircraft capacities. Hydrogen tanks can be placed either inside or outside
1512 the fuselage (referred to as integral or non-integral, respectively) [58,512]. Drag penalty can be reduced with the
1513 integral method [58] (hydrogen storage inside the fuselage), which may have an impact on overhead luggage storage
1514 for short-to-medium ranged airplanes [498]. Placed outside the fuselage, the passenger-carrying capacity remains
1515 unchanged, however, the drag is likely to be increased.

1516 Development in new materials (e.g. polymer matrix composites; [513]) for hydrogen tanks is needed in order to make
1517 these as light as possible. With the newly developed materials, the gravimetric energy density is expected to reach 10-
1518 21 kWh kg^{-1} (around $36\text{-}76 \text{ MJ kg}^{-1}$) of empty storage system [62,63]. If these values are achieved, the system becomes
1519 highly competitive with conventional storage systems (ca. 8.9 kWh kg^{-1} ; equivalent to ca. 32 MJ kg^{-1}) [514].
1520 Additionally, developments to improve the insulation system for cryogenic LH_2 allowing to minimize boil-off losses
1521 (e.g. vaporization) has been demonstrated [512].

1522 As for electric (battery) aviation, developments are needed to optimize the integration of propulsion system and
1523 hydrogen storage system, as well as for certifications and regulations ensuring safety through the overall supply chain.

1524 The optimal hybridization between fuel cells and hydrogen combustion engines at the different phases of the flight
1525 (i.e. takeoff and climb phase powered by hydrogen turbines; cruise powered by fuel cells) is also being investigated
1526 in order to reduce fuel consumption and NO_x emissions [63].

1527 Similarly, improvements are being performed on hydrogen internal combustion system to reduce NO_x emission. For
1528 instance, technological and environmental improvements have been obtained with a micro-mix combustor [63,396]
1529 or lean direct injection [515].

1530 *13.4 Other innovations towards sustainable aviation*

1531 One notable innovation is the recent AHEAD project, proposing a Multi-Fuel Blended Wing Body (MFBWB) aircraft
1532 with hybrid turbofan engines, capable of using both a cryogenic fuel (LH_2 and LNG are specifically mentioned), and
1533 a liquid fuel such as biofuel or conventional kerosene. While the BWB is expected to overcome the mass issues related
1534 to the cryogenic system, the multi-fuels approach is proposed in order to significantly reduce the overall emissions
1535 from engines [342]. A reduction of 50% CO_2 emission (in LNG/conventional kerosene mode) was shown compared

1536 to a traditional Boeing 777-200 LR model using fossil kerosene [313,342]. Emissions of NO_x, soot, and CO were also
1537 mitigated by ca. 80% relative to the baseline B777-200 ER aircraft [342].

1538 The Taxibot is another example of innovation to reduce the environmental impacts of the aviation sector. It is a pilot-
1539 controlled towing vehicle applied for assisting taxiing-aircraft between the terminals and the runway and vice versa
1540 while the aircraft's engines are switched off [516,517]. It is an emerging pushback approach to minimize aircraft fuel
1541 consumption (by 50 to 85% reduction) and noise (by 60% reduction) while taxiing [58,516]. Approximately 20 million
1542 tonnes of CO₂ emission of the world's airliners are estimated to be reduced during the taxi phase of flights if the
1543 TaxiBot is adopted [516]. The Taxibot is in operation at Schiphol [518], Delhi and Bangalore airports [519], and
1544 serves Lufthansa [517]. Currently, it is powered whether by electric or diesel engines [518], but the vision is to power
1545 them with 100% batteries or hydrogen in the future [21,520].

1546

1547 **Declaration of competing interest**

1548 The authors declare that they have no known competing financial interests or personal relationships that could have
1549 appeared to influence the work reported in this paper.

1550 **Acknowledgments**

1551 This work was carried out within the framework of the research project Cambioscop (<https://cambioscop.cnrs.fr>),
1552 partly financed by the French National Research Agency, Programme Investissement d’Avenir (ANR-17-MGPA-0006)
1553 and Region Occitanie (18015981). Pimchanok Su-ungkavatin was additionally funded by the French Ministry for
1554 Europe and Foreign Affairs (Doctoral grant).

1555 **Author contributions**

1556 **Pimchanok Su-ungkavatin:** Conceptualization, Visualization, Data curation, Formal analysis, Investigation,
1557 Methodology, Original draft preparation, Review & editing. **Ligia Tiruta-Barna:** Supervision, Writing – review &
1558 editing. **Lorie Hamelin:** Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Writing –
1559 Review & editing.

1560 **References**

- 1561 [1] Graver B, Rutherford D, Zheng S. CO2 emissions from commercial aviation 2013, 2018 and 2019 2020.
1562 <https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf>.
- 1563 [2] Friedlingstein P, O’Sullivan M, Jones MW, Andrew RM, Hauck J, Olsen A, et al. Global Carbon Budget
1564 2020. *Earth Syst Sci Data* 2020;12:3269–340. <https://doi.org/10.5194/essd-12-3269-2020>.
- 1565 [3] Air Transport Action Group (ATAG). Beginner’s Guide to Sustainable Aviation Fuel 2017.
1566 https://aviationbenefits.org/media/166152/beginners-guide-to-saf_web.pdf.
- 1567 [4] Lane J. Aviation biofuels: which airlines are doing what, with whom? : *Biofuels Digest*. *Biofuel Digest*
1568 2012. [https://www.biofuelsdigest.com/bdigest/2012/06/05/aviation-biofuels-which-airlines-are-doing-what-](https://www.biofuelsdigest.com/bdigest/2012/06/05/aviation-biofuels-which-airlines-are-doing-what-with-whom/)
1569 [with-whom/](https://www.biofuelsdigest.com/bdigest/2012/06/05/aviation-biofuels-which-airlines-are-doing-what-with-whom/) (accessed November 22, 2021).
- 1570 [5] Loh C. Which US Airlines Are Using Sustainable Aviation Fuel? - Simple Flying. *Simple Flying* 2020.
1571 <https://simpleflying.com/us-airlines-sustainable-aviation-fuel/> (accessed November 10, 2021).
- 1572 [6] Grewe V, Gangoli Rao A, Grönstedt T, Xisto C, Linke F, Melkert J, et al. Evaluating the climate impact of
1573 aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nat Commun*
1574 2021;12:3841. <https://doi.org/10.1038/s41467-021-24091-y>.
- 1575 [7] Klöwer M, Allen MR, Lee DS, Proud SR, Gallagher L, Skowron A. Quantifying aviation’s contribution to
1576 global warming. *Environ Res Lett* 2021;16:104027. <https://doi.org/10.1088/1748-9326/ac286e>.
- 1577 [8] ATAG. Fact sheet #4: Aviation 2050 goal and the Paris Agreement. ATAG 2019.
1578 https://aviationbenefits.org/media/166838/fact-sheet_4_aviation-2050-and-paris-agreement.pdf.
- 1579 [9] Airbus. Global Market Forecast: Cities, Airports and Aircraft 2019-2038 2019.
1580 [https://www.airbus.com/sites/g/files/jlcbta136/files/2021-07/GMF-2019-2038-Airbus-Commercial-Aircraft-](https://www.airbus.com/sites/g/files/jlcbta136/files/2021-07/GMF-2019-2038-Airbus-Commercial-Aircraft-book.pdf)
1581 [book.pdf](https://www.airbus.com/sites/g/files/jlcbta136/files/2021-07/GMF-2019-2038-Airbus-Commercial-Aircraft-book.pdf).
- 1582 [10] Eurocontrol. The aviation network - Decarbonisation issues. Eurocontrol Supporting European Aviation
1583 2019. <https://www.eurocontrol.int/publication/aviation-network-decarbonisation-issues> (accessed September
1584 20, 2022).
- 1585 [11] Gössling S, Humpe A. The global scale, distribution and growth of aviation: Implications for climate
1586 change. *Global Environmental Change* 2020;65. <https://doi.org/10.1016/j.gloenvcha.2020.102194>.
- 1587 [12] EASA. Decision no. 2003/2/RM of the executive director of the agency of 17 October 2003 on certification
1588 specifications, including airworthiness codes and acceptable means of compliance, for large aeroplanes (CS-
1589 25). European Aviation Safety Agency (EASA) 2003.
1590 https://www.easa.europa.eu/sites/default/files/dfu/decision_ED_2003_02_RM.pdf.
- 1591 [13] Susan H. ICAO Glossary. ICAO 2013.
1592 https://www.icao.int/dataplus_archive/Documents/20130807/GLOSSARY%20v1%202.pdf.
- 1593 [14] Chiamonti D. Sustainable aviation fuels: The challenge of decarbonization. *Energy Procedia*, vol. 158,
1594 2019, p. 1202–7. <https://doi.org/10.1016/j.egypro.2019.01.308>.
- 1595 [15] ICAO. The challenges for the development and deployment of sustainable alternative fuels in aviation:
1596 Outcomes of ICAO’s sustaf experts group 2013. <https://www.icao.int/environmental->

- 1597 protection/GFAAF/Documents/ICAO%20SUSTAF%20experts%20group%20outcomes_release%20May20
1598 13.pdf.
- 1599 [16] IATA. Fact Sheet 2 - Sustainable Aviation Fuel: Technical Certification. IATA 2020.
1600 <https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf>.
- 1601 [17] IATA. IATA Guidance Material for Sustainable Aviation Fuel Management. IATA 2015.
1602 <https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/iata20guidance20material20for20s>
1603 af.pdf.
- 1604 [18] Eurocontrol: Supporting European Aviation. The EU's "Fit for 55" Package: what does it mean for aviation?
1605 2021. <https://www.eurocontrol.int/article/eus-fit-55-package-what-does-it-mean-aviation> (accessed January
1606 6, 2022).
- 1607 [19] Drünert S, Neuling U, Zitscher T, Kaltschmitt M. Power-to-Liquid fuels for aviation – Processes, resources
1608 and supply potential under German conditions. *Applied Energy* 2020;277.
1609 <https://doi.org/10.1016/j.apenergy.2020.115578>.
- 1610 [20] Terwel R, Kerkhoven J. Carbon neutral aviation with current engine technology: The take-off of synthetic
1611 kerosene production in the Netherlands: The story and the report 2018. [https://s3-eu-west-
1612 1.amazonaws.com/static.quintel.com/publications/Carbon_Neutral_Aviation.pdf](https://s3-eu-west-1.amazonaws.com/static.quintel.com/publications/Carbon_Neutral_Aviation.pdf).
- 1613 [21] Chevron Product Company. Aviation Fuels Technical Review | Chevron Products Company 2007.
1614 <https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf> (accessed
1615 September 20, 2022).
- 1616 [22] American Petroleum Institute. Robust summary of information: substance group kerosene/jet fuel 2010.
1617 [https://www.petroleumhpv.org/-
1618 /media/PetroleumHPV/Documents/2010_sept21_Kerosene_Jet%20fuel%20robust%20summaries%20final.p
1619 df?la=en&hash=43AF43DE15BF9C62C4C436FEB1095B7D49A94356](https://www.petroleumhpv.org/-/media/PetroleumHPV/Documents/2010_sept21_Kerosene_Jet%20fuel%20robust%20summaries%20final.pdf?la=en&hash=43AF43DE15BF9C62C4C436FEB1095B7D49A94356).
- 1620 [23] IRENA. Biofuels for aviation: Technology brief. IRENA 2017. [https://www.irena.org/-
1621 /media/Files/IRENA/Agency/Publication/2017/IRENA_Biofuels_for_Aviation_2017.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/IRENA_Biofuels_for_Aviation_2017.pdf).
- 1622 [24] Ministry of Defence. Defence Standard 91-091 Turbine Fuel , Kerosene Type , Jet A- 1 ; NATO Code : F-
1623 35 ; Joint Service Designation : AVTUR. Ministry of Defence 2019. [http://inaca.or.id/wp-
1624 content/uploads/2019/11/Def-Stan-91-091-Issue-11-Oct-2019-Turbine-Fuel-Kerosene-Type-Jet-A-1-NATO-
1625 CodeF-35-Joint-Service-Designation-AVTUR.pdf](http://inaca.or.id/wp-content/uploads/2019/11/Def-Stan-91-091-Issue-11-Oct-2019-Turbine-Fuel-Kerosene-Type-Jet-A-1-NATO-CodeF-35-Joint-Service-Designation-AVTUR.pdf).
- 1626 [25] European Commission. Proposal for a regulation of the European Parliament and of the Council on ensuring
1627 a level playing field for sustainable air transport 2021. [https://eur-lex.europa.eu/legal-
1628 content/EN/ALL/?uri=CELEX:52021PC0561](https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561).
- 1629 [26] Humphris-Bach A, Groves L, Sikova I, Sharp J. Targeted aviation advanced biofuels demonstration
1630 competition - feasibility study: Final report 2020. [https://www.e4tech.com/uploads/files/final-report-
1631 aviation-abdc-feasibility-study-issue-v1-0.pdf](https://www.e4tech.com/uploads/files/final-report-aviation-abdc-feasibility-study-issue-v1-0.pdf).
- 1632 [27] Buttler A, Spliethoff H. Current status of water electrolysis for energy storage, grid balancing and sector
1633 coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*
1634 2018;82:2440–54. <https://doi.org/10.1016/j.rser.2017.09.003>.
- 1635 [28] Furler P, Marxer D, Scheffe J, Reinalda D, Geerlings H, Falter C, et al. Solar kerosene from H2O and CO2.
1636 *AIP Conference Proceedings* 2017;1850. <https://doi.org/10.1063/1.4984463>.
- 1637 [29] Ghiasian M. Biophotolysis-Based Hydrogen Production by Cyanobacteria. Springer International
1638 Publishing; 2019. https://doi.org/10.1007/978-3-030-14463-0_5.
- 1639 [30] Keith DW, Holmes G, St. Angelo D, Heidel K. A Process for Capturing CO2 from the Atmosphere. *Joule*
1640 2018;1–22. <https://doi.org/10.1016/j.joule.2018.05.006>.
- 1641 [31] Realmonte G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle AC, et al. An inter-model assessment of
1642 the role of direct air capture in deep mitigation pathways. *Nature Communications* 2019;10:1–12.
1643 <https://doi.org/10.1038/s41467-019-10842-5>.
- 1644 [32] Sunfire. Breakthrough for power-to-x: Sunfire puts first co-electrolysis into operation and starts scaling.
1645 Sunfire GmbH Press Release 2019. [https://www.sunfire.de/de/unternehmen/news/detail/durchbruch-fuer-
1646 power-to-x-sunfire-nimmt-erste-co-elektrolyse-in-betrieb-und-startet-die-skalierung](https://www.sunfire.de/de/unternehmen/news/detail/durchbruch-fuer-power-to-x-sunfire-nimmt-erste-co-elektrolyse-in-betrieb-und-startet-die-skalierung).
- 1647 [33] Padurean A, Cosmos CC, Agachi PS. Pre-combustion carbon dioxide capture by gas-liquid absorption for
1648 Integrated Gasification Combined Cycle power plants. *International Journal of Greenhouse Gas Control*
1649 2012;7:1–11. <https://doi.org/10.1016/j.ijggc.2011.12.007>.
- 1650 [34] Hornberger M, Spörl R, Scheffknecht G. Calcium Looping for CO2 Capture in Cement Plants - Pilot Scale
1651 Test. *Energy Procedia* 2017;114:6171–4. <https://doi.org/10.1016/j.egypro.2017.03.1754>.

- 1652 [35] Stec M, Tatarczuk A, Więclaw-Solny L, Krótki A, Ćiazko M, Tokarski S. Pilot plant results for advanced
1653 CO₂ capture process using amine scrubbing at the Jaworzno II Power Plant in Poland. *Fuel* 2015;151:50–6.
1654 <https://doi.org/10.1016/j.fuel.2015.01.014>.
- 1655 [36] Andika R, Nandiyanto ABD, Putra ZA, Bilad MR, Kim Y, Yun CM, et al. Co-electrolysis for power-to-
1656 methanol applications. *Renewable and Sustainable Energy Reviews* 2018;95:227–41.
1657 <https://doi.org/10.1016/j.rser.2018.07.030>.
- 1658 [37] Schmidt P, Weindorf W. Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable
1659 Aviation Fuel 2016.
1660 https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierefrei.pdf.
- 1661 [38] Zschocke A, Scheuermann S. High Biofuel Blends in Aviation (HBBA) ENER/C2/2012/ 420-1 Interim
1662 Report 2012. https://ec.europa.eu/energy/sites/ener/files/documents/final_report_for_publication.pdf.
- 1663 [39] Chan TW, Chishty W, Davison C, Buote D. Characterization of the Ultrafine and Black Carbon Emissions
1664 from Different Aviation Alternative Fuels. *SAE International Journal of Fuels and Lubricants* 2015;8:515–
1665 26. <https://doi.org/10.4271/2015-01-2562>.
- 1666 [40] Lobo P, Rye L, Williams PI, Christie S, Uryga-Bugajska I, Wilson CW, et al. Impact of Alternative Fuels on
1667 Emissions Characteristics of a Gas Turbine Engine – Part 1: Gaseous and Particulate Matter Emissions.
1668 *Environ Sci Technol* 2012;46:10805–11. <https://doi.org/10.1021/es301898u>.
- 1669 [41] Chan TW, Chishty WA, Canteenwalla P, Buote D, Davison CR. Characterization of Emissions from the Use
1670 of Alternative Aviation Fuels. *Journal of Engineering for Gas Turbines and Power* 2016;138:1–9.
1671 <https://doi.org/10.1115/1.4031226>.
- 1672 [42] Khandelwal B, Roy S, Lord C, Blakey S. Comparison of vibrations and emissions of conventional jet fuel
1673 with stressed 100% SPK and Fully Formulated Synthetic Jet Fuel. *Aerospace* 2014;1:52–66.
1674 <https://doi.org/10.3390/aerospace1020052>.
- 1675 [43] Baena-Zambrana S, Repetto SL, Lawson CP, Lam JK-W. Behaviour of water in jet fuel - A literature
1676 review. *Progress in Aerospace Sciences* 2013;60:35–44. <https://doi.org/10.1016/j.paerosci.2012.12.001>.
- 1677 [44] Wei H, Liu W, Chen X, Yang Q, Li J, Chen H. Renewable bio-jet fuel production for aviation: A review.
1678 *Fuel* 2019;254. <https://doi.org/10.1016/j.fuel.2019.06.007>.
- 1679 [45] Airbus. This A319neo is the latest to test 100% SAF 2021.
1680 <https://www.airbus.com/en/newsroom/stories/2021-10-this-a319neo-is-the-latest-to-test-100-saf> (accessed
1681 January 6, 2022).
- 1682 [46] Boeing. Boeing Commits to Deliver Commercial Airplanes Ready to Fly on 100% Sustainable Fuels.
1683 Boeing - Media Room 2021. <https://boeing.mediaroom.com/2021-01-22-Boeing-Commits-to-Deliver-Commercial-Airplanes-Ready-to-Fly-on-100-Sustainable-Fuels> (accessed September 19, 2022).
- 1684 [47] Rolls-Royce. Rolls-Royce to test 100% Sustainable Aviation Fuel in next generation engine demonstrator.
1685 Rolls-Royce 2020. <https://www.rolls-royce.com/media/press-releases/2020/12-11-2020-rr-to-test-100-percent-sustainable-aviation-fuel-in-next-generation-engine-demonstrator.aspx> (accessed September 20,
1686 2022).
- 1687 [48] Deutsche Aircraft. Deutsche Aircraft. Deutsche Aircraft 2022. <https://deutscheaircraft.com/> (accessed
1688 September 20, 2022).
- 1689 [49] The Faraday Institute. Faraday Report: High-energy battery technologies. The Faraday Institute 2020.
1690 <https://faraday.ac.uk/wp-content/uploads/2020/01/High-Energy-battery-technologies-FINAL.pdf>.
- 1691 [50] Cerdas F, Titscher P, Bognar N, Schmuch R, Winter M, Kwade A, et al. Exploring the effect of increased
1692 energy density on the environmental impacts of traction batteries: A comparison of energy optimized
1693 lithium-ion and lithium-sulfur batteries for mobility applications. *Energies* 2018;11:1–20.
1694 <https://doi.org/10.3390/en11010150>.
- 1695 [51] Rossi N. Conceptual Design of Hybrid-Electric Aircraft. Polytechnic University of Milan (Politecnico di
1696 Milano) 2017. https://www.politesi.polimi.it/bitstream/10589/139491/3/2018_04_Rossi.pdf.
- 1697 [52] Eviation. Aircraft – Eviation. Eviation - Alice 2022. <https://www.eviation.co/aircraft/> (accessed September
1698 20, 2022).
- 1699 [53] ByeAerospace. eFlyer - Bye Aerospace. ByeAerospace 2019. <https://bye aerospace.com/eflyer/> (accessed
1700 September 20, 2022).
- 1701 [54] Pipistrel Aircraft. Velis Electro EASA TC – Pipistrel Aircraft: The first and still the only type-certified
1702 electric aircraft in the world n.d. <https://www.pipistrel-aircraft.com/aircraft/electric-flight/velis-electro-easa-tc/>
1703 (accessed February 14, 2022).
- 1704
1705
1706

