INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 47 (2022) 3108–3130

Available online at www.sciencedirect.com

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

Review Article

Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps

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ARTICLE INFO

Article history:
Received 29 June 2021
Received in revised form
27 October 2021
Accepted 28 October 2021
Available online 26 November 2021

Keywords:
Hydrogen aviation
Fuel supply
Liquid hydrogen
Aircraft design
DOC Model
Economics

ABSTRACT

Aircraft powered by green hydrogen (H2) are a lever for the aviation sector to reduce the climate impact. Previous research already focused on evaluations of H2 aircraft technology, but analyses on infrastructure related cost factors are rarely undertaken.

Therefore, this paper aims to provide a holistic overview of previous efforts and introduces an approach to assess the importance of a H2 infrastructure for aviation. A short- and a medium-range aircraft are modelled and modified for H2 propulsion. Based on these, a detailed cost analysis is used to compare both aircraft and infrastructure related direct operating costs (DOC).

Overall, it is shown that the economy of H2 aviation highly depends on the availability of low-cost, green liquid hydrogen (LH2) supply infrastructure. While total DOC might even slightly decrease in a best LH2 cost case, total DOC could also increase between 10 and 70% (short-range) and 15–102% (medium-range) due to LH2 costs alone.

Contents

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https://doi.org/10.1016/j.ijhydene.2021.10.239
0360-3199/

List of abbreviations

AC	Aircraft
AF	Airframe
APU	Auxiliary power unit
ASK	Available seat kilometres
ATC	Air traffic control
CAPEX	Capital expenditures
CFRP	Carbon fibre reinforced polymer
CO2	Carbon dioxide
COC	Cash operating cost
DOC	Direct operating cost
EIS	Entry-into-service
GH2	Gaseous hydrogen
GSE	Ground support equipment
H2	Hydrogen
LH2	Liquid hydrogen
LOHC	Liquid hydrogen organic carrier
MTOM	Maximum take-off mass
NH3	Ammonia
NM	Nautical miles
NOx	Nitrogen oxides
OEM	Operating empty mass
OPEX	Operational expenditures
PAX	Passengers
PtL	Power-to-liquids
PV	Photovoltaics
RCE	Remote component environment
RES	Renewable energy supply
SAF	Sustainable aviation fuels
TSFC	Thrust specific fuel consumption

Nomenclature

a	Annuity factor
$ACAPEX$	Annualized CAPEX
$AOPEX$	Annualized OPEX
B	Maintenance cost burden
BE	Annual block energy consumption
c	Cost for aircraft components and systems
DOC	Direct operating costs
DP	Depreciation period
$E_{stored,max}$	Maximum energy stored in fuel tank
f_{ATC}	ATC cost factor
f_{ins}	Insurance rate
f_{misc}	Miscellaneous factor for aircraft spare parts
f_{RV}	Residual value factor
i	Supply component i
IR	Interest rate
$k_{LH2tank}$	LH2 tank cost factor
LR	Maintenance labor rate
$MTOM$	Maximum take-off mass
n_{AC}	Number of aircraft
n_{eng}	Number of engines
$n_{LH2tank}$	Number of LH2 tanks
NRC	Non recurring costs
OEM	Operating empty mass
p	Price for component, aircraft, handling or landing
$Payload$	Payload of aircraft
PM	Profit margin for components or aircraft
R	Range
RC	Recurring costs
t	Block time
TAD	Total amount delivered per annum
$T_{SL,Static}$	Static sea level thrust

Introduction

This paper is about the role of a hydrogen (H2) infrastructure for hydrogen-powered commercial aviation and the potential future research focus to investigate and steer the deployment of this. H2-powered aviation just recently regained high attention from the industry, because it is seen as a promising lever to address the challenge of decarbonizing and reducing climate impact from aviation [1,2].

Decarbonisation is one of the largest challenges for society and specifically in the hard-to-abate sector of aviation [3]. Directives such as the Green Deal of the European Commission were introduced to reach carbon neutrality by 2050 over all sectors [4]. Moreover, the COVID-19 health crisis led industries such as aviation to depend on financial aid from governments who made their support conditional to environmental sustainability goals. In France for instance, the government supports the national aviation industry financially, thereof EUR 1.5 Bn with the condition to develop a carbon-neutral aircraft by 2035 [5].

Even though only 2–3% of global carbon emissions stemmed from the aviation sector in 2019 [6], the pressure of developing more environmental-friendly aircraft concepts might increase even more with the predicted air traffic growth of the sector until 2050 – despite the current COVID crisis – and the planned emission reductions of other sectors [7]. In terms of aircraft segments, the major contributors of emissions in aviation are short- and medium-range aircraft with around two third of the total aviation's CO2 emissions [6]. Consequently, the focus of this research lies on these segments.

In addition to carbon emissions, aviation's climate impact is also caused by other non-CO2 emission effects [8]. Depending on the flight altitude and surrounding atmospheric conditions, other exhaust gas products such as nitrogen oxides (NOx) and the combination of soot particles and water vapour can cause the formation of climate harming ozone and contrails, respectively. While these effects are not as long lasting as CO2 emissions, recent studies show that the Global Warming Potential (GWP) and the Average Temperature Response (ATR) of the non-CO2 emission effects are on a similar or even higher scale than CO2 emissions alone [9,10].

As a response to the described challenges several levers to reduce climate impact of aviation have already been broadly investigated in previous research. Potential options are new propulsion technologies, e.g., battery-, hybrid-electric or H2 propulsion, and alternative drop-in fuels, e.g., sustainable aviation fuels (SAF) [11].

Battery-electric aircraft charged with renewable energy offer the advantage of causing no in-flight climate impact. However, investigations have shown that battery-electric propulsion will not be scalable to larger aircraft and longer flight ranges in the foreseeable future due to the low battery energy density [12–15]. In contrast to that, hybrid-electric aircraft are scalable to larger aircraft segments, but the reduction potential of emissions is seen to be very limited for segments larger than regional aircraft [16,17].

SAF, biofuels and synthetic fuels (synfuels, also called PtL, power-to-liquids), are kerosene-like drop-in fuels which makes them compatible for every aircraft segment without changes to the aircraft design. Biofuels are either based on biomass or residual waste and can lead to net CO2 reductions of up to 94% [18]. In the long-term, feedstock availability for biofuels might be limited and potentially come with competition against the use of biofuels in other sectors [1]. In comparison to that, synfuels only require renewable energy for the production and synthesis of hydrogen and CO2 captured from industrial processes or direct from air [19]. This makes synfuels – depending on the source of CO2 – carbon net neutral. However, the renewable energy supply (RES) needed to produce synfuels are significantly higher than for powering battery-, hybrid-electric or H2 propulsion due to synfuels' lower total energy efficiency [1]. Furthermore, both synfuels and biofuels might not offer larger reductions of the climate impact from non-CO2 effects [20,21].

H2 propulsion for aircraft is another option for full decarbonisation and potentially large reduction in climate impact of the aviation industry, if green hydrogen is used [22]. H2 can be used for aircraft propulsion through thermal conversion in H2 combustion engines, or through electro-chemical conversion in fuel cells. These propulsion concepts would also lead to new aircraft designs, because they require the integration of H2 storage on board [23,24]. Due to different system power and energy densities, H2 combustion could potentially be scalable for medium- and long-range aircraft, while designs powered by H2 fuel cell might be applicable up to short-range aircraft segments [18]. In flight, both concepts do not cause CO2 emissions or NOx and soot emissions can be reduced significantly with H2 combustion and fully eliminated with H2-fuel-cell-powered aircraft [25,26].

Although it becomes clear that H2-powered aviation is an important issue and larger research work has already been conducted, e.g., around the 1980s and 2000s (see Chapters 2 and 3), there has only been limited focus on the overall landscape of H2 propulsion including production and supply pathways of H2. Research in these "earlier" years could not take into account the current developments leading to a broader H2 economy with its role in a global renewable energy transition. For example, these more favourable developments for a H2 economy can be seen in recent announcements of several national H2 strategies and worldwide more than USD 300 Bn investments into H2 projects [27]. Furthermore, Airbus announced their H2-powered ZeroE aircraft program in 2020 [28] and the first commercial H2-powered flight was conducted by ZeroAvia [29].

Therefore, the goal of the present paper is to provide a holistic view from H2 fuel infrastructure to aircraft considering the recent advancements in the H2 economy and the effects on the economics of H2-powered aviation. For this investigation, first the relevance of operating costs in aviation is shown to evaluate the impact of introducing H2 aviation in Chapter 2. In the same chapter, cost impacts are analysed based on two calculated conventional (fossil) reference aircraft designs modified with H2 propulsion technology. To provide a broad view on these impacts, a first, high-level literature review is undertaken at this point. Then in Chapter 3, the detailed implications of fuelling H2 aircraft with LH2 at airports are determined with the help of a second, more specific literature review. Derived from these assessments, most relevant research gaps are tried to be identified. Finally, a research agenda is presented for further investigation and evaluation of an aviation-specific H2 infrastructure as well as its interconnections to other H2 and power-to-X sectors in Chapter 4.

Economics of hydrogen-powered aviation

In this chapter, the overall impact on the aviation industry by introducing H2-powered aircraft is analysed with the purpose to derive the importance which H2 infrastructure could have in this development (detailed analysis in Chapter 3). This is done in several steps. First, the framework for analysis, a direct operating cost (DOC) model, is introduced and applied to two fossil reference aircraft designs of different sizes, a short-range and a medium-range aircraft, which will be used for comparison. Second, the qualitative cost impacts of changing aircraft technology and fuels are explained on a high level to frame the complexity of introducing H2 propulsion. Third, two H2-powered aircraft are introduced based on the references and their impact on the aircraft related DOC factors are calculated as well as first insights on H2 fuel related cost are determined.

DOC model used for evaluation

The analysis of DOC is chosen as an “industry-standard” framework to evaluate the economics of changing the existing aviation environment by introducing technology innovation [30]. In contrast to the evaluation of energy efficiencies, climate impact and macro-economic factors such as impact on employment in the industry, the DOC analysis reflects the costs and hence the economic viability for one of the main stakeholders, the operator [31].

Since the industry is highly cost-driven and operators are working on the edge of profitability, the change of economics related to introducing new technologies can be a major enabler or barrier for a potential uptake of a new radical technology. Hence, these are investigated in the following.

DOC models can reflect all significant cost drivers. From aircraft manufacturing and vehicle performance, energy, and its infrastructure cost as well as differences in aircraft operation and utilization.

$$DOC_{Total,yearly} = DOC_{Cap} + DOC_{Maint} + DOC_{Crew} + DOC_{Fees,\ ATC} + DOC_{Fees,\ Airport} + DOC_{Energy} \tag{1}$$

As seen in Eq. (1), the total DOC consist of capital, maintenance, crew costs, fees for air traffic control (ATC) as well as for airport services and energy costs. By referring the yearly DOC to the number of passengers as well as the distance travelled, the utilization in terms of available seat kilometre (ASK) per year is calculated. This is influenced by the vehicle's speed, turnaround time and operational aspects as well as forced downtimes due to maintenance and night curfew.

Further description of the DOC model is provided in Appendix A.

Reference conventional aircraft for comparison

In this work, two exemplary commercial aircraft, short- and medium-range, are designed and investigated because, as mentioned earlier, they cause a major part of aviation's global emissions and are potentially easier to adopt to alternative energy carrier. They are used as a reference to compare the effect of introducing H2 propulsion for these segments. Interested readers can see further information about the modelling approaches for both the conventional aircraft design and the modifications for H2 aircraft in Appendix B.

