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Aviation fuels of the future – A techno-economic assessment of distribution, fueling and utilizing electricity-based LH2, LCH4 and kerosene (SAF)

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A B S T R A C T

This paper investigates the techno-economic implications on air travel when fossil-based kerosene is phased out of the market, specifically focusing on the comparison between liquid hydrogen, liquid methane and renewable kerosene for ten exemplary flight routes to estimate the cost of air travel per passenger and 100 km distance travelled $\left(\frac{€_{2020}}{PAX100km}\right)$ for every fuel type. By considering the entire supply chain, including hydrogen production from renewable sources, synthesis, oversea transport, domestic distribution, and utilization, this study addresses the overarching question of whether it is more economical to change the fuel source or the fuel itself to reduce fossil kerosene usage in the aviation industry. It is demonstrated that aircraft acquisition costs play a minor role compared to fuel supply costs and specific fuel demand. The study shows that for electricity-based fuels, liquid hydrogen is the most economic option, even with a potential energy penalty, followed by liquid methane and renewable kerosene. The results for an aircraft with a capacity 180 passengers are 3.08, 4.57 and 5.11 $\frac{€}{PAX100km}$ for liquid hydrogen, liquid methane and renewable kerosene, respectively. Challenges regarding storage and isolation requirements for cryogenic fuels in aviation are discussed, with assumptions made that these obstacles can be overcome to realize economic benefits. Additionally, the study suggests potential shifts in aircraft size selection by airlines to mitigate rising fuel prices in the future. The study advocates for the aviation industry's openness to new fuels like liquid hydrogen and liquid methane to alleviate the cost increase associated with phasing out fossil kerosene.

Introduction

Different groups from the aviation industry, like the "International Civil Aviation Organization" (ICAO) or the "Air Transport Action Group" (ATAG), announced their CO_2 emission reduction targets in the past [1,2]. Exemplary goals are the "50 % emissions reduction", referring to 2005 levels or the net-zero target as the ultimate target. To depict the implications of these targets, the CO_2 emissions of the aviation industry from the last 20 years as well as predicted emissions according to the corresponding target/actions are shown in Fig. 1 [2]. The main contribution to reduce CO_2 emissions is expected to come from the reduced consumption of fossil fuels, which leads to the question: What are the alternatives?

Fuel alternatives for the aviation industry

Currently the commercial aviation industry relies primarily on kerosene (ignoring the differences between Jet A and Jet A-1), a mixture of hydrocarbons with a carbon number between 8 and 16 [3]. It is mainly derived from crude oil via distillation and to a lesser extent from biomass–based processes as specified by ASTM–5766. The substitution of fossil kerosene with renewable kerosene (SAF for sustainable aviation fuel) is an approach to decarbonize the aviation industry where only the fuel source is changed, leaving all other aspects more or less untouched. Numerous studies have evaluated the synthesis of SAF via biomass-based processes, electricity-based processes or a combination of both [4–6]. A holistic evaluation has been conducted by Su–ungkavatin et al. [7]. In their study they also evaluate current regulatory frameworks like the EU initiative "ReFuelEU Aviation" [8]. This regulation requires a minimum SAF share of 2 % for the flights departing in the EU from 2025 onwards. The share will increase to 6 % in 2030 and to eventually to 70 % in 2050. Currently, the SAF share for an individual flight is limited to 50 % [9], although higher values are aspired and even required to reach the 70 % goal by 2050. A share of 100 % SAF has already been demonstrated [10].

The introduction of liquid hydrogen (LH_2) as an aviation fuel is a more drastic approach to decarbonize the aviation industry. It will affect

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Nomenclature

Abbreviations

BWB	Blended-wing body
CAPEX	Capital expenditures
EU	European Union
FC	Flight cycles
FH	Flight hours
FMS	Flight movement scenario
FT	Fischer Tropsch
FUS	Fuel utilization scenario
IATA	International Air Transport Association
ICCT	International Council on Clean Transportation
iLUC	Indirect land use change
IGU	International Gas Union
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LCH_4	Liquid methane
LF	Load factor
LH_2	Liquid hydrogen
LHV	Lower heating value
LNG	Liquefied natural gas
LOV	Limit of validity
MFR	Manufacturing
OPEX	Operating expenditures
PAX	Passenger
PtX	Power to X
RE	Renewable energy
R&D	Research and development
SAF	Sustainable aviation fuel (considers renewable fuel with Jet A-1 specifications)
SI	Supplementary information
TBW	Truss-braced wing
TFU	Theoretical first unit
tpa	tons per annum

Subscripts (together with an exemplary unit)

MWh_{LHV}	Used to indicate which heating value is used
$€_{xy}$/ $\$_{xy}$	"xy" is referring to the purchase power of the currency in the given year
FC_{Calc}	"Calculated", refers to the value that is ultimately used
$CAPEX_{Flight}$	Refers to the expenditures per flight

Latin symbols

d	Distance of the pipeline network in km
$\dot{M}$	Mass flow in t/h

Airport IATA codes

MUC	Munich
FRA	Frankfurt
CDG	Paris
MAD	Madrid
IST	Istanbul
KEF	Keflavík (close to Reykjavík)
CAI	Cairo
IKA	Teheran
DOH	Doha
JFK	New York
BKK	Bangkok

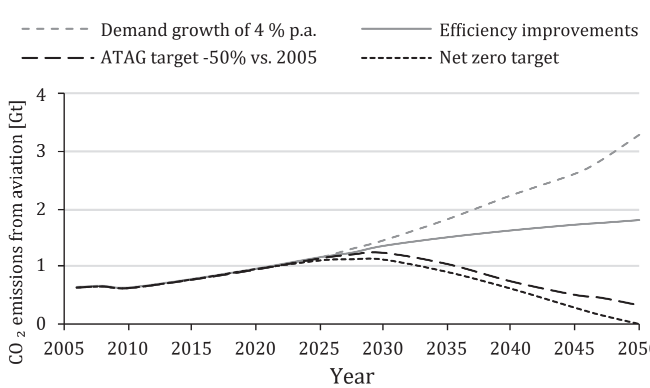

Fig. 1. Projected net CO_2 emissions from the aviation industry (neglecting the COVID 19 effects) (2).

every stakeholder group in the commercial aviation industry and in the current chain ranging from the fuel source to its utilization. Aircraft manufactures will have to design different aircraft, that might even be powered with fuel cells instead of turbines. Airports will have to invest in new fuel tanks and distribution infrastructure and the fuel supply to the airports has to change as well. First studies that evaluated the implications of introducing LH_2 as aviation fuel date back to the 1970 s [11]. A study published by Korycinski in 1978 evaluated the LH_2 demand at the airports of Chicago and San Francisco for a reference year between 1990 and 1995 [12]. Their study considered the daily LH_2 demand, required changes in airport infrastructure and a brief description of two conceptual 400 passenger (PAX) aircraft using LH_2. More recently, Hoelzen et al. evaluated the fuel supply system for different airports in Germany and concluded that depending on the demand a supply via a pipeline system or a truck system is the more economical option [13]. A detailed analysis of the turnaround and refuelling procedure at the airport is performed by Mangold et al. [14]. They outline the safety aspects and the need for tight connections between the aircraft and the refuelling systems. More detailed studies on aircraft design have been carried out by Airbus in the early 2000 s in the "Cryoplane" project and with the ZEROe program launched in 2020 [15–17]. Several smaller companies are working on the development of aircraft utilizing LH_2, such as "ZeroAvia", "H2Fly" and "Deutsche Aircraft". As LH_2 will need to be available at all the airports where these aircraft will operate, an overarching strategy is needed to avoid a chicken-and-egg problem.

The introduction of liquefied natural gas (LNG) as an aviation fuel was also explored by NASA in the 1970 s and recently proposed in a "Think paper" by EUROCONTROL [18,19]. A more recent program by NASA and Boeing evaluated different LNG–fuelled aircraft concepts that could enter the market in the 2040 s [20]. LCH_4, as the main component of LNG, has the advantage that LNG is already a globally available commodity. In addition, the synthesis of methane from biomass and electricity is less complex than the synthesis of SAF. Like hydrogen, it also has to be liquefied and would be a cryogenic fuel, requiring tremendous changes to the airport infrastructure. It is therefore not surprising that there has been no change in the fuel diversity, given the huge investments required. Simply because there has been no demand for change in the commercial aviation industry so far. This may change in the future if the economic or other incentives are high enough.

1.2. Research objective.

The three fuels considered in this study are LH_2, LCH_4 and SAF. Only the production pathway via the electricity based "Power-to-X" pathway is considered. While fuels based on biogenic components are a suitable option, their production capacity is limited. The "International Council on Clean Transportation" (ICCT) published a working-paper in 2021 assessing the production potential of SAF based on waste fats, used cooking oils, cover crops, agricultural and forestry residues [21]. They concluded, that in the year 2030 only 5.5 % of EU–wide SAF demand could be produced from these feedstocks within the EU. The "Intergovernmental Panel on Climate Change" (IPCC) is more conservative and in its latest report provides a value of only 2 % [22]. Furthermore, biofuel feedstocks with "high indirect land use change (high iLUC)" biofuel feedstocks are expected to be phased out by 2030 [23]. This will affect the availability of palm oil as a feedstock, as it has been considered by Pipitone et al. [24].

The aim of this study is to provide a techno-economic analysis of how the cost of air travel will be affected by a full transition to electricity-based fuels and how the costs will differ whether LH_2, LCH_4 or SAF are used for specific flight routes. While the abbreviation SAF stands for "sustainable aviation fuel" which can be produced in many ways, in this study, it is used for a substance with the same properties as kerosene that is produced via the Fischer-Tropsch synthesis and CO_2 that has been retrieved from ambient air. For the analysis, it is required to consider the whole chain from the renewable electricity supply up to fuel utilization. This is necessary in order to conduct a subsequent comparison based on the same input variables. The chain is illustrated in Fig. 2. Morocco is considered as exemplary fuel-exporting country with Germany as importing country. In a previous study, the first part of the chain, i.e. the methodological approach regarding electricity generation and hydrogen production based on local weather conditions was presented [25] (indicated as "RE generation and H_2 production" in Fig. 2). Another study evaluated, the steps considering the fuel synthesis and overseas transport to Germany [26]. In this study, the focus is on the remaining steps to evaluate the final cost for air travel which are expressed in costs per passenger (PAX) and per 100 km of flight distance i.e., $\frac{€}{PAX100km}$. This is achieved by including the fuel utilization into the evaluation, otherwise the comparison can only be conducted based on costs per energy supplied for every fuel type i.e., $\frac{€}{MWH_{LHV}}$. To date, no study has conducted this direct comparison of electricity-based LH_2, LCH_4 or SAF. In particular, LCH_4 has either not been considered, as by the IPCC [22] or has been excluded from the list of potential aviation fuels, as by Dray et al. [27]. Although the utilization of LH_2 and LCH_4 has been demonstrated in the past, both fuels are far from being ready to use in the aviation industry. Therefore, a fair and transparent assessment could help the stakeholders involved to implement and to support the most preferential route to phase out fossil fuels from the aviation industry. This is done in this study from a techno-economic perspective, the actual reduction of CO_2 emissions cannot be quantified with this study as since no life cycle assessment is conducted.