- 1707 [55] FutureFlight. Heart Aerospace ES-19 specification. FutureFlight 2021.
1708 <https://www.futureflight.aero/aircraft-program/heart-electric-airliner> (accessed May 27, 2022).
- 1709 [56] Ribeiro J, Afonso F, Ribeiro I, Ferreira B, Policarpo H, Peças P, et al. Environmental assessment of hybrid-
1710 electric propulsion in conceptual aircraft design. *Journal of Cleaner Production* 2020;247.
1711 <https://doi.org/10.1016/j.jclepro.2019.119477>.
- 1712 [57] Baroutaji A, Wilberforce T, Ramadan M, Olabi AG. Comprehensive investigation on hydrogen and fuel cell
1713 technology in the aviation and aerospace sectors. *Renewable and Sustainable Energy Reviews* 2019;106:31–
1714 40. <https://doi.org/10.1016/j.rser.2019.02.022>.
- 1715 [58] Bruce S, Temminghoff M, Hayward J, Palfreyman D, Munnings C, Burke N. Opportunities for Hydrogen in
1716 Commercial Aviation. CSIRO 2020. [https://www.csiro.au/-/media/Do-Business/Files/Futures/Boeing-
1717 Opportunities-for-hydrogen-in-commercial-aviation.pdf](https://www.csiro.au/-/media/Do-Business/Files/Futures/Boeing-Opportunities-for-hydrogen-in-commercial-aviation.pdf).
- 1718 [59] Ozbilen A, Dincer I, Rosen MA. A comparative life cycle analysis of hydrogen production via
1719 thermochemical water splitting using a Cu-Cl cycle. *International Journal of Hydrogen Energy*
1720 2011;36:11321–7. <https://doi.org/10.1016/j.ijhydene.2010.12.035>.
- 1721 [60] Mehmeti A, Angelis-Dimakis A, Arampatzis G, McPhail S, Ulgiati S. Life Cycle Assessment and Water
1722 Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. *Environments*
1723 2018;5:24. <https://doi.org/10.3390/environments5020024>.
- 1724 [61] Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange
1725 membrane water electrolysis in future energy systems. *Applied Energy* 2019;237:862–72.
1726 <https://doi.org/10.1016/j.apenergy.2019.01.001>.
- 1727 [62] Thomson R. A future fuel for aviation? 2020.
1728 <https://www.rolandberger.com/en/Insights/Publications/Hydrogen-A-future-fuel-for-aviation.html> (accessed
1729 September 20, 2022).
- 1730 [63] Fuel Cells and Hydrogen 2 Joint Undertaking. Hydrogen-powered aviation: a fact-based study of hydrogen
1731 technology, economics, and climate impact by 2050. Publications Office 2020.
1732 <https://data.europa.eu/doi/10.2843/471510>.
- 1733 [64] Pohl HW, Malychev VV. Hydrogen in future civil aviation. *International Journal of Hydrogen Energy*
1734 1997;22:1061–9. [https://doi.org/10.1016/s0360-3199\(95\)00140-9](https://doi.org/10.1016/s0360-3199(95)00140-9).
- 1735 [65] ICAO. Assembly — 40Th Session: Envisioning a “zero climate impact” international aviation pathway
1736 toward 2050: How governments and the aviation industry can step-up amidst the climate emergency for a
1737 sustainable aviation future. ICAO 2019. https://www.icao.int/Meetings/a40/Documents/WP/wp_561_en.pdf.
- 1738 [66] Yip HL, Srna A, Yuen ACY, Kook S, Taylor RA, Yeoh GH, et al. A Review of Hydrogen Direct Injection
1739 for Internal Combustion Engines: Towards Carbon-Free Combustion. *Applied Sciences* 2019;9:4842.
1740 <https://doi.org/10.3390/app9224842>.
- 1741 [67] Sefain MJ. Hydrogen aircraft concepts & Group support. Cranfield University 2005.
1742 <https://dspace.lib.cranfield.ac.uk/handle/1826/2998>.
- 1743 [68] Boucher O, Office M, Centre H. Aviation science and research needs 2009.
1744 https://theicct.org/sites/default/files/Boucher_2009-1.pdf.
- 1745 [69] Fichter C, Marquart S, Sausen R, Lee DS. The impact of cruise altitude on contrails and related radiative
1746 forcing. *Meteorologische Zeitschrift* 2005;14:563–72. <https://doi.org/10.1127/0941-2948/2005/0048>.
- 1747 [70] ICAO. ICAO document CORSIA Methodology for Calculating Actual Life Cycle Emissions Values 2022.
1748 [https://www.icao.int/environmental-
1749 protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-
1750 %20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf](https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf) (accessed
1751 July 5, 2022).
- 1752 [71] European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council on the
1753 promotion of the use of energy from renewable sources. European Commission 2018. [https://eur-
1754 lex.europa.eu/eli/dir/2018/2001/oj](https://eur-lex.europa.eu/eli/dir/2018/2001/oj).
- 1755 [72] Sala S, Amadei AM, Beylot A, Ardente F. The evolution of life cycle assessment in European policies over
1756 three decades. *Int J Life Cycle Assess* 2021;26:2295–314. <https://doi.org/10.1007/s11367-021-01893-2>.
- 1757 [73] Chen RX, Wang WC. The production of renewable aviation fuel from waste cooking oil. Part I: Bio-alkane
1758 conversion through hydro-processing of oil. *Renewable Energy* 2019;135:819–35.
1759 <https://doi.org/10.1016/j.renene.2018.12.048>.
- 1760 [74] Xing R, Subrahmanyam A V., Olcay H, Qi W, Van Walsum GP, Pendse H, et al. Production of jet and
1761 diesel fuel range alkanes from waste hemicellulose-derived aqueous solutions. *Green Chemistry*
1762 2010;12:1933–46. <https://doi.org/10.1039/c0gc00263a>.

- 1763 [75] Wang WC, Tao L. Bio-jet fuel conversion technologies. *Renewable and Sustainable Energy Reviews* 2016;53:801–22. <https://doi.org/10.1016/j.rser.2015.09.016>.
- 1764
- 1765 [76] Hari TK, Yaakob Z, Binitha NN. Aviation biofuel from renewable resources: routes, opportunities and challenges. *Renewable and Sustainable Energy Reviews* 2015;42:1234–44. <https://doi.org/10.1016/j.rser.2014.10.095>.
- 1766
- 1767
- 1768 [77] Goldmann A, Sauter W, Oettinger M, Kluge T, Schröder U, Seume JR, et al. A study on electrofuels in aviation. *Energies* 2018;11:1–23. <https://doi.org/10.3390/en11020392>.
- 1769
- 1770 [78] Brynolf S, Taljegard M, Grahn M, Hansson J. Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews* 2018;81:1887–905. <https://doi.org/10.1016/j.rser.2017.05.288>.
- 1771
- 1772
- 1773 [79] Hansson J, Hackl R, Taljegard M, Brynolf S, Grahn M. The potential for electrofuels production in Sweden utilizing fossil and biogenic CO₂ point sources. *Frontiers in Energy Research* 2017;5:1–12. <https://doi.org/10.3389/fenrg.2017.00004>.
- 1774
- 1775
- 1776 [80] Bauen A, Bitossi N, German L, Harris A, Leow K. Sustainable Aviation Fuels. *Johnson Matthey Technology Review* 2020:263–78. <https://doi.org/10.1595/205651320x15816756012040>.
- 1777
- 1778 [81] Wohlin C. Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14, London, England, United Kingdom: ACM Press; 2014, p. 1–10.* <https://doi.org/10.1145/2601248.2601268>.
- 1779
- 1780
- 1781
- 1782 [82] Huq NA, Hafenstine GR, Huo X, Nguyen H, Tiffitt SM, Conklin DR, et al. Toward net-zero sustainable aviation fuel with wet waste-derived volatile fatty acids. *Proc Natl Acad Sci USA* 2021;118:e2023008118. <https://doi.org/10.1073/pnas.2023008118>.
- 1783
- 1784
- 1785 [83] Bradin D. Process for producing renewable jet fuel compositions. WO 2014/008337 A1, 2014.
- 1786 [84] Davis R, Tao L, Scarlata C, Tan ECD, Ross J, Lukas J, et al. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons 2015. <https://www.nrel.gov/docs/fy14osti/60223.pdf>.
- 1787
- 1788
- 1789
- 1790 [85] Chheda JN, Powell JB. Direct aqueous phase reforming of bio-based feedstocks. US 9,303,226 B2, 2016.
- 1791 [86] Blommel PG, Cortright RD. Production of Conventional Liquid Fuels from Sugars. Madison, USA: Virent Energy System Inc.; 2008.
- 1792
- 1793 [87] Wang T, Tan J, Qiu S, Zhang Q, Long J, Chen L, et al. Liquid fuel production by aqueous phase catalytic transformation of biomass for aviation. *Energy Procedia* 2014;61:432–5. <https://doi.org/10.1016/j.egypro.2014.11.1142>.
- 1794
- 1795
- 1796 [88] Qiao M, Woods E, Myren P, Cortright R. Solvolysis of biomass and stabilization of biomass hydrolysate. US 2013/0019859 A1, 2013.
- 1797
- 1798 [89] Coronado I, Stekrova M, Reinikainen M, Simell P, Lefferts L, Lehtonen J. A review of catalytic aqueous-phase reforming of oxygenated hydrocarbons derived from biorefinery water fractions. *International Journal of Hydrogen Energy* 2016;41:11003–32. <https://doi.org/10.1016/j.ijhydene.2016.05.032>.
- 1799
- 1800
- 1801 [90] Pavlenko N. The cost of supporting alternative jet fuels in the European Union. ICCT 2021. https://theicct.org/sites/default/files/publications/Alternative_jet_fuels_cost_EU_20190320.pdf.
- 1802
- 1803 [91] Davis R, Bidy M, Tan E, Tao L, Jones S. Biological conversion of sugars to hydrocarbons technology pathway. National Renewable Energy Laboratory 2013. <https://www.nrel.gov/docs/fy13osti/58054.pdf>.
- 1804
- 1805 [92] Mawhood R, Gazis E, de Jong S, Hoefnagels R, Slade R. Production pathways for renewable jet fuel: a review of commercialization status and future prospects. *Biofuels, Bioproducts and Biorefining* 2016;10:462–84. <https://doi.org/10.1002/bbb.1644>.
- 1806
- 1807
- 1808 [93] Lane J. Amyris, Total to commercialize renewable, low-carbon jet fuel technology; Total takes 75% stake in JV. *Biofuels Digest* 2015. <https://www.biofuelsdigest.com/bdigest/2015/06/30/amyris-total-to-commercialize-renewable-low-carbon-jet-fuel-technology/> (accessed December 22, 2021).
- 1809
- 1810
- 1811 [94] Renninger NSM, Derek J, McPhee DJ. Fuel compositions comprising farnesane and farnesane derivatives and method of making and using same. US 7,399,323 B2, 2008.
- 1812
- 1813 [95] Gray D, Sato S, Garcia F, Eppler R, Cherry J. Amyris, Inc. Integrated Biorefinery Project Summary - Public Version. United States 2014. <https://doi.org/10.2172/1122942>.
- 1814
- 1815 [96] Ohler, Nicholas L., Vazquez R. Stabilization and hydrogenation methods for microbial-derived olefins. US 9,611,189 B2, 2017.
- 1816

- 1817 [97] Qureshi N, Lolas A, Blaschek HP. Soy molasses as fermentation substrate for production of butanol using
1818 *Clostridium beijerinckii* BA101. *Journal of Industrial Microbiology and Biotechnology* 2001;26:290–5.
1819 <https://doi.org/10.1038/sj.jim.7000131>.
- 1820 [98] Peters MW, Taylor JD. Renewable jet fuel blendstock from isobutanol. US8,975,461 B2, 2015.
- 1821 [99] Ma K, Ruan Z, Shui Z, Wang Y, Hu G, He M. Open fermentative production of fuel ethanol from food
1822 waste by an acid-tolerant mutant strain of *Zymomonas mobilis*. *Bioresource Technology* 2016;203:295–302.
1823 <https://doi.org/10.1016/j.biortech.2015.12.054>.
- 1824 [100] Yao G, Staples MD, Malina R, Tyner WE. Stochastic techno-economic analysis of alcohol-to-jet fuel
1825 production. *Biotechnol Biofuels* 2017;10:18. <https://doi.org/10.1186/s13068-017-0702-7>.
- 1826 [101] Geleynse S, Brandt K, Garcia-Perez M, Wolcott M, Zhang X. The Alcohol-to-Jet Conversion Pathway for
1827 Drop-In Biofuels: Techno-Economic Evaluation. *ChemSusChem* 2018;11:3728–41.
1828 <https://doi.org/10.1002/cssc.201801690>.
- 1829 [102] Evanko WA, Eyal AM, Glassner DA, Miao F, Aristidou AA, Evans K, et al. Recovery of higher alcohols
1830 from dilute aqueous solutions. US 8,101,808 B2, 2012.
- 1831 [103] David PR, Alto P. Compositions and methods for producing fermentation products and residuals. US
1832 7,309,602 B2, 2007.
- 1833 [104] Gevo. Gevo's Biofuels. Gevo, Inc 2019. <https://gevo.com/biofuels-reduce-greenhouse-gas-emissions/>
1834 (accessed May 15, 2022).
- 1835 [105] Jang YS, Malaviya A, Lee J, Im JA, Lee SY, Lee J, et al. Metabolic engineering of *Clostridium*
1836 *acetobutylicum* for the enhanced production of isopropanol-butanol-ethanol fuel mixture. *Biotechnology*
1837 *Progress* 2013;29:1083–8. <https://doi.org/10.1002/btpr.1733>.
- 1838 [106] Buijs NA, Siewers V, Nielsen J. Advanced biofuel production by the yeast *saccharomyces cerevisiae*.
1839 *Current Opinion in Chemical Biology* 2013;17:480–8. <https://doi.org/10.1016/j.cbpa.2013.03.036>.
- 1840 [107] Costa OYA, Souto BM, Tupinambá DD, Bergmann JC, Kyaw CM, Kruger RH, et al. Microbial diversity in
1841 sugarcane ethanol production in a Brazilian distillery using a culture-independent method. *J Ind Microbiol*
1842 *Biotechnol* 2015;42:73–84. <https://doi.org/10.1007/s10295-014-1533-1>.
- 1843 [108] Wang T, Li K, Liu Q, Zhang Q, Qiu S, Long J, et al. Aviation fuel synthesis by catalytic conversion of
1844 biomass hydrolysate in aqueous phase. *Applied Energy* 2014;136:775–80.
1845 <https://doi.org/10.1016/j.apenergy.2014.06.035>.
- 1846 [109] Liu K, Atiyeh HK, Stevenson BS, Tanner RS, Wilkins MR, Huhnke RL. Mixed culture syngas fermentation
1847 and conversion of carboxylic acids into alcohols. *Bioresource Technology* 2014;152:337–46.
1848 <https://doi.org/10.1016/j.biortech.2013.11.015>.
- 1849 [110] Taylor JD, Jenni MM, Peters MW. Dehydration of fermented isobutanol for the production of renewable
1850 chemicals and fuels. *Topics in Catalysis* 2010;53:1224–30. <https://doi.org/10.1007/s11244-010-9567-8>.
- 1851 [111] Choo HP, Liew KY, Liu HF, Seng CE. Hydrogenation of palm olein catalyzed by polymer stabilized Pt
1852 colloids. *Journal of Molecular Catalysis A: Chemical* 2001;165:127–34. [https://doi.org/10.1016/S1381-1169\(00\)00367-8](https://doi.org/10.1016/S1381-1169(00)00367-8).
- 1853 [112] Dahal K, Brynolf S, Xisto C, Hansson J, Grahn M, Grönstedt T, et al. Techno-economic review of
1854 alternative fuels and propulsion systems for the aviation sector. *Renewable and Sustainable Energy Reviews*
1855 2021;151:111564. <https://doi.org/10.1016/j.rser.2021.111564>.
- 1856 [113] Byogy Inc. Renewable Fuels For All Modes of Transport 2016.
1857 https://www.energy.gov/sites/prod/files/2016/09/f33/weiss_alternative_aviation_fuels_workshop.pdf.
- 1858 [114] Hull A. Jet fuel from ethanol and syngas Transition to a more sustainable society. Swedish BioFuel AB
1859 2019. https://ec.europa.eu/info/sites/default/files/9_angelica_hull.pdf (accessed May 10, 2022).
- 1860 [115] Han J, Tao L, Wang M. Well-to-wake analysis of ethanol-to-jet and sugar-to-jet pathways. *Biotechnology*
1861 *for Biofuels* 2017;10:1–15. <https://doi.org/10.1186/s13068-017-0698-z>.
- 1862 [116] Karan SK, Hamelin L. Crop residues may be a key feedstock to bioeconomy but how reliable are current
1863 estimation methods? *Resources, Conservation and Recycling* 2021;164:105211.
1864 <https://doi.org/10.1016/j.resconrec.2020.105211>.
- 1865 [117] Slade R, Bauen A, Gross R. Global bioenergy resources. *Nature Climate Change* 2014;4:99–105.
1866 <https://doi.org/10.1038/nclimate2097>.
- 1867 [118] Karan SK, Hamelin L. Towards local bioeconomy: A stepwise framework for high-resolution spatial
1868 quantification of forestry residues. *Renewable and Sustainable Energy Reviews* 2020;134:110350.
1869 <https://doi.org/10.1016/j.rser.2020.110350>.
- 1870