Table 1 shows the resulting specifications for the conventional short-range and medium-range aircraft. Both aircraft have been projected to an Entry-Into-Service (EIS) year 2035 with increased performances. The short-range aircraft is designed for a range of 1500 NM and to transport 180 passengers (PAX). On an average mission of 800 NM it consumes 150 GJ of kerosene. The medium-range aircraft is designed for 290 PAX and a design mission of 4000 NM. On a typical flight of 2000 NM it requires 719 GJ of kerosene. The flight cycles per year are calculated with forced downtimes of 2749 h based on [32] and block time supplements of 1.5 h per flight for the short-range and 1.8 h for the medium-range concept.

The total DOC, see Fig. 1, are calculated by applying the DOC model described in Eq. (1) and Appendix A, which results in 4.9 and 4.2 USD_{2020} per 100 available seat kilometre (ASK) for the short- and medium-range concept for 800 NM and 2000NM.

The reduced relative airport fees from 0.88 USD_{2020}/100ASK to 0.42 USD_{2020}/100ASK as well as the increased relative fuel costs from 0.78 USD_{2020}/100ASK to 0.92 USD_{2020}/100ASK with increased averaged operating range is a typical behaviour considering the comparison of short- and medium-range aircraft. These DOC values are calculated assuming constant kerosene fuel costs of 0.6 USD_{2020}/kg which is an averaged value from 2019 [18,33,34]. In this work, the kerosene price is kept constant due to the high uncertainty of price projections and the observed high price volatility in the last 10 years.

Changes to DOC from new technologies and fuels

To illustrate different cost effects on the DOC caused from new technologies or fuels three concepts are discussed. Next

Table 1 – Conventional kerosene aircraft specifications – design criteria and outputs from modelling.

Parameter	Unit	Short-range	Medium-range
Design Entry-Into-Service	–	2035	2035
Design Range	NM	1500	4000
Design PAX	–	180 (Single class layout)	290 (Two class layout)
Design Cruise Mach-Number	–	0.78	0.83
Calculated MTOM	t	65	171
Calculated OEM	t	40	105
Block-Energy for design mission	GJ	263	1457
Block-Energy for typical mission (used for further evaluation)	GJ	150 (800 NM mission)	719 (2000 NM mission)
Calculated annual flight cycles	–	1591 (800 NM mission)	932 (2000 NM mission)

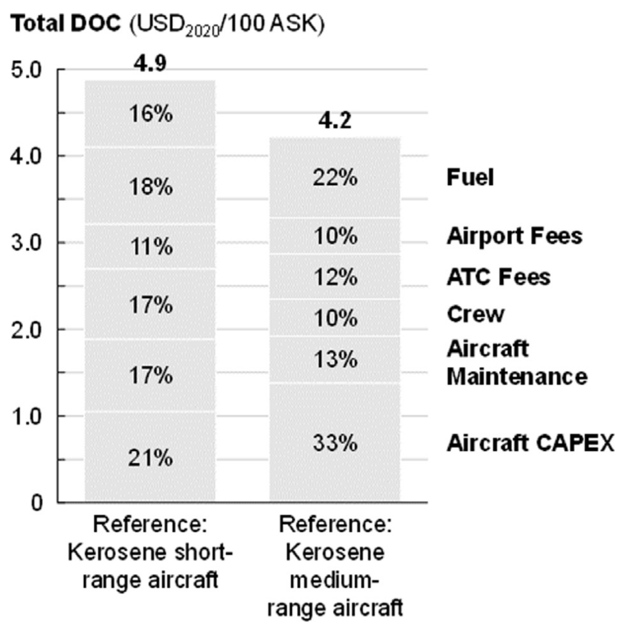

Fig. 1 – Total DOC evaluation of both reference kerosene-powered aircraft.

to H2 propulsion, which will be examined in detail hereafter, two examples are now shortly analysed on a qualitative level: the introduction of winglets and synfuels (first two levers of Table 2).

First, the development of winglets as a lever of evolutionary improvements of box size limited aircraft design is described. The "shark-tail like" looking ends of the wing-tip are used to decrease lift inducing vortex flows at the wing tips and increase aerodynamic efficiency and therefore reduce fuel burn [35].

Regarding the effects on DOC shown in Table 2 and Eq. (1), it is likely that the CAPEX might increase slightly due to development costs and potentially increased complexity in manufacturing of the wing. Accordingly, also the airframe maintenance costs might increase. There are no changes in labour costs or air traffic control fees, since they depend on the number of PAX on board, cabin design and distances flown – all factors are kept constant for all design changes including the introduction of new fuels or propulsion technologies.

Furthermore, same airport fees are expected, given that the aircraft re-design has been compliant with airport size regulations. Since winglets reduce the fuel burn of aircraft, it leads to decreased fuel cost which is the main impact. The aircraft utilization is not affected at all.

The second column in Table 2 describes the cost impact of synthetic kerosene which has similar properties as jet fuel and could be directly used as drop-in fuel [18]. This means that although the process of fuel production strongly changes, which leads to different fuel costs, the aircraft is barely affected which allows to use existing aircraft, supply and refuelling infrastructure.

In comparison to the presented levers of aerodynamic improvements and synfuels, introducing H2 propulsion for aircraft affects nearly all DOC factors as shown in the right-most column of Table 2. Starting from top to bottom, aircraft CAPEX and maintenance will be examined next. Then, a high-level overview of airport and operation related costs as well as a detailed analysis of fuel infrastructure costs will be presented. This will be then concluded in a total view on DOC at the end of Chapter 3.

H2 aircraft design and its influence on DOC

DOC for aircraft CAPEX and maintenance change, since H2 propulsion technology comes with different costs and require new aircraft design and system integration. Additionally, the aircraft energy efficiency changes mainly driven by the new energy carrier characteristics which has an impact on the fuel related DOC.

Most reviews and detailed papers such as [36,37] concentrate on H2 propulsion technology and its implications on the aircraft design – with a clear focus on liquid hydrogen for larger commercial aircraft due to the lower total storage mass compared to solid or metal hydride and also volume requirements compared to gaseous H2 (GH2). For smaller, regional aircraft the use of GH2 tanks might also be feasible as proposed by ZeroAvia [29]. However, such smaller aircraft are not part of this work's scope – hence, the infrastructure analyses will also focus on LH2 and not GH2 supply.

With the use of LH2 tanks on board many challenges arise concerning the passively insulated LH2 tanks such as lifetime and thermodynamic cycle stability, maintenance, or the highly complex and multidisciplinary integration into the overall aircraft concept. The ground handling and operational flexibility in terms of the duration without vented gaseous hydrogen (dormancy time) highly influences the required insulation quality and hence the tank mass and the aircraft performance. Achieving high LH2 aircraft performances as

Table 2 – High-level, qualitative impact on DOC factors by introducing new levers to reduce climate impact of aviation.

DOC factors	Exemplary levers to reduce climate impact of aviation		
	Winglets for improved aerodynamic design	New drop-in fuels such as synfuels	New propulsion technology based on hydrogen
Aircraft CAPEX	Slight change: costs depend on development, manufacturing/ material cost for aircraft design change	No change	Change: costs increase for propulsion system incl. LH2 tank and aircraft system integration
Aircraft Maintenance	Slight change: airframe related maintenance could be affected by new designs	No change	Change: New propulsion system incl. LH2 tank with different maintenance costs
Crew	No change		
ATC fees	No change		
Airport fees	No change	No change	Could change due to overall aircraft weight variation and more complex ground handling or other airport system costs affected by H2 aircraft
Fuel/energy	Slight change: Same fuel, but lower total energy consumption	Change: Different fuel costs for synfuel production	Change: Liquid H2 with different supply chain and supply costs
Aircraft utilization	No change	No change	Could change, if refuelling process increases the overall turnaround times or LH2 tank maintenance causes higher yearly forced downtimes

well as a flexible ground operation is a major challenge and generates an important interface to the airport infrastructure.

In this work, the modelled H2 aircraft concepts are powered by H2 turbofan engines. The two LH2 tanks are integrated into the fuselage, both behind the cabin for the short-range as well as one in front and behind the cabin for the medium-range concept. Further details can be found in Appendix B.

The resulting energy demand of the LH2 short-range concept compared to the kerosene baseline increases from 150 GJ to 168 GJ (by 12%) for the 800 NM mission, see Table 3. Roughly one-third of this drawback is caused by decreasing aerodynamic efficiencies due to the longer fuselage incorporating the relatively large volumes of the LH2 tank. Two-third of this effect come from the additional mass of the storage and structural snowball effects. The demand of the LH2 medium-range concept also increases by 18% for the 2000 NM mission with roughly the same aerodynamic and mass related contributions.

Since the cruise Mach number is the same for the kerosene and LH2 concepts, the flight times and yearly cycles are similar. Small variations still exist due to slightly different flight paths, i.e. climb rates and cruise altitudes, and hence changed flight times. Additional factors which could decrease the utilization are the turnaround time as well as additional forced downtimes due to LH2 storage related maintenance procedures. This topic is discussed later within this chapter.

As seen in Table 2, changing the energy carrier affects many DOC factors. To deal with these impacts, the conventional cost method is adapted (see details in Appendix A).

Based on the modelling and modified DOC evaluation, the costs increase by 12% for CAPEX, 11% for maintenance for the short-range and 13% for CAPEX, 17% for maintenance for the medium-range aircraft for 800 NM and 2000 NM, respectively (Fig. 2).

If the different energy efficiencies of the kerosene- versus H2-powered aircraft are considered assuming same energy costs like

Table 3 – Hydrogen aircraft specifications – design criteria and outputs from modelling.

Parameter	Unit	Short-range	Medium-range
Design Entry-Into-Service	–	2035	2035
Design Range	NM	1500	4000
Design PAX	–	180 (Single class layout)	290 (Two class layout)
Design Cruise Mach-Number	–	0.78	0.83
Calculated MTOM	t	68	175
Calculated OEM	t	48	132
Block-Energy for design mission	GJ	293	1662
Block-Energy for typical mission (used for further evaluation)	GJ	168 (800 NM mission)	847 (2000 NM mission)
Calculated annual flight cycles	–	1592 (800 NM mission)	936 (2000 NM mission)

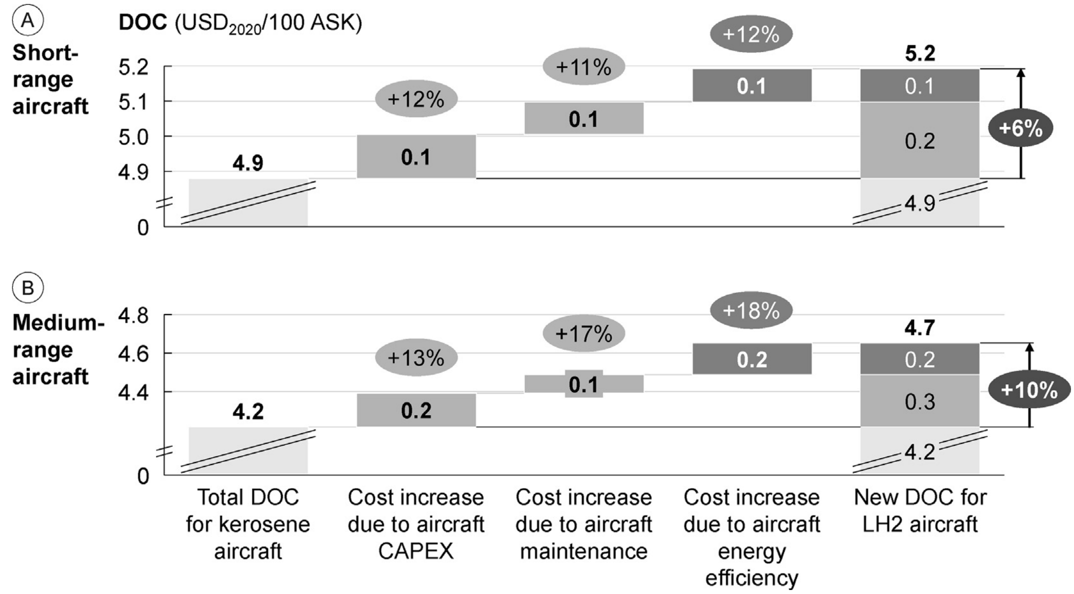

Fig. 2 – Change of selected DOC factors for LH2 short- (A) and medium-range (B) aircraft due to H2 aircraft technology impacting aircraft CAPEX and maintenance costs as well as fuel costs through lower energy efficiency – bubbles show relative cost increase for these levers.

in the kerosene reference, the additional fuel costs for the H2 aircraft are 12% and 18% for the short- and for the medium-range aircraft, respectively (Fig. 2). In relation to the total operating costs, this equals a 6% and 10% increase of total DOC.