Methodology

In this study, a comparative techno-economic assessment is conducted for the aviation fuels LH_2, LCH_4 and SAF, evaluating the steps of domestic distribution, fuel storage at the airport, fuelling and fuel utilization. In Germany, fuel is transported from Wilhelmshaven to the airports of Frankfurt and Munich. The costs are 157 €/MWh for LH_2, 220 €/MWh for LCH_4 and 279 €/MWh for SAF at the interface "importing harbour – domestic distribution" [26]. Different methodologies are applied to consider the respective steps and are described in this chapter. The most relevant input data is provided in chapter 3, remaining input is given in the section S.1 of the supplementary information (SI). The aim is to determine the technical and economic aspects under the assumption that the airports are supplied exclusively via the fuel supply chain depicted in Fig. 2. Perspective data is considered for the unit operations and costs are given in $€_{2020}$, as in Raab and Dietrich [26]. Aspects that are independent of the fuel type such as taxes, fees etc., are neglected. The evaluation is divided into two parts.

1. Determination of minimum fuel supply costs

Several scenarios are considered to evaluate how the annual fuel demand influences the costs for domestic distribution, fuel storage at the airport and fuelling. They are listed in Table 1. Based on these scenarios, the required changes at the airport infrastructure are estimated. Up to this point of the fuel chain a comparison of the different fuels is feasible in $\frac{€}{MW_{LHV}}$, as indicated in Fig. 2. The results of this first part are presented in section 4.1.

2. Estimating the specific costs for flying

The costs for air travel are determined in $\frac{€}{PAX\ 100\ km}$ by including the depreciation costs for different future aircraft types and the fuel demand for 10 exemplary flight routes. The flight routes are listed in Table 3. The results of this second part are presented in section 4.2. A detailed breakdown for an exemplary route and aircraft size is given in the SI. In

Table 1
Evaluated fuel utilization scenarios (FUS) to determine the minimum fuel supply costs.

Aircraft type PAX capacity	#1	#2	#3	#4	#5	#6
Commuter & Regional 0–100	SAF	LH_2	LH_2	LH_2	LH_2	LCH_4
Small 101–210	SAF	LH_2	LCH_4	LH_2	LH_2	LCH_4
Medium 211—300	SAF	SAF	LCH_4	LCH_4	LH_2	LCH_4
Large > 300	SAF	SAF	SAF	LCH_4	LH_2	LCH_4

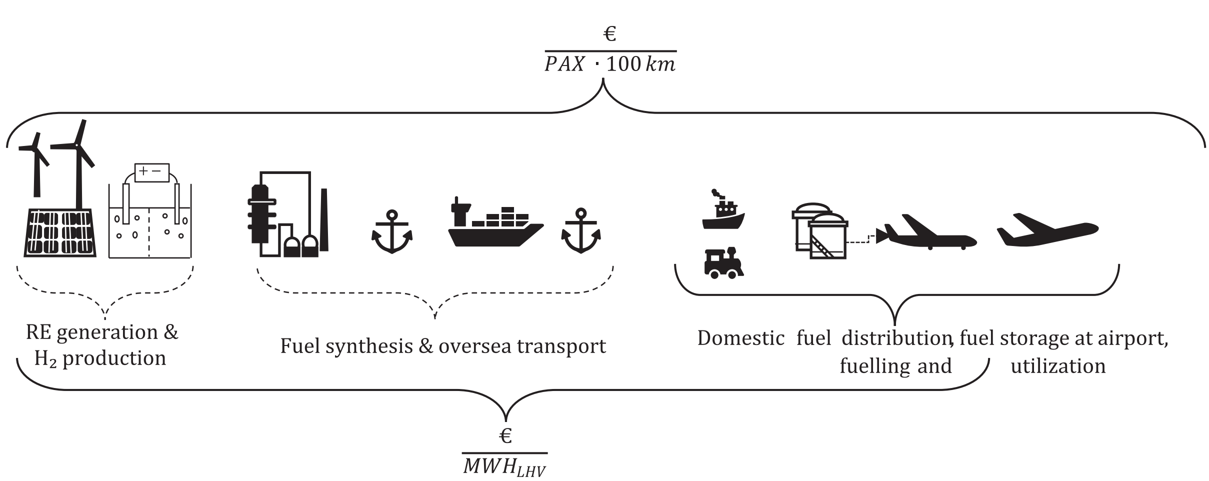

Fig. 2. Overall system boundaries of the renewable aviation fuel chain considered. Focus of this study is from domestic fuel distribution until utilization.

addition, the effect of the SAF supply costs on current ticket prices is estimated using real data from the 10 exemplary flight routes. These results are provided in section 4.3.

Determination of fuel supply costs

The fuel supply costs are evaluated by the methodology shown in Fig. 3. It is based on a flight movement scenario (FMS) for the year 2050 for two exemplary airports, Munich (MUC) and Frankfurt (FRA).

The development of the FMS is not part of this study but a relevant input dataset. Therefore, details of the FMS development are described in section 2.1.1. The FMS is a dataset containing all the flight movements from a given year. It includes the number of departures, the destination airport for each flight as well as the aircraft seat capacity and only considers kerosene as aviation fuel. This dataset is used to evaluate individual fuel utilization scenarios (FUS). There, each flight is assigned a specific fuel (LH_2, LCH_4 or SAF). For each evaluated FUS, the aspects of "Domestic fuel distribution, fuel storage at airport and fuelling" are re-evaluated. Inland waterway transport is considered for Frankfurt and railway transport for Munich. Specific input data is taken from literature and described in section 3.1. The investments required for domestic transport is depreciated over 20 years using an interest rate (WACC) of 5 %. The operating costs consider the required labour, energy costs and indirect costs for insurance, overhead factors etc. It is assumed, that the fuel for the flights is imported exclusively via the supply chain depicted in Fig. 2. The results include the total annual fuel demand, the required airport infrastructure for storage and fuelling and, if economically viable, reliquefication facilities at the airport.

Flight movement scenario

Flight movement scenarios are modelled using a multi-stage approach.

1. The first step is an econometric forecasting model of future air transport demand, focusing on passengers and flight movements. This approach uses various external forecasts on the development of the economy e.g., per capita income, population and fuel prices. Historical relationships between air transport development and the above external factors can be described by demand elasticities (e.g., price and income elasticities), which are estimated on a long time series over two decades to calibrate the air transport demand model. The methodological approach is described in detail by Gelhausen et al. [28]. Passenger demand estimates are combined with a seat load factor forecast in order to account for improvements in the efficiency of the air transport system and to forecast the number of seats offered. The output of this first stage of the forecasting model is the number of seats and the number of flight movements on each airport pair globally, in five–year increments up to 2050.
2. In a second modelling step, specific aircraft types are assigned to each airport pair. The starting point for this model is the base year aircraft fleet (as provided by the commercial database Cirium Fleets Analyzer [29]) and its allocation to airport pairs (as provided by the global flight schedules database OAG [30]). For each five-year period, aircraft retirements are calculated using ICAO's retirement model, based on a logistic regression for each aircraft category (turboprops and regional, narrowbody and widebody jets), as shown by Schaefer [31]. New aircraft to replace retired aircraft and to accommodate growth are drawn from a pool of aircraft representing the state-of-the-art in each forecast period. This approach allows for an accurate modelling of the market diffusion of more fuel-efficient aircraft and the fleet rollover over time. It also allows the modelling of different technological scenarios, such as the system-wide effects of the introduction of aircraft with varying propulsion technologies.
3. In a third step, the energy consumption is calculated for each combination of aircraft type and airport pair. This step uses the commercial flight performance software Piano-X, which models the fuel consumption of more than 100 civil aircraft types based on various sources like flight data recorders. For future aircraft types, assumptions have been made about efficiency improvements, based on technology roadmaps and studies such as Flightpath 2050 [32].

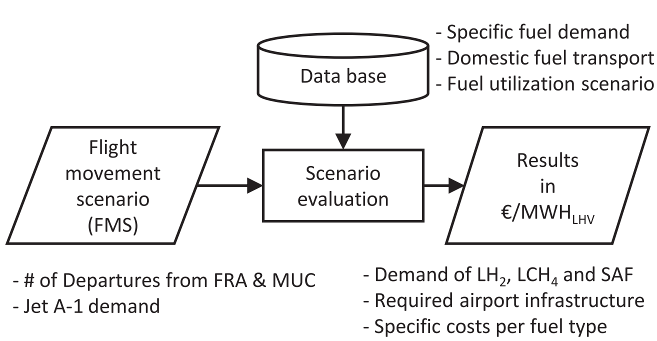

Fig. 3. Applied methodology to determine the fuel supply costs.

The output of the model is a dataset that includes the energy demand for each airport, the number of passengers departing from an airport, the number of flights etc. An exemplary visualization of the dataset is shown in Fig. 4 for Frankfurt for the year 2050.

Fuel demand evaluation

The FMS determines the fuel demand and therefore the chemical energy demand for a given year for a 100 % SAF scenario. In order to assess how the fuel demand changes with the introduction of LH_2 or LCH_4, two aspects are considered:

- The share of LH_2, LCH_4 and SAF for a given aircraft size and distance flown
- The different specific energy demand when cryogenic fuels are used instead of SAF

It is not possible to predict which aircraft types will be developed by the year 2050 and how these aircraft will be propelled. Therefore, for the first aspect different FUS have to be evaluated, assuming the appropriate fuel type for a given aircraft size and flight distance. The resolution of these scenarios is similar to the input shown in Fig. 4, except that the commuter and regional sized aircraft are summarized in one category. Therefore, for 11 different flight distance groups and 4 different aircraft categories the share of LH_2, LCH_4 and SAF has to be assumed for each FUS. Dual-fuel capable aircraft as proposed by Withers et al. [33] are not included in this study. Furthermore, as airlines are likely to prefer the flexibility in how an aircraft can be used, the fuel type will not change within a given category. Therefore, six scenarios are considered where the fuel type depends only on the aircraft type. The FUS evaluated are shown in Table 1.

Scenario #1 is the "no change" scenario used as a baseline. Scenario #2 introduces LH_2 for smaller aircraft. Given current research developments, this scenario could eventuate in the near future. Scenario #3 introduces LCH_4 as a second cryogenic aviation fuel. This scenario could eventuate if the energy storage density of LH_2 proves to be too great a hurdle. Scenario #4 is an all-cryogenic scenario, where SAF has been completely ousted from the market and smaller aircraft use LH_2 and larger ones LCH_4. Scenarios #5 and #6 are academic scenarios to show the effects of an all hydrogen and all methane aviation industry, respectively.