- 1871 [119] Hamelin L, Borzęcka M, Kozak M, Pudelko R. A spatial approach to bioeconomy: Quantifying the residual
1872 biomass potential in the EU-27. *Renewable and Sustainable Energy Reviews* 2019;100:127–42.
1873 <https://doi.org/10.1016/j.rser.2018.10.017>.
- 1874 [120] Lodato C, Hamelin L, Tonini D, Astrup TF. Towards sustainable methane supply from local bioresources:
1875 Anaerobic digestion, gasification, and gas upgrading. *Applied Energy* 2022;323:119568.
1876 <https://doi.org/10.1016/j.apenergy.2022.119568>.
- 1877 [121] Hamelin L, Naroznova I, Wenzel H. Environmental consequences of different carbon alternatives for
1878 increased manure-based biogas. *Applied Energy* 2014;114:774–82.
1879 <https://doi.org/10.1016/j.apenergy.2013.09.033>.
- 1880 [122] Amaro J, Rosado DJM, Mendiburu AZ, dos Santos LR, de Carvalho Jr. JA. Modeling of syngas composition
1881 obtained from fixed bed gasifiers using Kuhn–Tucker multipliers. *Fuel* 2021;287:119068.
1882 <https://doi.org/10.1016/j.fuel.2020.119068>.
- 1883 [123] Hu J, Yu F, Lu Y. Application of fischer-tropsch synthesis in biomass to liquid conversion. *Catalysts*
1884 2012;2:303–26. <https://doi.org/10.3390/catal2020303>.
- 1885 [124] Chiodini A, Bua L, Carnelli L, Zwart R, Vreugdenhil B, Vocciant M. Enhancements in Biomass-to-Liquid
1886 processes: Gasification aiming at high hydrogen/carbon monoxide ratios for direct Fischer-Tropsch
1887 synthesis applications. *Biomass and Bioenergy* 2017;106:104–14.
1888 <https://doi.org/10.1016/j.biombioe.2017.08.022>.
- 1889 [125] Susastriawan AAP, Saptoadi H, Purnomo. Small-scale downdraft gasifiers for biomass gasification: A
1890 review. *Renewable and Sustainable Energy Reviews* 2017;76:989–1003.
1891 <https://doi.org/10.1016/j.rser.2017.03.112>.
- 1892 [126] Klinghoffer NB, Castaldi MJ, Nzihou A. Influence of char composition and inorganics on catalytic activity
1893 of char from biomass gasification. *Fuel* 2015;157:37–47. <https://doi.org/10.1016/j.fuel.2015.04.036>.
- 1894 [127] Abdoulmoumine N, Adhikari S, Kulkarni A, Chattanathan S. A review on biomass gasification syngas
1895 cleanup. *Applied Energy* 2015;155:294–307. <https://doi.org/10.1016/j.apenergy.2015.05.095>.
- 1896 [128] Sun X, Atiyeh HK, Huhnke RL, Tanner RS. Syngas fermentation process development for production of
1897 biofuels and chemicals: A review. *Bioresource Technology Reports* 2019;7:100279.
1898 <https://doi.org/10.1016/j.biteb.2019.100279>.
- 1899 [129] Mohammadi M, Younesi H, Najafpour G, Mohamed AR. Sustainable ethanol fermentation from synthesis
1900 gas by *Clostridium ljungdahlii* in a continuous stirred tank bioreactor. *Journal of Chemical Technology and*
1901 *Biotechnology* 2012;87:837–43. <https://doi.org/10.1002/jctb.3712>.
- 1902 [130] Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life Cycle Assessments of Ethanol
1903 Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas
1904 Feedstocks. *Industrial and Engineering Chemistry Research* 2016;55:3253–61.
1905 <https://doi.org/10.1021/acs.iecr.5b03215>.
- 1906 [131] Kundiyana DK, Huhnke RL, Wilkins MR. Syngas fermentation in a 100-L pilot scale fermentor: Design and
1907 process considerations. *Journal of Bioscience and Bioengineering* 2010;109:492–8.
1908 <https://doi.org/10.1016/j.jbiosc.2009.10.022>.
- 1909 [132] Schultz M, Obern J. Methods and systems for the production of hydrocarbon products. WO 2010/058508
1910 A2, 2012. <https://doi.org/10.7868/s0002337x14020092>.
- 1911 [133] Harmon L, Hallen R, Lilga M, Heijstra B, Palou-Rivera I, Handler R. A hybrid catalytic route to fuels from
1912 biomass syngas. United States 2017. <https://doi.org/10.2172/1423741>.
- 1913 [134] LanzaTech. LanzaTech: Capturing carbon, fueling growth. LanzaTech 2019. <https://www.lanzatech.com/>
1914 (accessed January 24, 2022).
- 1915 [135] Morschbacker A. Bio-ethanol based ethylene. *Polymer Reviews* 2009;49:79–84.
1916 <https://doi.org/10.1080/15583720902834791>.
- 1917 [136] Finiels A, Fajula F, Hulea V. Nickel-based solid catalysts for ethylene oligomerization—a review. *Catalysis*
1918 *Science and Technology* 2014;4:2412–26. <https://doi.org/10.1039/c4cy00305e>.
- 1919 [137] Pechstein J, Kaltschmitt M. Liquid Hydrocarbon Fuels Derived from Alcohols. *Energy from Organic*
1920 *Materials (Biomass)* 2019:1023–46. https://doi.org/10.1007/978-1-4939-7813-7_1039.
- 1921 [138] Griffin DW, Schultz MA. Fuel and chemical products from biomass syngas: A comparison of gas
1922 fermentation to thermochemical conversion routes. *Environmental Progress and Sustainable Energy*
1923 2012;31:219–24. <https://doi.org/10.1002/ep.11613>.
- 1924 [139] Liu K, Atiyeh HK, Tanner RS, Wilkins MR, Huhnke RL. Fermentative production of ethanol from syngas
1925 using novel moderately alkaliphilic strains of *Alkalibaculum bacchi*. *Bioresource Technology*
1926 2012;104:336–41. <https://doi.org/10.1016/j.biortech.2011.10.054>.

- 1927 [140] Devarapalli M, Atiyeh HK, Phillips JR, Lewis RS, Huhnke RL. Ethanol production during semi-continuous
1928 syngas fermentation in a trickle bed reactor using *Clostridium ragsdalei*. *Bioresource Technology*
1929 2016;209:56–65. <https://doi.org/10.1016/j.biortech.2016.02.086>.
- 1930 [141] Shen N, Dai K, Xia XY, Zeng RJ, Zhang F. Conversion of syngas (CO and H₂) to biochemicals by mixed
1931 culture fermentation in mesophilic and thermophilic hollow-fiber membrane biofilm reactors. *Journal of*
1932 *Cleaner Production* 2018;202:536–42. <https://doi.org/10.1016/j.jclepro.2018.08.162>.
- 1933 [142] de Klerk A. Fischer-Tropsch jet fuel process. US 2010/0108568 A1, 2010.
- 1934 [143] de Klerk A. Fischer-Tropsch fuels refinery design. *Energy and Environmental Science* 2011;4:1177–205.
1935 <https://doi.org/10.1039/c0ee00692k>.
- 1936 [144] Boerrigter H. Economy of Biomass-to-Liquids (BTL) plants. An engineering assessment. Netherlands. US
1937 Department of Energy, Office of Scientific and Technical Information 2006.
1938 <https://www.osti.gov/etdeweb/biblio/20767385>.
- 1939 [145] Gruber H, Groß P, Rauch R, Reichhold A, Zweiler R, Aichernig C, et al. Fischer-Tropsch products from
1940 biomass-derived syngas and renewable hydrogen. *Biomass Conversion and Biorefinery* 2019.
1941 <https://doi.org/10.1007/s13399-019-00459-5>.
- 1942 [146] Gruber H, Groß P, Rauch R, Reichhold A, Zweiler R, Aichernig C, et al. Fischer-Tropsch products from
1943 biomass-derived syngas and renewable hydrogen. *Biomass Conversion and Biorefinery* 2019.
1944 <https://doi.org/10.1007/s13399-019-00459-5>.
- 1945 [147] Hanaoka T, Miyazawa T, Shimura K, Hirata S. Jet fuel synthesis from Fischer-Tropsch product under mild
1946 hydrocracking conditions using Pt-loaded catalysts. *Chemical Engineering Journal* 2015;263:178–85.
1947 <https://doi.org/10.1016/j.cej.2014.11.042>.
- 1948 [148] Bradin D. Process for producing renewable jet fuel composition. US 9,422,494 B2, 2016.
- 1949 [149] Dayton, David C, Turk B, Gupta R. Syngas cleanup, conditioning, and utilization. In: Brown RC, editor.
1950 *Thermochemical processing of biomass: conversion into fuels, chemicals, and power*, Wiley and Sons Ltd;
1951 2019. <https://doi.org/10.1002/9781119417637.ch5>.
- 1952 [150] Rahardjo BS. The Assessment of Syngas Utilization by Fischer Tropsch Synthesis in the Slurry-Bed Reactor
1953 Using Co/SiO₂ Catalyst. *International Journal of Engineering and Applied Sciences* 2012.
1954 <http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=116BEA5B99F8E944EBE52470846E92B1?doi=10.1.1.685.6055&rep=rep1&type=pdf>.
- 1955 [151] Marchese M, Giglio E, Santarelli M, Lanzini A. Energy performance of Power-to-Liquid applications
1956 integrating biogas upgrading, reverse water gas shift, solid oxide electrolysis and Fischer-Tropsch
1957 technologies. *Energy Conversion and Management: X* 2020;6:100041.
1958 <https://doi.org/10.1016/j.ecmx.2020.100041>.
- 1959 [152] Mena Subiranas A. Combining Fischer-Tropsch Synthesis (FTS) and Hydrocarbon Reactions in one
1960 Reactor. Karlsruhe Institute of Technology (KIT) 2009. <https://publikationen.bibliothek.kit.edu/1000010077>.
- 1961 [153] Bouchy C, Hastoy G, Guillon E, Martens JA. Fischer-Tropsch waxes upgrading via hydrocracking and
1962 selective hydroisomerization. *Oil and Gas Science and Technology* 2009;64:91–112.
1963 <https://doi.org/10.2516/ogst/2008047>.
- 1964 [154] Srinivas S, Malik RK, Mahajani SM. Fischer-Tropsch synthesis using bio-syngas and CO₂. *Energy for*
1965 *Sustainable Development* 2007;11:66–71. [https://doi.org/10.1016/S0973-0826\(08\)60411-1](https://doi.org/10.1016/S0973-0826(08)60411-1).
- 1966 [155] van Steen E, Claeys M. Fischer-Tropsch catalysts for the biomass-to-liquid process. *Chemical Engineering*
1967 *and Technology* 2008;31:655–66. <https://doi.org/10.1002/ceat.200800067>.
- 1968 [156] Fulcrum Bioenergy. Fulcrum BioEnergy. 2020 2015. <http://fulcrum-bioenergy.com/> (accessed March 5,
1969 2022).
- 1970 [157] Red Rock Biofuels. Red Rock Biofuels 2018. <https://www.redrockbio.com/> (accessed February 22, 2022).
- 1971 [158] Brassard P, Godbout S, Hamelin L. Framework for consequential life cycle assessment of pyrolysis
1972 biorefineries: A case study for the conversion of primary forestry residues. *Renewable and Sustainable*
1973 *Energy Reviews* 2021;138:110549. <https://doi.org/10.1016/j.rser.2020.110549>.
- 1974 [159] Jeong YW, Choi SK, Choi YS, Kim SJ. Production of biocrude-oil from swine manure by fast pyrolysis and
1975 analysis of its characteristics. *Renewable Energy* 2015;79:14–9.
1976 <https://doi.org/10.1016/j.renene.2014.08.041>.
- 1977 [160] Wang T, Qiu S, Weng Y, Chen L, Liu Q, Long J, et al. Liquid fuel production by aqueous phase catalytic
1978 transformation of biomass for aviation. *Applied Energy* 2015;160:329–35.
1979 <https://doi.org/10.1016/j.apenergy.2015.08.116>.
- 1980

- 1981 [161] Baldino AC, Berg R, Pavlenko N, Searle S. Advanced alternative fuel pathways: Technology overview and
1982 status. ICCT 2019. [https://theicct.org/publication/advanced-alternative-fuel-pathways-technology-overview-
1984 and-status/](https://theicct.org/publication/advanced-alternative-fuel-pathways-technology-overview-
1983 and-status/).
- 1984 [162] Mohan D, Pittman CU, Steele PH. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy and
1985 Fuels* 2006;20:848–89. <https://doi.org/10.1021/ef0502397>.
- 1986 [163] Bridgwater A V., Czernik S, Piskorz J. An Overview of Fast Pyrolysis. *Progress in Thermochemical
1987 Biomass Conversion* 2008:977–97. <https://doi.org/10.1002/9780470694954.ch80>.
- 1988 [164] Ramirez JA, Brown RJ, Rainey TJ. A review of hydrothermal liquefaction bio-crude properties and
1989 prospects for upgrading to transportation fuels. *Energies* 2015;8:6765–94.
1990 <https://doi.org/10.3390/en8076765>.
- 1991 [165] Vardon DR, Sharma BK, Scott J, Yu G, Wang Z, Schideman L, et al. Chemical properties of biocrude oil
1992 from the hydrothermal liquefaction of Spirulina algae, swine manure, and digested anaerobic sludge.
1993 *Bioresource Technology* 2011;102:8295–303. <https://doi.org/10.1016/j.biortech.2011.06.041>.
- 1994 [166] Shi W, Gao Y, Song S, Zhao Y. One-pot conversion of bio-oil to diesel- and jet-fuel-range hydrocarbons in
1995 supercritical cyclohexane. *Industrial and Engineering Chemistry Research* 2014;53:11557–65.
1996 <https://doi.org/10.1021/ie501682r>.
- 1997 [167] Watson J, Wang T, Si B, Chen WT, Aierzhati A, Zhang Y. Valorization of hydrothermal liquefaction
1998 aqueous phase: pathways towards commercial viability. *Progress in Energy and Combustion Science*
1999 2020;77. <https://doi.org/10.1016/j.peccs.2019.100819>.
- 2000 [168] Nazari L, Yuan Z, Souzanchi S, Ray MB, Xu C. Hydrothermal liquefaction of woody biomass in hot-
2001 compressed water: Catalyst screening and comprehensive characterization of bio-crude oils. *Fuel*
2002 2015;162:74–83. <https://doi.org/10.1016/j.fuel.2015.08.055>.
- 2003 [169] Dimitriadis A, Bezerianni S. Hydrothermal liquefaction of various biomass and waste feedstocks for
2004 biocrude production: A state of the art review. *Renewable and Sustainable Energy Reviews* 2017;68:113–25.
2005 <https://doi.org/10.1016/j.rser.2016.09.120>.
- 2006 [170] Zhang Q, Chang J, Wang T, Xu Y. Review of biomass pyrolysis oil properties and upgrading research.
2007 *Energy Conversion and Management* 2007;48:87–92. <https://doi.org/10.1016/j.enconman.2006.05.010>.
- 2008 [171] Shell inc. Integrated Hydropyrolysis and Hydroconversion 2020. [https://www.shell.com/business-
2011 customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-
2012 technology/hydropyrolysis.html](https://www.shell.com/business-
2009 customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-
2010 technology/hydropyrolysis.html) (accessed January 6, 2022).
- 2011 [172] Marker TL, Felix LG, Linck MB, Roberts MJ, Ortiz-Toral P, Wangerow J. Integrated hydropyrolysis and
2012 hydroconversion for the direct production of gasoline and diesel fuels or blending components from
2013 biomass, Part 2: continuous testing. *Environ Prog Sustainable Energy* 2014;33:762–8.
2014 <https://doi.org/10.1002/ep.11906>.
- 2015 [173] Marker T, Felix LG, Linck MB. Integrated Hydropyrolysis and Hydroconversion Process for Production of
2016 Gasoline and Diesel Fuel from Biomass. SEMANTIC SCHOLAR 2009.
2017 [https://www.semanticscholar.org/paper/Integrated-Hydropyrolysis-and-Hydroconversion-for-Marker-
2019 Felix/fad15a9b4909aecd9cad92c7ed229b1619df702#citing-papers](https://www.semanticscholar.org/paper/Integrated-Hydropyrolysis-and-Hydroconversion-for-Marker-
2018 Felix/fad15a9b4909aecd9cad92c7ed229b1619df702#citing-papers) (accessed January 24, 2022).
- 2019 [174] Marker T, Roberts M, Linck M, Felix L, Ortiz-Toral P, Wangerow J, et al. Long Term Processing Using
2020 Integrated Hydropyrolysis plus Hydroconversion (IH2) for the Production of Gasoline and Diesel from
2021 Biomass. 2013. <https://doi.org/10.2172/1082786>.
- 2022 [175] Zupko R. Life cycle assessment of the production of gasoline and diesel from forest residues using
2023 integrated hydropyrolysis and hydroconversion. *Int J Life Cycle Assess* 2019;24:1793–804.
2024 <https://doi.org/10.1007/s11367-019-01616-8>.
- 2025 [176] Karaj S, Müller J. Optimizing mechanical oil extraction of *Jatropha curcas* L. seeds with respect to press
2026 capacity, oil recovery and energy efficiency. *Industrial Crops and Products* 2011;34:1010–6.
2027 <https://doi.org/10.1016/j.indcrop.2011.03.009>.
- 2028 [177] Ben Amara A, Kaoubi S, Starck L. Toward an optimal formulation of alternative jet fuels: Enhanced
2029 oxidation and thermal stability by the addition of cyclic molecules. *Fuel* 2016;173:98–105.
2030 <https://doi.org/10.1016/j.fuel.2016.01.040>.
- 2031 [178] Buffi, M., Valera-Medina, A., Marsh, R., Pugh, D., Giles, A., Runyon, J., Chiamonti, D. Emissions
2032 characterization tests for HRJ fuel from used cooking oil and its blends.pdf. *Applied Energy* 2017;201:84–
2033 93. <https://doi.org/10.1016/j.apenergy.2017.05.104>.
- 2034 [179] Li T, Cheng J, Huang R, Zhou J, Cen K. Conversion of waste cooking oil to jet biofuel with nickel-based
2035 mesoporous zeolite Y catalyst. *Bioresource Technology* 2015;197:289–94.
2036 <https://doi.org/10.1016/j.biortech.2015.08.115>.

- 2037 [180] Yang J, Xin Z, He Q (Sophia), Corscadden K, Niu H. An overview on performance characteristics of bio-jet
2038 fuels. *Fuel* 2019;237:916–36. <https://doi.org/10.1016/j.fuel.2018.10.079>.
- 2039 [181] Verma D, Rana BS, Kumar R, Sibi MG, Sinha AK. Diesel and aviation kerosene with desired aromatics
2040 from hydroprocessing of jatropha oil over hydrogenation catalysts supported on hierarchical mesoporous
2041 SAPO-11. *Applied Catalysis A: General* 2015;490:108–16. <https://doi.org/10.1016/j.apcata.2014.11.007>.
- 2042 [182] Ameen M, Azizan MT, Yusup S, Ramli A, Yasir M. Catalytic hydrodeoxygenation of triglycerides: An
2043 approach to clean diesel fuel production. *Renewable and Sustainable Energy Reviews* 2017;80:1072–88.
2044 <https://doi.org/10.1016/j.rser.2017.05.268>.
- 2045 [183] Rabaev M, Landau M V., Vidruk-Nehemya R, Koukouliev V, Zarchin R, Herskowitz M. Conversion of
2046 vegetable oils on Pt/Al₂O₃/SAPO-11 to diesel and jet fuels containing aromatics. *Fuel* 2015;161:287–94.
2047 <https://doi.org/10.1016/j.fuel.2015.08.063>.
- 2048 [184] Zhao X, Wei L, Julson J, Qiao Q, Dubey A, Anderson G. Catalytic cracking of non-edible sunflower oil over
2049 ZSM-5 for hydrocarbon bio-jet fuel. *New Biotechnology* 2015;32:300–12.
2050 <https://doi.org/10.1016/j.nbt.2015.01.004>.
- 2051 [185] Kristiana T, Baldino C, Searle S. An estimate of current collection and potential collection of used cooking
2052 oil from major Asian exporting countries. *ICCT 2022*. <https://theicct.org/publication/asia-fuels-waste-oil-estimates-feb22/>.
- 2053 [186] van Grinsven A, van den Toorn E, van der Veen R, Kampman B. Used Cooking Oil (UCO) as biofuel
2054 feedstock in the EU 2020. [https://www.transportenvironment.org/wp-](https://www.transportenvironment.org/wp-content/uploads/2021/07/CE_Delft_200247_UCO_as_biofuel_feedstock_in_EU_FINAL%20-%20v5_0.pdf)
2055 [content/uploads/2021/07/CE_Delft_200247_UCO_as_biofuel_feedstock_in_EU_FINAL%20-](https://www.transportenvironment.org/wp-content/uploads/2021/07/CE_Delft_200247_UCO_as_biofuel_feedstock_in_EU_FINAL%20-%20v5_0.pdf)
2056 [%20v5_0.pdf](https://www.transportenvironment.org/wp-content/uploads/2021/07/CE_Delft_200247_UCO_as_biofuel_feedstock_in_EU_FINAL%20-%20v5_0.pdf).
- 2057 [187] Jiang C, Guan K, Khanna M, Chen L, Peng J. Assessing Marginal Land Availability Based on Land Use
2058 Change Information in the Contiguous United States. *Environ Sci Technol* 2021;55:10794–804.
2059 <https://doi.org/10.1021/acs.est.1c02236>.
- 2060 [188] Mehmood MA, Ibrahim M, Rashid U, Nawaz M, Ali S, Hussain A, et al. Biomass production for bioenergy
2061 using marginal lands. *Sustainable Production and Consumption* 2017;9:3–21.
2062 <https://doi.org/10.1016/j.spc.2016.08.003>.
- 2063 [189] Cai X, Zhang X, Wang D. Land Availability for Biofuel Production. *Environ Sci Technol* 2011;45:334–9.
2064 <https://doi.org/10.1021/es103338e>.
- 2065 [190] Naylor RL, Liska AJ, Burke MB, Falcon WP, Gaskell JC, Rozelle SD, et al. The Ripple Effect: Biofuels,
2066 Food Security, and the Environment. *Environment: Science and Policy for Sustainable Development*
2067 2007;49:30–43. <https://doi.org/10.3200/ENVT.49.9.30-43>.
- 2068 [191] Hirano K, Hara T, Ardianor, Nugroho RA, Segah H, Takayama N, et al. Detection of the oil-producing
2069 microalga *Botryococcus braunii* in natural freshwater environments by targeting the hydrocarbon
2070 biosynthesis gene SSL-3. *Sci Rep* 2019;9:16974. <https://doi.org/10.1038/s41598-019-53619-y>.
- 2071 [192] Pavlenko N, Kharina A. Policy and Environmental Implications of Using HEFA+ for Aviation. *ICCT 2018*.
2072 [https://theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCT-Working-](https://theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCT-Working-Paper_20180321_vF.pdf)
2073 [Paper_20180321_vF.pdf](https://theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCT-Working-Paper_20180321_vF.pdf).
- 2074 [193] Douvartzides SL, Charisiou ND, Papageridis KN, Goula MA. Green Diesel: Biomass Feedstocks,
2075 Production Technologies, Catalytic Research, Fuel Properties and Performance in Compression Ignition
2076 Internal Combustion Engines. *Energies* 2019;12:809. <https://doi.org/10.3390/en12050809>.
- 2077 [194] Li L, Coppola E, Rine J, Miller JL, Walker D. Catalytic hydrothermal conversion of triglycerides to non-
2078 ester biofuels. *Energy and Fuels* 2010;24:1305–15. <https://doi.org/10.1021/ef901163a>.
- 2079 [195] Li L. Method of converting triglycerides to biofuels. US 7,691,159 B2, 2010.
- 2080 [196] McGarvey E, Tyner WE. A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation
2081 biofuel technology. *Biofuels, Bioproducts and Biorefining* 2018;12:474–84.
2082 <https://doi.org/10.1002/bbb.1863>.
- 2083 [197] Malins C. What role is there for electrofuel technologies in European transport’s low carbon future?
2084 *Cerulogy* 2017. [https://www.transportenvironment.org/wp-](https://www.transportenvironment.org/wp-content/uploads/2021/07/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf)
2085 [content/uploads/2021/07/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf](https://www.transportenvironment.org/wp-content/uploads/2021/07/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf).
- 2086 [198] Albrecht FG, Nguyen TV. Prospects of electrofuels to defossilize transportation in Denmark – A techno-
2087 economic and ecological analysis. *Energy* 2020;192. <https://doi.org/10.1016/j.energy.2019.116511>.
- 2088 [199] Alhyari M, Al-Salaymeh A, Irshidat M, Kaltschmitt M, Neuling U. The Impact of Energy Source on the
2089 Life-Cycle Assessment of Power-to-Liquid Fuels. *J Ecol Eng* 2019;20:239–44.
2090 <https://doi.org/10.12911/22998993/104659>.
- 2091