This and the cost uncertainties caused by different technology assumptions, especially around the LH2 tank (further insights in Appendix B), underlines that H2 aircraft might come with higher DOC, which should be further targeted to be improved by research and development efforts.

H2 airport infrastructural and operational impacts on DOC

However, not only the aircraft CAPEX and maintenance costs but also the fuel costs and operational implications using hydrogen must be investigated. This could also influence the viability of the business case of introducing H2 aircraft. For a first framing of these potential impacts a brief, high-level overview of findings from previous studies is shown. In Chapter 3, a detailed literature review will pick up the relevant aspects for further analysis.

The DOC per flight also depend on the aircraft utilization. This is determined by the turnaround time of the aircraft on ground and the flight time, i.e. cruise speeds of the aircraft. This could change, if LH2 refuelling times increase due to more complex refuelling procedures. Or if H2 aircraft would be designed with slower cruise speeds to reduce power requirements for the fuel cell system [1].

Only few studies are available concerning the refuelling procedure of LH2-fuelled aircraft. Most describe only high-level implications on the turnaround process without going into detail [1,23,38,39]. Boeing [40], Brewer [37,41] and ISO/PAS [42] describe the refuelling process in more detail including flow rates and hose diameters. They indicate that similar energy flow rates and refuelling times like for the kerosene reference are possible. Only one more conservative estimate was found in Brewer [41] who showed a 20% increase in turnaround time for a long-range LH2 concept with no parallel fuelling.

In the following, same refuelling rates and safety standards are assumed to be feasible for the chosen aircraft segments. Insights on other factors influencing the aircraft utilization, e.g., the use of additional and larger LH2 refuelling vehicles, are not found.

The supply of LH2 does not only require LH2 production and logistic capacities, but also new fuel and refuelling infrastructure and operations at airports. Airport system costs implied by these changes mostly lead to costs for "into-plane" refuelling players at airports that must be added to the LH2 fuel costs at the dispenser. However, since H2 aircraft can be designed in a way, that they fit to the aerodrome regulations of the International Civil Aviation Organization for all segments, e.g., gate limits, potential further changes in ground handling and landing fees should be very low. No studies are found on this so far.

Also, no cost effects are expected from safety aspects of H2 aircraft handling at airports: many sources [40,43,44] state, that the safety measures of LH2 refuelling should not be higher than for kerosene ones. For kerosene-powered aircraft, regulation requires a safety radius of 3 m around the fuel hose where no ignition spark may occur [45]. With H2 as an aircraft fuel, different fuel properties have to be considered for handling. While spilled or leaking kerosene as a fluid would remain on the ground as a flammable safety risk, H2 disperses rapidly into the surrounding air [37,44,46]. Moreover, it can be expected that LH2 tanks, distribution and refuelling systems (hoses and couplings) will be hermetically sealed in normal operation and safety margins will be applied to the design of all systems to prevent any malfunctions due to, e.g., high pressures [47–49]. A similar system was already demonstrated for LH2-powered vehicles at Munich airport in the 2000s [50]. Consequently, it is assumed that no additional safety radius impacting the ground handling will be required for H2-powered aircraft.

Nevertheless, it has to be noted that a certification with an exact safety radius for H2 aircraft operation is not available yet and hence, it is identified as a research gap for future work when determining airport system cost.

Lastly, the largest uncertainty factor might be the LH2 fuel cost: Since 16% and 22% of the total DOC are related to fuel costs for a conventional short-range and medium-range aircraft, respectively (Fig. 1), the use of hydrogen as a direct fuel can have a significant impact. This will be further analysed in the next chapter.

Hydrogen infrastructure and its impact on the economics of H2-powered aviation

In the previous chapter, it was shown that the total DOC of H2-powered aviation might change with H2 aircraft technology and designs by 6% and 10% for short- and medium-range concepts, respectively. It was also highlighted that future research will be required to further investigate these economic effects and uncertainties behind larger commercial H2 aircraft. However, also cost impacts caused by hydrogen infrastructure implications should be investigated. Consequently, this section focuses on the LH2 fuel costs at the dispenser from production to transport and refuelling to elaborate on potential challenges for the introduction of H2-powered aviation besides aircraft technology aspects.

As a starting point, an overview of the components along a LH2 supply chain is provided and the underlying cost drivers are described with the help of a high-level cost model. After these descriptions, different supply pathways are derived, and first qualitative implications highlighted. In a third step, a literature review is conducted to enable a quantitative view on LH2 cost ranges in comparison to kerosene fuel costs. Thereafter, the quantitative effect of an aviation-specific LH2 infrastructure on the operational costs is set into the total DOC context comparing it against the results from Chapter 2.

LH2 supply chain components

To enable the use of LH2 as an aircraft fuel a new supply chain including components such as H2 production, liquefaction, transport, storage and LH2 refuelling equipment is required.

The production of green hydrogen is based on renewable energy sources to guarantee the aircraft fuel supply to be as environmental-friendly as possible [51]. This is most likely done through water electrolysis powered by electricity generated from wind, solar, hydro power or thermochemical processes [52].

As described in Chapter 2, H2 is fuelled and stored on board the aircraft in its liquid form. Consequently, the liquefaction process is a main part of the fuel supply chain for H2-powered aircraft. In this process, H2 is liquefied by cooling it to 20 K [53].

Storage facilities are needed along the supply chain as buffer storage for the production or at airports to ensure the reliability of fuel supply. In these facilities, H2 can be stored either in its gaseous form, in pure liquid form, in a liquid organic hydrogen carrier (LOHC), as ammonia (NH3) or in a solid state such as metal hydrides [24,54]. Depending on this, H2 conversion steps are required before and after storage.

Transportation is used to supply H2 over shorter or longer distances from its production to the airport on-site storage facility. Transportation modes depend on the storage form of H2 as described above. H2 can be transported via a truck, ship, train or also pipelines [55].

Last, the refuelling equipment in this work describes the “last mile” of LH2 supply to the aircraft including the dispenser and interconnection to the aircraft LH2 tank. Here, it also includes the last mile transport from the LH2 storage on-site the airport to the aircraft stand by a truck or pipeline-hydrant system.

Based on the different components of a LH2 value chain, a high-level cost model of the supply chain can be described based on the DOC model introduced in Chapter 2. If translated into the energy DOC factor DOC_{Energy} in Eq. (1), the costs are derived by multiplying the annual block energy consumption of an aircraft BE_{LH2} with the LH2 fuel price at the dispenser p_{LH2} in Eq. (2):

$$DOC_{Energy} = BE_{LH2} * p_{LH2} \quad (2)$$

with

$$p_{LH2} = p_{electrolysis} + p_{liquefaction} + p_{transport} + p_{storage} + p_{refuelling} \quad (3)$$

where the block energy consumption is a result of the H2 aircraft design described and accounted for in Chapter 2. Thus, the cost implication from less energy efficient aircraft is consequently not considered as cost implication from the LH2 fuel supply.

In Eq. (3), the fuel price at the dispenser per kg of LH2 is derived with the sum of all prices along the LH2 fuel supply chain including the electrolysis $p_{electrolysis}$, liquefaction $p_{liquefaction}$, transport $p_{transport}$, storage $p_{storage}$ and refuelling equipment $p_{refuelling}$.

The cost contribution from each of these components i depend on the annualized CAPEX ($ACAPEX_i$) and annualized OPEX ($AOPEX_i$). The latter consists of energy costs for electricity or fuel for transportation, H2 losses, maintenance, personnel, and other operating costs as well as the total amount of LH2 delivered per annum (TAD_{LH2}). On top of the fuel costs, a profit margin $PM_{LH2,\,i}$ is added for each supply component i to derive the LH2 fuel price:

$$\sum p_{LH2} = \sum_i \Big(\big(ACAPEX_i + AOPEX_{energy,i} + AOPEX_{H2losses,i} + AOPEX_{maintenance,i} + AOPEX_{personnel,i} + AOPEX_{other,i} \big) / TAD_{LH2} \Big) * \left(1 + PM_{LH2,\,i}\right) \quad (4)$$

Eq. (4) already indicates first major cost drivers for each component. For energy-intensive processes such as the electrolysis and liquefaction, not only CAPEX, but especially the energy efficiency and the cost for renewable energy supply (RES) determine their cost. For transportation, the costs are also affected by the distance of transport. For storage, costs also depend on minimum requirements of fuel supply days and can differ between seasonal and non-seasonal storage time periods. For the refuelling equipment including the fuel distribution on the last mile, economics depend on the refuelling setup, so if refuelling trucks or cryogenic pipelines are used.

Since these aspects, e.g., RES costs or transport distances, depend on the geographical supply and demand region, it becomes clear that the costs for each component must be thought in an overall context of supply pathways.

LH2 supply pathways

In a next step, the different LH2 supply pathways, also called topologies, are considered to further derive qualitative cost implications for LH2 at the dispenser.

Different topologies are available for an aviation LH2 supply chain and are influenced by the context of the supply and the demand region. In this work, topology setups are split into five sections shown in Fig. 3: central H2 supply or production sites, central processing and storage terminals, the transport route to airport, airport H2 facilities and the refuelling route at the airport.

While the shortest supply pathway would be an on-site electrolysis and liquefaction at the airport, the longest pathway could be a central H2 production at an international hub with an international supply chain transporting H2 over longer distances to an airport.

Given the highlighted cost factors before, the access to required resources and technology such as low-cost RES and low CAPEX for electrolysis, liquefaction, storage, and transport technologies can differ by supply region. When the access to these resources at an airport is insufficient, the installation of a supply infrastructure connecting to other low-cost, green H2 supply markets might be more economic. This could be the import of gaseous H2 through pipelines or LH2, NH3 or LOHC from overseas.

The amount of H2 demand TAD_{LH2} is also indicated in the cost model as a driver to reduce LH2 supply costs in two ways (Eq. (4)). First, if the utilization of each component is maximized, the cost per kg LH2 supplied is reduced. This might be reached at demand regions with a high LH2 or H2 demand from aviation or also other H2 applications near an airport. Second, since each component costs consist of CAPEX, economies of scale and learning rates might be assumed for larger (global) H2 demands [27,56]. This could cause a decrease of CAPEX per capacity for larger sizes and higher production rates of the supply chain components.

