Applied Energy 380 (2025) 124999

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

H2-powered aviation – Optimized aircraft and green LH2 supply in air transport networks

J. Hoelzen [a], D. Silberhorn [b], F. Schenke [a], E. Stabenow [a], T. Zill [b], A. Bensmann [a,*], R. Hanke-Rauschenbach [a]

[a] *Leibniz Universität Hannover, Institute of Electric Power Systems, 30167 Hanover, Germany*
[b] *DLR, Institute of System Architectures in Aeronautics, 21129 Hamburg, Germany*

HIGHLIGHTS

- Optimized LH_2 supply costs for 104 airports incl. Comparison of best supply pathways.
- Four optimized H_2-powered single-aisle aircraft designs and operational strategies.
- Comparison of total direct operating costs for kerosene, synthetic kerosene, and LH_2 in a given air traffic network.

ARTICLE INFO

Keywords:
Hydrogen aviation
Liquid hydrogen
Hydrogen fuel supply
Hydrogen airports
Tankering
Hydrogen aircraft design
Air transport network optimization

ABSTRACT

The final financial decisions on starting the commercialization of the next single-aisle aircraft programs for entry-into-service in the 2030s are due in less than 5 years. These programs will shape the future climate impact over the following 20–30 years of this aircraft segment and will determine if the sector can achieve its 2050 net-zero target. And so far, there are only limited holistic research perspectives available evaluating the best decarbonization options for such a crucial next product.

This study provides a first-of-its-kind holistic evaluation approach for the business case of single-aisle hydrogen-(H_2)-powered aircraft to enable true-zero CO_2 flying. It combines the optimization of green liquid hydrogen (LH_2) supply and aircraft designs as well as the investigation of operational strategies with such aircraft in one specific air traffic network.

It is found that LH_2 could cost around 2 to 3 USD/kg at main European airports in a 2050 scenario. Even though the aircraft with H_2 direct combustion would be less efficient, average total operating costs would be 3% lower than flying with synthetic kerosene in the given network in 2050. As an operational strategy to save fuel costs, tankering might play an essential role in reducing operating costs for H_2-powered aircraft in the early adoption phase with high differences in LH_2 supply costs.

Finally, it is derived that usage of LH_2 as a fuel would lead to lower installation requirements of renewable energy generation capacity compared to the synthetic kerosene option. Since green electricity will be a constrained resource in the next decades, this is another important aspect for choosing future decarbonization options in air travel.

All in all, the study proves the importance of the derived methodology leading to a broader techno-economic assessment for two decarbonization options in aviation. Such novel approaches might be further developed and applied to other related research topics in this field.

1. Introduction

This paper investigates the techno-economics of operating hydrogen-(H_2)-powered aircraft along three main perspectives: optimization of green LH_2 supply chains for airports, H_2-powered aircraft design, and operational strategies for such aircraft in a specific air traffic network.

Sector roadmaps outline potential pathways for aviation to tackle its climate impact challenge and to achieve the industry's goal of net-zero CO_2 emissions by 2050 [1–4]. In this aviation-specific energy transition,

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* Corresponding author.
E-mail addresses: hoelzen@ifes.uni-hannover.de (J. Hoelzen), astrid.bensmann@ifes.uni-hannover.de (A. Bensmann).

https://doi.org/10.1016/j.apenergy.2024.124999
Received 25 October 2023; Received in revised form 3 September 2024; Accepted 22 November 2024

Abbreviations

ASK	Available seat kilometers
CAPEX	Capital expenditures
DOC	Direct operating costs
ELY	Electrolysis system
ETS	European Emission Trading Scheme
H_2, GH_2, LH_2	Hydrogen, gaseous hydrogen, liquid hydrogen
LFP	Liquefaction plant
NM	Nautical Miles
OPEX	Operating expenditures
PAX	Passengers
PV	Photovoltaics
RES	Renewable energy source
SAF	Sustainable aviation fuels
SEC	Specific energy consumption
tpd	Tons per day

Symbols

a	Annuity payment factor
C	Cost in USD_{2020}
c	Specific cost in USD_{2020}
e	Specific energy consumption in kWh
f	(Product) factor
i	Interest rate in %
T_{DP}	Depreciation period in years
x	Design capacity

Subscripts

i	Supply component i
t	Time period / scenario
TAC	Total annual costs

one major ingredient is hydrogen, as also underlined by detailed previous research efforts [5–17]. It can help to decarbonize the sector in two main ways: H_2 can be used for direct propulsion onboard larger commercial aircraft via fuel cells and electric motors or H_2 combustion engines [3]. For this purpose, hydrogen must be liquefied to reach a higher volumetric energy density and to ensure more efficient storage in the aircraft. The other option is to produce synthetic kerosene (synfuel), which requires H_2 as the main feed. While the synfuel option leads to net-zero CO_2, the H_2 direct propulsion options enable true-zero CO_2 emissions in flight. For both approaches the use of green H_2 is required to also keep lifecycle CO_2 emissions upfront a flight as low as possible [18].

In current scientific debates, many uncertainties and challenges remain regarding the future of such new fuels and new propulsion systems in aviation. First, their non-CO_2-related climate impacts are still being investigated and no final evaluation can be made yet to favor one decarbonization option over the other [5,19,20]. Second, immensely expensive infrastructure deployment is needed for either sustainable aviation fuels (SAF) including synfuels, or for LH_2 used in new propulsion systems [1,21,22]. However, the magnitude of scale for these infrastructure costs and the resulting fuel costs are still uncertain [23]. Nevertheless, the need for having several fuel infrastructures at airports in parallel might definitely lead to higher investment costs [21]. Third, regarding the development of new fuels or even aircraft the geographic or also the air traffic network context is often not considered. It was previously found that direct operating cost (DOC) assessments for the isolated aircraft and supply infrastructure will not lead to a final answer on the economic competitiveness for H_2-powered aviation [23]. So, air traffic networks have to be considered to test feasibility or even synergistic effects when introducing H_2 supply for aviation. Only then, H_2 propulsion for aircraft can be evaluated more holistically and can be compared to different decarbonization options.

Literature regarding more holistic views of H_2-powered aviation can be divided into three groups of studies [23]. The first group of papers focuses on integrating renewable energy systems into an airport environment while deriving requirements from aircraft and airport perspectives. Such analyses develop insights on scales of LH_2 demand, the applicability of H_2 for other uses cases at the airport than aircraft, safety considerations, or qualitative LH_2 infrastructure deployment plans [22,24–28]. In a second group, the integration of H_2-powered aircraft into air traffic networks is investigated qualitatively [29–32]. There, high-level implications for the deployment of H_2 supply infrastructure are derived, while the flight range of future H_2-powered aircraft is projected and new operating principles are discussed. A recent report [21] combines topics from these two groups and determines capital costs for LH_2 supply infrastructure at airports based on different supply and refueling setups as well as demand scales. Nevertheless, in this report, the impacts on or options coming from different H_2-powered aircraft designs are not considered. This leads to a third group of studies, which analyze such novel aircraft's performance and derive cost metrics based on the DOC methodology [8,9,12,33–37]. However, these reports often use high-level estimates for energy costs and do not investigate impacts on local infrastructure or broader air traffic networks.

In the NAPKIN project [38] all three mentioned areas are combined. Therein, based on a UK air traffic network, LH_2 demands, case studies for two different H_2-powered aircraft segments, performance, and cost metrics are calculated. However, no clear optimization of broader supply pathways is undertaken from the infrastructure perspective, and also different operational strategies in the given air traffic network are not evaluated.

The main novelty of the present study is to bring the three groups of topics together in one more holistic assessment. Therefore, a detailed infrastructure optimization based on energy system modeling is combined with the design optimization of H_2-powered aircraft while considering different operational strategies in an existing air traffic network. The interconnections between aircraft design and infrastructure deployment optimization open up a new space for optimizing a broader transport system on multiple levels (aircraft fleet vs. airport network considerations). The three leading research questions are:

- What are the resulting fuel costs to deploy LH_2 infrastructure for H_2-powered flying in an exemplary air traffic network? Which supply pathways would be most promising at which airports?
- How do optimized H_2-powered aircraft designs look like and what are aircraft-related cost implications of operating these in a given air traffic network? How do new operational strategies affect these costs?
- What are the resulting total direct operating costs in such an air traffic network and how do these compare to fossil-based and synfuel-based flying? What are the final implications for the deployment of green LH_2 fuel infrastructure also given that new operational strategies are considered?

The paper is structured as follows. In Section 2, the study design including the selected flight network and the airports are introduced. Then, the resulting optimized LH_2 supply costs at each airport are calculated and discussed in Section 3. This is followed by presenting optimized H2-powered aircraft designs and their operating costs excluding aspects of energy costs in Section 4. Thus, impacts on aircraft performance from different operational strategies are investigated. In Section 5, the total DOC for H_2-powered aircraft in the given network as well as the resource requirements for the infrastructure are determined and compared to the fossil kerosene reference and a synfuel alternative. Finally, conclusions as well as limitations and future fields of research are discussed in Section 6.

For better readability, detailed techno-economic assumptions, and cost optimization results are presented in the Appendix and a Supplementary Material file, respectively.

2. Reference air traffic network

In this section, the reference air traffic network is introduced which determines the chosen airports for the LH_2 supply infrastructure analysis and the distribution of trip lengths for the operation of H_2-powered aircraft.

2.1. Main characteristics of chosen air traffic network

There are two main forms of airline operation characterizing the resulting air traffic network. In a hub-and-spoke operation, the airline has a central hub, from which all flights start followed by a return flight to that hub. In contrary to that, airlines with a point-to-point operation fly from one destination to another based on optimized networks, but without a repeating main airport [39]. For the present analysis, a hub-and-spoke air traffic network offers more options to test different operational strategies such as central refueling at the main hub, which is further explained in Section 4.

Here, Lufthansa is chosen as an exemplary airline that operates with a classic hub-and-spoke network and is in the top five list of most-flown airlines in Europe [40]. Their largest hub is Frankfurt, which is selected for the analysis. Flight data was collected for one representative week, September 5th–11th 2022 from Flightradar24 [41]. In total, 108 larger single-aisle aircraft were tracked: 19 Airbus A319, 42 A320, and 47 A321. These aircraft flew from Frankfurt to 103 additional airports, which therefore present the main airports of this study. Of these airports, ten destinations lay outside Europe in the MENA (Middle East North Africa) region – a list of all airports can be found in Appendix Table A1.1. Fig. 1 gives an overview of all flights in the chosen network and the cumulative frequency distribution of these flights sorted by different performance indicators. It shows that a single-aisle aircraft with a design range of 1500 NM could cover already 97% of all departures, which translates into 89% of all CO_2 emissions of the chosen network.

This study investigates H_2-powered aircraft which are especially discussed for smaller up to larger single-aisle aircraft [1]. Such aircraft caused around 85 Mt. CO_2 emissions in Europe only [42]. This accounts for ~9% of the global air travel emissions from passenger transport (785 Mt. CO_2 emissions) and 77% of all intra-European commercial air traffic [43]. Of the 85 Mt. CO_2 emissions, 68% were emitted by single-aisle and smaller aircraft departing at the 104 airports in the reference network. If also neighboring airports are included, e.g., London Gatwick, Stansted and others next to London Heathrow Airport, the share increases to 80%.

2.2. Relevant airport categories

The 104 considered airports are categorized by their size and potential future LH_2 demands which serve as main inputs for the cost optimization of the fuel supply. As shown in [44], larger annual LH_2 demands have significant supply cost impacts due to economies of scale. Hence, five demand categories are introduced to calculate more realistic supply costs at each airport.

The size of airports and therefore their LH_2 demand projection is based on a previous assessment, see [24] for more information. Total annual passenger handling statistics are used as a reference to distinguish between airport sizes, see Table 1.

The first projection refers to the years 2035–2040. These mark the planned potential entry-into-service for larger single-aisle aircraft, while regional H_2-powered aircraft could already be in use by then [3]. However, very low demands would be expected in these first years [1,45]. Only at very large airports/airline hubs several flights per day could already take off in this “early” timeframe. This is different for the reference time frame around the year 2050. After 15 years of manufacturing ramp-up and fleet renewing, larger H_2-powered fleets and hence, larger LH_2 demands are expected.