- 2092 [200] van der Giesen C, Kleijn R, Kramer GJ. Energy and Climate Impacts of Producing Synthetic Hydrocarbon
2093 Fuels from CO₂. *Environ Sci Technol* 2014;48:7111–21. <https://doi.org/10.1021/es500191g>.
- 2094 [201] Guo XM, Trably E, Latrille E, Carrre H, Steyer JP. Hydrogen production from agricultural waste by dark
2095 fermentation: A review. *International Journal of Hydrogen Energy* 2010;35:10660–73.
2096 <https://doi.org/10.1016/j.ijhydene.2010.03.008>.
- 2097 [202] Marxer D, Furler P, Scheffe J, Geerlings H, Falter C, Batteiger V, et al. Demonstration of the entire
2098 production chain to renewable kerosene via solar thermochemical splitting of H₂O and CO₂. *Energy and*
2099 *Fuels* 2015;29:3241–50. <https://doi.org/10.1021/acs.energyfuels.5b00351>.
- 2100 [203] Nabgan W, Tuan Abdullah TA, Mat R, Nabgan B, Gambo Y, Ibrahim M, et al. Renewable hydrogen
2101 production from bio-oil derivative via catalytic steam reforming: An overview. *Renewable and Sustainable*
2102 *Energy Reviews* 2017;79:347–57. <https://doi.org/10.1016/j.rser.2017.05.069>.
- 2103 [204] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. *Renewable and*
2104 *Sustainable Energy Reviews* 2017;67:597–611. <https://doi.org/10.1016/j.rser.2016.09.044>.
- 2105 [205] Hoes M, Ackermann S, Theiler D, Furler P, Steinfeld A. Additive-Manufactured Ordered Porous Structures
2106 Made of Ceria for Concentrating Solar Applications. *Energy Technology* 2019;7.
2107 <https://doi.org/10.1002/ente.201900484>.
- 2108 [206] Campanari S, Guandalini G, Coolegem J, Ten Have J, Hayes P, Pichel AH. Modeling, Development, and
2109 Testing of a 2 MW Polymeric Electrolyte Membrane Fuel Cell Plant Fueled with Hydrogen from a Chlor-
2110 Alkali Industry. *Journal of Electrochemical Energy Conversion and Storage* 2019;16:1–9.
2111 <https://doi.org/10.1115/1.4042923>.
- 2112 [207] Haneda T, Akisawa A. Technological assessment of PEFC power generation system using by-product
2113 hydrogen produced from a caustic soda plant. *International Journal of Hydrogen Energy* 2017;42:3240–9.
2114 <https://doi.org/10.1016/j.ijhydene.2016.10.142>.
- 2115 [208] IEA. The future of hydrogen Seizing today's opportunities. International Energy Agency (IEA) 2019.
2116 <https://www.oecd.org/fr/publications/the-future-of-hydrogen-1e0514c4-en.htm>.
- 2117 [209] Park JH, Kim S, Bard AJ. Novel carbon-doped TiO₂ nanotube arrays with high aspect ratios for efficient
2118 solar water splitting. *Nano Letters* 2006;6:24–8. <https://doi.org/10.1021/nl051807y>.
- 2119 [210] Joy J, Mathew J, George SC. Nanomaterials for photoelectrochemical water splitting – review. *International*
2120 *Journal of Hydrogen Energy* 2018;43:4804–17. <https://doi.org/10.1016/j.ijhydene.2018.01.099>.
- 2121 [211] Safari F, Dincer I. A review and comparative evaluation of thermochemical water splitting cycles for
2122 hydrogen production. *Energy Conversion and Management* 2020;205:112182.
2123 <https://doi.org/10.1016/j.enconman.2019.112182>.
- 2124 [212] Acar C, Dincer I. Review and evaluation of hydrogen production options for better environment. *Journal of*
2125 *Cleaner Production* 2019;218:835–49. <https://doi.org/10.1016/j.jclepro.2019.02.046>.
- 2126 [213] Ursúa A, Gandía LM, Sanchis P. Hydrogen production from water electrolysis: Current status and future
2127 trends. *Proceedings of the IEEE* 2012;100:410–26. <https://doi.org/10.1109/JPROC.2011.2156750>.
- 2128 [214] Carmo M, Fritz DL, Mergel J, Stolten D. A comprehensive review on PEM water electrolysis. *International*
2129 *Journal of Hydrogen Energy* 2013;38:4901–34. <https://doi.org/10.1016/j.ijhydene.2013.01.151>.
- 2130 [215] Choi IH, Hwang KR, Han JS, Lee KH, Yun JS, Lee JS. The direct production of jet-fuel from non-edible oil
2131 in a single-step process. *Fuel* 2015;158:98–104. <https://doi.org/10.1016/j.fuel.2015.05.020>.
- 2132 [216] Song Y, Zhang X, Xie K, Wang G, Bao X. High-Temperature CO₂ Electrolysis in Solid Oxide Electrolysis
2133 Cells: Developments, Challenges, and Prospects. *Advanced Materials* 2019;1902033:1–18.
2134 <https://doi.org/10.1002/adma.201902033>.
- 2135 [217] Zapantis A. Blue hydrogen. Global CCS Institute 2021. [https://www.globalccsinstitute.com/wp-](https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf)
2136 [content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf](https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf).
- 2137 [218] IRENA. Hydrogen from renewable power: Technology outlook for the energy transition. IRENA 2018.
2138 [https://www.irena.org/-](https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf)
2139 [/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf](https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf).
- 2140 [219] Li B, Duan Y, Luebke D, Morreale B. Advances in CO₂ capture technology: A patent review. *Applied*
2141 *Energy* 2013;102:1439–47. <https://doi.org/10.1016/j.apenergy.2012.09.009>.
- 2142 [220] Keith DW. Why capture CO₂ from the atmosphere? *Science* 2009;325:1654–5.
2143 <https://doi.org/10.1126/science.1175680>.
- 2144 [221] IEA. Putting CO₂ to use creating value from emissions. International Energy Agency (IEA) 2019.
2145 <https://www.iea.org/reports/putting-co2-to-use>.
- 2146 [222] Last GV, Schmick MT. Identification and Selection of Major Carbon Dioxide Stream Compositions. United
2147 States. 2011:PNNL-20493, 1019211. <https://doi.org/10.2172/1019211>.

- 2148 [223] IEA. Direct Air Capture. International Energy Agency (IEA) 2022. [https://www.iea.org/reports/direct-air-](https://www.iea.org/reports/direct-air-capture)
2149 capture (accessed September 27, 2022).
- 2150 [224] Zheng Y, Wang J, Yu B, Zhang W, Chen J, Qiao J, et al. A review of high temperature co-electrolysis of
2151 H₂O and CO₂ to produce sustainable fuels using solid oxide electrolysis cells (SOECs): Advanced materials
2152 and technology. *Chemical Society Reviews* 2017;46:1427–63. <https://doi.org/10.1039/c6cs00403b>.
- 2153 [225] Bahmanpour AM, Héroguel F, Kılıç M, Baranowski CJ, Artiglia L, Röthlisberger U, et al. Cu–Al Spinel as a
2154 Highly Active and Stable Catalyst for the Reverse Water Gas Shift Reaction. *ACS Catal* 2019;9:6243–51.
2155 <https://doi.org/10.1021/acscatal.9b01822>.
- 2156 [226] Liu H-X, Li S-Q, Wang W-W, Yu W-Z, Zhang W-J, Ma C, et al. Partially sintered copper–ceria as excellent
2157 catalyst for the high-temperature reverse water gas shift reaction. *Nat Commun* 2022;13:867.
2158 <https://doi.org/10.1038/s41467-022-28476-5>.
- 2159 [227] Zhang X, Zhu X, Lin L, Yao S, Zhang M, Liu X, et al. Highly Dispersed Copper over β -Mo₂C as an
2160 Efficient and Stable Catalyst for the Reverse Water Gas Shift (RWGS) Reaction. *ACS Catal* 2017;7:912–8.
2161 <https://doi.org/10.1021/acscatal.6b02991>.
- 2162 [228] González-Castaño M, Dorneanu B, Arellano-García H. The reverse water gas shift reaction: a process
2163 systems engineering perspective. *React Chem Eng* 2021;6:954–76. <https://doi.org/10.1039/D0RE00478B>.
- 2164 [229] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis - A
2165 review. *Journal of Cleaner Production* 2014;85:151–63. <https://doi.org/10.1016/j.jclepro.2013.07.048>.
- 2166 [230] Parhad PS, Nirukhe AB. Hydrogen production method by multi-step copper-chlorine thermochemical cycle.
2167 WO/2013/054340, 2013.
- 2168 [231] Furler P, Scheffe JR, Steinfeld A. Syngas production by simultaneous splitting of H₂O and CO₂ via ceria
2169 redox reactions in a high-temperature solar reactor. *Energy and Environmental Science* 2012;5:6098–103.
2170 <https://doi.org/10.1039/c1ee02620h>.
- 2171 [232] SUN to LIQUID project - SUN to LIQUID project n.d. <http://www.sun-to-liquid.eu/> (accessed February 27,
2172 2020).
- 2173 [233] Hankin A, Shah N. Process exploration and assessment for the production of methanol and dimethyl ether
2174 from carbon dioxide and water. *Sustainable Energy & Fuels* 2017;1:1541–56.
2175 <https://doi.org/10.1039/c7se00206h>.
- 2176 [234] Andika R, Nandiyanto ABD, Putra ZA, Bilad MR, Kim Y, Yun CM, et al. Co-electrolysis for power-to-
2177 methanol applications. *Renewable and Sustainable Energy Reviews* 2018;95:227–41.
2178 <https://doi.org/10.1016/j.rser.2018.07.030>.
- 2179 [235] Yurchak S. Developmbnt of mobil's H-IXBD-HKD methanol-to-gasoline (MTG) process. vol. 36. 1988.
2180 [https://doi.org/10.1016/S0167-2991\(09\)60521-8](https://doi.org/10.1016/S0167-2991(09)60521-8).
- 2181 [236] ExxonMobil. Synthetic Fuels (Methanol to gasoline) 2019.
2182 <https://www.exxonmobilchemical.com/en/catalysts-and-technology-licensing/synthetic-fuels> (accessed
2183 October 3, 2022).
- 2184 [237] Eurocontrol. Aviation sustainability briefing: News and views on how we can make aviation sustainable
2185 together Issue #6. EUROCONTROL 2022. [https://www.eurocontrol.int/sites/default/files/2022-](https://www.eurocontrol.int/sites/default/files/2022-05/eurocontrol-aviation-sustainability-briefing-edition-6_0.pdf)
2186 05/eurocontrol-aviation-sustainability-briefing-edition-6_0.pdf.
- 2187 [238] Lufthansa Group. From test tube to barrel - Lufthansa invests in first industrially produced carbon-neutral,
2188 electricity-based kerosene made in Germany. Lufthansa Group 2021.
2189 [https://www.lufthansagroup.com/en/newsroom/releases/from-test-tube-to-barrel-lufthansa-invests-in-first-](https://www.lufthansagroup.com/en/newsroom/releases/from-test-tube-to-barrel-lufthansa-invests-in-first-industrially-produced-carbon-neutral-electricity-based-kerosene-made-in-germany.html)
2190 [industrially-produced-carbon-neutral-electricity-based-kerosene-made-in-germany.html](https://www.lufthansagroup.com/en/newsroom/releases/from-test-tube-to-barrel-lufthansa-invests-in-first-industrially-produced-carbon-neutral-electricity-based-kerosene-made-in-germany.html) (accessed February
2191 22, 2022).
- 2192 [239] Lemmon EW, McLinden MO, Wagner W. Thermodynamic Properties of Propane. III. A Reference
2193 Equation of State for Temperatures from the Melting Line to 650 K and Pressures up to 1000 MPa. *J Chem*
2194 *Eng Data* 2009;54:3141–80. <https://doi.org/10.1021/je900217v>.
- 2195 [240] Ramesha DK. An Overview of Propane Based Domestic Refrigeration Systems. *Materials Today*
2196 2018;5:1599–606. <https://doi.org/10.1016/j.matpr.2017.11.252>.
- 2197 [241] Ashok B, Denis Ashok S, Ramesh Kumar C. LPG diesel dual fuel engine - A critical review. *Alexandria*
2198 *Engineering Journal* 2015;54:105–26. <https://doi.org/10.1016/j.aej.2015.03.002>.
- 2199 [242] Neste. Neste delivers first batch of 100% renewable propane to European market. *Green Car Congress* 2018.
2200 [https://www.neste.com/releases-and-news/renewable-solutions/neste-delivers-first-batch-100-renewable-](https://www.neste.com/releases-and-news/renewable-solutions/neste-delivers-first-batch-100-renewable-propane-european-market)
2201 [propane-european-market](https://www.neste.com/releases-and-news/renewable-solutions/neste-delivers-first-batch-100-renewable-propane-european-market) (accessed October 3, 2022).
- 2202 [243] Hart W. Global LPG: Opportunities and Challenges in an Evolving Market 2019.
2203 <https://www.lpgc.or.jp/corporate/information/images/Ph.D.,P.E.Hart.pdf> (accessed March 25, 2022).

- 2204 [244] Pyl SP, Schietekat CM, Reyniers MF, Abhari R, Marin GB, Van Geem KM. Biomass to olefins: Cracking of
2205 renewable naphtha. *Chemical Engineering Journal* 2011;176–177:178–87.
2206 <https://doi.org/10.1016/j.cej.2011.04.062>.
- 2207 [245] Piehl JA, Zyada A, Bravo L, Samimi-Abianeh O. Review of Oxidation of Gasoline Surrogates and Its
2208 Components. *Journal of Combustion* 2018;2018. <https://doi.org/10.1155/2018/8406754>.
- 2209 [246] Tamm DC, Devenish GN, Finelt DR, Kalt AL. Analysis of Gasoline Octane Costs Prepared for. 2018.
- 2210 [247] Neste. Neste MY Renewable Isoalkane™. Neste 2019.
2211 <https://www.neste.com/companies/products/renewable-products/neste-renewable-naphtha-0> (accessed
2212 October 3, 2022).
- 2213 [248] Neste. Accelerating the wide-scale adoption of sustainable aviation fuel. Neste 2019.
2214 <https://www.neste.com/products/all-products/saf> (accessed October 3, 2022).
- 2215 [249] Simpson SD, Tran PL, Mihalcea CD, Fung JMY, Liew F. Production of butanediol by anaerobic microbial
2216 fermentation. CA-2727549-C, 2014.
- 2217 [250] United State Food and Drug Administration. Code of Federal Regulations (CFR) Title 21, 2021.
2218 <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=173.220>.
- 2219 [251] Białkowska AM. Strategies for efficient and economical 2,3-butanediol production: new trends in this field.
2220 *World Journal of Microbiology and Biotechnology* 2016;32. <https://doi.org/10.1007/s11274-016-2161-x>.
- 2221 [252] Transparency Market Research. Market Research Report. Transparency Market Research 2019.
2222 <https://www.transparencymarketresearch.com/>.
- 2223 [253] Pinkos R, Erich Lorenz R, Alexander Beste Y. Process for preparing 1,4-butanediol. US 7,759,531 B2,
2224 2010.
- 2225 [254] Białkowska AM. Strategies for efficient and economical 2,3-butanediol production: new trends in this field.
2226 *World Journal of Microbiology and Biotechnology* 2016;32. <https://doi.org/10.1007/s11274-016-2161-x>.
- 2227 [255] Van Leeuwen BNM, Van Der Wulp AM, Duijnste I, Van Maris AJA, Straathof AJJ. Fermentative
2228 production of isobutene. *Applied Microbiology and Biotechnology* 2012;93:1377–87.
2229 <https://doi.org/10.1007/s00253-011-3853-7>.
- 2230 [256] GlobalBioenergies. First batch of isobutene from renewable resources delivered to Arkema. Global
2231 Bioenergies 2015. <https://www.global-bioenergies.com/first-batch-of-isobutene-from-renewable-resources-delivered-to-arkema/?lang=en> (accessed January 29, 2020).
- 2232 [257] Goortani BM, Gaurav A, Deshpande A, Ng FTT, Rempel GL. Production of isooctane from isobutene:
2233 Energy integration and carbon dioxide abatement via catalytic distillation. *Industrial and Engineering
2234 Chemistry Research* 2015;54:3570–81. <https://doi.org/10.1021/ie5032056>.
- 2235 [258] Gevo. Bio-Based Gasoline for High-Performance Engines. Gevo Inc 2019.
2236 <https://gevo.com/products/renewable-gasoline/> (accessed January 29, 2020).
- 2237 [259] Bhoot K. Isooctane Market to Increase Considerably. *Communal News* 2019.
2238 <https://communalnews.com/isooctane-market-to-increase-considerably/> (accessed March 4, 2020).
- 2239 [260] HCS Group. HCS Group signs purchase agreement with Gevo on renewable isooctane. HCS Group 2019.
2240 <https://www.h-c-s-group.com/hcs-group-signs-purchase-agreement-with-gevo-on-renewable-isooctane/>
2241 (accessed November 27, 2019).
- 2242 [261] Samimi A, Kavousi K, Zarinabadi S, Bozorgian A. Optimization of the Gasoline Production Plant in order to
2243 Increase Feed. *Progress in Chemical and Biochemical Research* 2020;3:7–19.
2244 <https://doi.org/10.33945/sami/pcbr.2020.1.2>.
- 2245 [262] Abrams MA, Dahdah NF, Francu E. Development of methods to collect and analyze gasoline range (C5–
2246 C12) hydrocarbons from seabed sediments as indicators of subsurface hydrocarbon generation and
2247 entrapment. *Applied Geochemistry* 2009;24:1951–70. <https://doi.org/10.1016/j.apgeochem.2009.07.009>.
- 2248 [263] de Klerk A. *Aviation Turbine Fuels Through the Fischer–Tropsch Process*. Elsevier Inc.; 2016.
2249 <https://doi.org/10.1016/b978-0-12-804568-8.00010-x>.
- 2250 [264] Durkin T, Kersey K, Paolini J. Synthesis of Green Hydrocarbons Using the AIR TO FUELS™ Technology
2251 . University of Pennsylvania. Penn Libraries, University of Pennsylvania 2019.
2252 https://repository.upenn.edu/cbe_sdr/114/.
- 2253 [265] David PR, Alto P. Compositions and methods for producing fermentation products and residuals. US
2254 7,309,602 B2, 2007.
- 2255 [266] Gevo. Gevo's Biofuels 2019. <https://gevo.com/biofuels-reduce-greenhouse-gas-emissions/> (accessed
2256 November 17, 2019).
- 2257