Quantifying LH2 supply chain costs – literature review

Building on the qualitative overview of cost drivers for LH2 supply components and different pathways, the supply costs are now tried to be quantified. Therefore, a literature review is conducted to identify detailed cost assessments that fit to the H2 aviation context and focus on green H2 supply. Relevant studies on H2-powered aviation are summarized in Table 4. As shown in the columns of the table, the literature is scanned for information on the different supply chain components, detailed cost assessments, LH2 supply pathway analysis and consideration of cost reducing effects from a broader, global H2 economy.

In general, only few recent studies are found with a focus on a LH2 fuel infrastructure for the aviation use providing a detailed fuel cost assessment. Most studies found investigate the technological feasibility of H2 aircraft and only provide a short or qualitative overview of potential factors influencing H2 fuel costs. The literature findings are clustered into older and more recent analyses as well as their thematic focus, describing H2 infrastructure for aviation or related topics.

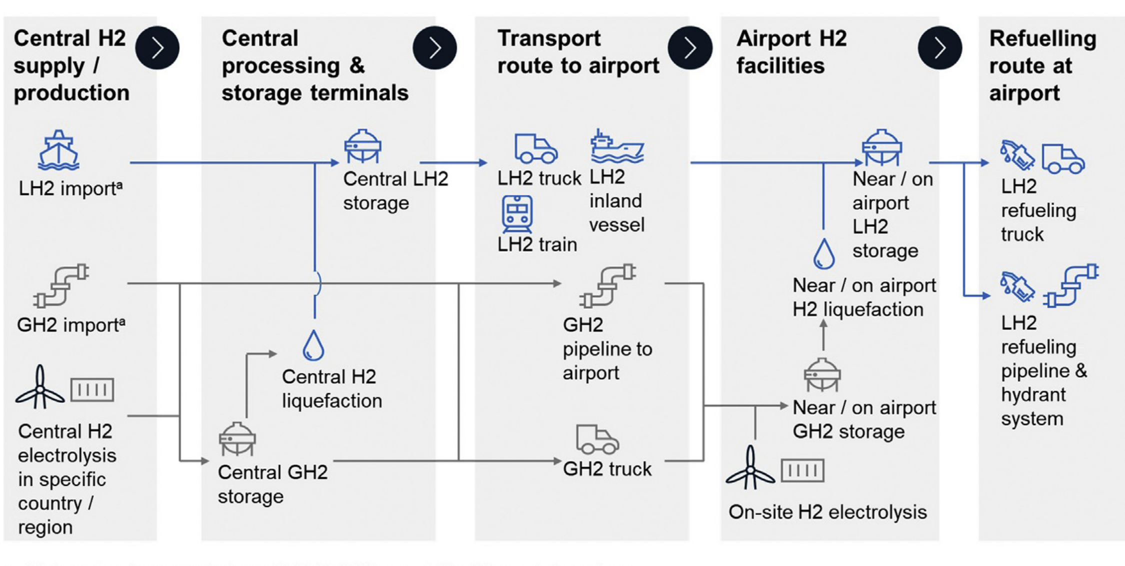

Fig. 3 – LH2 supply topologies split into 5 sections, represented by the boxes; not considered is import, storage, conversion or transportation of H2 in form of LOHC, NH3 or metal hydrides.

Table 4 – Selected literature review findings mentioning LH2 infrastructure for the use in aviation propulsion – displayed in a chronological order.

Authors	Fuel supply chain components considered					Cost assessment	Pathway analysis	Broader H2 economy context included
	H2 production	Liquefaction	Transport	Storage	Refuelling			
Johnson [57]	X (grey & nuclear)	X	X	X	X	X	–	–
Brewer & others [37,40,41,58,59]	- (grey H2 import)	X	X	X	X	X	–	–
Alder [60]	X (nuclear)	X	–	X	X	X	–	–
Contreras et al. [61]	X (green)	–	–	–	–	–	–	–
Schmidtchen et al. [46]	–	X	X	X	X	–	–	–
Cryoplane [36]	X (grey & green)	X	–	–	X	–	–	–
Cranfield [23,38,43,62,63]	X (grey & green)	X	X	X	X	–	–	–
Stiller and Schmidt [64]	X (grey & green)	X	X	X	X	–	X	–
Janic [65]	X (grey & green)	X	X	X	X	–	–	–
Stadler [66]	X (thermochemical)	X	X	–	–	X	–	–
Marksel et al. [67,68]	X (grey & green)	X	X	X	X	–	–	–
Amy and Kunycky [69]	X (green)	X	X	X	X	X	–	X
Fusaro et al. [70]	X (green)	X	–	–	–	X	–	X
Clean Sky JU and FCH JU [1]	X (green)	X	X	X	X	X	X	X

Older publications from the 1970s–1990s by Linde, NASA, Boeing, Lockheed, and other organizations as well as reports of the 2000s European Cryoplane project provided first broader insights into LH2 infrastructure for aviation.

Johnson [57], Brewer [37,41,59], Boeing [40] and Korycinski [58] developed comprehensive views on the technological feasibility for H2-powered aircraft and LH2 infrastructure setups at airports including refuelling systems and the design of the interface to the aircraft. However, their focus laid on grey H2 sourcing and did not reflect a general uptake of a green H2 economy. In 1983, Jones et al. [71] modelled cryogenic pipeline systems at airports to transport LH2 from central storage facilities to the aircraft refuelling stand, but without any economic evaluation or context to a broader setup of a LH2 supply chain. In 1987, Alder and team [60] investigated the LH2 supply costs for Zurich airport with a supply setup including an electrolysis on-site the airport fed by nuclear power. But their analysis considered a very small demand with 15–30 tons of LH2 per day only and neglected other topologies making use of a global H2 infrastructure. Other broader analyses including aircraft and infrastructure perspectives are from Contreras et al. [61] looking into H2 infrastructure at Chicago Airport. A similar overview is also provided by Armstrong et al. [72]. Schmidtchen et al. [46] qualitatively described the setup of LH2 energy systems but with the main research goal to analyse safety of H2 handling at airports. A topic which was just recently brought up again in the ENABLEH2 project by Benson et al. [73].

Around the 2000s, Sefain [38] analysed airport operations and the impact on the turnaround process for a LH2-fuelled aircraft. In the Cryoplane project [36], detailed overviews can be found for H2-powered aircraft designs, fleet transition scenarios, supply of H2 and refuelling options via truck and LH2 pipelines. In that time, a certification standard for airport H2 fuelling facility operations (ISO/PAS 15594 [42]) was issued. It describes the requirements for a safe refuelling setup at airports. However, it was withdrawn later. In the following years, further complementary, qualitative studies brought insights on H2 aircraft design, H2 fuel supply and airport refuelling implications, e.g., for a major airport in Sweden [62,63] or for other general overviews [23,74,75]. But in none of the mentioned studies a detailed LH2 cost analysis is conducted that reflects the developments of low-cost RES availability that have been observed in the recent years [76].

Other investigations also target H2 handling at airports, but with a focus on other applications than aircraft propulsion. These studies consider H2-powered Ground Supply Equipment (GSE), taxiing systems or Auxiliary Power Units (APUs) for aircraft – all with relatively low H2 demand scales.

In a demonstration project at Munich Airport, the feasibility of GH2 and LH2 supply was tested for GSE [50,77]. In addition to that, Testa et al. [78] looked into the potential to reduce emissions at airports by switching propulsion systems of GSE to H2. In 2010, Stiller and Schmidt [64] investigated H2 infrastructure topologies to fuel APU systems. Stockford et al. [79] analysed electric aircraft taxiing systems for an Airbus A320 powered by a fuel cell.

Furthermore, three studies are identified that research energy systems at airports. In the HYPORT project at Toulouse Airport [80], energy systems for the airport environment were modelled including H2 applications. However, no clear focus on H2 aircraft propulsion can be found, rather more highlights on other uses, e.g., ground transportation, general electrification, building heat. Similar studies including H2 use cases were also conducted by Robles [81] and Xiang [82].

Other analyses concentrate on climate impact from H2-powered aviation with a focus on the production ways of H2. Victor [83], Janic [51,84] and Yilmaz et al. [85] determined emission overviews from LH2 supply and propulsion in aviation based on different scenarios for H2 aircraft deployment. Similar research can be found in Refs. [86,87].

Only recent studies on H2-powered aircraft investigate the economic competitiveness of green H2 supply for aviation and include H2 cost reduction effects of an industry-overarching global H2 economy.

Stadler [66] conducted a techno-economic study of LH2 supply for aviation based on thermochemical electrolysis. Results from that study were picked up in Refs. [39,65]. Nøland [88] provided a brief projection of future LH2 costs for the aviation use, but his work concentrates mostly on H2 aircraft technology. In the MAHEPA project, Marksel et al. [67,68] looked into several infrastructure cost aspects for LH2 for a regional airport, but without deriving or even optimizing total LH2 supply costs. The Flying-V project at TU Delft [89] introduced a brief overview of LH2 logistics aspects and LH2 supply costs, but without providing any detailed insights.

In a case study for the Los Angeles Airport (LAX study), Amy and Kunycky [69] assessed the costs for green H2 on-site production and liquefaction. They included scaling factors for larger LH2 demands and considered a growing H2 economy that could lead to reduced CAPEX and optimized efficiencies. Nevertheless, the interconnection to off-site H2 production capacities and demands as well as a pathway optimization were not investigated.

Fusaro et al. [70] (Fusaro study) provided an assessment on LH2 supply costs for hypersonic H2 transportation systems. The study shows supply costs for key components, but supply pathways including transport costs, or their optimization were not considered.

Only a recent study by the Clean Sky 2 JU and FCH 2 JU [1], referred to as "JU study" in the following, provides more detail around supply topologies and their economics including on- and offsite H2 supply. It also includes a roadmap for cost-efficient infrastructure deployment and scenarios on potential H2 uptake.

From this literature survey it can already be summarized that there is a lack of research around LH2 infrastructure optimization for aviation. Only few recent studies touched cost effects depending on the supply topology and the access to low-cost RES. These effects will be further examined in the following.

First LH2 supply cost assessments from literature

The cost insights from the literature above are screened and then compared to other studies analysing non-aviation related H2 supply chains or selected components for cross validation.

The total costs for LH2 at the dispenser assessed in the LAX, Fusaro and the JU study range from 1.2 to 4.3 USD_{2020} per kg H2 delivered (left side of Fig. 4). Differences causing the broader ranges are either explained by the access to low-cost green H2 production sites through off-site supply pathways (JU study) or economies of scale effects from a global H2 economy driving down CAPEX and increasing energy efficiencies (LAX and Fusaro).

Furthermore, the cost assessments show that H2 electrolysis and liquefaction dominate the final LH2 costs. The LAX study considers on-site H2 production. In these cases, only 4%–6% of the total costs belong to LH2 storage and refuelling at the airport. Even if transportation costs in an off-site LH2 supply scenario are included, e.g., represented in the lower cost value from the JU study, the costs for transport, storage and refuelling equipment are only around 10% of the total LH2 costs. In this scenario, the main part of the LH2 costs are caused by H2 production (60%) and from liquefaction (31%). The rest is caused by transport (3%), LH2 storage (4%) and refuelling at airport (2%).