It has to be noted that the total PAX size for the very large airport category is set relatively low. However, no further cost scaling effects can be achieved for demands above 100 k–200 k tLH_2/a as shown in

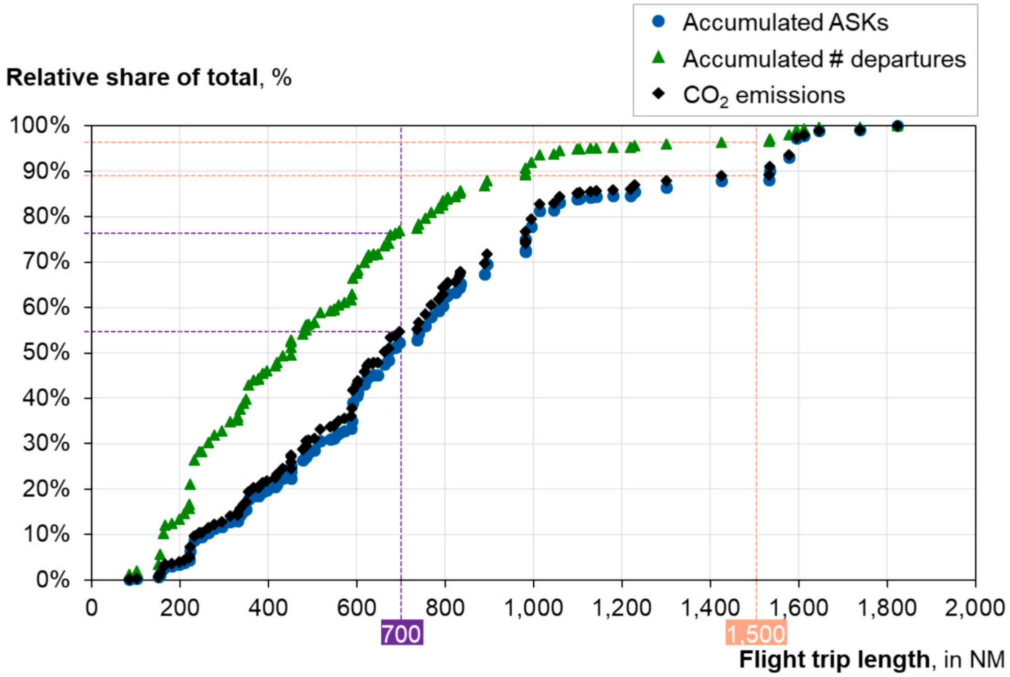

Fig. 1. Characteristics of selected air traffic network considering Lufthansa flights from Frankfurt-Main in the week of September 5th–11th 2022 and only flights of larger single-aisle aircraft (Airbus A320 family aircraft: all versions of A319, A320, A321 aircraft), based on data from [41]

Table 1
Overview of commercial airport categories used for LH_2 demand calculations in this study.

Commercial airport category (# of airports)	Total annual passenger (PAX), Mn	LH_2 demand range in 2035/40, tLH_2/a	LH_2 demand range in 2050, tLH_2/a	Exemplary airports
Very large (25)	>10	5000–10,000	100,000–300,000	London Heathrow Airport, Frankfurt Airport
Large (21)	5–10	1000–5000	50,000–100,000	Hamburg Airport, Birmingham Airport
Medium (28)	2.5–5	1000–5000	20,000–50,000	Valencia Airport, Gothenburg Airport
Small (19)	1–2.5	1000–5000	10,000–20,000	Bremen Airport, Madeira Airport
Regional (11)	<1	1000–5000	5000–10,000	Graz Airport, Mykonos Airport

[44]. In total, LH_2 demands at the 104 airports in 2050 would sum up to a range between 4.4 and 11.5 $MtLH_2/a$.

3. Optimized LH_2 supply costs at selected airports

In the first part of the study, optimal LH_2 supply costs at the 104 airports are investigated. Therefore, the methodology is introduced and then, the optimization results are presented.

3.1. *LH_2 infrastructure optimization and methodology*

This section introduces the study's scope of LH_2 supply and refueling setups, the optimization problem, and the relevant techno-economic assumptions.

3.1.1. *Possible LH_2 supply chains and refueling setups*

The following main system components are considered to supply green LH_2: renewable energy supply (RES) such as wind turbines or PV, water electrolysis (ELY), H_2 liquefaction plants (LFP), gaseous and liquid H_2 storages, and gaseous or liquid H_2 transportation modes.

Arranging these systems in supply pathways, three main options result to supply a specific airport (Fig. 2) and are described in detail in [23,24].

Airport A in Fig. 2 is considered as an example. The first option would be an LH_2 on-site production (1-LH2ON in Fig. 2) in which all components including the RES are located at or nearby the airport, so no transport is required.

Second, in an LH_2 off-site supply chain, all components converting energy are located at a central exporting site. Then, the LH_2 can either be transported over longer distances with vessels to a harbor and from there with trucks to the airport (2a-LH2OFF-V), or over shorter distances via truck if the export hub is close to the receiving airport or is even a neighboring airport (2b-LH2OFF-A).

In a third option, central H_2 production is also used in a GH_2 off-site pathway, but there the LFP is located at the receiving airport (3-GH2OFF in Fig. 2). In that case, GH_2 is transported via pipeline systems, and the LFP is powered by grid electricity. These pipelines can be retrofitted or newly built as well as subsea, or larger on-land transmission, or smaller distribution pipelines.

For all the supply chains at the airport, there are finally two options for designing the LH_2 refueling system: a hydrant-&-pipeline-system or a truck refueling system. More information on the refueling system design options is shown in [24].

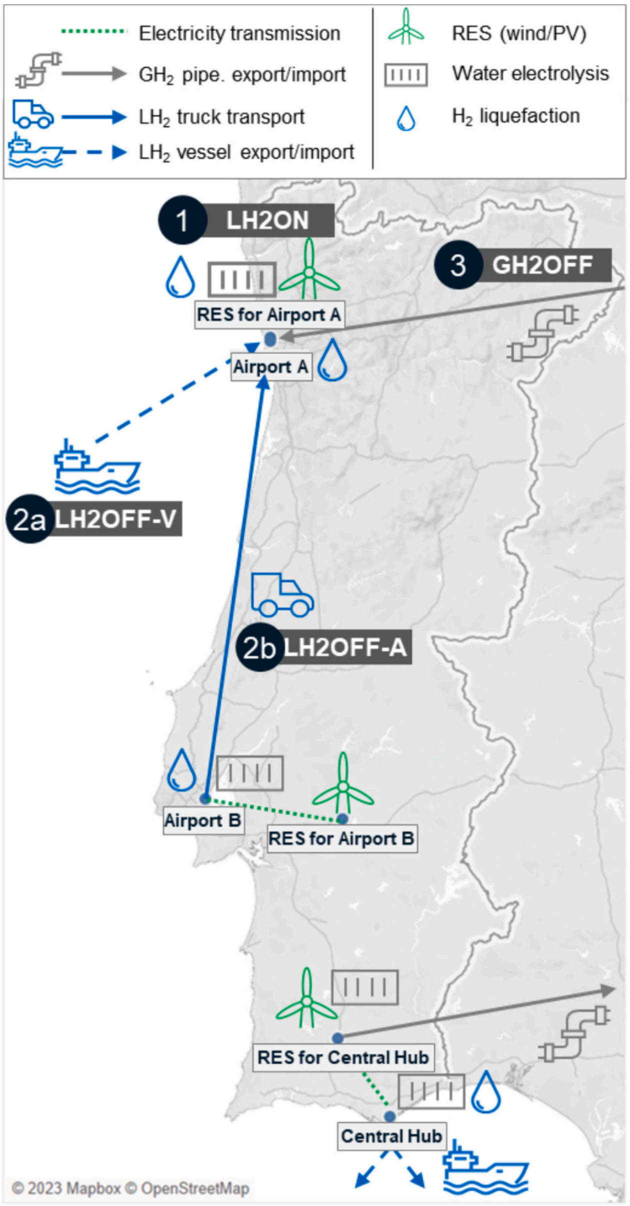

Fig. 2. Exemplary LH_2 supply pathways shown for an Airport A; 1 – LH_2 on-site supply at/close to the airport, 2a- LH_2 off-site import via vessels, 2b – LH_2 off-site import via road from a neighboring Airport B, 3 – GH_2 off-site import via pipelines and a LFP at the receiving Airport A; export hub perspective shown on bottom of map.

3.1.2. *Optimization of LH_2 supply chains*

A detailed overview of the optimization approach to select the optimal supply chain for a specific airport and to dimension the important components can be found in [44]. Here, only the main aspects are presented that are relevant for the specific investigations in this work.

The overall objective of the optimization is to minimize total annual LH_2 supply costs C_{TAC} delivered to an aircraft at one specific airport, so including refueling costs. Therefore, annualized capital expenditures (CAPEX) $C_{TAC,CAPEX,i,t}$ and operating expenditures (OPEX) $C_{TAC,OPEX,i,t}$ for each component i in a given time period (scenario) t are determined and minimized, see Eq.1:

$$min \sum_i \underbrace{C_{\mathrm{TAC,CAPEX},i,t} + C_{\mathrm{TAC,OPEX},i,t}}_{=C_{\mathrm{TAC},i,t}} \tag{1}$$

To calculate the annualized CAPEX, the annuity payment factor method is used. This is done based on the total costs $C_{\mathrm{CAPEX,total},i,t}(x_i)$ for each component in the chosen scenario and depending on its design capacity x_i, so scaling effects are reflected. By using the annuity factor $a_{i,t}$ the depreciation time of each component $T_{\mathrm{DP},i,t}$ as well as the costs of financing for RES and H_2 projects for different countries can be reflected with the interest rate $i_{i,t}$, see Eq. 2 and 3:

$$C_{\mathrm{TAC,CAPEX},i,t}(x_i) = C_{\mathrm{CAPEX,total},i,t}(x_i) \cdot a_{i,t} \tag{2}$$

with

$$a_{i,t} = \frac{\left(1 + i_{i,t}\right)^{T_{\mathrm{DP},i,t}} \cdot i_{i,t}}{\left(1 + i_{i,t}\right)^{T_{\mathrm{DP},i,t}} - 1} \tag{3}$$

The interest rate approach taken here is often called the weighted average cost of capital (WACC). In Table A1.1 in the Appendix, the financial costs considered for the interest rate for each country in this work are derived. All cost values in this study are presented in USD 2020.

The design of all component systems such as the RES, ELY, and LFP are taken as optimization variables. Further information on these and the main optimization constraints including non-linear component models are shown in [44].

Based on the modeling, the three main supply chain setups (LH2ON, LH2OFF-V, GH2OFF) and the underlying energy systems are optimized for each of the 104 airports independently. In the second step, the LH2OFF-A option is tested for all airports taking the previous LH2ON results and adding costs for the LH_2 truck to the neighboring airport calculated with the road distances between the different airports.

3.1.3. Study-specific techno-economic assumptions

The chosen optimization approach is built on three levels of techno-economic assumptions. General parameters for the techno-economics of each component are location-independent but vary with different time-dependent scenarios [44]. In the present study, the base case 2050 scenario assumptions from [44] are chosen for the main analysis and will be compared to a 2035 base case scenario.

The next level focuses on LH_2 on-site relevant assumptions, see Table A1.1 in the Appendix. The RES site is selected based on the best weather conditions in no larger distance than 100 km to the airport and given space availability – as possible to detect this based on satellite image research and not considering local regulations. Therefore, weather data is required to calculate the hourly resolved availability of RES. Here, data is taken from [46,47] for the reference year 2019, which is based on the MERRA-2 database. For an analysis of the uncertainties using one specific weather year for the chosen optimization approach, see [44]. At some sites only very limited land is available for RES, these airports are highlighted in Table A1.1. At two airports, Bergen and Tromsø in Norway, no possibility is seen to install additional wind or PV plants locally. However, current EU legislation shows that H_2 production could also be labeled as green when produced from electricity in a grid where more than 90% of electricity stems from RES (mostly hydropower). So, at airports like these two, without any space for RES but a grid qualifying for green H_2 generation, the grid option is also considered [48,49]. For Norway, which already fulfills these regulatory criteria today [50], the grid supply option is feasible and is used for the two airports with an assumed future electricity price of 50 USD/MWh [51]. RES generation from wind off-shore turbines is not considered in this study, since it is often more expensive than RES from hybrid wind on-shore and PV plants as shown in [44].

Besides the RES side, hourly-resolved demand profiles for LH_2 at the airports are inputs for the modeling. These are taken from [44] and are not further individualized for each airport. Furthermore, as found in [44], the availability of large-scale GH_2 underground storage can lead to significant cost reductions of the LH_2 supply costs, especially at weaker RES sites. Their assumed availability is also mapped for each airport in Table A1.1.