- 2258 [267] BusinessWire. Gevo and Land O'Lakes Purina Feed Sign Off-Take and Marketing Agreement | Business
2259 Wire. Business Wire 2012. <https://www.businesswire.com/news/home/20120110005824/en/Gevo-Land->
2260 O'Lakes-Purina-Feed-Sign-Off-Take (accessed December 12, 2019).
- 2261 [268] Chu PL, Vanderghem C, MacLean HL, Saville BA. Process modeling of hydrodeoxygenation to produce
2262 renewable jet fuel and other hydrocarbon fuels. *Fuel* 2017;196:298–305.
2263 <https://doi.org/10.1016/j.fuel.2017.01.097>.
- 2264 [269] Pearson M, Wollersheim C, Hileman J. A techno-economic review of hydroprocessed renewable esters and
2265 fatty acids for jet fuel production. *Biofuels*, Bioprod Bioref 2013;7:89–96. <https://doi.org/10.1002/bbb.1378>.
- 2266 [270] van Dyk S, Su J, Ebadian M, O'Connor D, Lakeman M, Saddler J (John). Potential yields and emission
2267 reductions of biojet fuels produced via hydrotreatment of biocrudes produced through direct thermochemical
2268 liquefaction. *Biotechnol Biofuels* 2019;12:281. <https://doi.org/10.1186/s13068-019-1625-2>.
- 2269 [271] Balzer G. Conversion of Douglas fir Biomass into Isobutanol and Biojet. Gevo, Inc 2014.
2270 <https://nararenewables.org/documents/2016/11/balzernwbcc2014.pdf/> (accessed October 3, 2022).
- 2271 [272] Johnston G. Alcohol to Jet - Isobutanol 2017.
2272 <https://www.icao.int/Meetings/altfuels17/Documents/Glenn%20Johnston%20-%20Gevo.pdf> (accessed
2273 December 12, 2021).
- 2274 [273] Virent Inc. BioForm ® SAK Jet Fuel. Virent, Inc 2015. [https://www.virent.com/wordpress/wp-](https://www.virent.com/wordpress/wp-content/uploads/2015/04/BioForm-SAK-Data-Sheet-Jan-2015.pdf)
2275 [content/uploads/2015/04/BioForm-SAK-Data-Sheet-Jan-2015.pdf](https://www.virent.com/wordpress/wp-content/uploads/2015/04/BioForm-SAK-Data-Sheet-Jan-2015.pdf) (accessed January 22, 2022).
- 2276 [274] Eswaran S, Subramaniam S, Geleynse S, Brandt K, Wolcott M, Zhang X. Techno-economic analysis of
2277 catalytic hydrothermolysis pathway for jet fuel production. *Renewable and Sustainable Energy Reviews*
2278 2021;151:111516. <https://doi.org/10.1016/j.rser.2021.111516>.
- 2279 [275] CARE-O-SENE project. CARE-O-SENE Catalyst Research for Sustainable Kerosene. CARE-O-SENE
2280 Research Project 2022. <https://care-o-sene.com/en/> (accessed September 19, 2022).
- 2281 [276] Domone J. The challenges and benefits of the electrification of aircraft. SNC-Lavalin's Atkins Business
2282 2018. [https://www.snc-lavalin.com/~media/Files/S/SNC-Lavalin/download-](https://www.snc-lavalin.com/~media/Files/S/SNC-Lavalin/download-centre/en/whitepaper/electrification%20white%20paper%20-%20digital.pdf)
2283 [centre/en/whitepaper/electrification%20white%20paper%20-%20digital.pdf](https://www.snc-lavalin.com/~media/Files/S/SNC-Lavalin/download-centre/en/whitepaper/electrification%20white%20paper%20-%20digital.pdf) (accessed March 15, 2022).
- 2284 [277] Thomson R, Sachdeva N, Nazukin M, Martinez N. Aircraft Electrical Propulsion – The Next Chapter of
2285 Aviation? 2017.
2286 [https://www.rolandberger.com/publications/publication_pdf/roland_berger_aircraft_electrical_propulsion.pd](https://www.rolandberger.com/publications/publication_pdf/roland_berger_aircraft_electrical_propulsion.pdf)
2287 [f](https://www.rolandberger.com/publications/publication_pdf/roland_berger_aircraft_electrical_propulsion.pdf) (accessed October 10, 2022).
- 2288 [278] European Commission. Batteries: European Battery cell R&I workshop 2018.
2289 [https://www.2zeroemission.eu/wp-content/uploads/2018/04/report_batteries-workshop_january-11-](https://www.2zeroemission.eu/wp-content/uploads/2018/04/report_batteries-workshop_january-11-12_final.pdf)
2290 [12_final.pdf](https://www.2zeroemission.eu/wp-content/uploads/2018/04/report_batteries-workshop_january-11-12_final.pdf).
- 2291 [279] Duffy KP, Jansen RH. Partially Turboelectric and Hybrid Electric Aircraft Drive Key Performance
2292 Parameters. 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, EATS 2018 2018.
2293 <https://doi.org/10.2514/6.2018-5023>.
- 2294 [280] Janovec M, Čerňan J, Škultéty F, Novák A. Design of Batteries for a Hybrid Propulsion System of a
2295 Training Aircraft. *Energies* 2021;15:49. <https://doi.org/10.3390/en15010049>.
- 2296 [281] Ulvestad A. A Brief Review of Current Lithium Ion Battery Technology and Potential Solid State Battery
2297 Technologies 2018. <http://arxiv.org/abs/1803.04317>.
- 2298 [282] Deng Y, Li J, Li T, Gao X, Yuan C. Life cycle assessment of lithium sulfur battery for electric vehicles.
2299 *Journal of Power Sources* 2017;343:284–95. <https://doi.org/10.1016/j.jpowsour.2017.01.036>.
- 2300 [283] Perathoner S, Centi G. Advanced nanocarbon materials for future energy applications. *Emerging Materials*
2301 *for Energy Conversion and Storage* 2018:305–25. <https://doi.org/10.1016/B978-0-12-813794-9.00009-0>.
- 2302 [284] Hansson N, Bradley M, Campbell M, Cherry DAJ, Cox K, Angelo DD, et al. Boeing Technical Journal
2303 Environmental Impacts of Aerospace Batteries 2018.
2304 [https://www.boeing.com/resources/boeingdotcom/features/innovation-](https://www.boeing.com/resources/boeingdotcom/features/innovation-quarterly/aug2018/BTJ_Batteries_AUG2018_FULL.pdf)
2305 [quarterly/aug2018/BTJ_Batteries_AUG2018_FULL.pdf](https://www.boeing.com/resources/boeingdotcom/features/innovation-quarterly/aug2018/BTJ_Batteries_AUG2018_FULL.pdf).
- 2306 [285] Imanishi N, Yamamoto O. Perspectives and challenges of rechargeable lithium–air batteries. *Materials*
2307 *Today Advances* 2019;4. <https://doi.org/10.1016/j.mtadv.2019.100031>.
- 2308 [286] Schmuch R, Wagner R, Hörpel G, Placke T, Winter M. Performance and cost of materials for lithium-based
2309 rechargeable automotive batteries. *Nature Energy* 2018;3:267–78. [https://doi.org/10.1038/s41560-018-0107-](https://doi.org/10.1038/s41560-018-0107-2)
2310 [2](https://doi.org/10.1038/s41560-018-0107-2).
- 2311 [287] Foss CEL, Müssig S, Svensson AM, Vie PJS, Ulvestad A, Mæhlen JP, et al. Anodes for Li-ion batteries
2312 prepared from microcrystalline silicon and enabled by binder's chemistry and pseudo-self-healing. *Scientific*
2313 *Reports* 2020;10:1–8. <https://doi.org/10.1038/s41598-020-70001-5>.

- 2314 [288] Sundén B. Hydrogen, Batteries and Fuel cells. United Kingdom: Elsevier Science; 2019.
2315 <https://doi.org/10.1016/B978-0-12-816950-6.00004-X>.
- 2316 [289] Wang C, Zhu K, Chi Z, Ke F, Yang Y, Wang A, et al. How far away are lithium-sulfur batteries from
2317 commercialization? *Frontiers in Energy Research* 2019. <https://doi.org/10.3389/fenrg.2019.00123>.
- 2318 [290] Li OL, Ishizaki T. Development , Challenges , and Prospects of Carbon-Based Electrode for Lithium-Air
2319 Batteries. Elsevier Inc.; 2018. <https://doi.org/10.1016/B978-0-12-813794-9.00004-1>.
- 2320 [291] Biemolt J, Jungbacker P, van Teijlingen T, Yan N, Rothenberg G. Beyond Lithium-Based Batteries.
2321 *Materials* 2020;13:425. <https://doi.org/10.3390/ma13020425>.
- 2322 [292] European Commission. Study on the EU's list of Critical Raw Materials - Final Report (2020). 2020.
- 2323 [293] Porzio J, Scown CD. Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Advanced*
2324 *Energy Materials* 2021;11:2100771. <https://doi.org/10.1002/aenm.202100771>.
- 2325 [294] Sripad S, Bills A, Viswanathan V. A review of safety considerations for batteries in aircraft with electric
2326 propulsion. *MRS Bulletin* 2021;46:435–42. <https://doi.org/10.1557/s43577-021-00097-1>.
- 2327 [295] Chin JC, Look K, McNichols EO, Hall DL, Gray JS, Schnulo SL. Battery Cell-to-Pack Scaling Trends for
2328 Electric Aircraft. *AIAA Propulsion and Energy 2021 Forum* 2021:15. <https://doi.org/10.2514/6.2021-3316>.
- 2329 [296] Kolly JM, Panagiotou J. The Investigation of a Lithium-Ion Battery Fire Onboard a Boeing 787 by the US
2330 National Transportation Safety Board. *International Society of Air Safety Investigators* 2013.
2331 <https://www.isasi.org/Documents/library/technical-papers/2013/ISASI%20NTSB%20Kolly.pdf>.
- 2332 [297] Li W, Li Y, Deng H, Bao L. Planning of Electric Public Transport System under Battery Swap Mode.
2333 *Sustainability* 2018;10:2528. <https://doi.org/10.3390/su10072528>.
- 2334 [298] Sarker MR, Pandzic H, Ortega-Vazquez MA. Optimal Operation and Services Scheduling for an Electric
2335 Vehicle Battery Swapping Station. *IEEE Trans Power Syst* 2015;30:901–10.
2336 <https://doi.org/10.1109/TPWRS.2014.2331560>.
- 2337 [299] United Nations. Commodities at a glance: Special issue on strategic battery raw materials No. 13. United
2338 Nations Conference on Trade and Development (UNCTAD) 2020. [https://unctad.org/system/files/official-](https://unctad.org/system/files/official-document/ditcom2019d5_en.pdf)
2339 [document/ditcom2019d5_en.pdf](https://unctad.org/system/files/official-document/ditcom2019d5_en.pdf).
- 2340 [300] Jara AD, Betemariam A, Woldetinsae G, Kim JY. Purification, application and current market trend of
2341 natural graphite: A review. *International Journal of Mining Science and Technology* 2019;29:671–89.
2342 <https://doi.org/10.1016/j.ijmst.2019.04.003>.
- 2343 [301] Chordia M, Nordelöf A, Ellingsen LA-W. Environmental life cycle implications of upscaling lithium-ion
2344 battery production. *Int J Life Cycle Assess* 2021;26:2024–39. <https://doi.org/10.1007/s11367-021-01976-0>.
- 2345 [302] Golmohammadzadeh R, Faraji F, Jong B, Pozo-Gonzalo C, Banerjee PC. Current challenges and future
2346 opportunities toward recycling of spent lithium-ion batteries. *Renewable and Sustainable Energy Reviews*
2347 2022;159:112202. <https://doi.org/10.1016/j.rser.2022.112202>.
- 2348 [303] Igogo T, Sandor D, Mayyas A, Engel-cox J. Supply chain of raw materials used in the manufacturing of
2349 light-duty vehicle lithium-ion batteries. *Clean Energy Manufacturing Analysis Center (CEMAC)* 2019.
2350 <https://www.nrel.gov/docs/fy19osti/73374.pdf>.
- 2351 [304] Wang L, Wu H, Hu Y, Yu Y, Huang K. Environmental sustainability assessment of typical cathode
2352 materials of lithium-ion battery based on three LCA approaches. *Processes* 2019;7.
2353 <https://doi.org/10.3390/pr7020083>.
- 2354 [305] Azimi N, Xue Z, Zhang SS, Zhang Z. 5 - Materials and technologies for rechargeable lithium-sulfur
2355 batteries. Elsevier Ltd.; 2015. <https://doi.org/10.1016/B978-1-78242-090-3.00005-5>.
- 2356 [306] Zackrisson M, Fransson K, Hildenbrand J, Lampic G, O'Dwyer C. Life cycle assessment of lithium-air
2357 battery cells. *Journal of Cleaner Production* 2016;135:299–311.
2358 <https://doi.org/10.1016/j.jclepro.2016.06.104>.
- 2359 [307] Wang F, Deng Y, Yuan C. Life cycle assessment of lithium oxygen battery for electric vehicles. *Journal of*
2360 *Cleaner Production* 2020;264:121339–121339. <https://doi.org/10.1016/j.jclepro.2020.121339>.
- 2361 [308] Wu Z, Kong D. Comparative life cycle assessment of lithium - ion batteries with lithium metal , silicon
2362 nanowire , and graphite anodes. *Clean Technologies and Environmental Policy* 2018;20:1233–44.
- 2363 [309] Yuan H, Huang JQ, Peng HJ, Titirici MM, Xiang R, Chen R, et al. A Review of Functional Binders in
2364 Lithium–Sulfur Batteries. *Advanced Energy Materials* 2018;8:1–20.
2365 <https://doi.org/10.1002/aenm.201802107>.
- 2366 [310] Doble A. New and Future Developments in Catalysis. *Catalytic Batteries*, Elsevier Inc.; 2013, p. 1–16.
2367 <https://doi.org/10.1016/B978-0-444-53880-2.00001-6>.
- 2368 [311] The Faraday Institution. Solid-State Batteries: The Technology of the 2030s but the Research Challenge of
2369 the 2020s 2020. https://faraday.ac.uk/wp-content/uploads/2020/04/Faraday-Insights-5_Updated.pdf.

- 2370 [312] Zenlabs. Clean Aerial and Ground Transport: Energy storage for the next generation of electric vehicles
2371 Zenlabs. Zenlabs 2022. <https://www.zenlabsinc.com> (accessed February 9, 2022).
- 2372 [313] Rao AG, Yin F, Werij HGC. Energy Transition in Aviation: The Role of Cryogenic Fuels. *Aerospace*
2373 2020;7:181. <https://doi.org/10.3390/aerospace7120181>.
- 2374 [314] Zohuri B. Hydrogen energy: Challenges and solutions for a cleaner future. *Hydrogen Energy: Challenges*
2375 *and Solutions for a Cleaner Future* 2018:1–283. <https://doi.org/10.1007/978-3-319-93461-7>.
- 2376 [315] Browne M. Clean Hydrogen Beckons Aviation Engineers. *The New York Times* 1988.
2377 <https://www.nytimes.com/1988/05/24/science/clean-hydrogen-beckons-aviation-engineers.html> (accessed
2378 September 27, 2022).
- 2379 [316] Klug HG, Faass R. CRYOPLANE: hydrogen fuelled aircraft — status and challenges. *Air & Space Europe*
2380 2001;3:252–4. [https://doi.org/10.1016/s1290-0958\(01\)90110-8](https://doi.org/10.1016/s1290-0958(01)90110-8).
- 2381 [317] Airbus. The ZEROe demonstrator has arrived | Airbus. Airbus 2022.
2382 <https://www.airbus.com/en/newsroom/stories/2022-02-the-zeroe-demonstrator-has-arrived> (accessed
2383 September 20, 2022).
- 2384 [318] Schuurman R. Airbus confirms the A380 as ZEROe hydrogen demonstrator. *AirInsight* 2022.
2385 <https://airinsight.com/airbus-confirms-the-a380-as-zeroe-hydrogen-demonstrator/> (accessed September 20,
2386 2022).
- 2387 [319] Boeing. Boeing: Phantom Eye 2013. <https://www.boeing.com/defense/phantom-eye> (accessed January 6,
2388 2022).
- 2389 [320] Hoelzen J, Silberhorn D, Zill T, Bensmann B, Hanke-Rauschenbach R. Hydrogen-powered aviation and its
2390 reliance on green hydrogen infrastructure – Review and research gaps. *International Journal of Hydrogen*
2391 *Energy* 2022;47:3108–30. <https://doi.org/10.1016/j.ijhydene.2021.10.239>.
- 2392 [321] IATA. Fact sheet 7: Liquid hydrogen as a potential low-carbon fuel for aviation. IATA 2020.
2393 [https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-](https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf)
2394 [sheet_072020.pdf](https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf).
- 2395 [322] Javed I, Baek SW, Waheed K. Autoignition and combustion characteristics of kerosene droplets with dilute
2396 concentrations of aluminum nanoparticles at elevated temperatures. *Combustion and Flame* 2015;162:774–
2397 87. <https://doi.org/10.1016/j.combustflame.2014.08.018>.
- 2398 [323] Airbus. ZEROe project: Towards the world’s first zero-emission commercial aircraft 2020.
2399 <https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe> (accessed January 6, 2022).
- 2400 [324] European Commission, Directorate-General for Research and Innovation. Environmental impact
2401 assessments of innovative bio-based product . Task 1 of “Study on Support to R&I Policy in the Area of
2402 Bio-based Products and Services “. Publications Office 2019. <https://data.europa.eu/doi/10.2777/251887>
2403 (accessed January 7, 2022).
- 2404 [325] IATA. Aircraft Technology Roadmap to 2050. IATA 2017.
2405 <https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf>.
- 2406 [326] Saaty TL. Decision making with the analytic hierarchy process. *International Journal of Services Sciences*
2407 2008;1:83–98. [https://doi.org/10.1016/0305-0483\(87\)90016-8](https://doi.org/10.1016/0305-0483(87)90016-8).
- 2408 [327] de Jong S, Antonissen K, Hoefnagels R, Lonza L, Wang M, Faaij A, et al. Life-cycle analysis of greenhouse
2409 gas emissions from renewable jet fuel production. *Biotechnology for Biofuels* 2017;10:1–18.
2410 <https://doi.org/10.1186/s13068-017-0739-7>.
- 2411 [328] ICAO. CORSIA Supporting document: CORSIA Eligible Fuels - Life Cycle Assessment Methodology.
2412 ICAO 2021. [https://www.icao.int/environmental-](https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_L)
2413 [protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_L](https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_L)
2414 [CA%20Methodology.pdf](https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_L).
- 2415 [329] IATA. Jet Fuel Price Monitor. IATA 2021. <https://www.iata.org/en/publications/economics/fuel-monitor/>
2416 (accessed January 7, 2022).
- 2417 [330] IATA. IATA Sustainable aviation fuel roadmap 1st Edition 2015.
2418 <https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/safr-1-2015.pdf>.
- 2419 [331] Stratton RW, Wong HM, Hileman JI. Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels
2420 2010. <http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf>.
- 2421 [332] IRENA. A pathway to decarbonise the shipping sector by 2050. International Renewable Energy Agency
2422 (IRENA) 2021. [https://www.irena.org/-](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf)
2423 [/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf).