Most studies consider LH2 truck refuelling at the airport, which is projected to be very cost competitive. However, few studies highlight that refuelling through cryogenic pipeline systems might be required for large LH2 demands to guarantee sufficient and safe refuelling pace [1,41,64,71]. This is indicated to cause significantly higher costs than LH2 truck refuelling, but no quantitative assessment was found.

Since the cost values and shares are derived from three studies only – all potentially looking into a best picture for aviation – other LH2 supply cost studies from different H2 applications are used to test the robustness of these results.

Most studies found in literature that investigate H2 supply chains focus on the use case of fuel cell electric vehicles (FCEV) [90–97]. Most of these analyses investigate the techno-economic optimization of H2 delivery pathways to a H2 refuelling station (HRS). In these studies, FCEV most often are not fuelled with LH2, but with gaseous H2. Consequently, the costs for the refuelling unit from these studies are not included in this cost comparison. However, this means that refuelling equipment costs for the aviation use case that account for 2% in the JU study [1] and less than 1% in the LAX study [69] are not considered.

Some of these investigations include the supply pathways of H2 in its liquid form which is then evaporated at the HRS. For the comparison in this work, the study from Reuss et al. [90] is chosen, in which, representative, similar LH2 supply cost to the HRS are derived compared to the other mentioned FCEV studies. Thus, it is selected because it provides a detailed overview of the underlying parameters and assumptions.

To not only compare the aviation-specific analyses to studies that look at off-site H2 production placed inside the same country (Reuss study), another study from Teichmann et al. [54] is also considered. These authors investigated off-site supply pathways over longer distances to access lower cost, green H2 production regions including the transportation of H2 in its liquid form. The cost assessments from these two studies are shown on the right side of Fig. 4, LH2

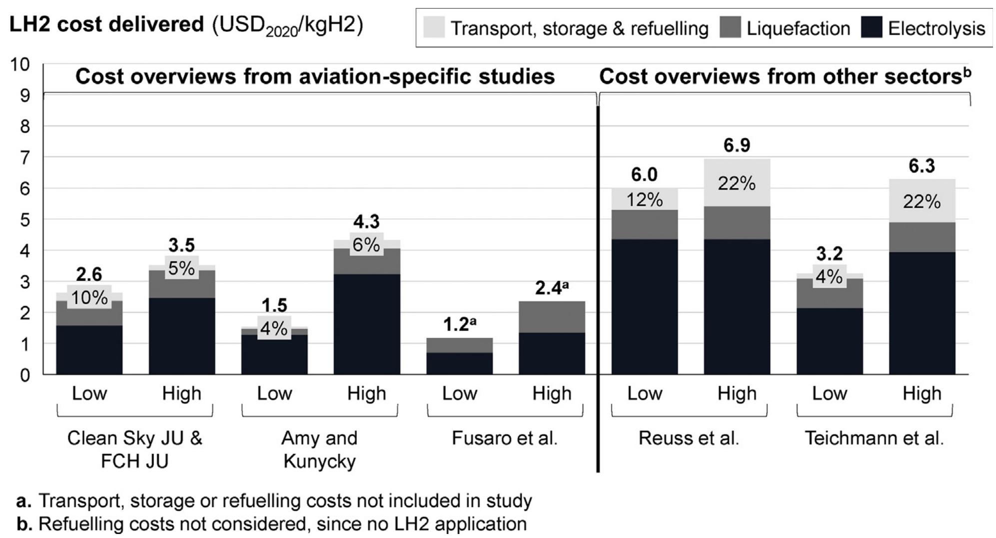

Fig. 4 – Low and high cost values from assessments found in literature for LH2 at the dispenser unit, shown in USD_{2020} values. Left side with results from selected aviation-specific studies. Results from non-aviation supply chain analyses on the right side. Percentage gives share of storage, refuelling and transport, if included in the study.

costs range from 3.2 to 6.9 USD $_{2020}/kg_{H2}$. Behind this range several trends are found. First, the cost for LH2 supply can be higher than 4.3 USD_{2020}/kg_{H2}, which is found as highest cost value in the aviation-specific studies. Second, if the H2 production is limited to one country, in this case Germany, the cost for different supply pathways might not differ largely (Reuss study). In contrast to that, Teichmann et al. show that the cost for electrolysis and hence the total LH2 costs can be significantly reduced, if better access to low-cost RES is ensured [1,54,98]. In this case, transportation costs depend on the distances between demand and supply – if international shipping is required, this could cause significantly higher costs. Third, even though these non-aviation-specific studies regard off-site supply pathways, the major cost shares are still caused by electrolysis and liquefaction – the sum of both accounting between 78% and 96% of the total LH2 costs in the selected studies.

Since this cost comparison already emphasizes a higher uncertainty range behind the cost expectation for LH2 supply for the aviation use, the underlying cost drivers are further detailed out.

Component specific cost assessments from literature

The selected studies underline that the LH2 supply costs mostly depend on the accessibility of low-cost RES and economies of scale for the CAPEX of each component. In a last step of this review-based cost assessment, these effects are tried to be further understood. For this, component cost perspectives for electrolysis and liquefaction are investigated since both mark the highest cost share for LH2 supply. Such detailed techno-economic studies are found in other sectors or without a sector focus. Insights from these studies are analysed and set into a more comparable context for the use in a LH2 supply for aviation.

Starting with the economics for electrolysis, several recent cost roadmaps and analyses with a focus on the underlying drivers can be found from the Hydrogen Council [98], IRENA [99,100] and BloombergNEF [101]. Main cost drivers in these studies are the electrolyzer CAPEX and renewable electricity cost. It is shown that CAPEX can be reduced when larger electrolysis modules are built, and global production rates are scaled up. Both potentially lead to economies of scale and learning effects in a global H2 economy. This is in accordance with findings from Refs. [102–106].

The costs for RES also depend on CAPEX for wind PV modules and wind turbines, but especially on regional conditions to reach maximum full load hours for PV (intensity of radiation from the sun) and for wind power (velocity of wind) [76].

Other identified drivers are the energy efficiency of electrolysis and its utilization. Since detailed assumptions behind the drivers were not always accessible in the chosen studies, they are not part of the further analysis.

Data points from the selected studies are plotted in Fig. 5A with the resulting H2 electrolysis costs shown in Fig. 5B. Based on these, the landscape of H2 electrolysis costs is clustered into three areas that are described in the following.

The first area (1) describes an optimistic H2 cost scenario considering low-cost RES: green electricity can be drawn at cost below 50 USD_{2020}/MWh_{el} and CAPEX for electrolysis are below 500 USD_{2020}/kW_{el} due to economies of scale and learning rates. Corresponding H2 costs from electrolysis then range from 0.8 to 2.5 USD_{2020}/kg_{H2} (Fig. 5B). In contrast to that, the second area (2) stands for a base case H2 cost scenario, in which cost reductions and low-cost RES access are rather limited. CAPEX for electrolysis range between 500 and 750 USD_{2020}/kW_{el} and RES costs between 50 and 80 USD_{2020}/MWh_{el} – resulting H2 costs are between 1.8 and 3.8 USD_{2020}/kg_{H2}. The third area (3) represents a pessimistic H2 cost scenario with no significant reduction in electrolysis costs (CAPEX above 750

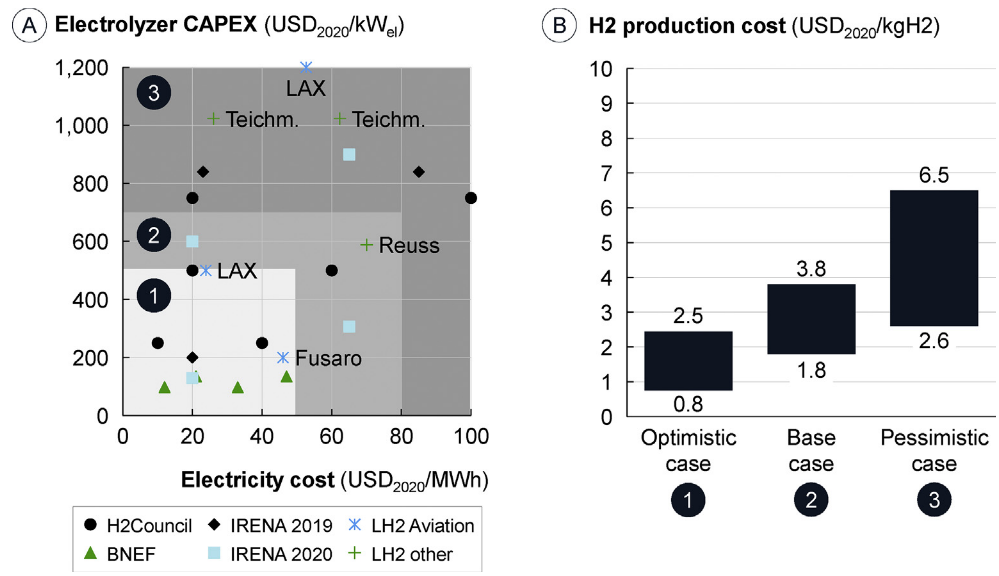

Fig. 5 – A-left side) assumptions behind cost studies for H2 electrolysis costs from cost roadmaps (Hydrogen Council, BNEF and IRENA) and previously shown studies (LH2 aviation, LH2 other); B-right side) resulting H2 production costs clustered into three scenarios – all values adjusted to USD_{2020}.

USD_{2020}/kW_{el}) and no access to low-cost RES – so the electricity supply would cost more than 80 USD_{2020}/MWh_{el}. In this scenario, the H2 production cost would be the highest: from 2.6 to 6.5 USD_{2020}/kg_{H2}.

At this stage, it is also important to note that in each of the three scenarios the lower H2 cost range is rather driven by lower electricity costs than by the CAPEX reduction potential of the electrolyzer. This means that the import of low-cost, green H2 over longer distances might be a superior option at airports without low-cost RES accessibility – depending on the transportation costs. Future analyses will be required to detail out the optimization behind such trade-offs.

In a next step, the data points from the previously discussed LH2 supply cost studies are also mapped out in Fig. 5. The lower cost values from the LAX and Fusaro study fall into the cluster of the optimistic scenario. While explicit cost assumptions are not found in the JU study, it references to the optimistic cost perspective from the Hydrogen Council study [98], which is also plotted in the first area (1). The assumptions in Reuss' and Teichmann's studies fit to the base and pessimistic scenarios in Fig. 5. The reason for that could be that their analyses determine LH2 costs for regional delivery capacities of several tons per day. In comparison to that, the aviation-specific studies rather count on high demand and good access to low-cost RES scenarios. With a LH2 demand of 1–30 tons per flight from only one aircraft, the total demand at airports could form high demand scenarios [1,38,41,69]. However, in the transition phases towards larger LH2 uptake in aviation the base or pessimistic H2 cost scenarios could become true, which would influence its economics and should be further investigated.

Regarding the economics of H2 liquefaction a similar approach is chosen (Fig. 6). Even though less work is found on H2 liquefaction costs including a detailed documentation of underlying cost assumptions, a clear picture can be derived. Selected studies are from the IDEALHY project [107,108], Cardella et al. [109,110], Yang and Ogden (Y&O) [55] and the Department of Energy of the United States (DOE) [111]. Main cost drivers found are the CAPEX and energy consumption of a liquefaction plant as well as the RES cost. Since most of the selected studies assume similar RES costs between 30 and 50 USD_{2020}/MWh_{el}, the focus of analysis here is set on the other two factors.