The second aspect is the change in specific energy demand when cryogenic fuels are used. For aircraft using LH_2, a distinction can be made between hydrogen used in fuel cells or turbines. For LCH_4, only combustion processes are considered. In literature, the change in specific energy demand is only available for a certain number of aircraft

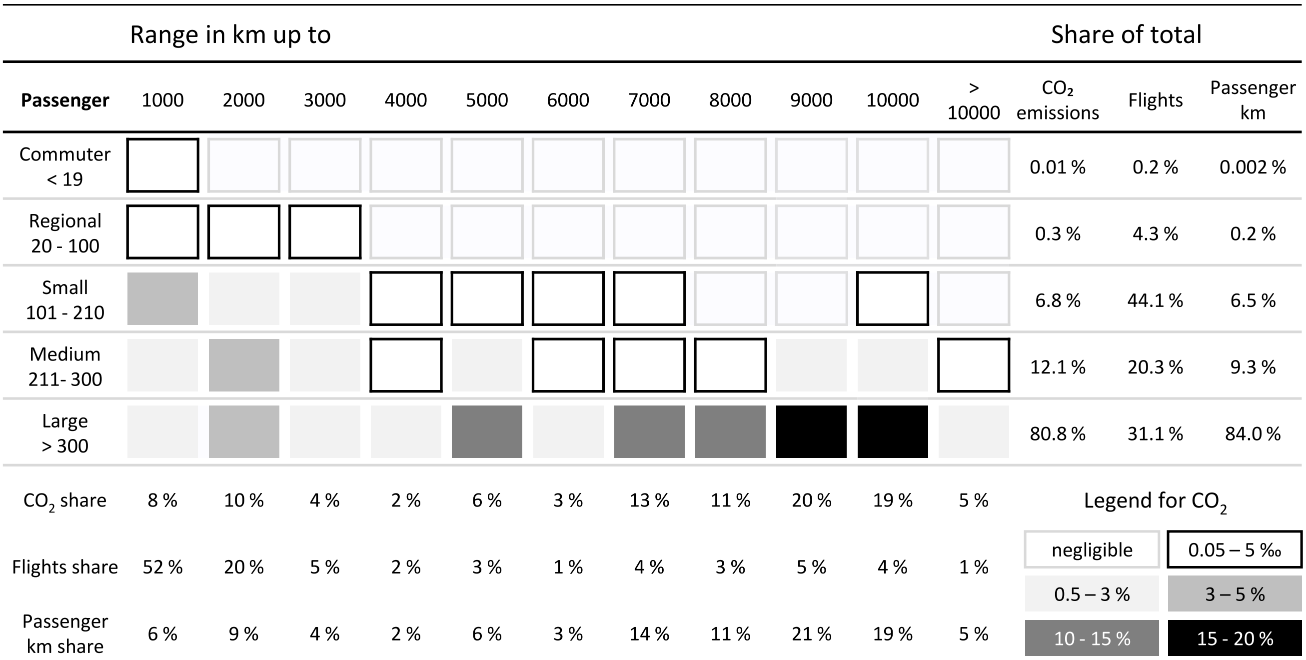

Fig. 4. Visualisation of the flight movement scenario of FRA, forecast year 2050.

types. The range and propulsion type are also given. Table 2 lists an excerpt of the currently available data.

Unfortunately, this data is not sufficient to give a value for every combination of aircraft type, flight range and fuel considered in this study. Furthermore, there is a great difference between the values given for large LH_2 powered aircraft. This study considers the value of +9 %, the implications of +42 % are given in detail in section S.3 of the SI. In addition, assumptions and simplifications have to be made where data is not available. The values used in this study are listed in Table 12.

Determining the specific costs of flying

By applying the methodology described in section 2.1, the fuel demand and supply costs are estimated in €/MWh_{LHV}, i.e. from a "well-to-tank" perspective. The following aspects are considered to determine the costs resulting from utilization and thus, to evaluate the whole chain depicted in Fig. 2 and obtain the costs in $\frac{€}{\text{PAX } 100\text{ km}}$:

- Flight distance → total fuel consumption for a given flight ($OPEX_{Flight}$)
- Number of passengers on board for a given flight
- Share of depreciation costs per flight ($CAPEX_{Flight}$)

Table 2
Literature data how the specific energy demand changes compared to SAF/Jet A-1 aircraft when cryogenic fuels are utilized.

Fuel	Capacity (PAX)	Range (km)	Propulsion	Change in specific energy demand	Source
LH_2	80	1,000	Fuel cell	− 8 %	[2]
LH_2	165	2,000	Fuel cell/ turbines	− 4 %	[2]
LH_2	250	7,000	Turbines	+ 22 %	[2]
LH_2	325	10,000	Turbines	+ 42 %	[2]
LH_2	401	11,800	Turbines	+ 9 %	[34]
LCH_4	154	≈ 6,500	Turbine	+ 5.6 %	[35]
LCH_4	≈ 189*	3,700	Turbine	+ 10 %	[36]

* Exact number not given – Boeing 737–800 is considered with 189 PAX maximum.

Ten sample routes departing from FRA are selected to determine the different flight costs. The routes are listed in Table 3, with the corresponding IATA airport codes as destinations. The distances are obtained by using an online calculator, which is also used to determine the CO_2 emissions of the corresponding flights [37] (details are given in section 3.4).

$OPEX_{Flight}$ is determined by the fuel supply costs, the change in specific energy demand given in Table 12 and the kerosene demand from the FMS. The seat capacity of each aircraft type is given in section 3.3, for every flight a load factor (LF) of 80 % is considered. Labor costs for the aircraft crew are neglected, since they will not depend on the fuel type.

The share of the depreciation costs per flight is determined by the acquisition cost and the lifetime of the aircraft. The methodology to estimate the acquisition cost is described in section 2.3. The lifetime of an aircraft is determined by the number of flight cycles (FC) or the total flight hours (FH). In aviation this is known as the limit of validity (LOV). An aircraft can be used after its LOV has been exceeded. However, this is generally not economically viable. In general, smaller aircraft that are used on shorter routes have several FC a day and can reach the FC limit first. Large widebody aircraft flying intercontinental routes are more likely to be limited by the FH rather than the FC. For this study, a certain number of FC is assumed for each aircraft and thus, $CAPEX_{Flight}$ is estimated by dividing the costs of the aircraft by the number of assumed flight cycles FC_{calc}. Exemplary values for FC and FH are given in the SI. The values used in this study are given in Table 12.

Estimating future aircraft costs

This study estimates future aircraft acquisition costs for three different aircraft sizes (see Fig. 4). A regional aircraft with a capacity of 100 PAX, a small aircraft with a capacity of 180 PAX and a large aircraft with a capacity of 425 PAX. For each aircraft size, a conventional tube-and wing design is considered. Other forms are evaluated as sensitivities, these are a blended-wing body (BWB) and a truss-braced wing (TBW). The results for these sensitivities are given in the SI in section S.3. The methodology for estimating the costs of future aircraft requires two models, namely the "modified Raymer-Dapca IV model" [38] and the "Markish model" [39]. How these models are used and what input

Table 3
Exemplary flights and their distances from Frankfurt.

ID	1	2	3	4	5	6	7	8	9	10
Destination	MUC	CDG	MAD	IST	KEF	CAI	IKA	DOH	JFK	BKK
Distance [km]	300	447	1,419	1,863	2,399	2,921	3,774	4,632	6,184	8,995

parameters are required is depicted in Fig. 5.

The baseline research and development (R&D) costs and the costs for the theoretical first unit (TFU) are determined using the Raymer-Dapca IV model. The calibration factors for the Raymer-Dapca IV model are determined by matching published R&D costs (see Table S.4) with the default model empty mass, cruise speed, NASA inflation factor and composite percentage of the Airbus A220-300 for the 100 and 180 PAX aircraft and the A350–900 for the 425 PAX aircraft. The model is then calibrated. Baseline costs for the 100, 180 and 425 PAX tube-and-wing aircraft are estimated by using the empty masses and cruise speeds from the Embraer E-190, Boeing 737–800 Max and Boeing 777–9, respectively (see Table S.5). Manufacturer bias in the model is minimized by using aircraft from Airbus to determine the calibration factor and aircraft from Embraer and Boeing for the baseline empty masses and cruise speeds.

The Markish model is used to estimate the changes in R&D and production costs due to modifications of the aircraft form factor (e.g., from a tube and wing design to a BWB) and due to modifications resulting from the utilization of LH_2 or LCH_4. This is achieved by estimating complexity factors for each subsystem and then adjusting the manufacturing margin of the new R&D costs to the baseline R&D costs. In the Markish model, “subsystem complexity factors” are metrics that indicate how much more effort it would cost to develop and produce a subsystem compared to the original system. Simplified changes in the complexity factors are assumed for each subsystem, as they are not considered to be determined at this stage. The values are given in section 3.3 in Table 10 and Table 11.

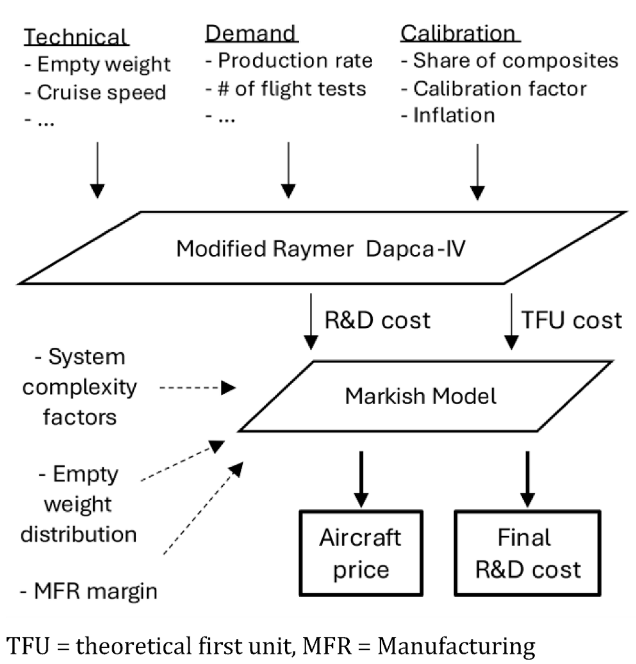

Fig. 5. Methodological approach to determine future aircraft costs TFU = theoretical first unit, MFR = Manufacturing.

Input data

Domestic distribution

Railway transport and inland waterway transport is considered for domestic distribution. The distance from Wilhelmshaven to MUC via railway transport is 840 km. The distance to FRA by waterway is 653 km. All distances are determined using an online tool [40].

Rail transport

The costs of transporting fuel by rail are based on a report by Panteia [41]. In that study, the costs are given on different specific bases e.g., € per km, € per hour or € per tonne-km. For this study “costs per km” is used. The values are listed in Table 4. “Fixed costs” result from leasing the locomotives and wagons. As different wagons are used for different types of fuel, it is not possible to give a single value. Instead, the costs are based on individual wagons which are depreciated over 20 years. The “General operating costs” are a 15 % surcharge on the remaining costs.