The last level of assumptions concerns H_2 off-site production and transport. Seven locations are chosen as potential export hubs: Scotland, Ireland, Portugal, Spain, Morocco, Saudi, and Australia. It is expected that these countries will have a surplus of green electricity to generate H_2 compared to their green electricity consumption in 2050 [52]. While the chosen sites in Scotland and Ireland qualify for a pure wind on-shore RES setup, the other sites have a hybrid setup with wind on-shore and PV plants. In addition to that, all hubs except Ireland should have geological preconditions to exploit the potential of integrating local GH_2 underground storages. See Table A1.2 for more information on the characteristics of all hubs.

On the transport side, the distances between airports, ports, and the hubs for LH_2 vessel import are shown in Supplementary Material Table S1.1. Costs for the LH_2 vessel and truck transports are based on [44] and a cost range results from varying future market sizes of 0.5–1.5 MtH_2 pr annum for such transport networks [53].

For GH_2 pipeline transport, all transport distances are given in Supplementary Material Table S1.2. These are based on the 2040 picture of the planned European Hydrogen Backbone pipeline network [54]. The GH_2 pipeline system is also considered for transmission routes with 1.5 MtH_2 per annum using the pipeline cost function from [44] and a share of 40% new and 60% retrofitted pipeline installations [55]. For the distribution pipeline connecting the airport with the European Hydrogen Backbone, on average a 0.15 MtH_2 pipeline and a 0.05 MtH_2 pipeline are considered to supply very large and large to all other airports, respectively. For the subsea transmission sections, an additional cost factor of 1.7 is used compared to land pipelines [55].

Assumptions on the interest rates were made individually for the component systems in the off-site pathways. All annual capital costs for the systems at the export hub are determined by the local interest rates. The GH_2 and LH_2 transport systems are seen as "international" encounters and hence, a central European interest rate of 6% for H_2 systems is taken [44]. The truck transport in the receiving country, as well as the refueling systems (incl. airport storage) at the airports, are calculated using the local interest rates again, see Table A1.1.

3.2. LH_2 cost results in the 2050 scenario

Based on the considerations made in Section 3.1, the LH_2 cost optimization results are shown for the selected airports. This is done for the 2050 base scenario as it represents a time frame of already established H_2-powered aviation. As a start, the overall results and then, the results for three selected airports are explained.

3.2.1. Optimized supply pathways

Fig. 3 shows the optimized LH_2 supply costs at the dispenser at each airport. In the following, average values of the optimized supply cost ranges are discussed for simpler comparability. The cost ranges result from low and high demand assumptions at the airport (Table 1) as well as from smaller or larger import market sizes as discussed above.

Based on the optimization results, on-site production (LH2ON) is the most economical supply pathway at 14 airports. These are mostly larger airports with high LH_2 demands leading to economies of scale for the CAPEX and efficiencies of main components like the LFP. The airports are either located close to export sites or in Northern-West European regions with good RES conditions. Some of these very large airports would also function as a broader H_2 supply hub for neighboring airports or other H_2 use cases, e.g., Edinburgh, Lisbon, Vienna, and Tel-Aviv airport. At some smaller neighboring airports, LH_2 on-site supply would also be a competitive option. However, due to smaller demand scales driving up costs, especially for the LFP, it is still less costly to import from the next very large airport with similar RES conditions. In

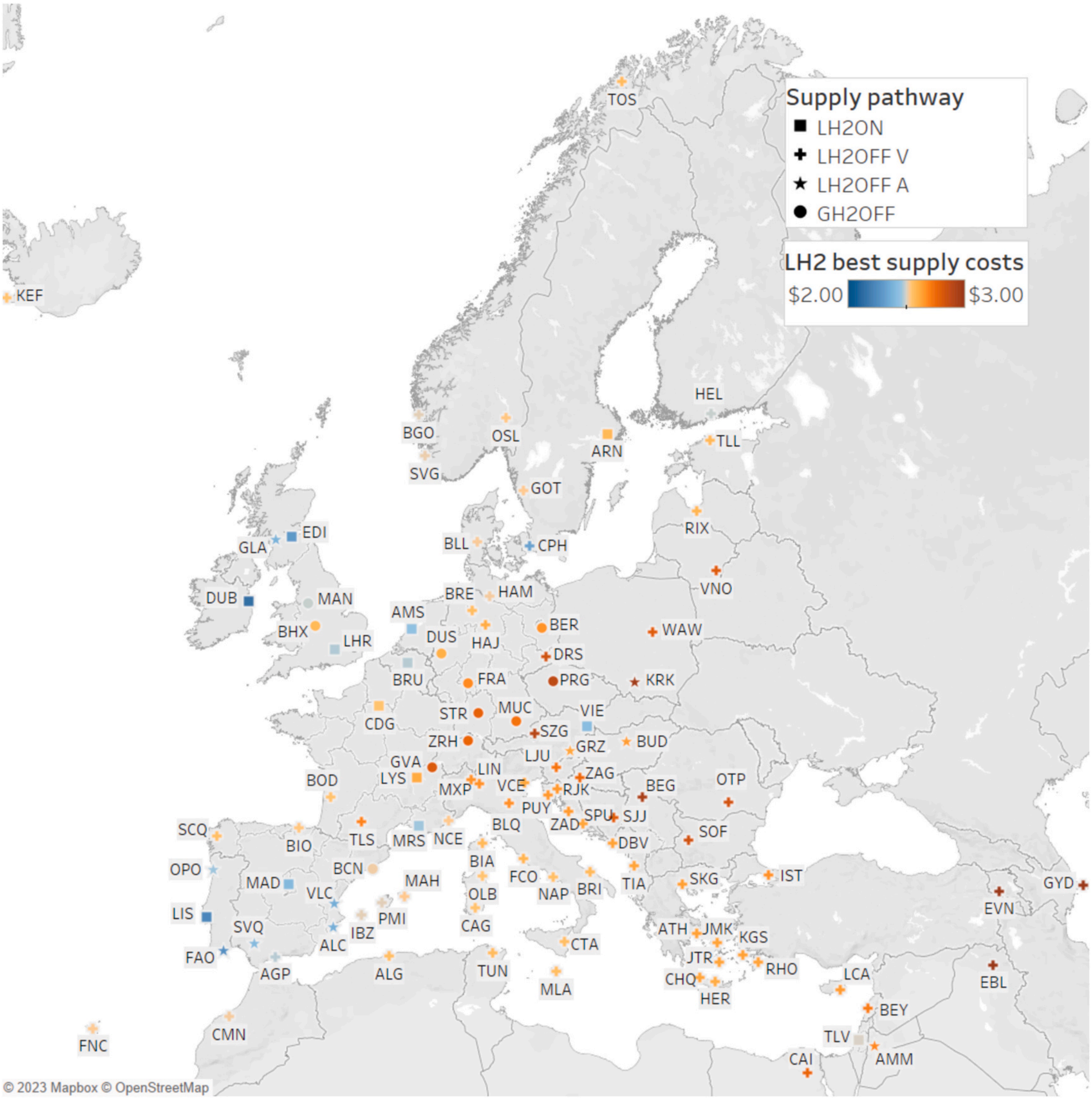

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Fig. 3. Optimized LH_2 supply costs at all selected 104 airports and 6 hubs – Australian hub not shown, costs at the dispenser (incl. LH_2 refueling system) in USD/kgLH_2, GH2OFF – GH_2 off-site supply via pipelines, LH2OFF A – LH_2 off-site supply from a neighboring airport/export hub via LH_2 trucks, LH2OFF V - LH_2 off-site supply from central hubs via vessel transport, LH2ON – LH_2 on-site supply at/close to the airport.

total, 10 airports are supplied by this “neighboring” option with 6 airports sourcing from a larger airport and 4 airports from a closely located hub (Portugal, Spain). Due to the very short distances to these H_2 supply hubs, it would be less costly to transport LH_2 via trucks to the smaller airports (LH2OFF-A) than using larger-scale off-site supply setups (pipelines or LH_2 vessels).

In general, the chosen hubs reach the best economies of scale due to the very large demand scales above 0.5 MtH_2/a. Plus, they will most likely function as main exporters for all H_2 markets and not only aviation. Australia, Portugal, and Scotland are the most competitive hubs with exporting costs of 2.06–2.13 USD/kgLH_2 before losses, the LH_2 transport and refueling system costs. However, the results indicate that no airport would be supplied from Australia given the very long LH_2 transport distances. At the sites in Saudi Arabia and Morocco, supply costs could also be slightly higher due to interest rates of 6% and 9% for RES projects, respectively. This leads to exporting costs of 2.34 and 2.65 USD/kgLH_2. In the Morocco example, which was also investigated in the author’s previous study [44], the cost increased by 24% due to higher costs of financing. Hence, it remains uncertain whether countries with currently higher costs of financing like Morocco will play an important exporting role in a global H2 economy in the next 10–30 years. If these financing risks decrease in the future as indicated by [56,57], then imports from such countries could become superior to the other European options.

From such central hubs, 69 airports would be supplied via LH_2 vessels (LH2OFF-V), most of them being located in more coastal areas or also being inland airports that might have very low LH_2 demands. 17 airports would import from Scotland and 52 from the Portugal hub. As an extreme, results from the Iraqi airport EBL and Azerbaijan airport GYD indicate that even though distances from the import harbor to the airport are nearly 1000 km, it might be less costly to import via LH_2 vessels and then trucks than having dedicated infrastructure due to weaker local RES and also high interest rates. For larger coastal sites such as Barcelona Airport, there is an exception to the rule, since it is closely located to the Spanish H_2 hub and it is cheaper to connect via the GH_2 pipeline system than importing LH_2.

GH_2 off-site supply (GH2OFF) is the best option for 11 airports, which are located farther inland and have higher LH_2 demands. Consequently, scaling effects for the LFP and storage at the airport are driving down costs as already explained previously.

This trend can be emphasized when investigating similarly located airports but with smaller demands like Dresden Airport. While surrounding airports like Berlin and Prague would be supplied by the GH_2 pipeline, the on-site LFP in Dresden would be very small, and hence, specific CAPEX and energy consumption are significantly higher. With higher energy requirements and more expensive grid electricity costs for the LFP, this trend is even more significant. This is why, longer LH_2 truck transport from a central LH_2 import terminal is still the more economical choice for such smaller inland airports.

3.2.2. Comparison of costs with LH_2 on-site supply only

To provide a perspective on the importance of such import supply options, the previous results are compared to a 2050 LH_2 fuel network where only on-site supply (LH2ON) would be available, see Fig. 4.

The cumulative frequency distribution of optimal results shows that if import options are available, only for 2% of airports or less than 0.5% of LH_2 amounts the supply costs would be above 3 USD/kgLH_2 (blue markers in Fig. 4). On the contrary, for on-site supply only LH_2 costs in the network would increase significantly. In that case, 50% of airports would have higher supply costs at the dispenser than 3 USD/kgLH_2. Considering the amount of delivered LH_2 this would be 26% (see orange markers). All on-site cost results are shown in Table S1.3 and a comparison between all supply options for each airport is in Figs. S1.2-S1.10 in the Supplementary Material.

Besides the higher costs in the on-site-only network, also the required resources like RES capacities differ. Since RES would be installed at even weaker weather sites, 44% larger on-shore wind and PV capacities would then have to be installed. However, since fewer H2 losses occur in on-site setups (no longer distance transport), the total energy efficiency per fuel delivered increases slightly.

3.2.3. Three airport case studies

To give an impression of the cost breakdown of different supply pathways and effects at different locations, the results are briefly discussed for three exemplarily selected airports, see Fig. 5.

At Vienna Airport (VIE), LH_2 on-site production achieves the lowest costs due to very good RES conditions and the availability of space in a 100-km radius around the airport. Otherwise, if RES availability would be limited, GH_2 off-site supply is the second best option like at Munich Airport. Due to the long distances to the next importing harbor, LH_2 off-site supply is the costliest.

Graz Airport (GRZ) has a smaller LH_2 demand scale (5–10 k t/a vs. Vienna Airport with 100–300 k t/a) which would lead to high costs for the LFP in the GH_2 pipeline setup. Even though LH_2 vessel import routes would be cheaper, the best option would be to transport LH_2 with trucks from Vienna to Graz (ca. 200 km distance). Then, Graz Airport could also profit from economies of scale at the central Vienna hub.

As the last site, Ibiza (IBZ) as an island airport without a potential connection to a GH_2 pipeline grid is presented. On-site production costs are comparably low because the levelized costs of electricity (LCOE) are already competitive and the medium-sized demand category leads to the before mentioned cost scaling effects. However, large-scale LH_2 import via vessels would enable the lowest supply costs for Ibiza where the truck distance for the "last mile transport" is also very short (<10 km from potential import terminal to airport). An overview of the levelized costs of electricity at or nearby all airports is shown in Fig. S1.1 in the Supplementary Material.