- 2424 [333] DNV GL. Maritime forecast to 2050 Energy Transition Outlook 2019 2019.
2425 [https://sustainableworldports.org/wp-content/uploads/DNV-GL_2019_Maritime-forecast-to-2050-Energy-](https://sustainableworldports.org/wp-content/uploads/DNV-GL_2019_Maritime-forecast-to-2050-Energy-transition-Outlook-2019-report.pdf)
2426 [transition-Outlook-2019-report.pdf](https://sustainableworldports.org/wp-content/uploads/DNV-GL_2019_Maritime-forecast-to-2050-Energy-transition-Outlook-2019-report.pdf).
- 2427 [334] SAVION Inc. SAVION Aerospace. FlySavion 2020. <https://www.flysavion.com/about-us> (accessed March
2428 24, 2022).
- 2429 [335] Burstone M, Conroy T, Spiteri L, Spiteri M, Bil C, Dorrington GE. Conceptual Design of Sustainable Liquid
2430 Methane Fuelled Passenger Aircraft, 20th ISPE International Conference on Concurrent Engineering; 2013,
2431 p. 391–400. <https://doi.org/10.3233/978-1-61499-302-5-391>.
- 2432 [336] Garcia Jarque S, Birgen C. Liquefied Synthesis Natural Gas from Woody Biomass - Investigation of
2433 Cryogenic Technique for Gas Upgrading. Universitat Politècnica de Catalunya 2013.
2434 <http://hdl.handle.net/2099.1/20309>.
- 2435 [337] Ghaib K, Ben-Fares F-Z. Power-to-Methane: A state-of-the-art review. *Renewable and Sustainable Energy*
2436 *Reviews* 2018;81:433–46. <https://doi.org/10.1016/j.rser.2017.08.004>.
- 2437 [338] Rompokos P, Kissoon S, Roumeliotis I, Nalianda D, Nikolaidis T, Rolt A. Liquefied natural gas for civil
2438 aviation. *Energies* 2020;13. <https://doi.org/10.3390/en13225925>.
- 2439 [339] Withers MR, Malina R, Gilmore CK, Gibbs JM, Trigg C, Wolfe PJ, et al. Economic and environmental
2440 assessment of liquefied natural gas as a supplemental aircraft fuel. *Progress in Aerospace Sciences*
2441 2014;66:17–36. <https://doi.org/10.1016/j.paerosci.2013.12.002>.
- 2442 [340] Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Pean C, Berger S, et al. IPCC 2021: Summary for
2443 Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the*
2444 *Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press;
2445 2021.
- 2446 [341] Bradley MK, Droncy CK. Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept
2447 Development. NTRS - NASA Technical Reports Server 2012. <https://ntrs.nasa.gov/citations/20120009038>.
- 2448 [342] Rao AG, Yin F. The AHEAD project: Advanced Hybrid Engines for Aircraft Development. CORDIS EU
2449 Research Results 2013. <https://cordis.europa.eu/project/id/284636/reporting>.
- 2450 [343] Bicer Y, Dincer I. Life cycle evaluation of hydrogen and other potential fuels for aircrafts. *International*
2451 *Journal of Hydrogen Energy* 2017;42:10722–38. <https://doi.org/10.1016/j.ijhydene.2016.12.119>.
- 2452 [344] Terpitz J. LNG for Aircraft 2019. [https://www.gti.energy/wp-content/uploads/2019/10/151-LNG19-](https://www.gti.energy/wp-content/uploads/2019/10/151-LNG19-03April2019-Terpitz-Julian-paper.pdf)
2453 [03April2019-Terpitz-Julian-paper.pdf](https://www.gti.energy/wp-content/uploads/2019/10/151-LNG19-03April2019-Terpitz-Julian-paper.pdf).
- 2454 [345] Reaction Engines. Reaction Engines, STFC engaged in ground-breaking study on ammonia fuel for a
2455 sustainable aviation propulsion system. *Reaction Engines* 2020.
2456 [https://www.reactionengines.co.uk/news/news/reaction-engines-stfc-engaged-ground-breaking-study-](https://www.reactionengines.co.uk/news/news/reaction-engines-stfc-engaged-ground-breaking-study-ammonia-fuel-sustainable-aviation-propulsion-system)
2457 [ammonia-fuel-sustainable-aviation-propulsion-system](https://www.reactionengines.co.uk/news/news/reaction-engines-stfc-engaged-ground-breaking-study-ammonia-fuel-sustainable-aviation-propulsion-system) (accessed September 28, 2022).
- 2458 [346] Raytheon Technologies. Ammonia could fuel the future of sustainable flight. Raytheon Technologies 2021.
2459 <https://www.rtx.com/News/2020/12/09/ammonia-could-fuel-the-future-of-sustainable-flight> (accessed
2460 October 7, 2022).
- 2461 [347] Smith L. Zero-carbon Ammonia-Powered Turboelectric Propulsion System (ZAPturbo) 2021. [https://arpa-](https://arpa-e.energy.gov/sites/default/files/2021-02/04_Smith_ZAPTurboKickoffJan2021_vIII.pdf)
2462 [e.energy.gov/sites/default/files/2021-02/04_Smith_ZAPTurboKickoffJan2021_vIII.pdf](https://arpa-e.energy.gov/sites/default/files/2021-02/04_Smith_ZAPTurboKickoffJan2021_vIII.pdf).
- 2463 [348] Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q, et al. The contribution of global aviation
2464 to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment* 2021;244:29.
2465 <https://doi.org/10.1016/j.atmosenv.2020.117834>.
- 2466 [349] Mulder TJ, Ruijgrok GJJ. On the reduction of NOx-emission levels by performing low NOx flights. 26th
2467 International Congress of the Aeronautical Sciences 2008.
2468 http://www.icas.org/ICAS_ARCHIVE/ICAS2008/PAPERS/532.PDF.
- 2469 [350] Snelgrove G. Oxford University Looks To Power Aircraft With Ammonia 2020.
2470 <https://simpleflying.com/ammonia-powered-aircraft/> (accessed March 25, 2022).
- 2471 [351] Ghavam S, Vahdati M, Wilson IAG, Styring P. Sustainable Ammonia Production Processes. *Front Energy*
2472 *Res* 2021;9:580808. <https://doi.org/10.3389/fenrg.2021.580808>.
- 2473 [352] Chatterjee S, Parsapur RK, Huang K-W. Limitations of Ammonia as a Hydrogen Energy Carrier for the
2474 Transportation Sector. *ACS Energy Lett* 2021;6:4390–4. <https://doi.org/10.1021/acsenrg.1c02189>.
- 2475 [353] Valera-Medina A, Amer-Hatem F, Azad AK, Dedoussi IC, de Joannon M, Fernandes RX, et al. Review on
2476 Ammonia as a Potential Fuel: From Synthesis to Economics. *Energy Fuels* 2021;35:6964–7029.
2477 <https://doi.org/10.1021/acs.energyfuels.0c03685>.
- 2478 [354] Kyriakou V, Garagounis I, Vasileiou E, Vourros A, Stoukides M. Progress in the Electrochemical Synthesis
2479 of Ammonia. *Catalysis Today* 2017;286:2–13. <https://doi.org/10.1016/j.cattod.2016.06.014>.

- 2480 [355] Brown T. Industry report sees multi-billion ton market for green ammonia. Ammonia Energy Association
2481 2020. [https://www.ammoniaenergy.org/articles/industry-report-sees-multi-billion-ton-market-for-green-](https://www.ammoniaenergy.org/articles/industry-report-sees-multi-billion-ton-market-for-green-ammonia/)
2482 [ammonia/](https://www.ammoniaenergy.org/articles/industry-report-sees-multi-billion-ton-market-for-green-ammonia/) (accessed April 15, 2022).
- 2483 [356] Wetering L. Zero-emissions aeroplanes that use ammonia as jet fuel rather than kerosene could take to the
2484 skies within years. *Daurzame Luchtvaart* 2020. [https://www.dailymail.co.uk/sciencetech/article-](https://www.dailymail.co.uk/sciencetech/article-8611587/Zero-emission-ammonia-fuelled-aeroplanes-skies-years.html)
2485 [8611587/Zero-emission-ammonia-fuelled-aeroplanes-skies-years.html](https://www.dailymail.co.uk/sciencetech/article-8611587/Zero-emission-ammonia-fuelled-aeroplanes-skies-years.html) (accessed December 10, 2021).
- 2486 [357] Imhoff TB, Gkantonas S, Mastorakos E. Analysing the Performance of Ammonia Powertrains in the Marine
2487 Environment. *Energies* 2021;14:7447. <https://doi.org/10.3390/en14217447>.
- 2488 [358] Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. Planetary boundaries:
2489 Guiding human development on a changing planet. *Science* 2015;347:1259855.
2490 <https://doi.org/10.1126/science.1259855>.
- 2491 [359] Erdemir D, Dincer I. A perspective on the use of ammonia as a clean fuel: Challenges and solutions. *Int J*
2492 *Energy Res* 2021;45:4827–34. <https://doi.org/10.1002/er.6232>.
- 2493 [360] Zhao Y, Setzler BP, Wang J, Nash J, Wang T, Xu B, et al. An Efficient Direct Ammonia Fuel Cell for
2494 Affordable Carbon-Neutral Transportation. *Joule* 2019;3:2472–84.
2495 <https://doi.org/10.1016/j.joule.2019.07.005>.
- 2496 [361] Kanchwala H. What Is A Solar-Powered Airplane? Can It Replace The Conventional Jet-fueled Airplanes?
2497 *Science ABC* 2018. [https://www.scienceabc.com/innovation/solar-powered-plane-future-aviation-](https://www.scienceabc.com/innovation/solar-powered-plane-future-aviation-industry.html)
2498 [industry.html](https://www.scienceabc.com/innovation/solar-powered-plane-future-aviation-industry.html) (accessed March 25, 2022).
- 2499 [362] Blais C. MIT School of Engineering | » Is it possible to make solar-powered airplanes? MIT School of
2500 Engineering 2016. [https://engineering.mit.edu/engage/ask-an-engineer/is-it-possible-to-make-solar-powered-](https://engineering.mit.edu/engage/ask-an-engineer/is-it-possible-to-make-solar-powered-airplanes/)
2501 [airplanes/](https://engineering.mit.edu/engage/ask-an-engineer/is-it-possible-to-make-solar-powered-airplanes/) (accessed January 7, 2022).
- 2502 [363] Svarc J. Most efficient solar panels 2021. *Clean Energy Reviews* 2021.
2503 <https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels> (accessed January 7, 2022).
- 2504 [364] Safyanu BD, Abdullah MN, Omar Z. Review of Power Device for Solar-Powered Aircraft Applications.
2505 *JAerosp Technol Manag* 2019:e4119. <https://doi.org/10.5028/jatm.v11.1077>.
- 2506 [365] Methanology. MY-Methanol for Aviation | METHANOLOGY 2021.
2507 <https://www.methanology.com/methaviation> (accessed December 23, 2021).
- 2508 [366] Green Car Congress. Element 1 and NEXA Capital partner on methanol-based hydrogen generation for
2509 electric vertical aircraft. *Green Car Congress* 2021. [https://www.greencarcongress.com/2021/11/20211130-](https://www.greencarcongress.com/2021/11/20211130-e1.html)
2510 [e1.html](https://www.greencarcongress.com/2021/11/20211130-e1.html) (accessed December 23, 2021).
- 2511 [367] Helder D, Behnken J, Aulich T. Design of Ethanol Based Fuels for Aviation. Section 1: *Journal of*
2512 *Aerospace* (2000) 2000;109:243–56. <https://doi.org/10.4271/2000-01-1712>.
- 2513 [368] Shauck ME, Zanin MG. Certification of an aircraft engine on ethanol fuel 1990.
2514 <https://afdc.energy.gov/files/pdfs/2896.pdf> (accessed January 20, 2022).
- 2515 [369] Christoph Vratny P. Conceptual Design Methods of Electric Power Architectures for Hybrid Energy
2516 Aircraft. *Technische Universität München* 2018. <https://d-nb.info/1183259239/34>.
- 2517 [370] Misra A. Energy Conversion and Storage Requirements for Hybrid Electric Aircraft. 40th International
2518 Conference and Expo on Advanced Ceramics and Composites 2016.
2519 <https://ntrs.nasa.gov/api/citations/20160010280/downloads/20160010280.pdf> (accessed March 3, 2022).
- 2520 [371] Hoelzen J, Liu Y, Bensmann B, Winnefeld C, Elham A, Friedrichs J, et al. Conceptual design of operation
2521 strategies for hybrid electric aircraft. *Energies* 2018;11:1–26. <https://doi.org/10.3390/en11010217>.
- 2522 [372] Baumeister S, Leung A, Ryley T. The emission reduction potentials of First Generation Electric Aircraft
2523 (FGEA) in Finland. *Journal of Transport Geography* 2020;85:102730–102730.
2524 <https://doi.org/10.1016/j.jtrangeo.2020.102730>.
- 2525 [373] MAHEPA project. D1.1 : Concept of Modular Architecture for Hybrid Electric Propulsion of Aircraft.
2526 Modular Approach to Hybrid Electric Propulsion Architecture (MAHEPA) 2017. [https://mahepa.eu/wp-](https://mahepa.eu/wp-content/uploads/2017/12/D1.1-Concept-of-Modular-Architecture-fro-Hybrid-Electric-Propulsion-of-Aircraft.pdf)
2527 [content/uploads/2017/12/D1.1-Concept-of-Modular-Architecture-fro-Hybrid-Electric-Propulsion-of-](https://mahepa.eu/wp-content/uploads/2017/12/D1.1-Concept-of-Modular-Architecture-fro-Hybrid-Electric-Propulsion-of-Aircraft.pdf)
2528 [Aircraft.pdf](https://mahepa.eu/wp-content/uploads/2017/12/D1.1-Concept-of-Modular-Architecture-fro-Hybrid-Electric-Propulsion-of-Aircraft.pdf).
- 2529 [374] Xie Y, Savvarisal, Antonios T, Dan Z, Jason G. Review of hybrid electric powered aircraft, its conceptual
2530 design and energy management methodologies. *Chinese Journal of Aeronautics* 2020.
2531 <https://doi.org/10.1016/j.cja.2020.07.017>.
- 2532 [375] Gil AA, Silva HL. Hybrid-Electric Aircraft: Conceptual Design, Structural and Aeroelastic Analyses.
2533 *Universidade Federal de Uberlândia* 2017:123.
2534 <https://repositorio.ufu.br/bitstream/123456789/20599/3/HybridElectricAircraft.pdf>.

- 2535 [376] Boggero L, Corpino S, De Martin A, Evangelista G, Fioriti M, Sorli M. A virtual test bench of a parallel
2536 hybrid propulsion system for UAVs. *Aerospace* 2019;6. <https://doi.org/10.3390/AEROSPACE6070077>.
- 2537 [377] Chen PT, Pai PH, Yang CJ, Huang KD. Development of transmission systems for parallel hybrid electric
2538 vehicles. *Applied Sciences (Switzerland)* 2019;9. <https://doi.org/10.3390/app9081538>.
- 2539 [378] Brelje BJ, Martins JRRA. Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts,
2540 models, and design approaches. *Progress in Aerospace Sciences* 2019;104:1–19.
2541 <https://doi.org/10.1016/j.paerosci.2018.06.004>.
- 2542 [379] Eviation. Eviation. Media - Eviation 2022. <https://www.eviation.co/media/> (accessed September 19, 2022).
- 2543 [380] Alcock C. Eviation’s Alice Electric Aircraft Catches Fire During Ground Tests. *AIN Online* 2020.
2544 [https://www.ainonline.com/aviation-news/business-aviation/2020-01-24/eviations-electric-alice-aircraft-](https://www.ainonline.com/aviation-news/business-aviation/2020-01-24/eviations-electric-alice-aircraft-catches-fire-during-ground-tests)
2545 [catches-fire-during-ground-tests](https://www.ainonline.com/aviation-news/business-aviation/2020-01-24/eviations-electric-alice-aircraft-catches-fire-during-ground-tests) (accessed November 13, 2021).
- 2546 [381] magniX. magniX. MagniX 2019. <https://www.magnix.aero/> (accessed August 30, 2022).
- 2547 [382] Pallini T. The world’s largest electric plane just took its first flight in the latest milestone for battery-
2548 powered passenger flights. *Business Insider* 2020. [https://www.businessinsider.com/magnix-all-electric-](https://www.businessinsider.com/magnix-all-electric-cessna-grand-caravan-takes-first-flight-2020-6)
2549 [cessna-grand-caravan-takes-first-flight-2020-6](https://www.businessinsider.com/magnix-all-electric-cessna-grand-caravan-takes-first-flight-2020-6) (accessed December 20, 2021).
- 2550 [383] Grad P. Groundbreaking all-electric plane paving way to greener aviation. *TechxploreCom* 2020.
2551 <https://techxplore.com/news/2020-05-groundbreaking-all-electric-plane-paving-greener.html> (accessed
2552 October 25, 2021).
- 2553 [384] Campbell M. World’s largest all-electric plane generates zero carbon emissions. *EuronewsGreen* 2020.
2554 [https://www.euronews.com/living/2020/06/01/world-s-largest-all-electric-plane-generates-zero-carbon-](https://www.euronews.com/living/2020/06/01/world-s-largest-all-electric-plane-generates-zero-carbon-emissions)
2555 [emissions](https://www.euronews.com/living/2020/06/01/world-s-largest-all-electric-plane-generates-zero-carbon-emissions) (accessed November 1, 2021).
- 2556 [385] easyJet. easyJet’s partner Wright Electric begins engine development program for 186 seat electric aircraft.
2557 *MediacentreEasyjetCom* 2020. [https://mediacentre.easyjet.com/story/13660/easyjet-s-partner-wright-](https://mediacentre.easyjet.com/story/13660/easyjet-s-partner-wright-electric-begins-engine-development-program-for-186-seat-electric-aircraft)
2558 [electric-begins-engine-development-program-for-186-seat-electric-aircraft](https://mediacentre.easyjet.com/story/13660/easyjet-s-partner-wright-electric-begins-engine-development-program-for-186-seat-electric-aircraft) (accessed November 20, 2021).
- 2559 [386] Sustainable Skies. Wright Electric Reveals Big Plans | Sustainable Skies n.d.
2560 <https://sustainableskies.org/wright-electric-reveals-big-plans/> (accessed December 20, 2021).
- 2561 [387] Barnes P. General Aviation Aircraft: Fuel cell hybrids for electric propulsion. *AerosocietyCom* 2019.
2562 <https://www.aerosociety.com/media/12868/raes-fuel-cell-presentation-v31.pdf> (accessed September 29,
2563 2022).
- 2564 [388] National Academies of Science, Engineering, Medicine. Commercial aircraft propulsion and energy systems
2565 research: Reducing global carbon emissions. Washington, DC: National Academies Press; 2016.
2566 <https://doi.org/10.17226/23490>.
- 2567 [389] Bassam AM, Phillips AB, Turnock SR, Wilson PA. An improved energy management strategy for a hybrid
2568 fuel cell/battery passenger vessel. *International Journal of Hydrogen Energy* 2016;41:22453–64.
2569 <https://doi.org/10.1016/j.ijhydene.2016.08.049>.
- 2570 [390] Sahoo S, Zhao X, Kyprianidis K. A review of concepts, benefits, and challenges for future electrical
2571 propulsion-based aircraft. *Aerospace* 2020;7. <https://doi.org/10.3390/aerospace7040044>.
- 2572 [391] Alrashed M, Nikolaidis T, Pilidis P, Jafari S. Utilisation of turboelectric distribution propulsion in
2573 commercial aviation: A review on NASA’s TeDP concept. *Chinese Journal of Aeronautics* 2021;34:48–65.
2574 <https://doi.org/10.1016/j.cja.2021.03.014>.
- 2575 [392] Rodrigo C. Basic Comparison of Three Aircraft Concepts: Classic Jet Propulsion, Turbo-Electric
2576 Propulsion and Turbo-Hydraulic Propulsion. Master Thesis. Hamburg : Aircraft Design and Systems Group
2577 (AERO), Department of Automotive and Aeronautical Engineering, Hamburg University of Applied
2578 Sciences 2019. <https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2019-09-22.014>.
- 2579 [393] Rendón MA, Sánchez R. CD, Gallo M. J, Anzai AH. Aircraft Hybrid-Electric Propulsion: Development
2580 Trends, Challenges and Opportunities. *J Control Autom Electr Syst* 2021;32:1244–68.
2581 <https://doi.org/10.1007/s40313-021-00740-x>.
- 2582 [394] Welstead JR, Felder JL. Conceptual design of a single-aisle turboelectric commercial transport with fuselage
2583 boundary layer ingestion. *54th AIAA Aerospace Sciences Meeting* 2016;0:1–17.
2584 <https://doi.org/10.2514/6.2016-1027>.
- 2585 [395] Del Rosario R. A Future with Hybrid Electric Propulsion Systems: A NASA Perspective. *NASA* 2015.
2586 <https://ntrs.nasa.gov/search.jsp?R=20150000748>.
- 2587 [396] Nalianda D, Singh R. Turbo-Electric distributed propulsion - Opportunities, benefits and challenges. *Aircraft
2588 Engineering and Aerospace Technology* 2014;86:543–9. <https://doi.org/10.1108/AEAT-03-2014-0035>.