Rail transport of Jet A-1 and LNG is state of the art with volumetric capacities per railway car of 85 m^3 and 110 m^3 for Jet A-1 and LNG, respectively [42,43]. While the transport of LH_2 by rail dates back to the1960s [44], due to the lack of LH_2 demand the technology is not yet as commercialized. To determine the “fixed costs” for different fuel types i.e., the depreciation costs for the wagons, the investment for the rail undercarriage and the actual tanks are considered. Other railcar costs such as installation, delivery etc. are neglected. Costs for the undercarriage and the LH_2 tank are taken from Amos [45]. The costs of the undercarriage are $\$_{1995}$ 100,000, which translates to 137,000 €$_{2020}$. The costs of the LH_2 tank are $\$_{1995}$ 400,000. Costs for the Jet A-1 tank are based on a truck trailer tank system. Here, the cost of transporting liquid hydrocarbons is in the range of 100,000 – 150,000 € [46,47]. Assuming that the tank is one third of the cost of a truck trailer tank system and a scaling factor of 0.67, the costs for the Jet A-1 tank amount to 75,000 €$_{2020}$. Thus, the costs for the Jet A-1 rail car are 225,000 €$_{2020}$. The costs for a small scale LNG tank are taken from Mariani and Lebrato [48]. They reported costs for LNG tanks with a capacity from 20 – 60 m^3 in the range of 95,000 – 135,500 €$_{2016}$. Based on their data, the cost of a 126 m^3 tank is estimated to be around 171,000 €$_{2020}$. The input data for each rail tank car are listed in Table 5 where the total volumetric capacity is given. For cryogenic tanks a usable capacity of 4 – 98 % of the total capacity is assumed, while SAF can use 0–98 % of the total capacity. The number of cars per train is determined by a maximum length of all wagons of 600 m due to the handling at the airport or by the total maximum weight of 2,200 t [49]. Boil-off that occurs during transport is flared. The values for boil-off are given in the SI.

Inland waterway transport

Fuel transport costs via inland waterways are based on a report from Panteia [41]. As for rail transport, costs are retrieved in “costs per km”.

Table 4
Literature cost data for railway transport.

Cost component	Liquid bulk | €/km (41)
Fixed costs	6.29
Variable (energy) costs	4.56
Staff costs	1.49
Mode-specific costs (track access and shunting)	3.59
General operating costs	2.39

Table 5
Technical and economic data for fuel transport via railway vehicles.

Fuel	Capacity [t]	Capacity [m^3]	Railway cars per train	Cost per railway car [$€_{2020}$]
LH_2	9.07	128	24	686,150
LCH_4	49.91	111	24	308,000
Jet A-1	70.4	88	22	225,000

The values are listed in Table 6 "Fixed costs" are depreciations, insurance and partly maintenance. Variable costs are fuel costs and other maintenance costs. General operating costs result from permits and other operating costs like administration, IT, communications etc. As for the railway transport, it is not possible to give a single value due to the different fuel types. Instead, the costs are based on individual ships which are depreciated over 20 years.

The transport of Jet A–1 by inland waterways is state of the art and is one of the fuel sources for Frankfurt Airport [50]. Vessels of up to 110 m in length deliver fuel to the airport with fuel via the port of Raunheim [51]. The reference vessel for the transport of Jet A-1 is the "Eline" (IMO: 9652727), with a length of 110 m and a volumetric capacity of 3,019 m^3 [52]. Since 2013, LNG has been transported on the Rhine by the vessel "Greenstream" (IMO: 9664990) [53]. It has the same external dimensions as the "Eline" and a volumetric capacity of 3,130 m^3. For LH_2, there is no direct reference inland vessel. Although the first LH_2 carrier, the "Suiso Frontier" was launched in 2019 [54], the shape of the ship is not suitable for inland waterways up to the port of Raunheim. The "Greenstream" is therefore used as a reference. The volumetric capacity is reduced by 5 % due to the higher insulation requirements. As for the railway cars, a usable capacity of 4 – 98 % of the total capacity is assumed for cryogenic vessels, while 0–98 % of the total capacity can be used for SAF. The costs for the Jet A-1 ship is taken from Hekkenberg, where the costs are divided into the costs for the hull, propulsion, other equipment and navigation [55]. A rough estimate of the costs for large LNG vessels is given in the IGU report [56]. It gives specific costs in the order of \$ 1200/m^3. As these values are for large-scale vessels, the value for the inland waterway ship will be higher, i.e. the lower benchmark is \$ 3.76 million. With the cost structure given in Hekkenberg the costs for a LCH_4 carrier are estimated at 5 million €. The costs for the LH_2 vessel are assumed to be 2 million € higher due to stricter safety regulations and higher insulation requirements that occur when using LH_2 instead of LCH_4. The values are summarized in Table 7. Boil-off that occurs during transport is flared. The values for boil-off are given in the SI.

Airport infrastructure

The introduction of cryogenic fuels in aviation will require significant investments in airport infrastructure. Fig. 6 shows the components required, with a reliquefication plant as an example of a boil-off management unit. However, depending on the of boil-off amount, other utilization approaches like burning, supplying fuel cells for electricity production etc. could be pursued.

A holistic evaluation of the changes in the airport infrastructure when LH_2 is introduced as aviation fuel has been published by Hoelzen et al. [13]. Their study shows, how the departures per month vary over the course of the year compared to the annual average. The range is

Table 6
Literature cost data for waterway transport with large ships.

Cost component	Liquid bulk | €/km (41)
Fixed costs	9.90
Variable costs (energy + maintenance)	3.51
Staff costs	8.80
Mode-specific costs (port fees)	0.43
General operating costs	0.40

Table 7
Technical and economic data for fuel transport via inland waterway vessels.

Fuel	Capacity [t]	Capacity [m^3]	Cost per ship [Mio. €]	Source
LH_2	210.6	2,974	7.0	Assumption
LCH_4	1,407.4	3,130	5.0	Based on [55,56]
Jet A-1	2,415.2	3,019	3.79	[55]

from + 10 % in the summer to −15 % in February. This range is relevant for assessing the storage capacity required at the airport. The current Jet A–1 storage capacity at Munich airport amounts to 44,000 m^3 (4 x 4,500 m^3 + 12,000 m^3 + 14,000 m^3) [57]. In 2019, the total demand for Jet A–1 was in the order of 2.2 billion litres [58]. The storage capacity is therefore able to supply the airport with Jet A-1 for approximately one week at peak demand. This timeframe of storage capacity is considered for each fuel type according to the fuel utilization scenarios evaluated. The equipment costs for the kerosene storage tank are taken from Woods [59]. To obtain the final costs of the installed tank so called "Lang-factors" are used, as described in a previous study [25]. The final costs of kerosene storage amount to 250 €/m^3. The costs for large-scale LNG storage vessels are given in a report by Baker [60]. Converting the costs to $€_{2020}$ result in specific costs of 2,660 €/m^3 for a fully installed LCH_4 storage tank with a capacity of 29,000 m^3. Using data from Hoelzen et al., specific costs for LH_2 storage are in the order of 2,025–2,422 €/m^3 for tanks in the size of 280–7,800 m^3. Since it is unlikely that LH_2 storage is cheaper than LCH_4 storage, specific LH_2 storage costs of 3,000 €/m^3 are assumed. Costs for cryopumps are taken from Hoelzen et al., the costs for kerosene pumps are taken from Peters et al. [61]. The LH_2 fuelling system was also evaluated by Hoelzen et al. They concluded that an underground fuelling system with hydrants could save 0.01 $\$_{2020}/kg_{LH_2}$ compared to a fuelling system with trucks, if the demand of the airport exceeds 125 kt $_{LH_2}$/a. As they further stated that the choice of design may not only be based on economics but also on safety issues, an underground fuelling system will be considered in this study. The techno-economic input data for an underground LH_2 fuelling system are taken from Hoelzen et al. The same input data for LH_2 is also considered for LCH_4. The techno-economic input data for an underground SAF fuelling system is taken from Hromádka and Cíger [62]. The current lengths of these underground pipeline systems are 17 and 60 km in Munich and Frankfurt, respectively [63,64]. To reduce the costs, it is assumed that the pipeline system is optimized and a total length of 15 km is assumed for Munich and 50 km for Frankfurt. This is a more conservative estimate than the 3 km considered by Hoelzen et al. If an underground fuelling system is used, so called "dispenser trucks" are required to fuel the aircraft. They act as a final filter system and are the interface between the hydrant of the pipeline and the aircraft. Average costs are 204,000 $€_{2013}$ for a Jet A–1 dispenser truck according to Hromádka and Cíger. In comparison, Hoelzen et al. quoted $\$_{2020}$ 90,000 for a LH_2 dispenser truck. It is unlikely, that the trucks for LH_2 will be cheaper than the trucks for (renewable) Jet A-1. As the costs in Hromádka and Cíger were obtained through a data collection questionnaire, their costs are considered. Therefore, costs for cryogenic dispenser trucks are assumed to be around 400,000 €. Back-up fuel trucks, as mentioned in Hromádka and Cíger, are neglected. The number of required dispenser trucks is determined with the number of flights, i.e. by the FMS. It is assumed that fuelling takes 10, 20, 30 or 40 min depending on the aircraft size. The time increases with the aircraft capacity, which is given in Table 12. Dispenser trucks have a utilization rate of 60 % during the considered 18 h of operation per day. A liquefaction unit is considered if reliquefication is more economical than flaring. The costs for the hydrogen liquefaction unit are taken from the "IdealHy" project, the cost curve is shown in a previous study [65,66]. For methane liquefaction a conservative estimate of 2000 \$/tpa (tons per annum) is considered, based on a study from Songhurst [67]. The input data are summarized in Table 8. Costs for hydrants are neglected

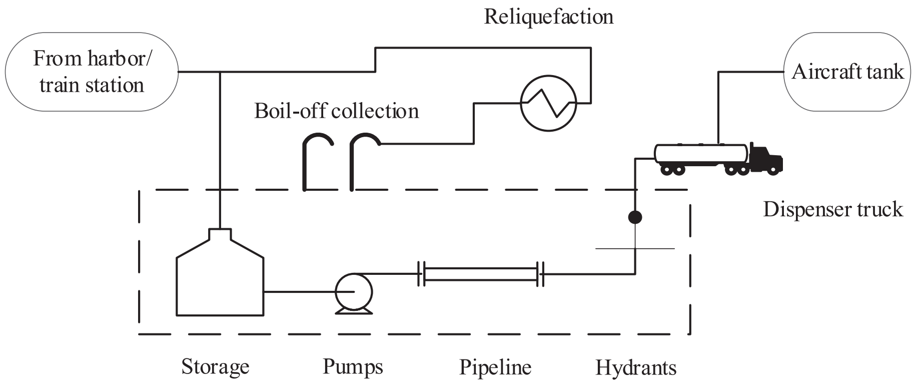

Fig. 6. Required airport infrastructure to provide cryogenic fuels to aircraft.

Table 8
Technical and economic input data for underground fuelling systems.

Fuel	Storage costs [€/m^3]	Pump costs [€/(kg/h)]	Pipeline costs in Mio $_{2020}$	Dispenser truck [€]
LH_2	3,000	256.3	$\frac{5}{72} \bullet \dot{M}_{H_2} \bullet 2 \bullet d$	400,000
LCH_4	2,660	42.9	$\frac{5}{429.8} \bullet \dot{M}_{CH_4} \bullet 2 \bullet d$	400,000
Jet A-1	250	0.66	$0.679 \bullet d$	250,000

since they are low compared to the remaining costs.

Future aircraft

As stated in section 2.3 three different designs are being considered for future aircraft, each with unique implications for R&D costs, aircraft production costs and fuel demand.

- The conventional tube-and-wing design uses a stretched fuselage of varying lengths to accommodate the cylindrical storage of the cryogenic fuels.
- The blended-wing-body (BWB) maintains a constant aerodynamic shape with common cylindrical fuel storage for all fuel types.
- The truss braced wing (TBW) also uses fuselages of different lengths but with a longer wingspan supported by a truss.