4. H_2-powered aircraft design

In the second step, the aircraft-related cost aspects are considered. As a start, the underlying aircraft design methodology is briefly introduced. Then, the resulting H_2-powered aircraft designs and potential operational strategies with these are investigated to evaluate the operational cost impact of green LH_2 supply for aviation.

4.1. Aircraft design methodology and results

As shown in [23], calculating direct operating costs (DOC) is a common approach to evaluating new aircraft technologies and designs. DOC consists of five cost categories: (1) fees for air traffic control and airport services, (2) crew, (3) aircraft CAPEX, (4) aircraft maintenance, and (5) energy costs. While fees and crew costs are not affected by changing the aircraft propulsion from kerosene- to, e.g., H_2-powered, the impacts on the latter three categories are investigated in this study.

Existing airlines' single-aisle fleets are often built on one aircraft type

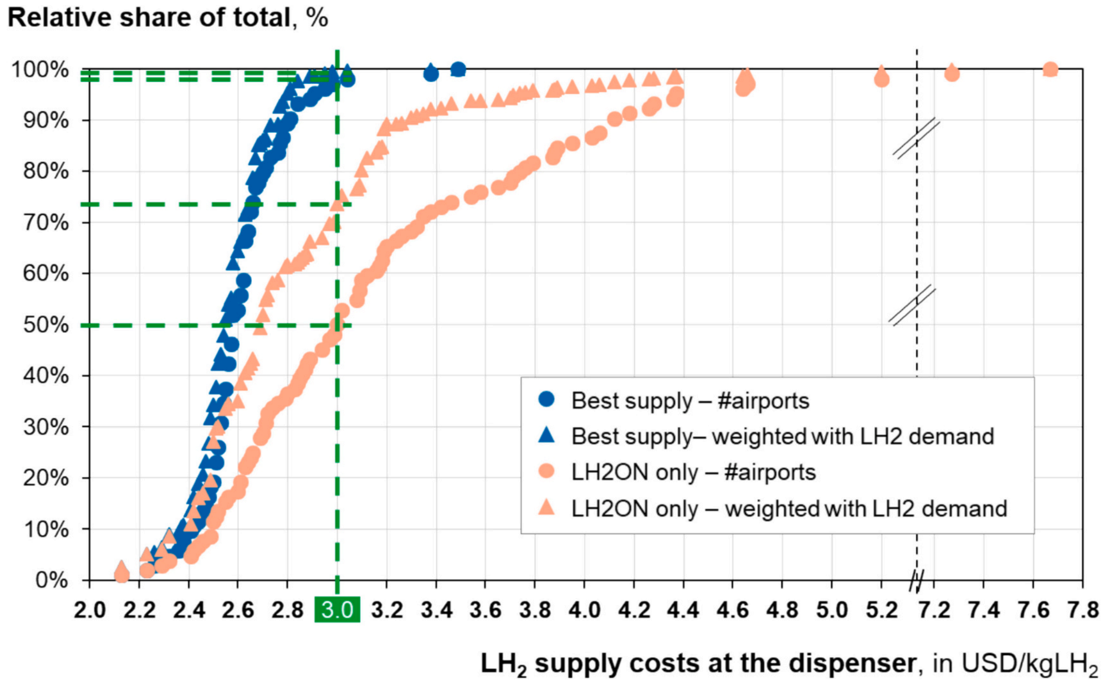


Fig. 4. Cumulative frequency distribution of cost results for the best-supply-cost-pathways and LH2ON only supply, either weighted by the LH_2 demand scale of each airport or only by the number of airports.

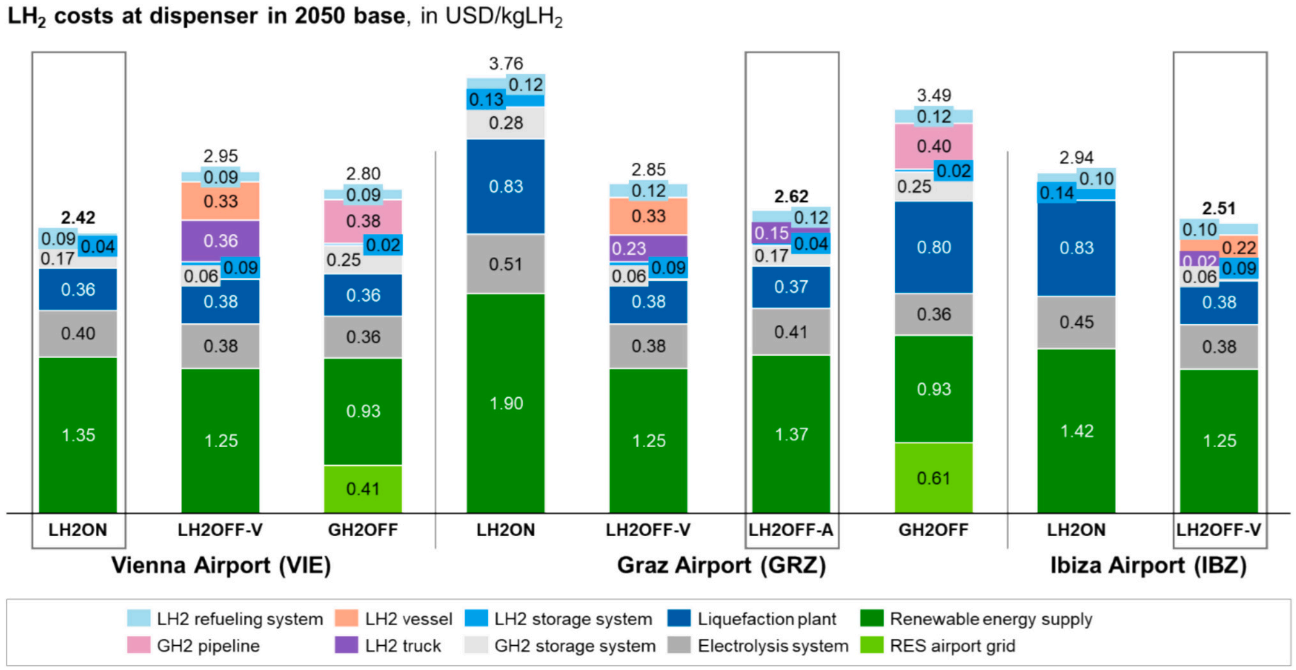


Fig. 5. LH_2 costs at dispenser for three selected airports, LH2OFF-V import for all cases from Portugal for best costs, GH2OFF import from Scotland but not available for Ibiza (island); Graz Airport with LH2OFF-A supply from neighboring airport VIE; RES airport grid means that LFP at the airport in GH2OFF setups is supplied with green grid electricity, see [44] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with slightly different performances for specified use in the airline's network, e.g., different flight lengths. In the reference case study, the airline's fleet consists of Airbus A320-family aircraft (A319, A320, A321). To reflect a similar family-aircraft approach, four single-aisle aircraft with differing design ranges but constant payload (PAX) capabilities are analyzed with both propulsion options, i.e. kerosene/synfuel and H_2 direct combustion. The aircraft design optimization is based on the methodology described in Hoelzen et al. [23] and Silberhorn et al. [12,58,59] and shortly outlined in Appendix A2. As part of this, general fuel efficiency improvements are accounted for all propulsion types, because a new technology should be compared to a similarly advanced kerosene-powered aircraft with entry-into-service in 2035 [23].

Flight trips in the reference air traffic network are below 2000 NM, shown in Section 2. However, the four chosen aircraft designs differ in their design ranges from 1500 NM to even 3000 NM. The reason is that there is an operational strategy, called tankering, which might make use of these different design ranges. Tankering means that instead of refueling the aircraft for the return trip at the destination airport, it is already loaded with enough fuel at the origin airport for both flights. Such a strategy is used today already when the fuel costs between the origin and destination airport differ greatly. To enable longer flight trips with a tankering strategy, aircraft with longer design ranges are needed.

First analyses showed that this strategy might be of interest when operating H_2-powered aircraft in a network with highly differing LH_2 fuel costs at airports [21,31,32,37,38]. The underlying logic is that H_2-powered aircraft require a heavy LH_2 tank onboard while the mass of the LH_2 itself takes only a small portion of the total weight when the aircraft is fully fueled. Consequently, the increase in fuel consumption for longer distances vs. shorter distances due to the fuel weight is relatively low. This is different for kerosene-powered aircraft. First, kerosene is stored in the wings of the aircraft and does not require an extra heavy tank. Second, the kerosene weight is roughly three times higher for the same energy content vs. LH_2, because of its lower gravimetric energy density. This is why for kerosene-powered aircraft the fuel consumption for the outbound trip can increase significantly due to the higher takeoff weight when a tankering strategy is applied [60].

Therefore, in the present study, designs with longer single trip lengths (>2000 NM) are modeled enabling tankering over distances up to 1425/1430 NM.

All resulting aircraft designs and their performances are presented in Table 2. For the four kerosene-powered aircraft, no significant change in the block energy demand can be observed for a fixed trip length (here 800 NM). This is because the kerosene is stored in the wings and thus, the maximum operating empty mass does not increase too much between a 1500 NM and a 3000 NM design. However, for the H_2-powered aircraft, this effect is stronger. Due to the total resulting increase of the LH_2 tank volume and mass despite decreasing gravimetric tank indexes, the fuselage has to be extended and total aircraft efficiencies decrease. Further aircraft design parameters are shown in Appendix Table A2.

Fig. 6 shows the resulting DOC for the four aircraft designs at a fixed trip length of 800 NM. It underlines the same trend – no big changes for kerosene- but for H_2-powered aircraft – for the DOC from aircraft CAPEX and maintenance when comparing both fuel technologies. Due to the larger LH_2 tanks, and increasing aircraft size and mass, these two DOC factors become costlier. Crew costs and fees stay constant for all designs.

4.2. Operation of H_2-powered aircraft

Next, the impacts of the operational strategy, tankering, are investigated for the previously derived four aircraft designs. While tankering could lead to better fuel costs with H_2-powered aircraft, the changes in the aircraft's performance and operating costs have to be investigated.

In Fig. 7A, the four individual H_2-powered aircraft cost curves (DOC excluding energy costs) are shown compared to the kerosene reference. Two general trends can be observed. First, the cost increase is lower for each aircraft when flying longer distances. The underlying cause is that the cost increase of aircraft CAPEX and maintenance for H_2-powered versions weighs more on very short trips. With shorter trips, the ground time of the aircraft increases, and fewer annual flight cycles can be flown. Hence, the costs per available seat kilometer (ASK) increase. Second, the longer the aircraft's design ranges the higher the cost change vs. kerosene. This is also due to the heavy LH_2 tank weight and related enlargement of the aircraft design explained in the previous section.

Evaluating the results on a fleet level, this study assumes that always

Table 2
Future kerosene vs. H_2-powered aircraft specifications for the four single-aisle (SA) designs; MTOM: maximum take-off mass, OEM: operating empty mass (no payload, no fuel on board the aircraft).

	Unit	SA – 1500 NM	SA-2000 NM	SA-2500 NM	SA-3000 NM
Input parameters valid for both aircraft technologies					
Design Entry-Into-Service	–	2035	2035	2035	2035
Design PAX (Single class layout)	–	180	180	180	180
Design Cruise Mach-Number	–	0.78	0.78	0.78	0.78
Design Range^{a}	NM	1500	2000	2500	3000
Results for kerosene-powered reference aircraft					
Calculated MTOM	t	65.6	68.1	70.6	73.2
Calculated OEM	t	39.7	40.0	40.3	40.6
Block-Energy for design mission	GJ	286	376	470	567
Block-Energy for typical 800 NM mission	GJ	166	167	167	168
Calculated annual flight cycles (800 NM)	–	1512	1512	1512	1512
Max. trip length for tankering^{b}	NM	670	920	1170	1425
Results for H_2-powered reference aircraft					
Calculated MTOM	t	68.7	71.6	74.7	77.7
Calculated OEM	t	48.2	50.5	52.3	54.3
Block-Energy for design mission	GJ	303	408	522	641
Block-Energy for typical 800 NM mission	GJ	177	183	190	196
Calculated annual flight cycles (800 NM)	–	1514	1515	1516	1516
Max. trip length for tankering^{b}	NM	675	925	1175	1430

a) Considering 200 NM, 30 min loiter, and 3% contingency reserves that are on top of the shown design range.
b) Assuming no additional losses at the intermediate airport.

the smallest aircraft is used to fly the specific trip distance, see the resulting blue line in Fig. 7A. It has to be noted that this assumption is required as a simplification for the total DOC calculations in Section 5. However, in reality, this rule is not fully realizable when optimizing flexibilities in the fleet portfolio and the network routes.