- 2589 [397] Baldino C, Searle S. Changes to the Renewable Energy Directive revision and ReFuel EU proposals:
2590 Greenhouse gas savings and costs in 2030. ICCT 2021. <https://theicct.org/publication/changes-to-the-renewable-energy-directive-revision-and-refuel-eu-proposals-greenhouse-gas-savings-and-costs-in-2030/>.
- 2591 [398] EASA. European Aviation Environmental Report 2019. European Union Aviation Safety Agency (EASA)
2592 2019. www.easa.europa.eu/eaer.
- 2593 [399] Searle S. Alternative transport fuels elements of the European Union's "Fit for 55" package. ICCT 2021.
2594 [https://theicct.org/publication/alternative-transport-fuels-elements-of-the-european-unions-fit-for-55-](https://theicct.org/publication/alternative-transport-fuels-elements-of-the-european-unions-fit-for-55-package/)
2595 [package/](https://theicct.org/publication/alternative-transport-fuels-elements-of-the-european-unions-fit-for-55-package/).
- 2596 [400] IATA. Fact Sheet Climate and CORSIA. IATA 2018.
2597 <https://www.iata.org/contentassets/713a82c7fbf84947ad536df18d08ed86/fact-sheet-climate-change.pdf>.
- 2598 [401] ICCT. International Council on Clean Transportation consultation response on Proposal for a Directive of
2599 the European Parliament and of the Council amending Directive 2003/87/EC as regards aviation's
2600 contribution to the Union's economy-wide emission reduction target and appropriately implementing a
2601 global market-based measure 2021. [https://www.europarl.europa.eu/doceo/document/A-6-2007-](https://www.europarl.europa.eu/doceo/document/A-6-2007-0402_EN.html)
2602 [0402_EN.html](https://www.europarl.europa.eu/doceo/document/A-6-2007-0402_EN.html).
- 2603 [402] European Commission. Mobility Strategy. European Commission 2020.
2604 https://transport.ec.europa.eu/transport-themes/mobility-strategy_en (accessed June 3, 2022).
- 2605 [403] European Commission. Communication from the Commission to the European parliament, the Council, the
2606 European Economic and Social Committee and the Committee of the regions: Sustainable and Smart
2607 Mobility Strategy - putting European transport on track for the future. European Commission 2020.
2608 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789> (accessed December 15,
2609 2022).
- 2610 [404] European Commission. 2030 Climate Target Plan 2021. [https://ec.europa.eu/clima/eu-action/european-](https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en)
2611 [green-deal/2030-climate-target-plan_en](https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en) (accessed January 7, 2022).
- 2612 [405] European Commission. Directive 2009/28/EC of the European Parliament and of the Council of 23 April
2613 2009 on the promotion of the use of energy from renewable sources and amending and subsequently
2614 repealing Directives 2001/77/EC and 2003/30/EC. European Commission 2009. [https://eur-](https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028)
2615 [lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028](https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028).
- 2616 [406] The European Parliament and of the Council. Directive (EU) 2015/1513 of the European Parliament and of
2617 the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel
2618 fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable 2015.
2619 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32015L1513>.
- 2620 [407] Meijerink O, Valk M, Junginger M. The voluntary RED opt-in for aviation biofuels 2016.
2621 [https://fdocuments.net/document/the-voluntary-red-opt-in-for-aviation-biofuels-in-could-be-implemented-](https://fdocuments.net/document/the-voluntary-red-opt-in-for-aviation-biofuels-in-could-be-implemented-into-the.html?page=1)
2622 [into-the.html?page=1](https://fdocuments.net/document/the-voluntary-red-opt-in-for-aviation-biofuels-in-could-be-implemented-into-the.html?page=1) (accessed June 27, 2022).
- 2623 [408] Mai-Moulin T, Hoefnagels R, Grundmann P, Junginger M. Effective sustainability criteria for bioenergy:
2624 Towards the implementation of the european renewable directive II. Renewable and Sustainable Energy
2625 Reviews 2021;138:110645. <https://doi.org/10.1016/j.rser.2020.110645>.
- 2626 [409] European Commission. Commission delegated regulation (EU) of 13.3.2019 supplementing Directive (EU)
2627 2018/2001 as regards the determination of high direct land-use change-risk feedstock for which a significant
2628 expansion of the production area into land with high carbon stock is observed and the certification of low
2629 indirect land-use change-risk biofuels, bioliquids, and biomass fuels. European Commission 2019.
2630 <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0807>.
- 2631 [410] European Commission. Proposal for a directive of the European Parliament and of the council: amending
2632 directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the
2633 European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the
2634 Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU)
2635 2015/652 2021. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0557>.
- 2636 [411] European Parliament and of the Council. Directive 2008/101/EC of the European Parliament and of the
2637 Council of 19 November 2008 amending Directive 2003 87 EC so as to include aviation activities in the
2638 scheme for greenhouse gas emission allowance trading within the Community 2008. [https://eur-](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0101)
2639 [lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0101](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0101).
- 2640 [412] European Parliament and of the Council. Regulation (EU) 2017/2392 of the European Parliament and of the
2641 Council of 13 December 2017 amending Directive 2003/87/EC to continue current limitations of scope for
2642 aviation activities and to prepare to implement a global market-based measure from 2021 2017. [https://eur-](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.350.01.0007.01.ENG)
2643 [lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.350.01.0007.01.ENG](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.350.01.0007.01.ENG).
- 2644

- 2645 [413] Ministry of Ecological and Solidarity Transition. French strategy for energy and climate: Multi annual
2646 energy plan 2019-2023 and 2024-2028. Ministry of Ecological and Solidarity Transition 2019.
2647 https://www.ecologie.gouv.fr/sites/default/files/0-PPE%20English%20Version%20With%20Annex_0.pdf
2648 (accessed December 3, 2021).
- 2649 [414] EMBER. Carbon pricing: The latest data on EU ETS. Ember 2022. [https://ember-climate.org/data/data-
2650 tools/carbon-price-viewer/](https://ember-climate.org/data/data-tools/carbon-price-viewer/) (accessed June 3, 2022).
- 2651 [415] ICAP. EU Emission Trading System (EU ETS) ETS Detailed Information. International Carbon Action
2652 Partnership (ICAP) 2021. <https://icapcarbonaction.com/en/ets/eu-emissions-trading-system-eu-ets> (accessed
2653 May 15, 2022).
- 2654 [416] Preston H, Lee DS, Hooper PD. The inclusion of the aviation sector within the European Union's Emissions
2655 Trading Scheme: What are the prospects for a more sustainable aviation industry? *Environmental
2656 Development* 2012;2:48–56. <https://doi.org/10.1016/j.envdev.2012.03.008>.
- 2657 [417] Leggett JA, Elias B, Shedd DT. Aviation and the European Union's Emission Trading Scheme 2012.
2658 <https://sgp.fas.org/crs/row/R42392.pdf>.
- 2659 [418] European Commission. Allocation to aviation. An Official Website of the European Union 2022.
2660 [https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/allocation-
2661 aviation_en](https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/allocation-aviation_en) (accessed June 3, 2022).
- 2662 [419] European Commission. Notice on the Union-wide quantity of allowances for 2021 and the Market Stability
2663 Reserve under the EU Emissions Trading System (Text with EEA relevance) 2020/C 428 I/01 2020.
2664 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.CI.2020.428.01.0001.01.ENG>
2665 (accessed February 22, 2022).
- 2666 [420] De Clercq G, Psaledakis D. EU nations aim high with plan to tax air travel. *ReuterCom* 2019.
2667 <https://www.reuters.com/article/us-climate-change-eu-airlines-idUSKCN1TL1I7> (accessed June 6, 2022).
- 2668 [421] Jensen L. Aviation's contribution to European Union climate action: Revision of EU ETS as regards aviation
2669 2022.
2670 [https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698882/EPRS_BRI\(2022\)698882_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698882/EPRS_BRI(2022)698882_EN.pdf).
- 2671 [422] European Commission. Aviation and the EU ETS. An Official Website of the European Union 2022.
2672 [https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/aviation-and-eu-
2673 ets_en](https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/aviation-and-eu-ets_en) (accessed June 3, 2022).
- 2674 [423] Duch Guillot J. Fit for 55: Parliament pushes for greener aviation fuels. *News European Parliament* 2022.
2675 [https://www.europarl.europa.eu/news/en/press-room/20220701IPR34357/fit-for-55-parliament-pushes-for-
2677 greener-aviation-fuels](https://www.europarl.europa.eu/news/en/press-room/20220701IPR34357/fit-for-55-parliament-pushes-for-
2676 greener-aviation-fuels) (accessed June 21, 2022).
- 2677 [424] SkyNRG. A summary of the proposed Sustainable Aviation Fuel mandate. SkyNRG 2021.
2678 <https://skynrg.com/a-summary-of-the-proposed-sustainable-aviation-fuel-mandate/> (accessed December 7,
2679 2021).
- 2680 [425] European Commission. Revision of the Energy Taxation Directive (ETD): Questions and Answers.
2681 European Commission 2021.
2682 [https://ec.europa.eu/commission/presscorner/api/files/document/print/en/qanda_21_3662/QANDA_21_3662
2684 _EN.pdf](https://ec.europa.eu/commission/presscorner/api/files/document/print/en/qanda_21_3662/QANDA_21_3662
2683 _EN.pdf).
- 2684 [426] KPMG. Energy Taxation Directive. KPMG 2021. [https://home.kpmg/xx/en/home/insights/2021/08/energy-
2686 taxation-directive.html](https://home.kpmg/xx/en/home/insights/2021/08/energy-
2685 taxation-directive.html) (accessed July 7, 2022).
- 2686 [427] Euractiv. LEAK: EU to propose aviation fuel tax in green policy push 2021.
2687 [https://www.euractiv.com/section/alternative-renewable-fuels/news/leak-eu-to-propose-aviation-fuel-tax-in-
2689 green-policy-push/](https://www.euractiv.com/section/alternative-renewable-fuels/news/leak-eu-to-propose-aviation-fuel-tax-in-
2688 green-policy-push/) (accessed January 7, 2022).
- 2689 [428] European Commission. Proposal for a Regulation of the European Parliament and of the Council
2690 establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999
2691 (European Climate Law). European Commission 2020. [https://eur-lex.europa.eu/legal-
2693 content/EN/TXT/?uri=CELEX%3A52020PC0080](https://eur-lex.europa.eu/legal-
2692 content/EN/TXT/?uri=CELEX%3A52020PC0080) (accessed July 10, 2022).
- 2693 [429] European Commission. Launch of the European Advanced Biofuels Flightpath. European Commission
2694 2011. https://ec.europa.eu/energy/sites/ener/files/20110622_biofuels_flight_path_launch.pdf (accessed June
2695 27, 2022).
- 2696 [430] Grand-Perret S, Maniatis K, Pylkkanen O, Roger P, Cobror S, Zschocke A, et al. 2 million tons per year: A
2697 performing biofuels supply chain for EU aviation: Revision of the version initially published June 2011
2698 2013. https://ec.europa.eu/energy/sites/ener/files/20130911_a_performing_biofuels_supply_chain.pdf
2699 (accessed February 1, 2022).

- 2700 [431] Ministry of Ecological and Solidarity Transition, Ministry of Economy and Finance. Engagements pour la
2701 croissance verte. *EcologieGouvFr* 2017. [https://www.ecologie.gouv.fr/loi-transition-energetique-croissance-](https://www.ecologie.gouv.fr/loi-transition-energetique-croissance-verte)
2702 [verte](https://www.ecologie.gouv.fr/loi-transition-energetique-croissance-verte) (accessed May 22, 2022).
- 2703 [432] Ministry for the Ecological and Inclusive Transition. Feuille de route française pour le déploiement des
2704 biocarburants aéronautiques durables. *EcologieGouvFr* 2020.
2705 <https://www.ecologie.gouv.fr/sites/default/files/Feuille%20de%20route%20fran%20C3%A7aise%20pour%20l%20d%20C3%A9ploiement%20des%20biocarburants%20a%20C3%A9ronautiques%20durables.pdf> (accessed
2706 June 15, 2022).
- 2707 [433] Ministry of Economy and Finance. Presentation of the aeronautical support plan 2020.
2708 <https://www.economie.gouv.fr/plan-soutien-aeronautique#> (accessed January 22, 2022).
- 2709 [434] Carroll SG. First clean jets will be ready for commercial flight by 2035, industry says 2022.
2710 [https://www.euractiv.com/section/aviation/news/first-clean-jets-will-be-ready-for-commercial-flight-by-](https://www.euractiv.com/section/aviation/news/first-clean-jets-will-be-ready-for-commercial-flight-by-2035-industry-says/)
2711 [2035-industry-says/](https://www.euractiv.com/section/aviation/news/first-clean-jets-will-be-ready-for-commercial-flight-by-2035-industry-says/) (accessed June 2, 2022).
- 2712 [435] Derber A. France Boosts Clean Aircraft Technologies. *Aviation Week Network* 2020.
2713 <https://m.aviationweek.com/mro/france-boosts-clean-aircraft-technologies> (accessed June 2, 2022).
- 2714 [436] IATA. An Airline Handbook on CORSIA 2019.
2715 <https://www.iata.org/contentassets/fb745460050c48089597a3ef1b9fe7a8/corsia-handbook.pdf> (accessed
2716 March 10, 2022).
- 2717 [437] ICAO Secretariat. Session 5: CORSIA Calculation of Offsetting Requirements 2018.
2718 https://www.icao.int/Meetings/RS2018/Documents/5_1_Offsetting_Requirements_Presentation.pdf
2719 (accessed March 30, 2022).
- 2720 [438] Air Transport Action Group (ATAG). Sustainable Aviation Fuel (SAF) 2019. [https://www.atag.org/our-](https://www.atag.org/our-activities/sustainable-aviation-fuels.html)
2721 [activities/sustainable-aviation-fuels.html](https://www.atag.org/our-activities/sustainable-aviation-fuels.html) (accessed January 22, 2022).
- 2722 [439] ICAO. ICAO document CORSIA Sustainability Criteria for CORSIA Eligible Fuels 2021.
2723 [https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2005%20-](https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2005%20-%20Sustainability%20Criteria%20-%20November%202021.pdf)
2724 [%20Sustainability%20Criteria%20-%20November%202021.pdf](https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2005%20-%20Sustainability%20Criteria%20-%20November%202021.pdf) (accessed June 22, 2022).
- 2725 [440] European Commission. Proposal for a decision of the European Parliament and of the Council amending
2726 Directive 2003/87/EC as regards the notification of offsetting in respect of a global market-based measure
2727 for aircraft operators based in the Union 2021. [https://eur-lex.europa.eu/legal-](https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0567)
2728 [content/en/TXT/?uri=CELEX%3A52021PC0567](https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0567).
- 2729 [441] Stafford W, Lotter A, Brent A, Maltitz G von. Biofuels technology: A look forward, WIDER Working
2730 Paper, No. 2017/87. The United Nations University World Institute for Development Economics Research
2731 (UNU-WIDER) 2017. <https://www.econstor.eu/bitstream/10419/163049/1/884531538.pdf>.
- 2732 [442] Teigiserova DA, Hamelin L, Thomsen M. Review of high-value food waste and food residues biorefineries
2733 with focus on unavoidable wastes from processing. *Resources, Conservation and Recycling* 2019;149:413–
2734 26. <https://doi.org/10.1016/j.resconrec.2019.05.003>.
- 2735 [443] Tonini D, Hamelin L, Astrup TF. Environmental implications of the use of agro-industrial residues for
2736 biorefineries: application of a deterministic model for indirect land-use changes. *GCB Bioenergy*
2737 2016;8:690–706. <https://doi.org/10.1111/gcbb.12290>.
- 2738 [444] Chen WT, Zhang Y, Zhang J, Yu G, Schideman LC, Zhang P, et al. Hydrothermal liquefaction of mixed-
2739 culture algal biomass from wastewater treatment system into bio-crude oil. *Bioresource Technology*
2740 2014;152:130–9. <https://doi.org/10.1016/j.biortech.2013.10.111>.
- 2741 [445] Lew L, Biddle T. Evaluation of Amyris Direct Sugar to Hydrocarbon (DSHC) Fuel, DOT/FAA/AEE/2014-
2742 07. US Department of Transportation, Federal Aviation Administration 2014.
2743 [https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/clean/reports/m-](https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/clean/reports/media/PW_Amyris_Final.pdf)
2744 [edia/PW_Amyris_Final.pdf](https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/clean/reports/media/PW_Amyris_Final.pdf).
- 2745 [446] Virent Inc. Virent technology. Virent, Inc 2019. <https://www.virent.com/technology/> (accessed September
2746 27, 2022).
- 2747 [447] Xing R, Subrahmanyam A V., Olcay H, Qi W, Van Walsum GP, Pendse H, et al. Production of jet and
2748 diesel fuel range alkanes from waste hemicellulose-derived aqueous solutions. *Green Chemistry*
2749 2010;12:1933–46. <https://doi.org/10.1039/c0gc00263a>.
- 2750 [448] Weng Y, Qiu S, Ma L, Liu Q, Ding M, Zhang Q, et al. Jet-Fuel range hydrocarbons from biomass-derived
2751 sorbitol over Ni-HZSM-5/SBA-15 catalyst. *Catalysts* 2015;5:2147–60.
2752 <https://doi.org/10.3390/catal5042147>.
- 2753

- 2754 [449] Li T, Cheng J, Huang R, Zhou J, Cen K. Conversion of waste cooking oil to jet biofuel with nickel-based
2755 mesoporous zeolite Y catalyst. *Bioresource Technology* 2015;197:289–94.
2756 <https://doi.org/10.1016/j.biortech.2015.08.115>.
- 2757 [450] Xu J, Long F, Jiang J, Li F, Zhai Q, Wang F, et al. Integratd catalytic conversion of waste triglycerides to
2758 liquid hydrocarbons for aviation biofuels. *Journal of Cleaner Production* 2019;222:784–92.
2759 <https://doi.org/10.1016/j.jclepro.2019.03.094>.
- 2760 [451] ICAO. ICAO Long-Term Traffic Forecasts: Passenger and Cargo 2018;April.
2761 https://www.icao.int/sustainability/documents/ltf_charts-results_2018edition.pdf.
- 2762 [452] Ellen Mac Arthur Foundation. The new plastics economy: rethinking the future of plastics & catalysing
2763 action. Ellen Mac Arthur Foundation 2017. [https://ellenmacarthurfoundation.org/the-new-plastics-economy-](https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics-and-catalysing)
2764 [rethinking-the-future-of-plastics-and-catalysing](https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics-and-catalysing) (accessed February 23, 2022).
- 2765 [453] Svenja Dahl. How much biomass do bio-based plastics need? *Renewable Carbon News* 2020.
2766 <https://renewable-carbon.eu/news/how-much-biomass-do-bio-based-plastics-need/> (accessed June 22, 2022).
- 2767 [454] O’Connell A, Kousoulidou M, Lonza L, Weindorf W. Considerations on GHG emissions and energy
2768 balances of promising aviation biofuel pathways. *Renewable and Sustainable Energy Reviews*
2769 2019;101:504–15. <https://doi.org/10.1016/j.rser.2018.11.033>.
- 2770 [455] Staples MD, Malina R, Barrett SRH. The limits of bioenergy for mitigating global life-cycle greenhouse gas
2771 emissions from fossil fuels. *Nature Energy* 2017;2:1–8. <https://doi.org/10.1038/nenergy.2016.202>.
- 2772 [456] Moretti C, Junginger M, Shen L. Environmental life cycle assessment of polypropylene made from used
2773 cooking oil. *Resources, Conservation and Recycling* 2020;157:104750.
2774 <https://doi.org/10.1016/j.resconrec.2020.104750>.
- 2775 [457] Sanz-Pérez ES, Murdock CR, Didas SA, Jones CW. Direct Capture of CO₂ from Ambient Air. *Chemical*
2776 *Reviews* 2016;116:11840–76. <https://doi.org/10.1021/acs.chemrev.6b00173>.
- 2777 [458] Supekar SD, Lim T-H, Skerlos SJ. Costs to achieve target net emissions reductions in the US electric sector
2778 using direct air capture. *Environ Res Lett* 2019;14:084013. <https://doi.org/10.1088/1748-9326/ab30aa>.
- 2779 [459] Pritchard C, Yang A, Holmes P, Wilkinson M. Thermodynamics, economics and systems thinking: What
2780 role for air capture of CO₂? *Process Safety and Environmental Protection* 2015;94:188–95.
2781 <https://doi.org/10.1016/j.psep.2014.06.011>.
- 2782 [460] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO₂ direct air capture plants. *Journal of*
2783 *Cleaner Production* 2019;224:957–80. <https://doi.org/10.1016/j.jclepro.2019.03.086>.
- 2784 [461] Breyer C, Fasihi M, Aghahosseini A. Carbon dioxide direct air capture for effective climate change
2785 mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitig Adapt Strateg*
2786 *Glob Change* 2020;25:43–65. <https://doi.org/10.1007/s11027-019-9847-y>.
- 2787 [462] Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, et al. Negative emissions—Part 2:
2788 Costs, potentials and side effects. *Environ Res Lett* 2018;13:063002. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/aabf9f)
2789 [9326/aabf9f](https://doi.org/10.1088/1748-9326/aabf9f).
- 2790 [463] Mortensen AW, Mathiesen BV, Hansen AB, Pedersen SL, Grandal RD, Wenzel H. The role of
2791 electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system – A study
2792 on the Danish energy system. *Applied Energy* 2020;275:115331.
2793 <https://doi.org/10.1016/j.apenergy.2020.115331>.
- 2794 [464] Hanna R, Abdulla A, Xu Y, Victor DG. Emergency deployment of direct air capture as a response to the
2795 climate crisis. *Nature Communications* 2021;12:368. <https://doi.org/10.1038/s41467-020-20437-0>.
- 2796 [465] Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V, et al. Energy system transformations
2797 for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change* 2015;5:519–27.
2798 <https://doi.org/10.1038/nclimate2572>.
- 2799 [466] Millar RJ, Fuglestedt JS, Friedlingstein P, Rogelj J, Grubb MJ, Matthews HD, et al. Emission budgets and
2800 pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience* 2017;10:741–7.
2801 <https://doi.org/10.1038/ngeo3031>.
- 2802 [467] Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, Gernaat D, et al. Scenarios towards limiting global
2803 mean temperature increase below 1.5 °C. *Nature Climate Change* 2018;8:325–32.
2804 <https://doi.org/10.1038/s41558-018-0091-3>.
- 2805 [468] Jones CW. CO₂ capture from dilute gases as a component of modern global carbon management. *Annual*
2806 *Review of Chemical and Biomolecular Engineering* 2011;2:31–52. [https://doi.org/10.1146/annurev-](https://doi.org/10.1146/annurev-chembioeng-061010-114252)
2807 [chembioeng-061010-114252](https://doi.org/10.1146/annurev-chembioeng-061010-114252).