The TWB is assumed to fly slower than the BWB and tube-and-wing but maintains block time with a twin–aisle configuration to speed up de/-boarding. The ONERA TBW concept includes a twin–aisle configuration with an elongated aft fuselage to store hydrogen source. A DLR study found that between 5 and 8 min of block time can be covered with a twin-aisle configuration featuring 180 seats [68]. This study uses the NASA N + 4 TBW which has a conventional single–aisle configuration [35].

The input parameters used to determine the future aircraft costs are listed in the following section. First, the empty weight distributions of the corresponding aircraft types are listed in Table 9. The empty weight distributions are taken directly from the Markish model. The truss-brace-wing configuration is assumed to have the same empty weight distribution as the tube and wing configuration.

The increases in the complexity factors of the aircraft subsystem due to the different designs are shown in Table 10. By default, each subsystem is assigned a complexity factor of 1, representing no additional development or production effort compared to a conventional aircraft of the same subsystem empty weight. Each entry corresponds to all aircraft sizes unless there are multiple entries, these are assigned to the 100, 180 and 425 PAX sizes respectively. The simplifying assumptions used to estimate the complexity factors are as follows: A 66 % factor is applied to the BWB centre body system to accommodate internal structural pressurization in addition to the supporting wing structure. A 25 % increase is applied to the BWB “systems” to account for the increase in the number flight control surfaces relative to a tube-and-wing aircraft. A 26 % increase in the swing complexity factor for the TBW wing subsystem was added to reflect the average difference between the span and the wing area between the NASA N + 4 TBW and the Boeing 737 Max 8 [35].

Increases in aircraft subsystem complexity factors due to the different fuel types are listed in Table 11. Each entry corresponds to all aircraft sizes for all alternative fuel types. In cells with multiple entries, each entry corresponds to LCH_4 and LH_2, respectively. The complexity factors for the fuel types are multiplied by the complexity factors for the aircraft form when both are present for the same subsystem. Simplifying assumptions for the fuel type complexity factors are as follows: The 14.8 % and 29.6 % increases for the fuselage subsystem in the tube-and-wing and TBW designs correspond to the ratio of the baseline length to the increased length required to store cryogenic fuel in the cargo bay under the forward cabin and directly behind the aft pressure bulkhead. For the payload subsystem, the 25 % increase results due to the strengthening of the aft-bulkhead to meet crash resistance requirements to store cryogenic fuel behind the cabin. For the installed engine, a 25 % increase is estimated for changing the combustor to either LCH_4 or LH_2 while the other 3 major engine subsystems, the fan, compressor and turbine are assumed to remain unchanged. Lastly, a 10 % increase in systems factor is estimated to cover changes to the fuel system and flight computers to handle the different fuel types. The BWB retains a common aerodynamic shape and therefore requires only installed engine and systems energy complexity factors.

The final aircraft costs, the change in fuel demand as well as the limits of validity are listed in Table 12. The R&D costs for all aircraft and the aircraft production prices for the remaining aircraft designs are listed in the SI in section S.2. Furthermore, a sensitivity analysis is conducted where the change in specific fuel demand of cryogenic fuels is varied from −20 % to + 50 %. These results are given in the SI as well.

Table 9
Empty weight distribution in the corresponding aircraft types.

Aircraft Shape	Wing	Empennage	Landing Gear	Fuselage/Centre Body	Installed Engine	Systems	Payloads
Tube-and-wing/ TBW	23 %	3 %	8 %	23 %	18 %	10 %	15 %
BWB	18.2 %	4 %	10.3 %	24.9 %	14.5 %	8.6 %	13 %

Table 10
Increase in complexity factors & composite percentage and manufacturing margin in the Markish model.

Aircraft Shape	Composite percentage	Wing	Empennage	Fuselage/Centre Body	Installed Engine	Systems	Payloads	Manufacturing Margin
Tube and Wing	30 % 30 % 50 %*							5.7 %
BWB	50 %			66 %		25 %		11.4 %
TBW	30 %	26 %						6.9 %

* Values are valid in the given order for aircraft with 100, 180 and 425 seats.

Table 11
Energy complexity factor difference by aircraft type.

Aircraft Shape	Wing	Empennage	Fuselage/Centre Body	Installed Engine	Systems	Payload
Tube and Wing			29.6/14.8 % *	25 %	10 %	25 %
BWB				25 %	10 %	
TBW			29.6/14.8 % *	25 %	10 %	25 %

* Values are valid in the given order for LH_2 and LCH_4.

Table 12
Input data to determine costs for flying with LH_2, LCH_4 and SAF.

Plane type Capacity	Aircraft cost [Mio. €]			Change in fuel demand		LOV [FC_{calc}]
	SAF	LH_2	LCH_4	LH_2	LCH_4	All fuels
Regional jet 100 PAX	48.8	53.5	52.3	−8 %	+5.6 %	50,000
Small narrowbody 180 PAX	83.2	91.1	89.1	−4 %	+10 %	50,000
Large widebody 425 PAX	255.9	280.3	274.1	+9%	+12 %	44,000

Current costs for air travel

The introduction of SAF is the current politically-endorsed pathway to decarbonize the aviation industry. Only the fuel source is different from fossil Jet A–1, the rest of the distribution chain is unaffected and the existing infrastructure can be used. Ticket prices are obtained using a common metasearch engine [69]. The tickets are economy class, return trip and for one person. The cheapest flights are selected with a time window from November 2023 to March 2024. The Jet A–1 demand is obtained from an online calculator that determines the personal carbon footprint of a given flight [37]. This methodology is independent of the other evaluations in this study. A typical modern aircraft is assumed. A ratio of 3.16 kg CO_2 emitted per burned kg of Jet A–1 is considered. Based on the kerosene demand, the fuel cost for fossil Jet A–1 as well as the costs for renewable SAF are estimated. The same flight routs as introduced in Table 3 are selected. The emissions, fuel demand, ticket prices and fuel costs are listed in Table 13. Fuel specific costs of 0.66 €/kg are assumed, which applied in July 2023 [70]. The implications how these costs might change SAF is utilized are given in section 4.3.

Results and discussion

This work focuses on aspects of how the future cost of air travel will change depending on the fuel used. In this section, first the fuel supply costs to the exemplary airports are given. Then based on the costs of future aircraft, the costs for flying excl. airport taxes, fees etc. will be evaluated. The introduction of sustainable aviation fuel (SAF) is the most likely scenario. From 2025, there will be quotas for the blending of SAF in the EU, starting at 2 % and to 70 % by 2050 [8]. The impact on current air travel costs with 100 % SAF share is assessed in section 4.3. As some of the properties of these fuels are relevant to the further discussion, the main physical properties are listed in Table 14.

Evaluation of the fuel supply chain

In the following, first the main results of the fuel supply chain are

Table 14
Physical properties of the evaluated aviation fuels. Liquefaction energy demand is taken from Cardella et al. [71] and Al-Breiki et al. [72].

Property	Unit	LH_2	LCH_4	SAF
Density (liq./ @ 1 bar)	kg/m^3	70.8	422.6	810*
Energy density – volumetric	MJ_{LHV}/m^3	8.50	21.13	34.83
Energy content – mass based	MJ_{LHV}/kg	120	50	43*
Energy demand for (re)-liquefaction	kWh_{El}/kg	6	0.34	–
Ratio energy content/ energy demand for (re)-liquefaction	kWh_{El}/kWh_{LHV}	0.18	0.025	–

* Average value.

Table 13
Exemplary flight paths and their kerosene demand per person – return trip.

ID	To	Plane	Distance [km]	CO_2 emitted [kg]	Kerosene demand [kg]	Ticket price [$€_{2023}$]	Fuel costs [$€_{2023}$]
1	MUC	A320 neo	300	57	18	186	12
2	CDG	A320 neo	447	72	23	134	15
3	MAD	A320 neo	1,419	166	53	125	35
4	IST	A321 neo	1,863	194	61	161	41
5	KEF	A321 neo	2,399	245	78	177	51
6	CAI	A321 neo	2,921	306	97	475	64
7	IKA	B787-900	3,774	480	152	421	100
8	DOH	B787-900	4,584	576	182	498	120
9	JFK	A350-1000	6,184	693	219	420	145
10	BKK	A350-1000	8,995	1,155	366	880	241
6*	CAI			347	110	311	73
10*	BKK			1,444	457	573	302

* The indirect flight was cheaper than a non-stop connection in the considered time period.

presented. Details are given in the supplementary information.

Total fuel demand

Based on the flight movement scenario (FMS), the fuel utilization scenarios (FUS) from Table 1 and the changes of the specific energetic fuel demand given in Table 12, the total annual fuel demand for the year 2050 is estimated for FRA and MUC. Due to the different physical properties the gravimetric, volumetric and energetic results are given in Fig. 7.

From an airport operator's point of the volumetric changes are the most relevant results as there may be spatial limitations at the airport. The required tank capacities are listed in Table 15 and Table 16. For comparison, the current fuel capacities in FRA and MUC are 186,000 m^3 and 44,000 m^3, respectively [57,63]. The capacity at FRA is therefore already higher than it should be based on the definition in section 3.2. This fact does not affect the general comparison of this paper. Any FUS with a cryogenic fuel increases the volumetric storage demand at the airport. In particular if no SAF is considered the demand increases by at least a factor of 2 compared to scenario #1.

Regarding the energetic fuel demand, it can be seen that there is little change between scenario #1 and #2. If the share of cryogenic fuels is increased, the energetic fuel demand increases and is highest in scenario #5. However, the energetic fuel demand at the airport is only one aspect. In order to evaluate the whole supply chain depicted in Fig. 2, it is also necessary to consider the fuel production efficiency, which was evaluated in a previous study [26]. The fuel supply efficiencies (defined as fuel output divided by electrical input at the sweet spot) are 52.8 % for LH_2, 43 % for LCH_4 and 18.5 % for SAF (34.7 % if the by-product of the FT-synthesis is included). The total annual electrical energy demand is depicted in Fig. 8. It can be seen that although the scenario #1 requires the least energy at the airport, it has the highest electrical energy

Table 15
Required tank capacity in m^3 in Frankfurt – depending on the scenario.

Fuel type \Scenario	#1	#2	#3	#4	#5	#6
LH_2	0	44,606	1,731	44,606	620,814	0
LCH_4	0	0	47,219	231,587	0	249,215
SAF	137,483	127,723	111,019	0	0	0
Sum	137,483	172,329	159,969	276,193	771,696	249,215

Table 16
Required tank capacity in m^3 in Munich – depending on the scenario.