In the next step (Fig. 7B), the tankering option is compared to the normal single-trip operation on the fleet level. So, the DOC for tankering is always mapped against the DOC of the smallest required aircraft operated on single trips without tankering. Since the maximum flight distance between the origin and destination airport can be 675 NM with the SA-1500 aircraft, a drastic increase in the DOC result from longer flight trips with tankering using larger, more expensive aircraft (see orange line). So, the benefit of lower energy costs must be even greater for such trips to compensate for the higher aircraft-related operating costs.

Similar effects are found when comparing the specific energy consumption (SEC) as a function of the trip distance in Fig. 7C. Here, the SEC change vs. kerosene increases for the larger H_2-powered aircraft. Furthermore, the tankering option up to 675 NM leads to slight increases in SEC and very high increases for tankering flights (up to 8% increase in SEC).

In general, the SEC with the tankering strategy increases by 4% for a kerosene- vs. less than 1.5% for an H_2-powered aircraft compared to the non-tankering flight on a 1430 NM trip with the SA-3000 NM designs. This explains why tankering is not too often considered with kerosene-powered aircraft but might be a valid option when introducing H_2 propulsion in aviation. Additional data on the aircraft design optimization are given in Supplementary Material Table S2 and Figs. S2.1-S2.2.

As a brief intermediate conclusion, it can be emphasized that the aircraft-related cost increase of flying with H_2 is lowest for aircraft with the shortest design ranges. Furthermore, tankering strategies could lead to significant cost penalties for flights above 675 NM – requiring high benefits in saving LH_2 fuel costs at a destination airport to compensate for the additional aircraft costs. Consequently, the supply and aircraft cost perspectives have to be evaluated together.

5. Resulting operating costs for H_2-powered aircraft

In this final step, the costs for the LH_2 supply infrastructure at the selected airports and the H_2-powered aircraft are combined. This is done

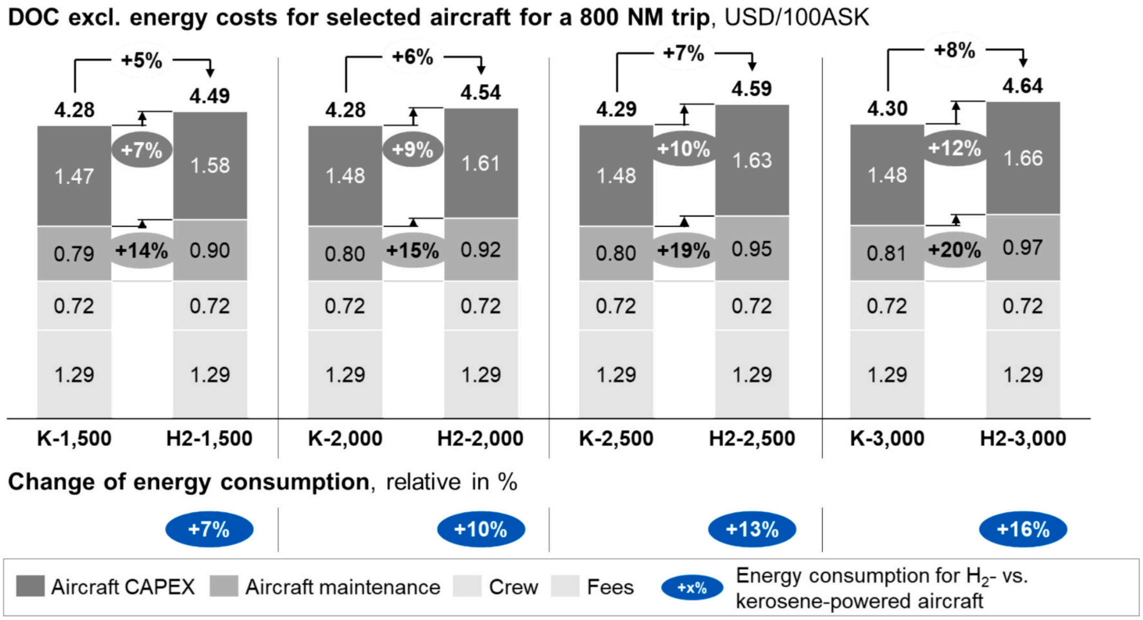
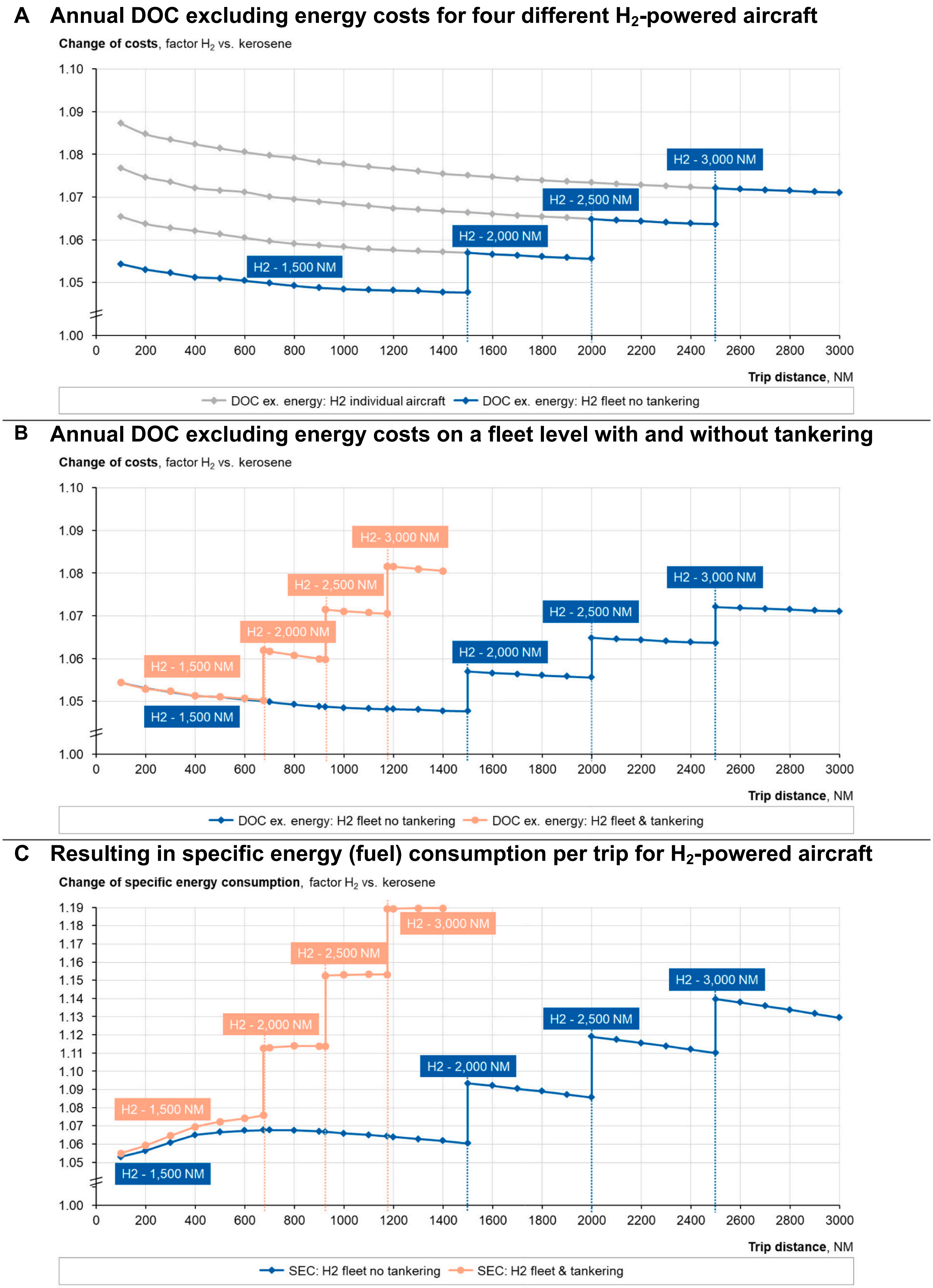


Fig. 6. Change of selected DOC factors excluding energy costs and energy consumption for kerosene- (K-XXXX) vs. H_2-powered aircraft (H2-XXXX), XXXX representing the design range of the aircraft – grey bubbles show relative cost increase for the aircraft DOC levers.



A Annual DOC excluding energy costs for four different H_2-powered aircraft

B Annual DOC excluding energy costs on a fleet level with and without tankering

C Resulting in specific energy (fuel) consumption per trip for H_2-powered aircraft

Fig. 7. H_2-powered aircraft results (design ranges indicated by boxes) compared to kerosene equivalent designs – A. DOC excl. Energy costs comparison, B. DOC excl. Energy costs comparison against best kerosene aircraft option, C. SEC comparison against best kerosene aircraft option.

with the calculation of total DOC for all flights in the given network, which are discussed in comparison with kerosene and synfuel cost benchmarks. This should enable a more holistic answer on the competitiveness of H_2-powered single-aisle aircraft based on the 2050 scenario assumptions. Then, the analyses are repeated for a different scenario representing an early phase (2035–2040) of the introduction of H_2 in aviation to also evaluate economics in such a scenario. Lastly, resource efficiency aspects are investigated for conclusions on the future of single-aisle H_2-powered aircraft.

5.1. Comparison of kerosene-, synfuel- and H_2-powered aircraft in the 2050 scenario

The direct operating costs are calculated based on the flight data of the reference air traffic network for the one exemplary week (see Section 2). Then, the sum of all flights' costs is divided by the total flown available seat kilometers to derive an average DOC value. Moreover, the tankering strategy is analyzed reflecting the change in aircraft-related DOC and higher energy consumption per flight.

For the technology comparison, the energy cost benchmarks are derived first for the calculation of the total DOC in the given network for also kerosene- and synfuel-powered aircraft.

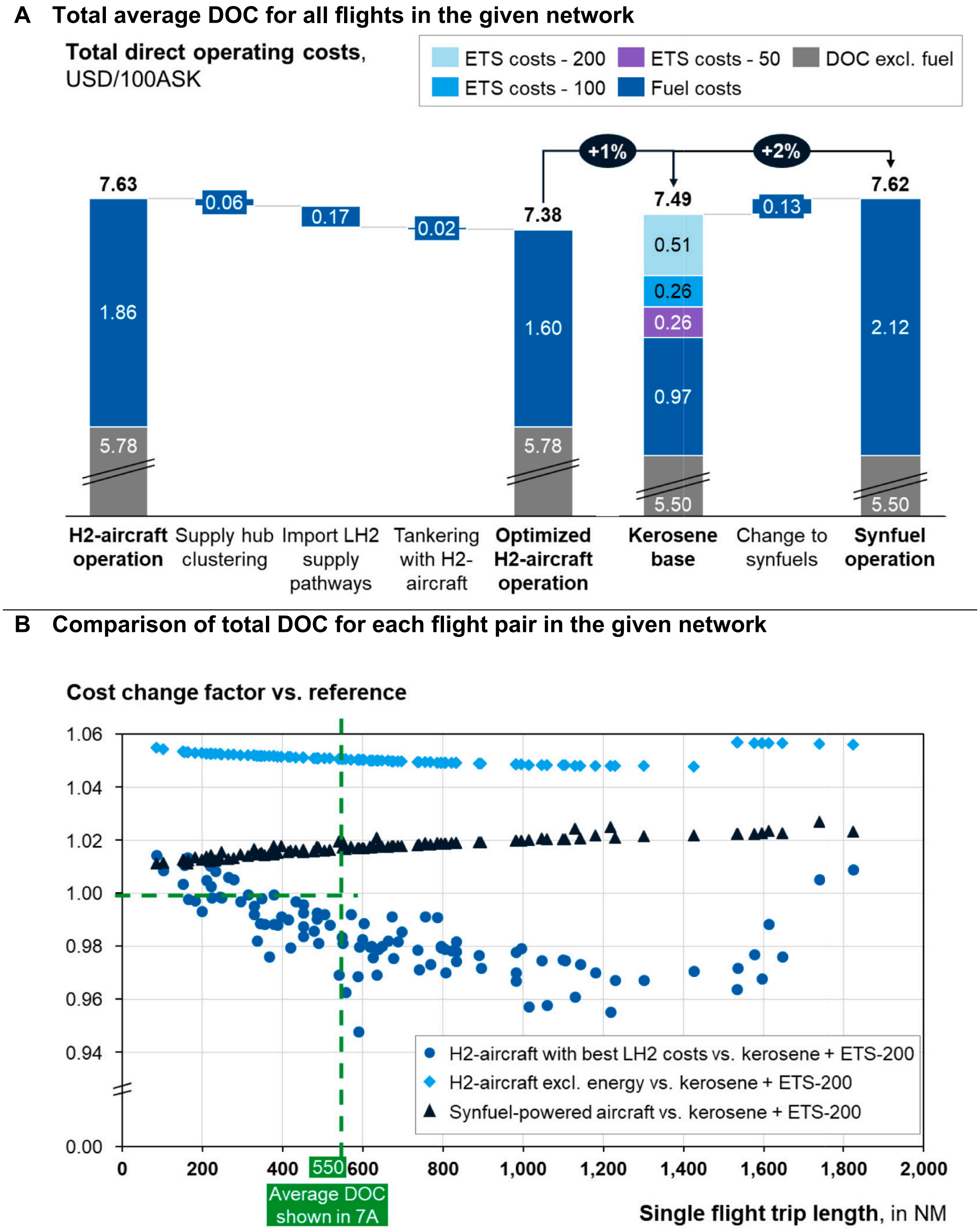


Fig. 8. A) Average total DOC of kerosene-powered aircraft in a given air traffic network including different ETS-CO_2-cost scenarios in USD/tCO_2 compared to synfuel- and H_2-powered aircraft operation; B) Total DOC for H_2- and synfuel-powered aircraft for each flight pair concerning kerosene-powered aircraft operation incl. 200 USD/tCO_2 costs.