- 2808 [469] Didas SA, Choi S, Chaikittisilp W, Jones CW. Amine-Oxide Hybrid Materials for CO₂ Capture from
2809 Ambient Air. *Accounts of Chemical Research* 2015;48:2680–7.
2810 <https://doi.org/10.1021/acs.accounts.5b00284>.
- 2811 [470] Stern MC, Simeon F, Herzog H, Hatton TA. Post-combustion carbon dioxide capture using
2812 electrochemically mediated amine regeneration. *Energy and Environmental Science* 2013;6:2505–17.
2813 <https://doi.org/10.1039/c3ee41165f>.
- 2814 [471] Chen C, Tavoni M. Direct air capture of CO₂ and climate stabilization: A model based assessment. *Climatic*
2815 *Change* 2013;118:59–72. <https://doi.org/10.1007/s10584-013-0714-7>.
- 2816 [472] Friedlingstein P, O’Sullivan M, Jones MW, Andrew RM, Hauck J, Olsen A, et al. Global Carbon Budget
2817 2020. *Earth System Science Data* 2020;12:3269–340. <https://doi.org/10.5194/essd-12-3269-2020>.
- 2818 [473] U.S. Department of Energy. HYDROGEN STRATEGY: Enabling A Low-Carbon Economy, Office of
2819 Fossil Energy, Washington, DC 20585 2020.
2820 https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf.
- 2821 [474] Ritchie H, Roser M. Water Use and Stress. *Our World in Data* 2017. [https://ourworldindata.org/water-use-](https://ourworldindata.org/water-use-stress)
2822 [stress](https://ourworldindata.org/water-use-stress) (accessed October 10, 2022).
- 2823 [475] Baharudin L, Watson MJ. Hydrogen applications and research activities in its production routes through
2824 catalytic hydrocarbon conversion. *Reviews in Chemical Engineering* 2017;34:43–72.
2825 <https://doi.org/10.1515/revce-2016-0040>.
- 2826 [476] Ishimoto Y, Sugiyama M, Kato E, Moriyama R, Tsuzuki K, Kurosawa A. Putting Costs of Direct Air
2827 Capture in Context. *SSRN Journal* 2017. <https://doi.org/10.2139/ssrn.2982422>.
- 2828 [477] IEA. Electricity consumption – Electricity Information: Overview – Analysis. International Energy Agency
2829 (IEA) 2020. <https://www.iea.org/reports/electricity-information-overview/electricity-consumption> (accessed
2830 October 15, 2022).
- 2831 [478] Michailos S. Process design, economic evaluation and life cycle assessment of jet fuel production from
2832 sugar cane residue. *Environmental Progress and Sustainable Energy* 2018;37:1227–35.
2833 <https://doi.org/10.1002/ep.12840>.
- 2834 [479] Ganguly I, Pierobon F, Charles Bowers T, Huisenga M, Johnston G, Eastin IL. ‘Woods-to-Wake’ Life Cycle
2835 Assessment of residual woody biomass based jet-fuel using mild bisulfite pretreatment. *Biomass and*
2836 *Bioenergy* 2018;108:207–16. <https://doi.org/10.1016/j.biombioe.2017.10.041>.
- 2837 [480] de Jong S. Green horizons: On the production costs, climate impact and future supply of renewable jet fuels.
2838 Copernicus Institute of Sustainable Development, Utrecht University 2018.
2839 <https://dspace.library.uu.nl/handle/1874/364514>.
- 2840 [481] de Jong S, Hoefnagels R, Wetterlund E, Pettersson K, Faaij A, Junginger M. Cost optimization of biofuel
2841 production – The impact of scale, integration, transport and supply chain configurations. *Applied Energy*
2842 2017;195:1055–70. <https://doi.org/10.1016/j.apenergy.2017.03.109>.
- 2843 [482] Pierobon F, Eastin IL, Ganguly I. Life cycle assessment of residual lignocellulosic biomass-based jet fuel
2844 with activated carbon and lignosulfonate as co-products. *Biotechnology for Biofuels* 2018;11:1–18.
2845 <https://doi.org/10.1186/s13068-018-1141-9>.
- 2846 [483] Fuglestedt JS, Shine KP, Berntsen T, Cook J, Lee DS, Stenke A, et al. Transport impacts on atmosphere
2847 and climate: Metrics. *Atmospheric Environment* 2010;44:4648–77.
2848 <https://doi.org/10.1016/j.atmosenv.2009.04.044>.
- 2849 [484] Lund MT, Aamaas B, Berntsen T, Bock L, Burkhardt U, Fuglestedt JS, et al. Emission metrics for
2850 quantifying regional climate impacts of aviation. *Earth System Dynamics* 2017;8:547–63.
2851 <https://doi.org/10.5194/esd-8-547-2017>.
- 2852 [485] Lee DS, Pitari G, Grewe V, Gierens K, Penner JE, Petzold A, et al. Transport impacts on atmosphere and
2853 climate: Aviation. *Atmospheric Environment* 2010;44:4678–734.
2854 <https://doi.org/10.1016/j.atmosenv.2009.06.005>.
- 2855 [486] Braun-Unkoff M, Riedel U, Wahl C. About the emissions of alternative jet fuels. *CEAS Aeronaut J*
2856 2017;8:167–80. <https://doi.org/10.1007/s13272-016-0230-3>.
- 2857 [487] Köhler MO, Rädcl G, Shine KP, Rogers HL, Pyle JA. Latitudinal variation of the effect of aviation NO_x
2858 emissions on atmospheric ozone and methane and related climate metrics. *Atmospheric Environment*
2859 2013;64:1–9. <https://doi.org/10.1016/j.atmosenv.2012.09.013>.
- 2860 [488] Shine KeithP, Berntsen TK, Fuglestedt JS, Skeie RB, Stuber. Comparing the climate effect of emissions of
2861 short- and long-lived climate agents. *Philosophical Transactions of the Royal Society A: Mathematical,*
2862 *Physical and Engineering Sciences* 2007;365. <https://doi.org/10.1098/rsta.2007.2050>.

- 2863 [489] Forster PMDF, Shine KP, Stuber N. It is premature to include non-CO₂ effects of aviation in emission
2864 trading schemes. *Atmospheric Environment* 2006;40:1117–21.
2865 <https://doi.org/10.1016/j.atmosenv.2005.11.005>.
- 2866 [490] Collins L. Offshore wind to power giant green-hydrogen carbon-neutral aviation-fuel plant 2019.
2867 [https://www.rechargenews.com/transition/offshore-wind-to-power-giant-green-hydrogen-carbon-neutral-](https://www.rechargenews.com/transition/offshore-wind-to-power-giant-green-hydrogen-carbon-neutral-aviation-fuel-plant/2-1-696907)
2868 [aviation-fuel-plant/2-1-696907](https://www.rechargenews.com/transition/offshore-wind-to-power-giant-green-hydrogen-carbon-neutral-aviation-fuel-plant/2-1-696907) (accessed August 30, 2022).
- 2869 [491] Gauss M, Isaken ISA, Wong S, Wang WC. Impact of H₂O emissions from cryoplanes and kerosene aircraft
2870 on the atmosphere. *Journal of Geophysical Research: Atmospheres* 2003;108:1–11.
2871 <https://doi.org/10.1029/2002jd002623>.
- 2872 [492] Grassl H, Brockhagen D. Climate forcing of aviation emissions in high altitudes and comparison of metrics.
2873 An update according to the Fourth Assessment Report, IPCC 2007. IPCC 2007.
2874 https://earthjustice.org/sites/default/files/black-carbon/grassl_brockhagen-2007-aviation-forcing.pdf.
- 2875 [493] Chan T, Chishty WA, Canteenwalla P, Davison CR, Chalmers J. Benchmarking data from the experience
2876 gained in engine performance and emissions testing on alternative fuels for aviation. *Journal of the Global*
2877 *Power and Propulsion Society* 2017;1:195–210. <https://journal.gpps.global/a/S5WGLD>.
- 2878 [494] Rypdal K. Background papers: IPCC Expert meetings on good practice guidance and uncertainty
2879 management in National Greenhouse Gas Inventories. 2000. <https://doi.org/10.1021/es60082a602>.
- 2880 [495] Guynn MD, Freh JE, Olson ED. Evaluation of a Hydrogen Fuel Cell Powered Blended-Wing-Body Aircraft
2881 Concept for Reduced Noise and Emissions 2004.
2882 <https://ntrs.nasa.gov/api/citations/20040033924/downloads/20040033924.pdf>.
- 2883 [496] ICAO. Electric, Hybrid, and Hydrogen Aircraft-State of Play. International Civil Aviation Organization
2884 (ICAO) 2016. [https://www.icao.int/environmental-](https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg124-130.pdf)
2885 [protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg124-130.pdf](https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg124-130.pdf) (accessed September
2886 15, 2022).
- 2887 [497] CISION PR Newswire. magniX Continued Flight Testing Reveals Electric Aircraft Significantly Reduce
2888 Noise Pollution 2021. [https://www.prnewswire.com/news-releases/magnix-continued-flight-testing-reveals-](https://www.prnewswire.com/news-releases/magnix-continued-flight-testing-reveals-electric-aircraft-significantly-reduce-noise-pollution-301264765.html)
2889 [electric-aircraft-significantly-reduce-noise-pollution-301264765.html](https://www.prnewswire.com/news-releases/magnix-continued-flight-testing-reveals-electric-aircraft-significantly-reduce-noise-pollution-301264765.html) (accessed December 18, 2021).
- 2890 [498] Rondinelli S, Sabatini R, Gardi A. Challenges and Benefits offered by Liquid Hydrogen Fuels in
2891 Commercial Aviation Aviation 2014. <https://doi.org/10.13140/2.1.2658.9764>.
- 2892 [499] Moses CA. Comparative evaluation of semi-synthetic jet fuels: Final Report, CRC Project No. AV-2-04a
2893 2008. [http://www.ncfap.org/documents/biofuels_aviation/Comparison%20of%20SSJF%20-](http://www.ncfap.org/documents/biofuels_aviation/Comparison%20of%20SSJF%20-%20CRC%20Final.pdf)
2894 [%20CRC%20Final.pdf](http://www.ncfap.org/documents/biofuels_aviation/Comparison%20of%20SSJF%20-%20CRC%20Final.pdf).
- 2895 [500] Kosir S, Heyne J, Graham J. A machine learning framework for drop-in volume swell characteristics of
2896 sustainable aviation fuel. *Fuel* 2020;274:117832. <https://doi.org/10.1016/j.fuel.2020.117832>.
- 2897 [501] Graham JL, Rahmes TF, Kay MC, Belieres J-P, Kinder JD, Millett SA, et al. Impact of Alternative Jet Fuel
2898 and Fuel Blends on Non-Metallic Materials Used in Commercial Aircraft Fuel Systems, DTFAWA-10-C-
2899 0030 2011.
2900 [https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/reports/m](https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/reports/media/Impact_of_Alternative_Jet_Fuel_and_Fuel_Blends.pdf)
2901 [edia/Impact_of_Alternative_Jet_Fuel_and_Fuel_Blends.pdf](https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/reports/media/Impact_of_Alternative_Jet_Fuel_and_Fuel_Blends.pdf).
- 2902 [502] Miller B, Johnson D, Thompson T, Rosenberg FL, Driver J, Biscardi GP, et al. R&D Control Study: Plan for
2903 Future Jet Fuel Distribution Quality Control and Description of Fuel Properties Catalog,
2904 DOT/FAA/AEE/2014-11, VNTSC-FAA-14-11 2014.
2905 [https://www.faa.gov/about/office_org/headquarters_offices/apl/research/alternative_fuels/media/Metron_Fu](https://www.faa.gov/about/office_org/headquarters_offices/apl/research/alternative_fuels/media/Metron_Fuel_Quality_Final.pdf)
2906 [el_Quality_Final.pdf](https://www.faa.gov/about/office_org/headquarters_offices/apl/research/alternative_fuels/media/Metron_Fuel_Quality_Final.pdf).
- 2907 [503] Canteenwalla P, Davison CR, Chishty WA, Ginestra C, Dally B. Testing of Synthesized Aromatic Kerosene
2908 (SAK) Aviation Fuel Blends at Simulated Altitudes. *Proceedings of the ASME Turbo Expo*, vol. 3, 2016.
2909 <https://doi.org/10.1115/GT2016-57570>.
- 2910 [504] Cortright R, Rozmiarek B, Van Straten M. Catalytic Upgrading of Thermochemical Intermediates to
2911 Hydrocarbons: Conversion of Lignocellulosic Feedstocks to Aromatic Fuels and High Value Chemicals.
2912 *United States* 2017. <https://doi.org/doi:10.2172/1410413>.
- 2913 [505] Kosir ST, Behnke L, Heyne JS, Stachler RD, Flora G, Zabarnick S, et al. Improvement in jet aircraft
2914 operation with the use of high-performance drop-in fuels. *AIAA Scitech 2019 Forum* 2019:1–27.
2915 <https://doi.org/10.2514/6.2019-0993>.
- 2916 [506] Muldoon JA, Harvey BG. Bio-Based Cycloalkanes: The Missing Link to High-Performance Sustainable Jet
2917 Fuels. *ChemSusChem* 2020;13:5777–807. <https://doi.org/10.1002/cssc.202001641>.

- 2918 [507] Cheng F, Brewer CE. Producing jet fuel from biomass lignin: Potential pathways to alkyl-benzenes and
2919 cycloalkanes. *Renewable and Sustainable Energy Reviews* 2017;72:673–722.
2920 <https://doi.org/10.1016/j.rser.2017.01.030>.
- 2921 [508] Zhang X, Lei H, Zhu L, Wu J, Chen S. From lignocellulosic biomass to renewable cycloalkanes for jet fuels.
2922 *Green Chemistry* 2015;17:4736–47. <https://doi.org/10.1039/c5gc01583a>.
- 2923 [509] van Dyk S, Saddler J. Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF):
2924 Technologies, potential and challenges. *IEA Bioenergy* 2021. [https://www.ieabioenergy.com/wp-](https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf)
2925 [content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-](https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf)
2926 [2021-1.pdf](https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf).
- 2927 [510] Suas News - The business of drones. Deutsche Aircraft Selects HEGGEMANN AG for D328ecoTM Wing
2928 Industrialization and Production. *SUAS News - The Business of Drones* 2021.
2929 [https://www.suasnews.com/2021/09/deutsche-aircraft-selects-heggemann-ag-for-d328ecotm-wing-](https://www.suasnews.com/2021/09/deutsche-aircraft-selects-heggemann-ag-for-d328ecotm-wing-industrialization-and-production/)
2930 [industrialization-and-production/](https://www.suasnews.com/2021/09/deutsche-aircraft-selects-heggemann-ag-for-d328ecotm-wing-industrialization-and-production/) (accessed December 17, 2021).
- 2931 [511] Madavan N, Heidmann J, Bowman C, Kascak P, Jankovsky A, Jansen R. A NASA Perspective on electric
2932 propulsion technologies for commercial aviation. *National Aeronautics and Space Administration (NASA)*
2933 2016. [https://dokumen.tips/documents/a-nasa-perspective-on-electric-propulsion-a-hybrid-electric-](https://dokumen.tips/documents/a-nasa-perspective-on-electric-propulsion-a-hybrid-electric-propulsion-system.html?page=1)
2934 [propulsion-system.html?page=1](https://dokumen.tips/documents/a-nasa-perspective-on-electric-propulsion-a-hybrid-electric-propulsion-system.html?page=1).
- 2935 [512] Khandelwal B, Karakurt A, Sekaran PR, Sethi V, Singh R. Progress in Aerospace Sciences Hydrogen
2936 powered aircraft : The future of air transport. *Progress in Aerospace Sciences* 2013;60:45–59.
2937 <https://doi.org/10.1016/j.paerosci.2012.12.002>.
- 2938 [513] Mital SK, Gyekenyesi JZ, Arnold SM, Sullivan RM, Manderscheid JM, Murthy PLN. Review of Current
2939 State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage
2940 Tank Structures for Aircraft Applications October 2006, NASA/TM-2006-214346. *National Aeronautics*
2941 *and Space Administration (NASA)* 2006.
2942 <https://ntrs.nasa.gov/api/citations/20060056194/downloads/20060056194.pdf>.
- 2943 [514] Winnefeld C, Kadyk T, Hanke-rauschenbach R. Modelling and Designing Cryogenic Hydrogen Tanks for
2944 Future Aircraft Applications. *Energies* 2018:1–23. <https://doi.org/10.3390/en11010105>.
- 2945 [515] Marek CJ, Smith TD, Kundu K. Low Emission Hydrogen Combustors For Gas Turbines Using Lean Direct
2946 Injection. *NTRS - NASA Technical Reports Server* 2005. <https://ntrs.nasa.gov/citations/20080002274>.
- 2947 [516] TLD Displays TaxiBot At Dubai Airport Show 2013.
2948 <https://www.aviationpros.com/gse/news/10940291/taxiing-equipment-saves-fuel-for-aircraft> (accessed May
2949 2, 2022).
- 2950 [517] Taxiing without engines running. *Lufthansa Group* 2013. [https://www.lufthansa-](https://www.lufthansa-leos.com/documents/438370/444077/2013_10_TaxiBot.pdf)
2951 [leos.com/documents/438370/444077/2013_10_TaxiBot.pdf](https://www.lufthansa-leos.com/documents/438370/444077/2013_10_TaxiBot.pdf) (accessed January 23, 2022).
- 2952 [518] TLD Group. TaxiBot Semi-Robotic Towing Tractor to Trial at Schiphol Airport. 2020. [https://www.tld-](https://www.tld-group.com/technologies/taxibot/)
2953 [group.com/technologies/taxibot/](https://www.tld-group.com/technologies/taxibot/) (accessed December 18, 2021).
- 2954 [519] The Times of India. Air India becomes first airline to use “TaxiBot” on A320 aircraft with passengers
2955 onboard. *The Times of India* 2019. [https://timesofindia.indiatimes.com/business/india-business/air-india-](https://timesofindia.indiatimes.com/business/india-business/air-india-becomes-first-airline-to-use-taxibot-on-a320-aircraft-with-passengers-onboard/articleshow/71592913.cms)
2956 [becomes-first-airline-to-use-taxibot-on-a320-aircraft-with-passengers-onboard/articleshow/71592913.cms](https://timesofindia.indiatimes.com/business/india-business/air-india-becomes-first-airline-to-use-taxibot-on-a320-aircraft-with-passengers-onboard/articleshow/71592913.cms)
2957 (accessed January 23, 2022).
- 2958 [520] Gokulakrishnan P, Gaines G, Klassen M, Roby R. Autoignition of Aviation Fuels: Experimental and
2959 Modeling Study. 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati,
2960 OH: American Institute of Aeronautics and Astronautics; 2007. <https://doi.org/10.2514/6.2007-5701>.
- 2961