Fuel type \Scenario	#1	#2	#3	#4	#5	#6
LH_2	0	46,295	2,376	46,295	266,810	0
LCH_4	0	0	37,441	88,124	0	106,423
SAF	58,746	48,601	37,518	0	0	0
Sum	58,746	94,896	77,335	134,419	318,318	106,423

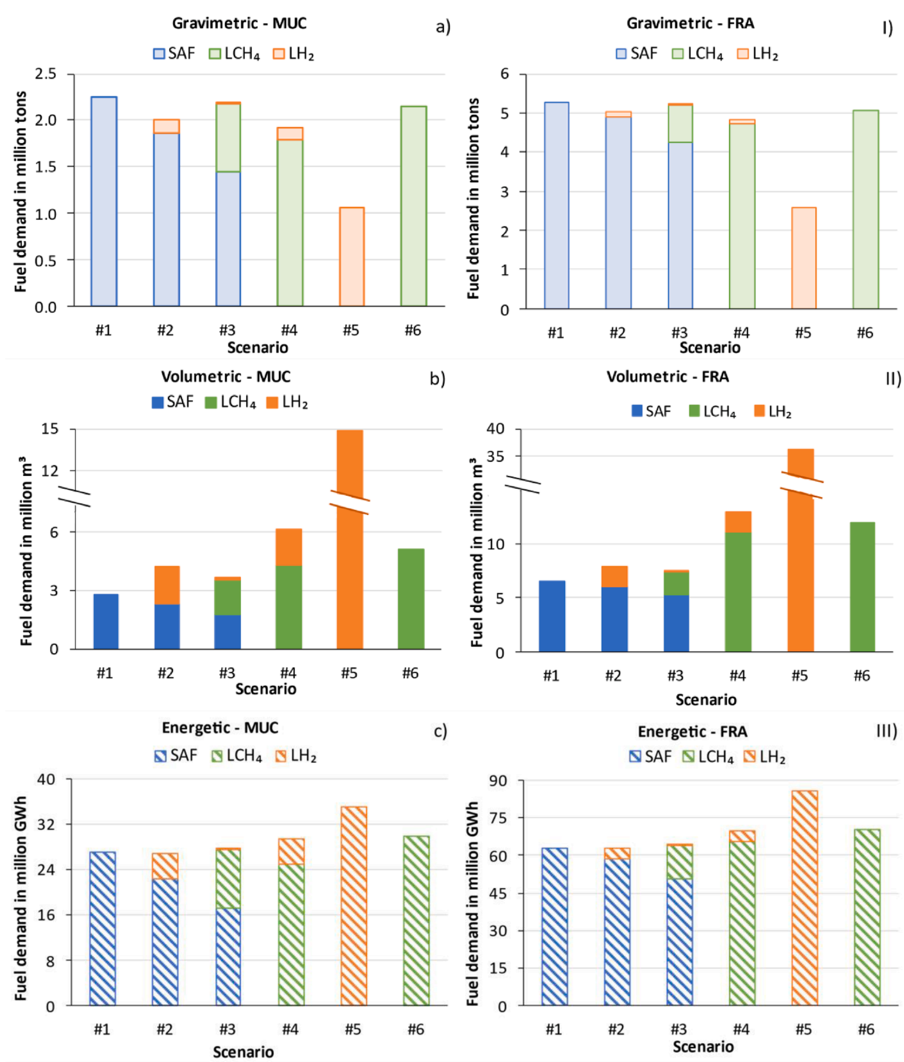

Fig. 7. Gravimetric (a, I), volumetric (b, II) and energetic (c, III) fuel demand for MUC (a, b, c) and FRA (I, II, III).

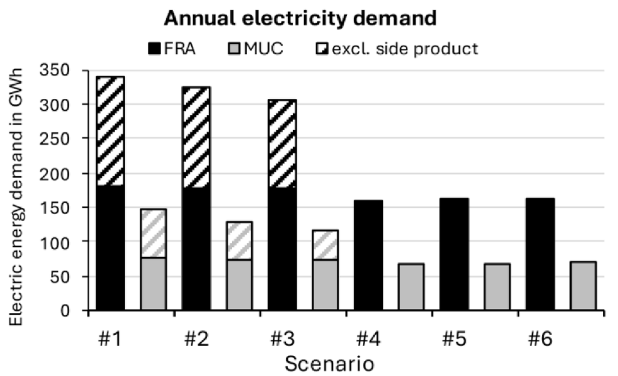

Fig. 8. Annual electrical energy demand at the sweet spot to produce the required aviation fuels.

demand at the fuel source. The hatched area indicates the influence of the two given efficiencies of the SAF supply (with and without the by-product). When the by-product is excluded, the efficiency is lower and thus, the electricity demand is higher.

In addition to the efficiencies, it is relevant to know how much of the corresponding fuel demand given in Fig. 7, could be met by the plants evaluated in Raab and Dietrich [26]. In this previous study a gaseous hydrogen mass flow of 25.74 t/h is converted to the different aviation fuels. In the supply chain considered, the amount of fuel arriving in Wilhelmshaven is either 217.7 kt/a of LH_2, 425.87 kt/a of LCH_4 or 218.5 kt/a of SAF. The percentages given in Table 17 therefore indicate how much of the corresponding fuel demand could be met by the individual supply chains based on 25.74 t/h hydrogen production abroad.

For example, to meet the fuel demand of scenario #1, a total of 10 of the plants considered in Raab and Dietrich are required to supply kerosene to MUC, while 25 are required for FRA. If the amount of cryogenic fuels is increased, the total number of plants required to meet the demand is reduced. This is an aspect to be considered in order to keep the overall investments low (fuel productions plants + airport infrastructure + aircraft research and development).

Total fuel supply costs

The fuel import costs are 157 €/MWh for LH_2, 220 €/MWh for LCH_4 and 279 €/MWh for SAF based on the previous study [26]. These costs are valid at the import terminal shown in Fig. 2. With the input data given in section 3, the costs for the domestic distribution and the airport infrastructure are estimated to obtain the final fuel supply costs. Fig. 9 shows the costs that are added to the import costs for MUC for the scenarios considered in Table 1. The pillars within a scenario represent LH_2, LCH_4 and SAF from left to right. If a certain fuel type is not considered in the given scenario, no pillar is shown. A logarithmic scale is used to better illustrate the different cost elements.

For SAF, it can be seen that the costs in addition to the import costs are of the order of 1.1 €/MWh for each scenario which equals to 1.3 ct/kg. The order of magnitude of this figure has been confirmed by personal communication with a person from Munich Airport. The costs for handling of cryogenic fuels are higher and depend on the total amount

Table 17
Share of fuel demand coverage depending on the analysed scenarios.

	MUC			FRA		
Scenario	LH_2	LCH_4	SAF	LH_2	LCH_4	SAF
#1	–	–	10 %	–	–	4 %
#2	163 %	–	12 %	169 %	–	4 %
#3	2,968 %	58 %	15 %	4,073 %	46 %	5 %
#4	163 %	24 %	–	169 %	9 %	–
#5	25 %	–	–	10 %	–	–
#6	–	20 %	–	–	8 %	–

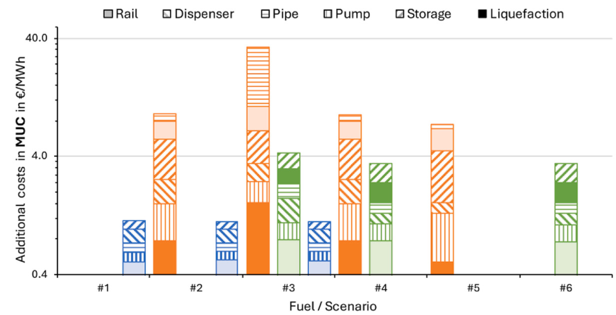

Fig. 9. Costs for domestic distribution and fuelling at Munich airport.

that is handled (the annual amount of fuel that is handled is shown in Fig. 7). For LH_2 and LCH_4 the costs for domestic distribution and airport infrastructure are highest in scenario #3. This is due to the fact, that in this scenario the smallest quantities are required for both fuels. In particular, the costs for the LH_2 pipeline system are very high in scenario #3. In this scenario, the amount of LH_2 handled would not justify a pipeline system and a truck delivery system might be the better choice to transport the fuel from the tank farm to the aircraft. In scenario #5 and #6 the fuel handling costs are lowest for LH_2 and LCH_4. It can be seen, that after a certain amount of fuel that is handled per year, the handling costs do not decrease any further. This lower limit is around 9 €/MWh for LH_2 (ignoring scenario #5 as it is only an academic scenario) and 3.5 €/MWh for LCH_4. This corresponds to 30 ct/kg and 4.9 ct/kg for LH_2 and LCH_4, respectively. Hoelzen et. al obtained costs of 0.19 $\$_{2020}$/kg for handling liquid hydrogen at the airport but also considered a shorter pipeline length. Fig. 10 shows the costs in addition the import costs for FRA for the scenarios considered in Table 1. A logarithmic scale is used to better illustrate the different cost elements.

The same aspects from the case of MUC can be concluded for FRA. The costs are slightly different due to the different transport pathway to the airport and the longer length of the pipeline system, resulting in a higher boil-off of the cryogenics. The costs for SAF amount to 1.5 €/MWh which equals to 1.8 ct/kg, the lower threshold for LH_2 handling costs is 14 €/MWh, equal to 47 ct/kg (neglecting scenario #5). For LCH_4, handling costs are 4.7 €/MWh, equal to 6.5 ct/kg. The fuel supply costs are summarized in Table 18. These are the "minimum fuel supply costs" mentioned in section 2. With these costs, the flight costs are evaluated in $\frac{€}{\mathrm{PAX}\ 100\ \mathrm{km}}$.

Costs for fuel utilization

This section presents the results for the total costs of flying for the conventional tube-and-wing aircraft designs utilizing either LH_2, LCH_4 or SAF. The results for the BWB and TBW are depicted in the section S.2 of the SI. Ten exemplary routes are considered, starting from Frankfurt, and are listed in Table 3. Based on the fuel supply costs from Table 18, the specific fuel demand given in the FMS for future aircraft as well as

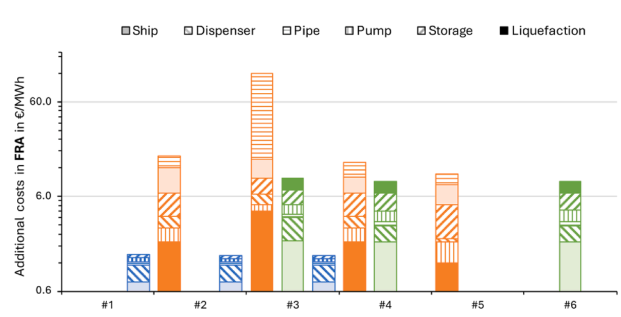

Fig. 10. Costs for domestic distribution and fuelling at Frankfurt airport.

Table 18
Summary of fuel supply costs in €/MWh_{LHV}.

Fuel type	Import costs	Fuelling in MUC	Fuelling in FRA
LH_2	157	9	14
LCH_4	220	3.5	4.7
SAF	279	1.1	1.5

the aircraft costs and number of flight cycles given in Table 12, the costs for flying are determined. Boil-off losses once the fuels are inside the aircraft are not considered. A load factor (LF) of 80 % is assumed for each aircraft, meaning that only 80 % of the available seats are occupied. The results for the regional jet sized aircraft with a total capacity of 100 passengers are shown in Fig. 11.