5.1.1. Energy cost benchmarks for kerosene and synfuels

While the oil price is highly volatile and hence, the future cost development of kerosene is very uncertain, costs of 0.60 USD/kg kerosene at the dispenser are assumed [23,61]. Additionally, European commercial aviation is increasingly becoming a subject for regulating CO_2 emissions with the European Trading Scheme (ETS) in the future [62]. In this study, three mid- to long-term ETS cost scenarios are assumed – 50, 100, and 200 USD/tCO_2 – which are in line with investigations in [63]. The CO_2 emissions for kerosene-powered aircraft can be calculated using a factor of 3.16 kgCO_2/kg kerosene consumption [3]. This mechanism and calculation does however not consider any non-CO_2 emission effects caused by conventional aircraft.

Synfuel costs are calculated based on the same energy system assumptions discussed in Section 3. Since synfuel production also requires green H_2 and a well-utilized fuel conversion afterward – which has a comparable power/energy consumption share like the LFP – energy system design and cost assumptions are taken from the LH_2 calculations. In [44] it was shown that utilization of the LFP of ~90% is achievable with RES and GH_2 storages. The conversion of hydrogen to its liquid form is comparable to the fuel conversion in the synfuel process. Hence, the same utilization is taken for the synfuel processes behind the electrolysis. The calculation method and techno-economic assumptions are shown in Appendix A3 including the costs for direct air capture, the Fischer-Tropsch synthesis, fuel transportation, and refueling.

The resulting costs for the 2050 base case assumptions [44] range from 1.25 to 1.43 USD per kg synfuel at central production hubs like Scotland, Portugal, Saudi Arabia, or Australia. This includes transport and refueling to the 104 selected airports. Based on that an average synfuel cost of 1.31 USD/kg synfuel is assumed in the following.

5.1.2. Cost of aircraft operation in the 2050 scenario

Both synfuel- and H_2-powered single-aisle aircraft would be costlier to operate in this air traffic network compared to a future kerosene-powered aircraft, if the costs for CO_2 emissions are 100 USD/tCO_2 or lower, see Fig. 8A. In a scenario with 200 USD/tCO_2 costs in the EU, synfuel-powered aircraft would still be slightly (2%) more expensive while LH_2-fueled aircraft would be 1% less expensive. In all cases, the energy costs for kerosene plus ETS, synfuel, or LH_2 have a major share of the total DOC. For LH_2 fuel costs, the main lever to achieve competitive energy costs is the availability of import supply pathways with 0.17 USD/100ASK total operating cost reduction potential. Then, energy DOC costs with H_2 propulsion would be 24% lower than with synfuels including the change in aircraft efficiency.

Nevertheless, the switch to novel aircraft with H_2 propulsion causes a cost increase of 0.28 USD/100ASK in the DOC aircraft categories (CAPEX and maintenance) compared to the kerosene and synfuel versions. Combining both fuel cost and aircraft perspectives, the H_2 aircraft would be 3% less expensive to operate than a synfuel alternative.

In total, the energy costs still account for only 22% of the operating costs with H_2- and 28% with synfuel-powered aircraft. This is a typical characteristic when considering DOC for single-aisle aircraft operated on shorter routes where fixed costs for crew or each landing plus passenger handling are the main cost drivers.

The DOC dependency on the trip length is also emphasized in Fig. 8B. While the costs for synfuel-powered flying do not change drastically with longer trip distances (slight increase only; also highlighted in Section 4), this is different for H_2-powered operation. Three effects explain this: first, the share of energy costs for total DOC is decreasing for short vs. longer trips as explained before. The LH_2 costs account for 19% of the total DOC for all flights below 675 NM, but for 27% for flight lengths between 1000 and 1500 NM, see also Fig. S3.1 in the Supplementary Material. Since the H_2 aircraft has significantly lower energy costs vs. the synfuel alternative, this advantage only leads to greater cost-saving potentials for longer distances. Second, the cost increase for H_2 aircraft CAPEX and maintenance is higher for shorter distances as shown in Fig. 7A. Next to the fuel costs, this also increases total DOC for shorter flights.

Moreover, the DOC further increases when switching to the next larger aircraft with a design range > 1500 NM (Fig. 8B). Third, the variation of total DOC for H_2-powered aircraft can be explained by the highly differing LH_2 supply costs whereas synfuel costs are assumed to be constant at all airports. Another effect explaining higher energy costs for the three airport pairs above 1600 NM is that these non-EU destination airports come with significantly higher LH_2 fuel costs (Fig. 2: EBL, EVN, GYD).

Overall, this means that H_2-powered single-aisle aircraft is an economic choice for air traffic networks which do not only consist of very short trip lengths.

In the 2050 scenario, the role of tankering is found to be minor in reducing total DOC (0.02 USD/100ASK in Fig. 8A), if all supply pathways including the import options are available. In this case, tankering would be economically eligible only on shorter trips below 675 NM and on 59 routes with minor energy cost savings, see also Fig. S3.2 in the Supplementary Material. On 14 of the 59 routes aircraft would be refueled at the hub in Frankfurt, not requiring LH_2 fuel supply at the destination airports. Otherwise (45 routes), the aircraft would be refueled at the destination airports and not in Frankfurt. The tankering trips could still be flown with the smallest and most economical H_2-powered aircraft (1500 NM) design with only minor cost penalties coming from a slightly higher SEC. Consequently, the aircraft design ranges in the optimized fleet are identical for kerosene−/synfuel-powered aircraft and the H_2 versions.

However, if no import supply options would be available, tankering becomes more relevant. Then, tankering from Frankfurt could be applied to 28 destination airports not requiring a fuel supply over single-trip lengths up to ~925 NM. This leads to an average DOC for H_2-powered aircraft of 7.49 USD/100ASK and a DOC fuel cost reduction due to tankering of 0.08 USD/100ASK. Further information on tankering routes and DOC cost-saving potentials are presented in the Supplementary Material.

5.2. Re-evaluation of results in 2035–2040 (early adoption) scenario

In an early deployment phase, the DOC for H_2 aircraft CAPEX and maintenance do not change while techno-economic assumptions for green LH_2 infrastructure would be more conservative. Also, the LH_2 demands at airports, as shown in Table 1, are significantly lower, since it would be the beginning of fleet renewal with the first H_2-powered aircraft entering into service. This is why, the analyses from Sections 3 and 5.1 are repeated for the 2035 base case described in [44] to re-evaluate the economics of H_2-powered aviation versus the other options in that time frame. All results are shown in Table S1.4, Figs. S1.11-S.1.12, and Figs. S3.4-S3.6 in the Supplementary Material. Here, only the main findings are briefly described.

LH_2 supply costs increase significantly above 3 to even 5 USD/kgLH_2. The main driver for these results is not only the higher costs for each component. Another cause is also the smaller installation size of LFP at an airport and hence, only LH_2 off-site supply pathways would be an economic choice – if available in this early adoption phase. Then, LH_2 would be supplied via vessels from Scotland, Portugal (97 airports) or via truck around the European hubs (7 airports). In an on-site and GH_2 off-site supply setup, limited to no economies of scale could be achieved for such on-site components (e.g., the LFP). The average LH_2 costs would then increase by 53% compared to the import supply to beyond 5 USD/kgLH_2.

The total DOC (analog to Fig. 8A) for flying with H_2 increased by 8% due to higher fuel costs in 2035–2040. Despite the higher costs, the comparison with synfuels shows even greater advantages in that case for H_2-powered aircraft. Taking the same techno-economic assumptions for synfuels with the best production setups in this earlier scenario, synfuel would cost on average 2.14 USD/kg. This leads to an 11% decrease in total DOC with H_2- compared to synfuel-powered aircraft.

Similarly to the 2050 picture, tankering is only a relevant cost improvement option for H_2-powered aircraft, when no LH_2 import options would be available. That might be more likely in such an early adoption phase with not too many other large LH_2 markets. In that case, tankering reduces energy DOC by 0.37 USD/100ASK – with the availability of LH_2 import supply the direct operational cost improvement would be 0.97 USD/100ASK though.

5.3. Resource perspectives for the future of H_2-powered aviation versus synfuel option for single-aisle aircraft

Lastly, the implications of deploying green LH_2 vs. synfuel supply are discussed from a resource efficiency perspective. Besides the cost results, this is another important aspect since resources like RES capacities will always be a constraint [3,64].

Comparing both decarbonization options based on the fuel supply perspective (well-to-tank) and the same 2050 scenario assumptions, the energy efficiency is significantly higher with green LH_2 vs. synfuel supply, see Table 3. This already includes all H_2 losses like boil-off and flash losses when transporting LH_2 over longer distances – on average 4.3% in the total supply network. Furthermore, in the given optimization, 40% less renewable energy generation is required for the LH_2 supply setup including import described in Section 3 compared to the synfuel option. In that comparison, synfuels would be produced for best costs purely at central sites like Portugal, Scotland, Saudi, and Australia and distributed via ship like most of the fossil kerosene/oil products are traded today. The same trend can also be observed for the needed electrolysis capacity installation for synfuel vs. the LH_2 supply network for the 104 airports, see Table 3. As a side fact, the LH_2 supply network for the 104 airports would then require the installation of liquefaction plants with a capacity of approximately 26,000 tpd in 2050.

Resulting from the lower capacity deployments, also the required capital expenditures are lower for green LH_2 fuel supply. The CAPEX required for the synfuel production is 73% higher than for green LH_2 supply, not including the extra-CAPEX for the H_2-powered aircraft development vs. a 2035-updated aircraft design as well as the transport and refueling system CAPEX for both fuels.

From a fleet-level perspective, which includes the slightly lower efficiencies of the H_2-powered aircraft, the differences between green LH_2 and synfuels are slightly reduced but still significant. On average (considering all trips flown in the network), 11% more fuel energy is required for 100 ASK when flying with hydrogen. However, still, 34% less renewable electricity is required for the H_2-powered aircraft fleet when all losses are considered (fuel and flight efficiencies).

In total, the analyses in this study showed that the total DOC picture and also resource efficiency could be more positive for H_2-powered aircraft in the single-aisle segment than for synfuel. However, this is not argumentation against synfuels or SAF in general. Since decarbonization of air travel is needed as soon as possible and the entry-into-service of H_2-powered aircraft and a meaningful renewal of existing fleets will take longer than until the year 2050, SAF is also required to power these "smaller" commercial aircraft – at least in the intermediate time period. Also, there is still no holistic, clear perspective on DOC and resource efficiency for wide-body aircraft. In such larger segments, SAF including synfuels will most likely be the main decarbonization choice.

6. Conclusions

The novelty of this study is the holistic assessment of H_2-powered aviation's future business case combining three main aspects: optimization of LH_2 supply infrastructure, H_2-powered aircraft designs, and operational strategies in an exemplary European air traffic network. It delivers the first overarching conclusions on the future of H_2 propulsion in the single-aisle commercial aviation segment based on the taken techno-economic assumptions. Furthermore, the study enables other researchers to investigate LH_2 fuel costs and/or the use of H_2-powered single-aisle aircraft in other air traffic networks.

Overall, it is found that LH_2 fuel costs would be between 2 and 3 USD/kgLH_2 for airports that have access to larger H_2 import markets or great renewable energy supply conditions for on-site fuel production. For smaller airports, it might be cheaper to import LH_2 from larger markets despite potentially good local renewable energy supply conditions. The reason for that are limited economies of scale effects for capital expenditures and energy efficiency for airport LH_2 supply chain equipment, especially for the liquefaction plant and storage. Similar effects are identified for importing H_2 in its gaseous form at such smaller airports.