In the literature, it is shown that CAPEX per capacity and the specific energy consumption decrease with the scale of the plant. It is also described that with higher production volumes of liquefaction plants, further economies of scale and learning rates can be expected [70,112]. As a result, again three scenarios are derived. In an optimistic LH2 cost scenario, which considers high amounts of installed liquefaction plants with large capacities beyond 100 tons of liquefied H2 per day, CAPEX for liquefaction is below 1.5 Mn USD_{2020} per t_{H2}/day. In addition, the specific energy consumptions of these plants would fall below 8 kWh_{el} per kg H2 delivered. The resulting liquefaction costs are between 0.2 and 1 USD_{2020}/kg_{H2}. In a base case LH2 cost scenario, the liquefaction costs range between 0.8 and 2 USD_{2020}/kg_{H2}, CAPEX would be between 1.5 and 2.5 Mn USD_{2020} per t_{H2}/day capacity and the specific energy consumption between 8 and 11 kWh_{el}/kg_{H2}. In the pessimistic LH2 cost scenario, plant capacities are smaller, and no significant economies of scale are reached. This would lead to relatively high CAPEX above 2.5 Mn USD_{2020} per t_{H2}/day capacity, high specific energy consumption with more than 11 kWh_{el}/kg_{H2} and resulting liquefaction costs of 1.7–3 USD_{2020}/kg_{H2}.

Again, it can be observed that the liquefaction costs from the aviation-specific studies mostly consider an optimistic scenario with high cost savings and highly energy-efficient

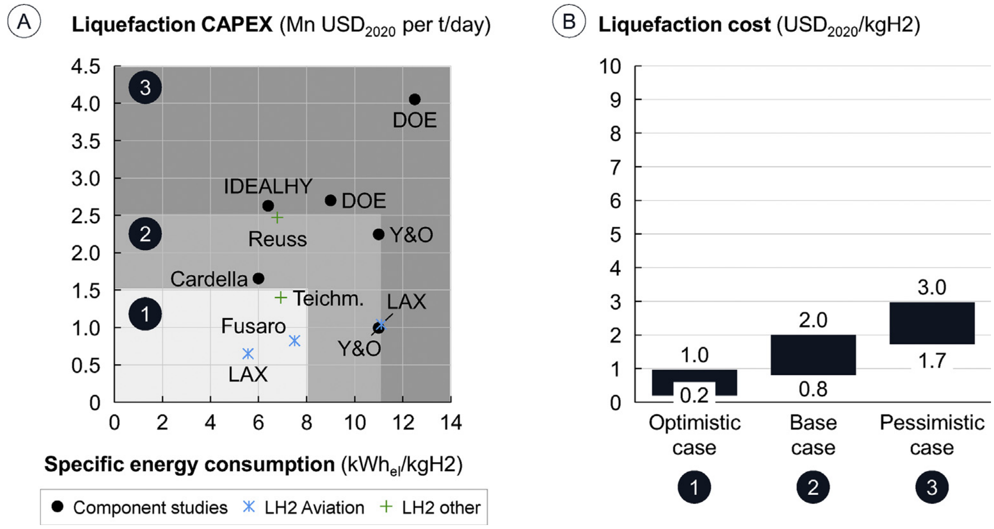

Fig. 6 – A-left side) assumptions behind cost studies for H2 liquefaction costs from component studies and previously shown studies (LH2 aviation, LH2 other); B-right side) resulting liquefaction costs clustered into three scenarios – all values adjusted to USD_{2020}.

liquefaction. Also, the other LH2 studies assume rather low liquefaction costs around 1.0 USD $_{2020}$/kg_{H2}, since they use large scale, centrally placed liquefaction plants.

Resulting LH2 supply cost insights from literature

To sum up the LH2 cost findings based on three different cost scenarios, the costs for H2 production and liquefaction are added as well as an additional factor to consider transport, storage, and refuelling costs. Derived from the findings in Fig. 5, a 5% margin for these cost drivers is assumed for the low values as the best possible case. For the high values, a higher cost case is taken with a 20% margin which is indicated in the studies from Reuss et al. [90] and Teichmann et al. [54].

Summing up these detailed insights for total LH2 costs, two trends are emphasized (Fig. 7). First, in optimistic scenarios, higher H2 demands might lead to significantly lower LH2 costs due to scaling and learning effects and only if access to low-cost RES is given. Second, the cost assumptions from the aviation-specific studies mostly rely on such optimistic LH2 cost assumptions, while the other two studies rather consider base and pessimistic case scenarios. This means that either the assumptions for LH2 use in aviation might have been too positive, or that there are reasonable aspects supporting this. Latter could be that the H2 demand for aircraft would trump the demand from other industries or that special, large-scale supply pathways could be enabled for the aviation use case. Both aspects require further investigation in future research.

If the total LH2 fuel costs are now compared to kerosene costs, a clear picture evolves. For the comparison, kerosene costs (see Chapter 2) are converted into LH2-equivalent cost based on its gravimetric energy densities. As already highlighted in Chapter 2, the H2-powered aircraft in this study are less energy efficient than the kerosene-powered reference aircraft. To distinguish the economic effects between fuel

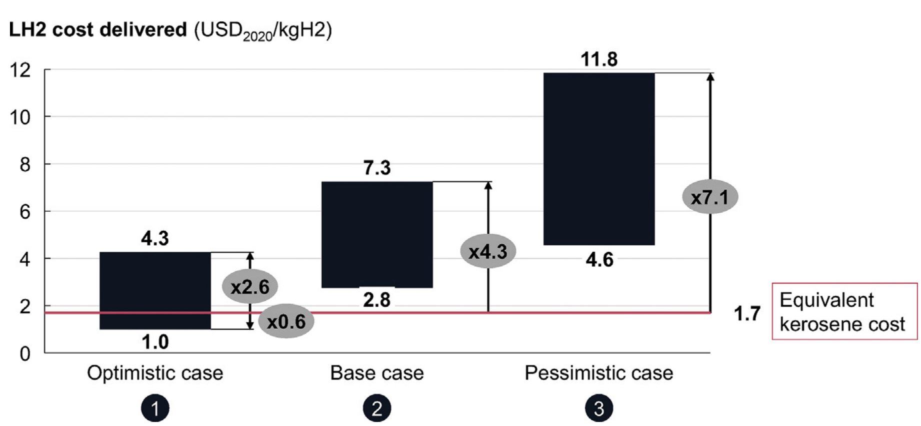

Fig. 7 – Cost ranges for liquid hydrogen at the dispenser derived from literature review and cost assessments depending on the H2 cost scenario (from optimistic to pessimistic); comparison to kerosene costs translated into LH2-equivalent costs based on LHV of kerosene and LH2 – not considering different aircraft efficiencies, which cost implications are already included in Chapter 2.

supply and aircraft energy efficiency, the efficiency impact is not considered in this LH2 fuel cost analysis here.

As a result, it is shown that only in an optimistic scenario fuel costs for H2-powered aircraft could be competitive or even less expensive by a factor 0.6. Taking an average LH2 cost in this scenario of 2.6 USD_{2020}/kg_{H2}, this results in higher fuel DOC by a factor of 1.6. In a base case scenario, this cost premium factor would already be 3.0 for an average LH2 cost of 5.0 USD_{2020}/kg_{H2}. The uncertainty range for the cost premium is even broader for pessimistic scenarios, in which the difference of fuel costs could be up to a factor of 7.1 for LH2 fuel.

These findings emphasize the high volatility and uncertainty coming from the LH2 fuel costs and hence, the setup of a scaled up, low-cost and green H2 infrastructure. While the aviation-specific studies count on scenarios with high H2 demand and good RES accessibility, transition scenarios might cause significantly higher fuel costs.

Nevertheless, it is also important to consider the uncertainty behind the development of kerosene costs over the next decades including potential emission taxes for fossil fuels.

Impact on total DOC for selected aircraft segments

To be able to draw a conclusion on the impact on the business case for H2-powered aviation, the role of LH2 fuel costs as part of the total DOC is investigated in a final step. Chapter 2 and 3 laid out that the introduction of H2-powered aviation changes the operating costs caused by different aircraft CAPEX, maintenance costs and energy efficiencies as well as LH2 fuel costs.

For H2 aircraft technology, aircraft CAPEX and maintenance are projected to increase by 12% and 14% for the computed short- and medium-range aircraft, respectively. Since also the energy efficiency of the LH2 aircraft are impacted, a 12% and 18% cost increase of fuel costs is the result. Comparing the sum of these aircraft technology related cost implications with the total DOC this equals a total increase of 6% for the short- and 10% for the medium-range aircraft (Fig. 2, summarized as second bar in Fig. 8A and B).

For aircraft operation and utilization, no clear evidence was found in literature that this would change the economics of H2-powered aircraft. Hence, no cost impact is assumed in this study. However, uncertainty remains around the refuelling times with LH2 and their influence on turnaround processes or maintenance downtimes.

Finally, it was shown in this chapter that the costs for LH2 at the dispenser determine a very large uncertainty for the total DOC. On the one side, it was found that in a “best case”-assessment the energy costs could even decrease by 40%. On the other side and based on the average LH2 cost for three different scenarios, the energy costs increase in each scenario as shown in Fig. 8.

In a pessimistic LH2 costs scenario, the total DOC increase caused by higher fuel costs would be 70% for short-range and 102% for medium-range H2 aircraft. In contrast to that, an optimistic LH2 cost scenario would lead to 10% higher total DOC for a short-range and 15% for medium-range H2 aircraft.

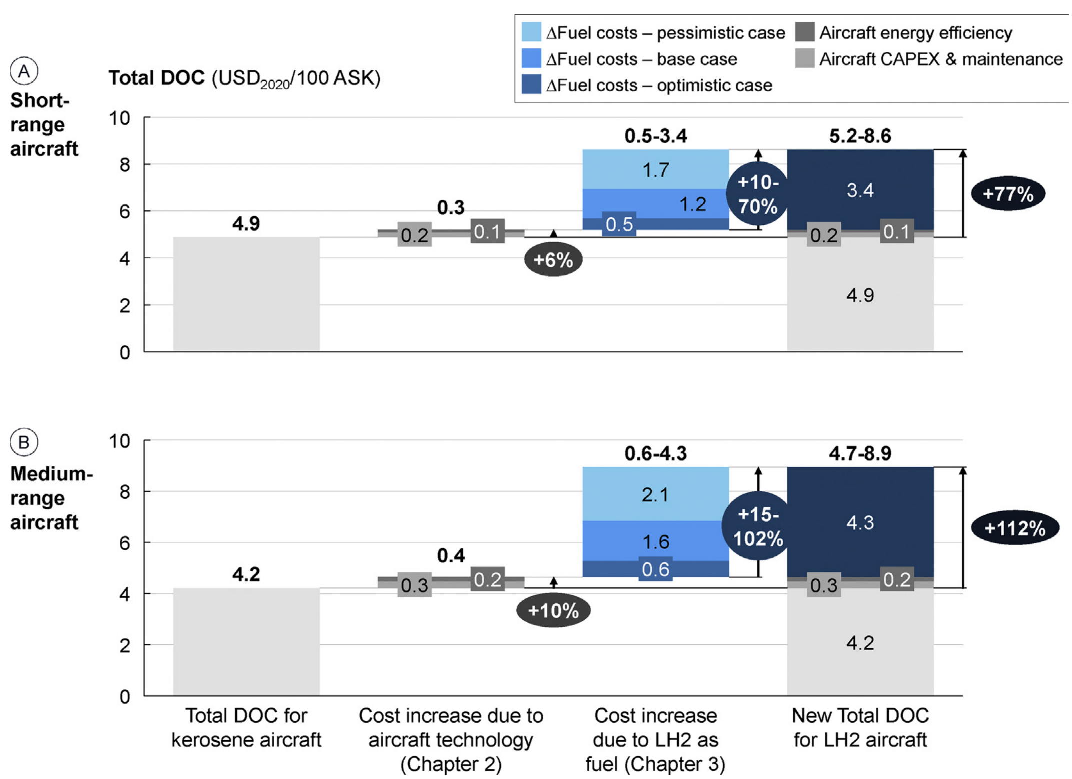

Fig. 8 – Total direct operating costs (DOC) for A) short-range and B) medium-range H2-powered aircraft compared to kerosene-powered reference aircraft; DOC increase due to aircraft technology (CAPEX, maintenance, energy efficiency); DOC increase due to LH2 fuel costs based on average cost values taken from three scenarios laid out in Fig. 7.