The values of the columns are represented by the left axis and indicate the specific costs in $\frac{€}{\text{PAX 100 km}}$. The dashed part of the column corresponds to the fuel costs while the blank part represents the depreciation costs of the aircraft. The distances that are covered increase from left to right. It can be seen that the absolute share of depreciation costs decreases with increasing flight distance and almost negligible for flights to IKA (3774 km). For this distance the total corresponding values are 4.73, 7.01 and 8.14 $\frac{€}{\text{PAX 100 km}}$ LH_2, LCH_4 or SAF, respectively. The total costs per passenger in $\frac{€}{\text{PAX}}$ for any given flight are shown by the pyramid, circle and diamond shaped dots. The values are given on the right axis. While the difference between the different fuel types is rather small for short distances, the cost advantage of LH_2 over LCH_4 over SAF becomes more pronounced as the flight distance increases. The results for the small aircraft with a total capacity of 180 passengers are shown in Fig. 12.

The same convention for both axes as in Fig. 11 is considered in Fig. 12. Comparing the total costs for the flight to IKA (Tehran, Iran) as example destination, it can be seen that the costs for the small aircraft are between 94 and 193 €/PAX for the corresponding fuel, while they are in the range of 180 and 309 €/PAX for the regional jet sized aircraft. The longer the distance, the greater is the cost advantage of LH_2 over LCH_4 and SAF. For the longest distance covered (6184 km to JFK), the total corresponding values are 3.08, 4.57 and 5.11 $\frac{€}{\text{PAX 100 km}}$ for LH_2, LCH_4 and SAF, respectively. As aircraft depreciation is not a major factor over long distances, the ranking is hardly affected by higher acquisition costs for cryogenic aircraft. The results for the large aircraft with a total capacity of 425 passengers are shown in Fig. 13.

Fig. 13 uses the same convention for both axes as in Fig. 11. Comparing the total costs for the flight to JFK (New York, USA) as example destination, it can be seen that the costs for the small aircraft are between 190 and 316 €/PAX for the corresponding fuel, while they are in the range of 263 and 385 €/PAX for the large aircraft. Thus, the specific costs increase for the larger aircraft. The specific costs also increase, for the highest distance covered (8995 km to BKK) the corresponding values are 4.25, 5.72 and 6.09 $\frac{€}{\text{PAX 100 km}}$ for LH_2, LCH_4 and SAF, respectively. The higher costs for the larger aircraft result from the specific higher fuel demand, given in Table S.6 and are provided by the FMS. The increase from a small aircraft to the larger aircraft can be explained with the equation for the hydraulic drag, the force acting on a body in the opposite direction of its motion. The force of the hydraulic drag is directly proportional to the cross-sectional area of the body, in this case the aircraft. Considering two exemplary aircraft, namely the A321 and the A350, the cross-sectional area of the fuselage per passenger is lower for an A321, than for an A350. The calculation is given in the SI. Therefore, the higher the fuel supply costs, the more prominent is the cost advantage of narrowbody aircraft over widebody aircraft. The results for LH_2 shown in Fig. 13 are valid for a 9 % increase in the specific energy demand compared to an aircraft using SAF. As a value of + 42 % is also reported in literature, the implications of the higher increase have also been considered and the results are shown as a sensitivity in Figure S.1.

Impact of 100 % SAF on current air travel costs

In section 3.4, current ticket prices are given for return trips from FRA to the destinations listed in Table 3. Using current Jet A–1 costs, the fuel cost share is estimated of these ticket prices. This is depicted with the columns in Fig. 14. To evaluate the impact if fossil Jet A–1 is completely substituted by SAF, the specific fuel demand is determined and multiplied by the SAF supply costs of this study. The results are indicated with the black dots in Fig. 14. The "error-bars" represent the share of the current ticket prices excl. the current fuel costs. Thus, the total height represents the total ticket prices if 100 % SAF had been used. An example: The current indirect return trip costs to CAI* are roughly 300 €, made up of 72 € for "fossil Jet A-1 share" and 235 € for "Ticket price excl. fuel". The costs for SAF for this return trip are 370 € (shown by the black dot), now adding 235 € for "Ticket price excl. fuel", the perspective total ticket price amounts to 605 € (higher end of the error bar). It can be seen, that for short-haul flights the absolute increase is rather small and in the order of expected price fluctuations. For long-distance flights the cost increase is very significant. As stated above,

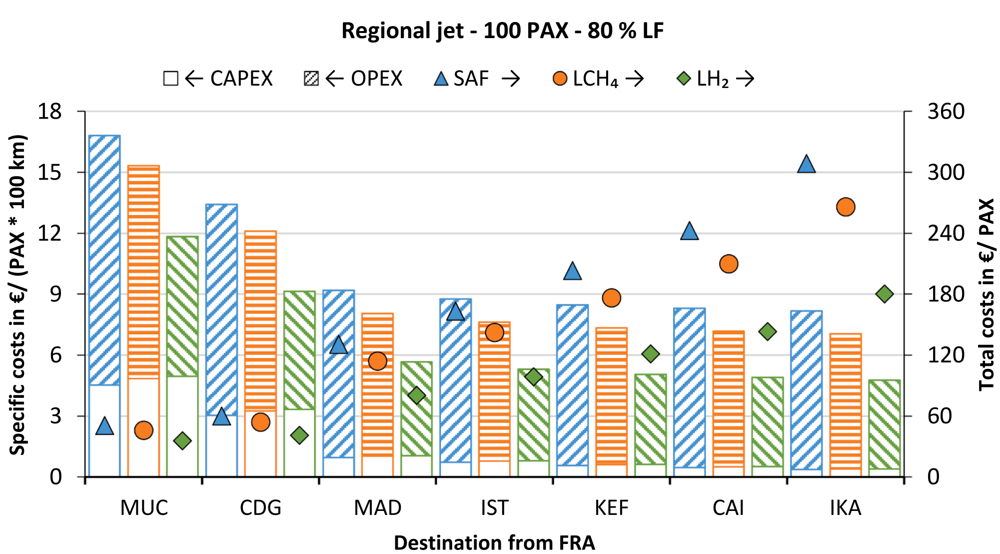

Fig. 11. Cost of flying with a conventional tube-and-wing design regional jet sized aircraft.

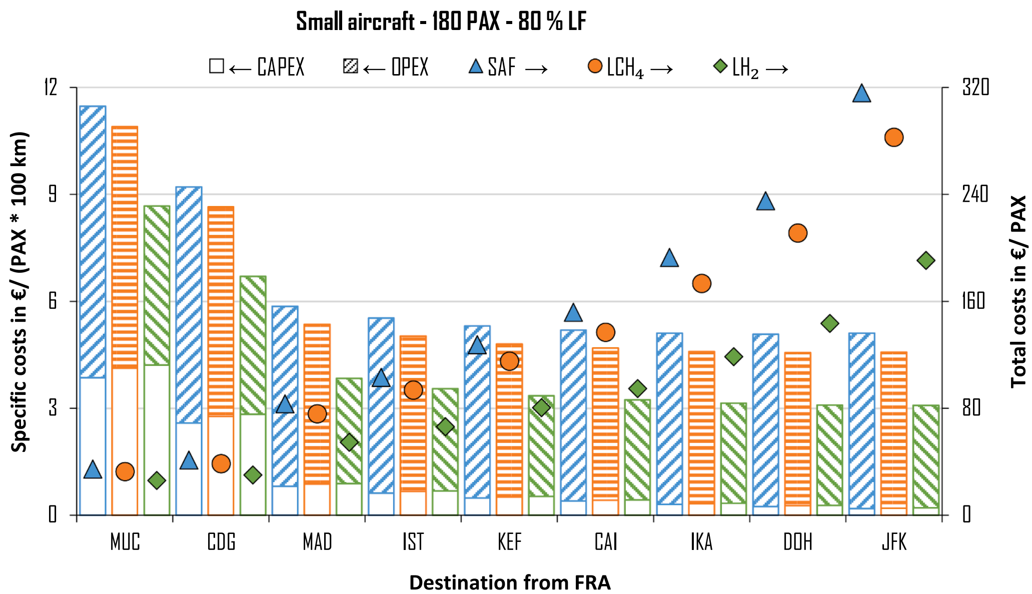

Fig. 12. Cost of flying with a conventional tube-and-wing design small sized aircraft.

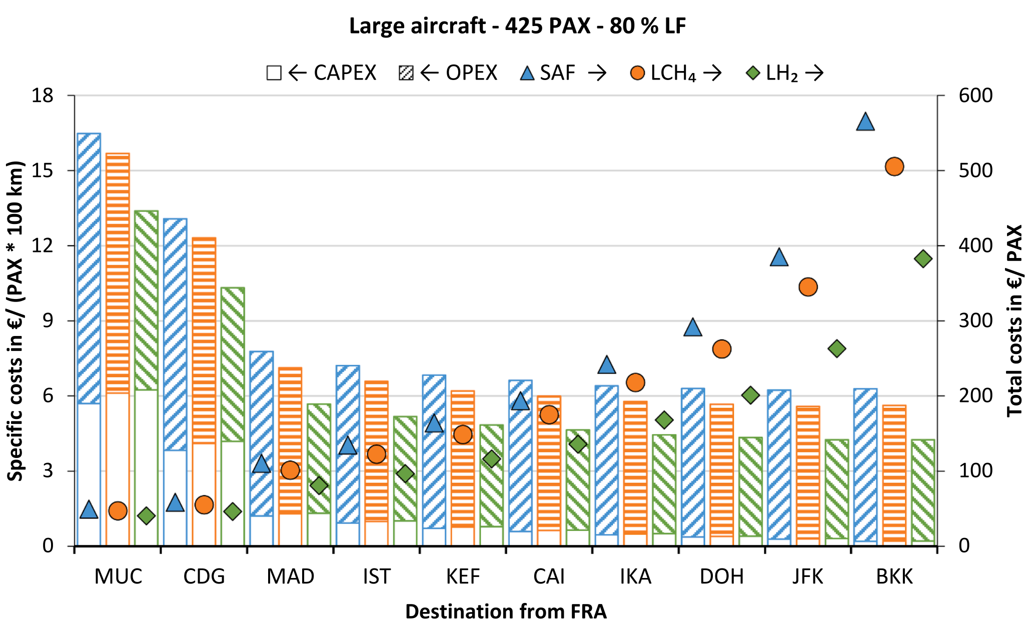

Fig. 13. Cost of flying with a conventional tube-and-wing design large sized aircraft.

all trips are non-stop routes except those marked with an asterisk (*).