Regarding the H_2-powered single-aisle aircraft designs, direct operating costs and specific energy consumptions will most likely increase versus kerosene-powered aircraft. As a main operational strategy, tankering was found to be an option to potentially reduce infrastructure deployment needs. However, this would have the largest effect with a 12% reduction of energy direct operating costs in an early adoption time frame (2035–2040), when LH_2 supply costs would still be high.

In total, the combined perspective of single-aisle H_2-powered aircraft and green LH_2 fuel economics revealed an average cost benefit of 3% flying with H_2 vs. synfuels and 1% compared to burning kerosene plus 200 USD/tCO_2 Emission Trading Scheme (ETS) costs. Thereof, the main cost reduction driver is LH_2 as a fuel which would lead to 24% less energy direct operating costs than with synfuels despite an increase of the specific energy consumption with the H_2-powered aircraft. In an early adoption phase, the total direct operating costs benefit vs. synfuels even increases to 11%.

Moreover, it was found for the given segment that H_2-powered aircraft would lead to more efficient use of constraint resources. For an exemplary fleet, 34% less renewable energy would be required per 100 available seat kilometers flown with the H_2- vs. synfuel-powered aircraft.

Regarding the limitations of this study, four points should be emphasized.

First, the presented LH_2 supply cost results are specific for the considered airports and regions. Further studies would be required to

Table 3

Comparison of fuel technologies for decarbonizing the existing air traffic network, so LH_2 demands at all 104 airports – for all techno-economic assumptions on green LH_2 supply, see [44]; for synfuel supply, see Appendix A3.

Decarbonization option for single-aisle aircraft	Impact on average DOC vs. kerosene (ETS-200) – Fig. 7A	Fuel supply perspective (well-to-tank)				Fleet perspective (well-to-thrust)	
		Well-to-tank av. energy efficiency, before aircraft propulsion	RES capacity requirement per annual MWh output of fuel[a]	ELY capacity requirement per annual MWh output of fuel[a]	Total capital costs[b] per annual MWh output of fuel[a]	Fuel requirements for aircraft fleet per 100ASK	RES energy for aircraft fleet (well-to-thrust) per 100 ASK
H_2-powered aircraft – best supply setups	-1%	56%	52 kW	31 kW	602 USD	21 kWh	37 kWh
Synfuel supply	+1%	35%	87 kW	51 kW	1041 USD	19 kWh	56 kWh

a) using the lower heating value of each fuel.

b) excluding CAPEX for transportation and refueling systems for both fuels.

address the economics of single-aisle H_2-powered aircraft in other major air traffic markets like in Northern American or Asian regions.

Second, one supply setup was not considered in the present study which could be relevant to reduce LH_2 supply costs to medium and smaller airports: GH_2 off-site with flexible locations for hydrogen liquefaction centers connected to the GH_2 pipeline network but not necessarily co-located at one of the airports. Then, the geographic position of that central liquefaction plant would be subject to optimization for best distribution costs to surrounding airports and other $(L)H_2$ demand centers.

Third, as highlighted in [44] already, the supply costs for green LH_2 and hence, also green synfuel highly depend on the weather data source and the underlying reference year. Sensitivity studies should be of future research interest.

Fourth, there are still major techno-economic uncertainties for most of the energy system components, especially when investigating a 2050 scenario. As discussed also in [44], the 2050-assumptions might be too optimistic given high learning rates for LH_2 and GH_2 equipment. The potential cost reduction in manufacturing these and reaching high efficiencies as well as low (boil-off) losses depends on relatively high growth of $(L)H_2$ market demands, investment in technology breakthrough and regulation/policy supporting the currently slow H_2 project development in this early-stage and higher cost market phase. Demonstrations of the main components, e.g., large liquefaction plant, will be needed to prove the chosen techno-economics in this paper.

Besides the mentioned research proposals to tackle the study's limitations, three additional analyses are found worth investigating:

- The same holistic assessment but for H_2-powered smaller regional aircraft that might enter service before 2035
- A transition cost approach instead of a static point for evaluation to account for inefficiencies of first years of LH_2 supply deployment scenarios with lower demands
- Design analyses of future H_2 markets such as auction-based markets [65] and their macroeconomics effects such as job creation or increase in gross domestic product, GDP,(e.g., see [66,67]).

Finally, the present study showed that single-aisle H_2-powered aircraft could potentially be a key option to decarbonize this segment saving costs and resources compared to a synfuel option. It will most likely require stricter regulations or cost mechanisms for, e.g., CO_2 emissions, to incentivize the switch to H_2-powered aircraft as shown in the total direct operating costs picture (Fig. 7). Additionally, clarity on policy actions and directions influencing the future economics of aviation is required now. Since the large-scale deployment of both green LH_2 and synfuel infrastructure might easily take another decade from now, investment decisions have to be steered by such policies as soon as possible.

CRediT authorship contribution statement

J. Hoelzen: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **D. Silberhorn:** Validation, Software, Resources, Methodology, Data curation. **F. Schenke:** Writing – original draft, Validation, Methodology, Data curation. **E. Stabenow:** Data curation. **T. Zill:** Writing – review & editing, Visualization. **A. Bensmann:** Writing – review & editing, Validation, Resources, Project administration, Methodology. **R. Hanke-Rauschenbach:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Acknowledgements

Julian Hoelzen and Richard Hanke-Rauschenbach acknowledge funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC2163/1 – Sustainable and Energy Efficient Aviation (Project-ID 390881007). Finn Schenke and Astrid Bensmann gratefully acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the framework of HyNEAT under grant no 03SF0670A. The results presented were achieved by computations carried out on the cluster system at the Leibniz Universität Hannover, Germany.

Appendix A. Data on LH_2 supply network.

Table A1.1
104 airports, country-wise interest rate for renewable energy projects based on [68–71], coordinates based on renewable.ninja [46,47], cavern storage availability based on [54,55,72–75]

City	IATA code	Country	Demand category	Interest rate	Coordinates for RES site	Space constraints	Cavern storage
Tirana	TIA	Albania	Small	8%	41.182, 19.507		
Sofia	SOF	Bulgaria	Medium	5%	42.647, 23.567		Yes
Prague	PRG	Czech R.	Large	6%	50.016, 14.925		Yes
Tallinn	TLL	Estonia	Small	8%	59.422, 24.994		
Budapest	BUD	Hungary	Large	5%	47.320, 18.630		Yes
Riga	RIX	Latvia	Medium	9%	57.055, 24.796		Yes
Vilnius	VNO	Lithuania	Medium	10%	54.583, 25.376		
Krakow	KRK	Poland	Medium	6%	50.171, 20.068		Yes
Warsaw	WAW	Poland	Large	6%	52.114, 20.109		Yes
Bucharest	OTP	Romania	Large	8%	44.388, 26.489		Yes
Algiers	ALG	Algeria	Medium	16%	36.615, 2.851		Yes
Zvartnots	EVN	Armenia	Small	8%	40.335, 44.473		Yes
Baku	GYD	Azerbaijan	Small	8%	40.377, 49.625		
Cairo	CAI	Egypt	Large	10%	29.754, 30.855		Yes
Erbil	EBL	Iraq	Regional	18%	36.231, 43.915		Yes
Tel Aviv	TLV	Israel	Very large	4%	31.245, 35.183		Yes
Amman	AMM	Jordan	Medium	12%	31.452, 36.305		

(*continued on next page*)

Table A1.1 (*continued*)

City	IATA code	Country	Demand category	Interest rate	Coordinates for RES site	Space constraints	Cavern storage
Beirut	BEY	Lebanon	Medium	22%	33.835, 36.013		Yes
Casablanca	CMN	Morocco	Large	9%	33.283, −8.053		Yes
Tunis	TUN	Tunisia	Medium	11%	36.418, 10.038		Yes
Billund	BLL	Denmark	Small	4%	55.747, 9.243	Yes	Yes
Copenhagen	CPH	Denmark	Very large	4%	55.766, 12.004	Yes	Yes
Birmingham	BHX	England	Large	4%	52.546, −1.634		Yes
London	LHR	England	Very large	4%	51.770, −0.853		Yes
Manchester	MAN	England	Very large	4%	53.571, −3.008		Yes
Helsinki	HEL	Finland	Very large	4%	60.374, 24.917	Yes	
Keflavik	KEF	Iceland	Medium	4%	64.035, −22.658		
Dublin	DUB	Ireland	Very large	4%	53.228, −6.212		
Bergen	BGO	Norway	Medium	4%	Grid connection	Yes	
Oslo	OSL	Norway	Very large	4%	59.629, 10.666	Yes	
Stavanger	SVG	Norway	Small	4%	58.826, 5.608	Yes	
Tromso	TOS	Norway	Small	4%	Grid connection	Yes	
Edinburgh	EDI	Scotland	Large	4%	57.489, −2.256		Yes
Glasgow	GLA	Scotland	Medium	4%	55.660, −4.783		Yes
Stockholm	ARN	Sweden	Very large	4%	59.695, 18.083		
Gothenburg	GOT	Sweden	Medium	4%	58.257, 12.877		Yes
Sarajevo	SJJ	Bosnia-Herzegovina	Regional	8%	43.979, 17.217	Yes	Yes
Dubrovnik	DBV	Croatia	Small	8%	42.567, 18.264	Yes	
Pula	PUY	Croatia	Regional	8%	44.884, 13.920		
Rijeka	RJK	Croatia	Regional	8%	45.199, 14.583		
Split	SPU	Croatia	Small	8%	43.669, 16.703		
Zadar	ZAD	Croatia	Regional	8%	44.045, 15.469		
Zagreb	ZAG	Croatia	Small	8%	45.795, 16.439		
Larnaca	LCA	Cyprus	Medium	5%	35.030, 33.892		
Athens	ATH	Greece	Very large	6%	37.939, 23.915		
Chania	CHQ	Greece	Small	6%	35.528, 24.114		
Heraklion	HER	Greece	Medium	6%	35.178, 25.312		
Mykonos	JMK	Greece	Regional	6%	37.447, 25.359	Yes	
Santorini	JTR	Greece	Small	6%	36.358, 25.434		
Kos	KGS	Greece	Small	6%	36.788, 27.085		
Rhodes	RHO	Greece	Medium	6%	35.945, 27.781		
Thessaloniki	SKG	Greece	Medium	6%	40.448, 22.892		
Bologna	BLQ	Italy	Medium	4%	44.561, 11.073		Yes
Bari	BRI	Italy	Medium	4%	40.953, 17.163		Yes
Cagliari	CAG	Italy	Small	4%	39.374, 8.982		
Catania	CTA	Italy	Large	4%	37.477, 14.867	Yes	Yes
Rome	FCO	Italy	Very large	4%	41.86, 12.221		Yes
Milan	LIN	Italy	Large	4%	45.299, 10.241		Yes
Milan	MXP	Italy	Very large	4%	45.299, 10.241		Yes
Naples	NAP	Italy	Large	4%	40.965, 14.464		Yes
Olbia	OLB	Italy	Small	4%	40.885, 9.521	Yes	
Venice	VCE	Italy	Large	4%	45.085, 11.900		Yes
Malta	MLA	Malta	Medium	5%	35.875, 14.376	Yes	
Faro	FAO	Portugal	Medium	5%	37.197, −8.307	Yes	Yes
Funchal	FNC	Portugal	Small	5%	32.809, −17.252		
Lisbon	LIS	Portugal	Very large	5%	38.676, −8.172		Yes
Porto	OPO	Portugal	Large	5%	41.267, −8.679		Yes
Belgrade	BEG	Serbia	Medium	8%	44.918, 20.992		
Ljubljana	LJU	Slovenia	Regional	5%	46.015, 14.469		
Malaga	AGP	Spain	Large	5%	36.684, −4.746		Yes
Alicante	ALC	Spain	Large	5%	38.533, −1.536		Yes
Barcelona	BCN	Spain	Very large	5%	41.332, 1.269		Yes
Bilbao	BIO	Spain	Medium	5%	42.971, −3.218		Yes
Ibiza	IBZ	Spain	Medium	5%	39.022, 1.423	Yes	
Madrid	MAD	Spain	Very large	5%	40.165, −3.244		Yes
Mahon	MAH	Spain	Small	5%	39.852, 4.234		
Palma de Mallorca	PMI	Spain	Very large	5%	39.41, 2.796		
Santiago de Compostela	SCQ	Spain	Small	5%	42.956, −8.467		
Seville	SVQ	Spain	Medium	5%	37.085, −6.619		Yes
Valencia	VLC	Spain	Medium	5%	39.505, −1.254		Yes
Istanbul	IST	Turkey	Very large	8%	41.168, 28.310		
Graz	GRZ	Austria	Regional	4%	46.965, 15.821		Yes
Salzburg	SZG	Austria	Regional	4%	47.899, 13.041		Yes
Vienna	VIE	Austria	Very large	4%	48.085, 16.745		Yes
Brussels	BRU	Belgium	Very large	4%	50.687, 3.521		Yes
Bastia	BIA	France	Regional	4%	42.191, 9.500		
Bordeaux	BOD	France	Medium	4%	44.745, −0.853		Yes
Paris	CDG	France	Very large	4%	49.033, 2.600		Yes
Lyon	LYS	France	Large	4%	45.798, 4.276		Yes
Marseille	MRS	France	Large	4%	43.517, 4.903		Yes
Nice	NCE	France	Large	4%	43.350, 6.220	Yes	Yes
Toulouse	TLS	France	Medium	4%	43.243, 1.972		Yes
Berlin	BER	Germany	Very large	4%	52.699, 13.681		Yes