Overall, this means that the total operational costs of a H2-powered vs. kerosene-powered short-range aircraft could decrease by 1%, if fuel can be supplied for 1.0 USD_{2020}/kg_{H2} or increase by 77%, if fuel is supplied at 8.2 USD_{2020}/kg_{H2}. For a H2-powered medium-range aircraft, total DOC would not change in a best case or increase by 112% in an average low H2 demand case.

Conclusions: derived research agenda for an aviation-specific hydrogen infrastructure

In this paper, the implications of introducing H2 propulsion for larger commercial aircraft and the role of a H2 infrastructure were investigated. It was shown that operational costs for H2-powered aircraft could differ significantly compared to kerosene-powered aircraft – from a slight decrease of total operating costs to an increase by 77%–112%. Furthermore, it was emphasized that in a pessimistic LH2 cost scenario (average LH2 costs at the dispenser around 8.2 USD_{2020}/kg_{H2}), the business case for H2-powered aviation would not be given – mostly due to higher costs for renewable electricity. Even if an increase of kerosene costs by a factor 5 is assumed, H2 aircraft would not be competitive in such a scenario. For example, this could be caused by a carbon emission tax, in this case of up to 722 USD_{2020}/t_{CO2} and 778 USD_{2020}/t_{CO2} for the short- and medium-range H2 aircraft, respectively. Consequently, it was highlighted that these economic uncertainties are not only caused by the development of competitive H2 aircraft technology influencing aircraft energy efficiency but also by the setup of a green H2 infrastructure and the resulting LH2 supply costs. This also means that like for synfuels (Table 2 in Chapter 2), the fuel costs of LH2 could be a main challenge for the adoption of this clean aviation lever by the industry.

In addition to that, further economic uncertainties were found caused by implications of H2-powered aircraft operation. Either different H2 aircraft designs with slower cruise speeds or longer refuelling procedures with LH2 could lead to lower utilization of aircraft and hence higher operating cost.

All in all, the findings underline the necessity for a stronger research focus on infrastructure related H2 topics as a driver for a positive business case of H2 aviation – a focus that was not found to be sufficiently addressed in previous aviation related research as shown in the literature survey. This is why, we see major research fields along the aviation-specific H2 infrastructure value chains to be addressed in future work, which is proposed in the following and shown in Fig. 9.

Local and global LH2 supply chain setups – on- or off-site of airports

In Chapter 3, the importance of access to low-cost renewable energy supply was shown – especially for reducing costs of electrolysis and liquefaction. While the costs for RES highly depend on geographic location factors such as solar radiation and wind velocities, low-cost transport pathways from these places to airports without such beneficial conditions might also enable competitive LH2 supply costs. H2 transport options could range from regional to national or even international distances. Since no techno-economic studies were found that would allow the cost optimization of such pathways for the aviation use, this should be addressed in future research. Then, analyses might not only focus on optimizing production sites and transport options, but also on the placing of liquefaction plants and H2 storages.

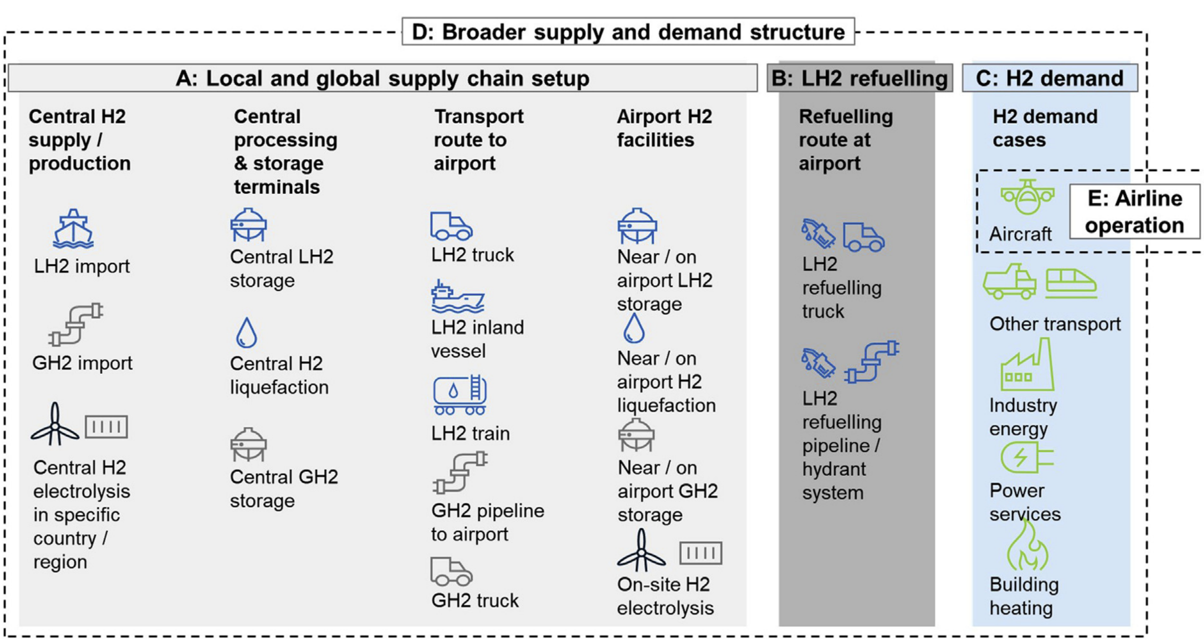

Fig. 9 – Proposed research fields for aviation-specific H2 infrastructure.

LH2 refuelling infrastructure at airports

Even though it was found that costs for LH2 refuelling systems might account for a smaller share of total LH2 supply costs, the design and economics of larger scale refuelling systems was identified as a research gap. Such systems supplying LH2 via truck or cryogenic pipeline to the aircraft are required as enabler for H2 aircraft operation, especially in high demand scenarios. A study in this field might also investigate safety and certification aspects that must be considered in an airport environment as well as technology solutions for the interconnection between the LH2 dispenser and the aircraft.

Furthermore, the implications from the design of LH2 refuelling systems and refuelling procedures might also change aircraft ground operation, turnaround times and related costs.

H2 demand setups at and around airports

Hydrogen demand setups and scales were identified as another important factor that enable competitive economics for LH2 supply. The analysis of electrolysis and liquefaction costs showed that such high demands for hydrogen could drive down costs for H2 supply components due to economies of scale and learning rates. For this, not only H2 demands from aircraft propulsion, but also other H2 applications around airports could influence the supply cost – potentially forming a H2 hub. Examples could be the supply to other transport sectors such as airport ground traffic, heavy-duty trucking or the production of synthetic fuels that might be used for aircraft as well. However, these demands could not only lead to synergies in lower supply costs, but also supply conflicts, if resources for low-cost RES are limited. To further analyse this, potential scales of demand, the need for gaseous or liquid H2 and timelines for realization of the different H2 use cases should be assessed.

Broader supply and demand structure

Incorporating the described analyses for H2 supply and demand setups, broader investigations of their role in an overall energy transition of air transport and all other sectors should be considered as well. Focus could be region-specific analyses that investigate the energy supplies and demands of different sectors in driving the energy transition towards less climate impact. For this, two further aspects should also be considered. First, not only long-term perspectives are of interest, but also transition scenarios and related costs. Second, the evaluation for such setups might go beyond cost and climate impact indicators. Multi-criteria evaluation including, e.g., macroeconomic analyses of specific H2 supply and demand structures might be determined. Macroeconomic criteria could be the influence on social welfare or changes in employment for a specific economy.

Based on these findings, recommendations for specific regions and stakeholders such as governments and industry organizations could be derived.

Airline operation and network implications

Finally, the impact of introducing H2-powered aircraft on air transport networks is another related research field. As already mentioned, refuelling with H2 might affect turnaround times and therefore the availability of aircraft for airline operation. Furthermore, these aircraft might also come with different flight mission specifications (Chapter 2), e.g., flying slower and at lower altitudes, so that current routing of aircraft might change. Another aspect is that the different availability and access to low-cost, green LH2 might influence the design of airline networks. Hub and spoke systems could arise, where the H2-powered aircraft would only be fuelled at a central hub, to avoid high fuel costs at other airports. All these potential modifications to air transport systems should be targeted in future research.

Overall, the identified research items A to E related to the importance of H2 infrastructure for positive economics of H2-powered aviation can be built on insights from the work shown in the literature survey – from aviation-specific H2 analyses to research from other H2 systems. As a result, insights in these fields would further enable decision making for all stakeholders in short- to more long-term perspectives – from government instrumentation to industry strategies.

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, Boris Bensmann and Richard Hanke-Rauschenbach gratefully acknowledge funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2163/1 Sustainable and Energy Efficient Aviation, Project-ID 390881007.

Appendix

A. Direct Operating Cost modelling and implications of LH2

The Direct Operating Cost (DOC) model is based on Thorbeck [32,113] and modified to ensure a proper comparison between kerosene- and hydrogen-powered aircraft. Further information about the DOC model can also be found in Refs. [17,114].

The main aspects considered are already described in Eq. (1) (Chapter 2). Building on this, the different DOC shares are laid out in the following. Thus, modifications for assessing DOC for H2-powered aircraft are highlighted.

In comparison to DOC, COC (cash operating cost) – DOC without CAPEX for aircraft manufacturing – are often used to compare rather conventional technologies or aircraft concepts. However, if more radical changes such as new energy carriers are applied, the capital costs should be included since they have a major influence.

General data inputs

The yearly flight cycles are 1591 and 1592 for the short-range kerosene and LH2 concept and 932 as well as 936 for the medium-range kerosene and LH2, respectively. The slight differences result from different optimum flight altitudes and climb gradients of each concept which were computed in the aircraft design model (Appendix B). Besides the flight time, yearly downtimes of 2749 h which consist of C-Checks (3.2 days p.a. and 4 days per 15 months), D-Checks (5.6 days p.a. and 4 weeks per 5 years), repairs (statistical average of 2.6 days p.a.) and night curfew (7 days p.a., from 11:00 p.m. until 6:00 a.m. at operations days) are considered [32,113]. Additionally, block time supplements of 1.5 h per flight for the short-range and 1.8 h for the medium-range concepts are applied leading to block-times for the evaluation mission of 2.3 h and 4.6 h for the short-range and medium-range designs.