(*continued on next page*)

Table A1.1 (*continued*)

City	IATA code	Country	Demand category	Interest rate	Coordinates for RES site	Space constraints	Cavern storage
Bremen	BRE	Germany	Small	4%	53.003, 8.747		Yes
Dresden	DRS	Germany	Regional	4%	51.173, 13.769		Yes
Dusseldorf	DUS	Germany	Very large	4%	51.063, 6.439		Yes
Frankfurt	FRA	Germany	Very large	4%	50.221, 8.715		Yes
Hannover	HAJ	Germany	Medium	4%	52.470, 9.561		Yes
Hamburg	HAM	Germany	Large	4%	54.016, 9.091		Yes
Munich	MUC	Germany	Very large	4%	48.474, 11.791		Yes
Stuttgart	STR	Germany	Large	4%	48.640, 8.857		Yes
Amsterdam	AMS	Netherlands	Very large	4%	52.256, 4.670		Yes
Geneva	GVA	Switzerland	Large	4%	46.693, 6.592		Yes
Zurich	ZRH	Switzerland	Very large	4%	47.573, 8.727		Yes

Table A1.2

7 export hubs; same sources as in Table A1.1 for interest rates, coordinates and cavern availability.

Port for export	Country	Demands	Interest rate for RES[a]	Coordinates for RES site	Cavern storage
Rosslare	Ireland	0.5–1.5 MtH2/a	4%	52.265, −6.620	
Aberdeen	Scotland	0.5–1.5 MtH2/a	4%	57.489, −2.256	Yes
Faro/Olhao	Portugal	0.5–1.5 MtH2/a	5%	37.459, −8.200	Yes
Alicante	Spain	0.5–1.5 MtH2/a	5%	37.804, −2.426	Yes
New	Morocco	0.5–1.5 MtH2/a	9%[b]	28.357, −11.291	Yes
Duba	Saudi Arabia	0.5–1.5 MtH2/a	6%	29.048, 37.169	Yes
Port Hedland	Australia	0.5–1.5 MtH2/a	5%	−25.42, 113.964	Yes

a) Interest rate 2 percentage points higher for hydrogen projects due to higher risks [44].

b) Moroccan pipeline built to connect with European Hydrogen Backbone (see Table S1.2 in the Supplementary Material) calculated with the Moroccan-specific interest rate.

Appendix B. Data on aircraft design.

Table A2 shows all performance parameters of the H_2-powered aircraft modeling. The Lift-to-Drag (LoD) ratio in mid cruise conditions decreases with increasing design range due to the increasing maximum LH_2 tank volume and hence, the increasing fuselage length. The thrust specific fuel consumption (TSFC) in mid cruise decreases and the total propulsion efficiency increases with increasing design range due to the higher thrust requirements and engine size. The gravimetric index of the LH_2 tank structure and fuel systems is increasing from 42% up to 48% due to scaling effects. The thermodynamic and structural methods for the LH_2 tank design are described in [59,76].

Table A2

Hydrogen aircraft specifications – performance characteristics.

Parameter	Unit	H2–1500 NM	H2–2000 NM	H2–2500 NM	H2–3000 NM
Lift to Drag (mid. cruise)	–	17.5	17.3	17.2	17.1
TSFC (mid. cruise)	kg/s/N	4.90e-06	4.88e-06	4.86e-06	4.84e-06
Total propulsion efficiency (mid. cruise)	–	39.2%	39.4%	39.6%	39.8%
Total thrust required (mid. cruise)	kN	37.7	39.6	41.3	43.0
Fuselage length	m	41.3	43.4	45.3	46.4
Total LH_2 tank volume	m^3	59	75	93	110
LH_2 tank gravimetric index including fuel systems	–	42%	44%	46%	48%

Appendix C. Calculations and techno-economic assumptions for synthetic kerosene benchmark.

For the benchmark in Section 5, synthetic kerosene produced with green H_2 and CO_2 from a direct air capture plant (DAC) is used. Therefore, techno-economic assumptions and optimization results from the LH_2 calculations are used (see also Table A3.1): the RES, electrolysis, GH_2 tanks and compressors. Then, the GH_2 is converted into syngas with the reverse water gas shift (RWGS) reaction. In the Fischer-Tropsch-synthesis (FT), it is advanced into long-chain hydrocarbons. These are also called syncrude and can be separated into kerosene-like jet fuel and by-products, which also result from the process. In this cost calculation, the by-products naphtha and liquid petroleum gas (LPG) are resold at a constant market price (see Table A3.2).

As the synfuel will most likely be produced at a main hub and then imported like it is currently done in the kerosene supply chain, only off-site production of synfuel is assumed in this study. The synfuel is transported via vessels and then via fuel-cell-powered trucks to the airport. Same transport cost models are used than for the LH_2 calculations which are described in [44]. Since the conventional refueling infrastructure can be used, fixed refueling costs of 0.01 USD/kg synfuel are assumed for this last step in the supply to the aircraft [3]. Table A3.2 shows the techno-economic assumptions for synfuel production as well as for the transportation. The TAC of the individual components i are calculated with sum of the specific CAPEX $c_{\mathrm{CAPEX},i}$ multiplied by the annuity factor a_i and the specific OPEX $c_{\mathrm{OPEX},i}$ with

$$c_{\mathrm{TAC},i} = c_{\mathrm{CAPEX},i} \cdot a_i + c_{\mathrm{OPEX},i}. \tag{A1}$$

The synfuel costs are calculated analogous to the LH_2 models using the annuity factor from Eq. 3. The specific synfuel costs c_{TAC} are calculated as shown in Eq. A2 to A4:

$$c_{TAC} = \left(c_{TAC,H2} \cdot f_{H2} + c_{TAC,DAC} \cdot f_{CO2} + c_{TAC,synfuel}\right) \cdot f_{syncrude} \tag{A2}$$

with

$$c_{TAC,H2} = c_{TAC,Ely} + c_{TAC,GH2storrage} + c_{TAC,H2comp} \tag{A3}$$

and

$$c_{TAC,synfuel} = c_{TAC,FT+RWGS} + c_{TAC,synfueltank} \tag{A4}$$

The specific costs of the H_2, CO_2 and synfuel components $c_{TAC,H2}$, $c_{TAC,CO2}$ and $c_{TAC,synfuel}$ are multiplied by the factors for the H_2 and CO_2 demand f_{H2} and f_{CO2} which are shown in Table A3.2. More than 1 kg syncrude has to be produced to get 1 kg synfuel because of the by-products. This effect is taken into account by the factor $f_{syncrude}$, which is also shown in Table A3.2. The specific energy demand for the synfuel production $e_{synfuel}$ is calculated with

$$e_{synfuel} = \left(e_{Ely} \cdot f_{H2} + e_{DAC} \cdot f_{CO2} + e_{FT+RWGS}\right) \cdot f_{syncrude} \tag{A5}$$

where the energy demands for the H_2 and CO_2 production, e_{Ely} and e_{DAC}, are multiplied by the corresponding factors (Table A3.2). Then, also the energy demands of the Fischer-Tropsch and RWGS process $E_{FT+RWGS}$ are accounted to determine the overall total specific energy demand for the syncrude production. Finally, the specific energy demand for synfuel production is derived by multiplying with the syncrude-to-synfuel-factor (Eq. A5).

It is important to note that the lower heating value of synfuel is 12.28 kWh/kg which differs slightly from conventional kerosene [77,78].

Table A3.1
Utilization of the synfuel components for four locations in 2035 and 2050 – results from LH_2 off-site system optimization.

Component	Unit	Scotland		Portugal		Saudi Arabia		Australia	
		2035	**2050**	**2035**	**2050**	**2035**	**2050**	**2035**	**2050**
Utilization									
Electrolysis system	h/a	5619	5242	5309	4602	4942	4483	5396	5619
Direct Air Capture Plant	h/a	7833	7920	7993	7911	7929	7639	7884	7724
Fischer-Tropsch + RWGS	h/a	7833	7920	7993	7911	7929	7639	7884	7724
Energy demand									
Electrolysis system	kWh/ kgH_2	49.09	48.95	47.83	47.89	48.03	48.52	47.70	47.62
Direct Air Capture Plant	kWh/ $kgCO_2$	1.73	1.28	1.73	1.28	1.73	1.28	1.73	1.28
Fischer-Tropsch + RWGS	kWh/ kgsyncrude	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Levelized costs of electricity	USD/ MWh	24	18	28	20	32	22	27	21

Table A3.2
Techno-economic assumptions for the synfuel production.

Component	2035	2050	Sources
Direct Air Capture Plant (low temperature)			
Specific CAPEX	1 USD/$kgCO_2$ per year	0.60 USD/$kgCO_2$ per year	[79–81]
Depreciation period	25 years	25 years	[79–81]
O&M factor	4%	4%	[79–81]
Electricity consumption (electricity demand + heat demand[a])	1.73 kWh/$kgCO_2$	1.28 kWh/$kgCO_2$	[79–83]
Fischer-Tropsch + RWGS			
Specific CAPEX	0.46 USD/kg syncrude p.a.	0.40 USD/kg syncrude p.a.	[79,84,85]
Depreciation period	30 years	30 years	[84–86]
O&M factor	4%	4%	[84,85,87]
Electricity consumption[a]	0.37 kWh/kg syncrude	0.37 kWh/kg syncrude	[77,84]
Specific H_2 demand f_{H2}	0.48 kgH_2/kg syncrude	0.48 kgH_2/kg syncrude	[77,78]
Specific CO_2 demand f_{CO2}	3.06 $kgCO_2$/kg syncrude	3.06 $kgCO_2$/kg syncrude	[77,78]
Product shares			
Naphtha	24%	19%	[88]
LPG	6%	3%	[88]
Synfuel	70%	78%	[88]
Factor for synfuel production $f_{syncrude}$	1.43 kg syncrude per kg synfuel	1.28 kg syncrude per kg synfuel	
Naphtha selling price	0.50 USD/kg naphtha	0.50 USD/kg naphtha	
LPG selling price	0.50 USD/kg LPG	0.50 USD/kg LPG	

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Table A3.2 (*continued*)

Component	2035	2050	Sources
Synfuel tank			
Specific CAPEX	0.24 USD/kg synfuel capacity	0.24 USD/kg synfuel capacity	[87]
Depreciation period	20 years	20 years	[87,89]
O&M factor	3%	3%	[87]
Synfuel truck transport			
Total CAPEX truck	305,500 USD	305,500 USD	[89,90]
Depreciation period	12 years	12 years	[24,44,89]
Availability	40%	40%	[91]
O&M factor	3%	3%	[24,44]
Capacity	30,000 kg synfuel	30,000 kg synfuel	
Synfuel vessel transport			
Total CAPEX vessel	48 Mn USD	48 Mn USD	[92]
Depreciation period	25 years	25 years	[92]
Availability	95%	95%	[92]
Capacity	90,000 t synfuel	90,000 t synfuel	[92]
Ullage	0.1%	0.1%	[92]
O&M	3%	3%	[92]
Other OPEX (crew etc.)	5000 USD/d	5000 USD/d	[92]
Specified maximum continuous rating	11,500 kW	11,500 kW	[93]
Fuel consumption	449.96 kWh/km	449.96 kWh/km	[93]
Fuel costs synthetic diesel	0.16 USD/kWh	0.16 USD/kWh	[90,94]
Speed	25.56 km/h	25.56 km/h	[93]
Loading & unloading time	48 h	48 h	[92]
Maximal distance	13,400 km	13,400 km	[92]

a) Full electric heat supply assumed – not enough excess heat in 2050.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124999.

Data availability

Data will be made available on request.

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