DOC energy

The energy DOC are affected by both the vehicle's performance and the energy specific costs. The interface between the aircraft fuel system and the general fuel supply is the refuelling dispenser or fueling adapter. Every losses and costs before are accounted within the energy price, see Chapter 3. The block-energy of the evaluation mission is shown in Tables 1 and 3.

DOC fees

The fees consist of ground handling, air traffic control (ATC) and landing fees. The payload dependent ground handling fees are calculated with the assumption of 0.1 USD_{2020} per kg payload represented by p_{handling} in Eq. (A1).

The strong dependency on maximum take-off mass (MTOM) of air traffic control and airport landing fees is correct for conventional aircraft powered with kerosene, since it roughly correlates with the profitability of the vehicle. However, if new energy carriers are applied, this correlation is not given, and new cost structures are likely to be implemented. To cope with this, same fees are assumed for the kerosene baseline and the H2 concepts. However, this must be seen carefully since todays “conventional” airport fee structures highly depend on the MTOM.

Consequently, the MTOM dependent fees in this study are calculated with the MTOM of the kerosene based short-range and medium-range concept (see Table 1) and the fees are kept constant for the LH2 designs. The price per landing p_{landing} per MTOM is set to 0.01 USD_{2020}/kg, see Eq. (A2). The ATC factor f_{ATC} is set to 0.5 and the evaluation range R in Eq. (A3) is 800 NM and 2000 NM. Eq. (A1) to A3 are taken from Refs. [32,113].

$$DOC_{\text{handling}} = p_{\text{handling}} \cdot Payload \tag{A1}$$

$$DOC_{\text{landing}} = p_{\text{landing}} \cdot MTOM \tag{A2}$$

$$DOC_{\text{ATC}} = f_{\text{ATC}} \cdot R \cdot \sqrt{\frac{MTOM}{50,000}} \tag{A3}$$

DOC crew

There is no reason to expect differences in crew DOC from a methodology standpoint. This is why the method from Thorbeck [32,113] is applied in this work. Since the cruise speed and ground times are assumed to be similar as for conventional kerosene-powered aircraft, there is no effect for crew DOC. The average yearly salary is 175,000 USD_{2020} for each flight crew member and 85,000 USD_{2020} for each flight attendant. For every 50 passengers one flight attendant is considered in addition to two pilots and in total 5 crews per aircraft.

DOC maintenance

Due to the absence of literature dealing with aviation-specific LH2 tank maintenance processes and costs, the same mass related approach for the averaged airframe including systems is applied for the LH2 tanks. In other words, the LH2 tank and fuel system have the same maintenance expenditures per mass as the rest of the airframe. According to Refs. [32,113], the maintenance related DOC are split into the airframe material (Eq. (A4)), airframe personnel efforts (Eq. (A5)) and the total engine maintenance (Eq. (A6)).

$$DOC_{\text{Maint,AF,Material}} = \frac{OEM}{1,000} \cdot (0.21 \cdot t + 13.7) + 57.5 \tag{A4}$$

$$DOC_{\text{Maint,AF,Pers}} = LR \cdot (1 + B) \cdot \left(\left(0.655 + 0.01 \cdot \frac{OEM}{1,000} \right) \cdot t + 0.254 + 0.01 \cdot \frac{OEM}{1,000} \right) \tag{A5}$$

$$DOC_{\text{Maint,Engine}} = n_{\text{eng}} \cdot (1.5 \cdot T_{\text{SL,Static}} + 30.5 \cdot t + 10.6) \tag{A6}$$

within the previous three equations, t is the block time which is 2.3 h and 4.6 h for the short-range and medium-range concepts, LR is the labour rate which is 50 USD_{2020}/h, B is the cost burden and according to Refs. [32,113] n_{eng} represents the number of engines ($n_{\text{eng}}= 2$) and $T_{\text{SL,Static}}$ is the static thrust per engine at sea level in tonnes.

Specific cost differences in maintenance costs between H2 and kerosene combustion chambers and gas turbines are not considered.

DOC aircraft CAPEX

As shown in Eq. (A7), the CAPEX consist of the depreciation (annuity factor a, see Eq. (A8)) and the insurance rate ($f_{\text{ins}} = 0.5\%$) multiplied with the aircraft's delivery price (p_{AC}). This assembles of Recurring Costs (RC) and Non-Recurring Costs (NRC) multiplied by the profit margins ($PM_{\text{AC}} = 20\%$) for the manufacturer as well as the miscellaneous factor (f_{misc}) which includes additional costs such as spare parts, see Eq. (A9). The annuity factor a in Eq. (A8) consists of the residual value factor f_{RV} which is 0.05, the interest rate IR of 5% and the depreciation period DP is set to 14 years.

$$DOC_{cap} = p_{AC} \cdot (a + f_{ins}) \quad (A7)$$

$$a = IR \cdot \frac{1 - f_{RV} \cdot \left(\frac{1}{1+IR}\right)^{DP}}{1 - \left(\frac{1}{1+IR}\right)^{DP}} \quad (A8)$$

$$p_{AC} = \left(RC_{kerosene} + \frac{NRC}{n_{AC}}\right) \cdot (1 + PM_{AC} + f_{misc}) \quad (A9)$$

$$RC_{kerosene} = \sum c_i + c_{load\&handling} + c_{finalAssembly\&delivery} + n_{eng} \cdot p_{eng} \quad (A10)$$

The share of the NRC per aircraft produced (n_{AC}, 1000 for medium-range and 4000 for short-range) which mainly consists of development, flight testing and prototype expenditures, is rather small for successful commercial aircraft families. The RC, shown in Eq. (A10), represent the major part of the aircraft price and consist of the production related costs. They are calculated by applying the RC method from Beltramo et al. [115] also applied in Ref. [114]. It consists of the sum of each individual component and system costs (c_i) as well as additional terms for loading and handling ($c_{load\&handling}$) and final assembly ($c_{finalAssembly\&delivery}$). The equations for each component can be found in Ref. [115]. Since the engine is a purchased part, the price per engine (p_{eng}) is added and multiplied by the number of engines (n_{eng}). This approach allows an aircraft component wise evaluation.

Even if there are many unknowns in estimating the aircraft delivery price, which often strongly differs from list prices, the described approach provides much more realistic capital cost sensitivities than the operating empty mass (OEM) related approach, described in Refs. [32,113,116]. If more radical changes in propulsion technology or energy carriers are compared with conventional aircraft, the described approach is mandatory.

$$RC_{LH2} = RC_{kerosene} + n_{LH2tank} \cdot p_{LH2tank} \quad (A11)$$

with

$$p_{LH2tank} = E_{stored,max} \cdot k_{LH2tank} \quad (A12)$$

For the LH2 application, the RC described in Eq. (A10) are extended by the LH2 tank price ($p_{LH2tank}$) multiplied by the number of tanks ($n_{LH2tank}$), see Eq. (A11). It is approximated by the maximum energy stored in the tank ($E_{stored,max}$) multiplied by the factor $k_{LH2tank}$ in USD_{2020} per kg LH2, see Eq. (A12). An averaged factor of $k_{LH2tank} = 650\ USD_{2020}/kg_{LH2}$ from Ref. [117] is used. Differences between the kerosene and the hydrogen concepts in terms of additional non-recurring factors like development expenditures are not considered in this study.

DOC related uncertainties

If the costs for fuel are excluded (detailed analysis in Chapter 3), key uncertainties for the economic evaluation of H2-powered aircraft arise from the main assumptions around the LH2 tank in two ways. First, aircraft CAPEX and maintenance costs depend on different cost assumption for the LH2 tank. Considering the most conservative and optimistic tank CAPEX factors from Ref. [117], the uncertainty in total CAPEX are ±6% and ±9% for the short and medium-range concepts. Based on the total DOC, this results in a variation of around ±1% and ±3%. The uncertainties for the maintenance costs cannot be predicted yet due to the missing research in this field.

Second, the LH2 tank mass also influences the performance of the short- and medium-range H2 aircraft. By varying the LH2 tank mass assumptions between very optimistic and pessimistic scenarios, the design block energy consumption decreases by 5% in a best and increases by 25% in a worst case compared to the kerosene baseline. This indicates the importance of detailed aviation-specific LH2 tank research.

B. Aircraft design methodology

The aircraft design has been conducted with a multidisciplinary sizing loop build in RCE (Remote Component Environment) [118] including the conceptual design tool openAD [119]. Additionally, higher fidelity methods comprising aerodynamics, engine performance, mission performance as well as liquid hydrogen (LH2) tank thermodynamics and structural sizing are implemented. To assure a seamless communication within the sizing process, the data scheme CPACS [120] is applied. An overview about the models involved can be found in Ref. [121].

The short-range design is based on a recalculated Airbus A320neo whereas the medium-range design uses the Airbus A330 as a reference. This means that the models are calibrated with data from existing aircraft. These aircraft have been projected to the Entry-Into-Service (EIS) year 2035 by applying new conventional technologies such as Carbon Fibre Reinforced Polymer (CFRP) wing and new high-bypass ratio geared turbofan engines. The total engine efficiency has been increased by 10% compared to the reference. Furthermore, the cabin layouts are applied for the design case and the cost evaluation case. The short-range concept is equipped with a 180 PAX single class standard layout with a seat pitch of 28/29 inch which is described in Ref. [122]. The medium-range concept is equipped with a 290 PAX dual class layout – also a typical arrangement of A330-300 aircraft.

For H2-powered aircraft, the propulsion system can be either fuel cell systems paired with electric motors creating

Table B1: Hydrogen aircraft specifications – performance characteristics

Parameter	Unit	Short-range	Medium-range
Lift to Drag (mid. cruise)	–	16.6	18.1
TSFC (mid. cruise)	kg/s/N	4.705e-06	4.950e-06
Total propulsion efficiency (mid. cruise)	–	40.8%	42.2%
Total LH2 tank volume	m^3	49	240
LH2 tank gravimetric index	–	40%	50%

thrust through fans or propellers, direct hydrogen combustion in a combustion engine or turbine, or a hybrid system of both fuel cells and H2 combustion [1].

In general, it can be stated that the lower the power class of the air-vehicle, the higher the potentials for fuel-cell propulsion since the core efficiency of gas turbines highly depend on the overall maximum power rating whereas fuel-cells hardly show sensitivities to scaling. However, the contrary behaviour of efficiency versus throttle settings offers new hybrid potentials: whereas high throttle settings result in high efficiencies and vice versa for gas turbines, the opposite is true for fuel cells [123]. The LH2 tank sizing is conducted with conceptual tank structural and thermodynamic design methodologies [124–126]. These thermodynamic models allow to simulate the thermodynamic behaviour of the storage tanks throughout the entire mission. That means losses such as vented gaseous hydrogen to stay below the maximum pressure of 2.5 bar due to the heat input through the tank walls are considered. It is assumed that hydrogen is supplied in its liquid state to the propulsion units where it is pressurized via high pressure pumps and evaporated via heat exchangers in the turbofan core exhaust. To avoid evaporation inside the delivery lines, a slight pressure increase via low pressure pumps nearby the storage tanks has to be realized to ensure a subcooled liquid. However, this fuel system is not designed in detail due to the conceptual design characteristic of this study. The mass of the whole fuel systems and delivery lines are included and estimated by correlations from Brewer [37].

Characteristic mid. cruise parameters as well as total LH2 tank volumes and gravimetric indexes are listed in Table B1. The gravimetric index is defined as LH2 mass divided by total tank structural and maximum LH2 mass, including the fuel delivery and subsystems mass.

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