Discussion

Two consecutive assessments have been carried out in this study to compare the implications of LH_2, LCH_4 and SAF as potential aviation fuels. The study was carried out with an exclusive focus on technical and economic aspects and did not consider regulatory issues related to certification, allowances or a life cycle assessment. Firstly, the fuel demand together with the fuel storage requirements were evaluated for several scenarios. Based on these results, the costs for domestic distribution and fuelling at the respective airport were assessed. It has been shown that the introduction of cryogenic fuels leads to a high increase in storage demand at the airports, mainly due to their lower volumetric energy density. Based on the scenario evaluations, a lower threshold for the fuel supply costs to the aircraft has been determined. It is shown that the overall fuel supply costs are dominated by the import costs and that the costs for domestic distribution and costs for the airport infrastructure have a less dominant role. The case where this cost share is highest, is the case of LH_2 supply to FRA. There, the costs account for 9 % of the overall supply costs (14 €/MWh out of 171 €/MWh). For SAF the additional costs are even lower. The accuracy of the cost estimation used in a previous study [26] to determine the fuel import costs for SAF is likely to be a source of greater uncertainty than the additional costs resulting from domestic distribution, storage and fuelling. Secondly, based on the fuel supply costs and the estimated aircraft acquisition costs, the costs for air travel were estimated in $\frac{€}{\text{PAX 100 km}}$ for different aircraft sizes and different fuel types. Furthermore, the total costs for the considered flights were determined in $\frac{€}{\text{PAX}}$. The lower threshold for the specific air travel costs for each aircraft type considered is listed in Table 19. The values are valid for the maximum distance that could be flown with the corresponding aircraft type. In addition, the values are listed for the case where new aircraft but fossil Jet A-1 are used (in

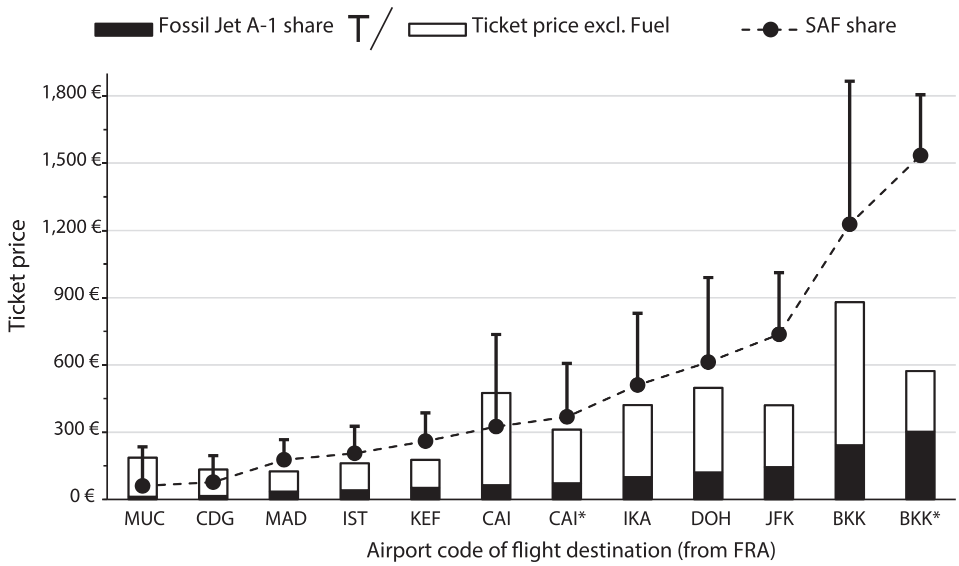

Fig. 14. Current return trip costs of air travel from FRA and the implication of SAF introduction. The share of fuel costs is determined by the individual CO_2 emissions.

Table 19

Lowest specific costs for flying in $\frac{€_{2020}}{\text{PAX}\,100\,\text{km}}$.

	LH_2	LCH_4	SAF	Fossil Jet A-1
Regional jet	4.73	7.01	8.14	1.53
Small aircraft	3.08	4.57	5.11	1.15
Large aircraft	4.25/ 5.48*	5.72	6.09	1.39

* This value is valid for an increase in energy demand of + 42 % compared to SAF.

contrast to section 4.3 where current aircraft data are considered). Specific costs of 0.66 €/kg are considered for fossil Jet A-1 which is equivalent to 55.3 €/MWh.

The values show, that for each aircraft type the costs are highest when SAF is utilized, followed by LCH_4 and LH_2 as the most economic option to replace fossil Jet A-1. These results are valid if the production of renewable hydrogen is the first step and both, SAF and LCH_4 are assumed to be converted from hydrogen as depicted in Fig. 2 and not from biogenic origins. Biofuels have been excluded from this study, as discussed in section 1.2. The costs given Table 19 depend mainly on the overall fuel supply costs, as shown in Fig. 11, Fig. 12 and Fig. 13. The fuel supply costs are dominated by the costs for importing these fuels to Wilhelmshaven. A thorough analysis and literature comparison for these costs was carried out in a previous study [26]. The values listed in Table 19 also show the huge cost increase between the use of fossil Jet A-1 and electricity-based renewable fuels. The socio-economic implications of this aspect must be taken into account in future research.

It has been shown that the aircraft acquisition costs given in Table 12 have a minor role and that the overall ranking is determined by the fuel supply costs and the specific fuel demand. These results are valid under the assumption that it is technically and economically feasible to manufacture the respective aircraft. Hydrogen and methane powered aircraft with a tube-and-wing design face the challenge, that cryogenic fuels cannot be stored in the wings in the conventional way. This challenge is compounded by the lower volumetric energy density of cryogenic fuels as shown in Table 14. Due to the additional isolation requirements of cryogenic fuels, there are hurdles that need to be overcome for the introduction of cryogenic fuels in aviation. For the purpose of this study, it has only been considered that the obstacles can be overcome to demonstrate the economic benefits of aircraft propelled with cryogenic fuels.

The lower fuel supply costs of LH_2 and LCH_4 allow a certain energy penalty i.e., a higher specific energy "consumption" for propulsion. Even if the increase amounts to + 42 %, as it is considered in a sensitivity for LH_2 (results are in Figure S.1), the utilization of LH_2 is still more economical than the utilization of LCH_4 or SAF. The fact that costs for air travel listed in Table 19 are higher for the large aircraft than for the small aircraft can be explained with the higher cross-sectional area of the aircraft. Moreover, no belly cargo has been assumed for the large aircraft, which typically contributes significantly to the capacity offered. As current ticket prices include fees, taxes etc. and considering that slots at airports are limited, the aspect of the specific higher fuel demand may not be too relevant for comparably low fuel costs. With rising fuel prices in the future, airlines might focus on using smaller (narrowbody or single-aisle) aircraft to decrease the fuel demand for their services. However, this must be offset by the generally shorter range and lower passenger capacity of smaller aircraft.

In this study the cost implications of phasing out fossil fuels from aviation industry are evaluated. Similar studies have been conducted by Proesmans et al. [73] and Dray et al. [27]. However, Proesmans et al. performed an optimisation approach where either the cost optimal or climate optimal solution was determined and thus, included a life cycle assessment in their study. While Dray et el. considered a feedback from increased costs of air travel on the demand for air travel. Both aspects have not been considered in this study. However, Proesmans et al and Dray et al. both state how the cost of air travel will be increased by reducing the climate impact. The results are given in Table 20 together with the cost increase of this study based on the values from Table 19. It has to be mentioned that the cost of air travel of this study considers the fuel costs and depreciation costs of the aircraft. Remaining aspects like salary of cabin crew, fees, taxes etc. are not considered. Therefore, the values from Table 20 do not indicate, that ticket prices will increase by the corresponding factor.

In Dray et el. a generic cost increase in the range of 10 – 16 % is

Table 20

Increase in air travel costs compared to fossil kerosene – comparison with literature data.

	LH_2	LCH_4	SAF	LH_2 [73]	SAF [73]
Regional jet	309 %	458 %	532 %	30 %	8 %
Small aircraft	268 %	397 %	444 %	42 %	14 %
Large aircraft	306 %	412 %	438 %	69 %	26 %

given. The vast difference between the results of this study and can to a certain extent be explained by different fuel cost assumptions. Proesmans et al. considers costs of 132 and165 $/MWh_{LHV}$ for LH_2 and eSAF, respectively. Dray et al. considers an upper limit of 130 $/MWh_{LHV}$ for SAF based on hydrogen and atmospheric CO_2 in the year 2050. In this manuscript, SAF costs of roughly 280 €/MWh_{LHV} are considered. Also, different fossil kerosene baseline costs and fuel demand scenarios lead to different outcomes.

Another aspect that is an indirect result of this study is the fact, that if cryogenic fuels are introduced as aviation fuel in the future, enormous amounts of energy will be stored at airports in the state of a *meta*-stable cryogenic liquid. In scenario #2 (and #4) the LH_2 storage capacity in Munich amounts to 46,295 m^3, as given in Table 16. At the density given in Table 14, a fully loaded tank has the capacity to store 3,200 tons, the energy content of which is equivalent to 92 kT TNT (1 kt TNT = 4.184 $\cdot 10^{12}$ J). This potential hazard could lead to discussions with the local authorities and neighbourhoods who could be affected in the event of an incident. Spatial constraints on the installation of the required tank capacity at the airports have not been considered in this study. Other safety issues that could be caused from cryogenic fuels or potential GHG emissions from leakage, slip or utilization have also been excluded. Maintenance costs have been neglected in this study but might be different for planes with fuel cells and turbines. The engines of smaller planes have a lifetime of roughly 20,000 h [74]. Small aircraft usually have their engines replaced twice before they reach their end of life i.e. after 60,000 flight hours.

Conclusion

The research question of this paper is how the costs of air travel will be affected by a complete transition to electricity-based fuels and how the costs will differ if LH_2, LCH_4 or SAF are used for specific flight routes. Based on two previous studies the whole chain was evaluated including the hydrogen production based on renewable energy at a remote location [25], the subsequent synthesis and transport to Germany [26] as well as the domestic distribution and utilization. To the authors' knowledge, no study has yet compared the fuels including their entire supply chain to answer the following overarching question: If the aviation industry wants to reduce the use of fossil kerosene, is it more economical to simply change the fuel source or should the fuel itself be changed? Assuming that it is possible to manufacture aircraft utilising cryogenic fuels, it is concluded that the fuel supply costs dominate the overall costs and therefore LH_2 is the most economic option, followed by LCH_4 and SAF.

In view of the results of this study, future research should focus on the aspects with the highest leverage on the overall costs. These are the changes in the specific fuel demand for the different aircraft given in Table 12 and the fuel import costs. Only the former has been considered in this study, therefore future research suggestions focus on this matter. The change in specific fuel demand could improve from developments in fuel cells or by improvements in tank materials allowing better on-board storage of cryogenic liquids. Dual-fuel aircraft could also reduce cost of flying, as not all the energy would have to be supplied from SAF. If for example, SAF is stored in the wings and LCH_4 is stored in a fuselage tank the overall costs for a given flight could be reduced. Moreover, acceptance by operators could be improved with dual-fuel aircraft, as these types could also be operated from airfields not equipped with LCH_4 refuelling infrastructure.

Another field of research could be the utilization of the cryogenic temperature level in the power electronics i.e., superconductive electric engines. Since it is the overall target to reduce the GHG emissions of the aviation industry, the GHG emissions of the whole chain should also be considered to evaluate the environmental impact of cryogenic fuels in aviation. This aspect has been excluded from this study since estimating the emissions resulting from utilization alone is a very complex task with numerous variables like flight height, flight time, slip of unburned fuel (−components) etc. [75–78]. Assuming that SAF is equal to $C_{12}H_{26}$, it can be said that the water vapor emissions resulting from fuel combustion are roughly 2.3 times higher for LH_2 than for SAF for every energy unit provided. This, as well as the aspects mentioned above, has to be considered in order to find the most appropriate pathway to decarbonize the aviation industry.

CRediT authorship contribution statement

Moritz Raab: Writing – original draft, Investigation. **Ralph-Uwe Dietrich:** Writing – review & editing, Supervision. **Paula Philippi:** Software. **Jonathan Gibbs:** Writing – review & editing, Validation, Investigation. **Wolfgang Grimme:** Writing – review & editing, Validation, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jonathan Gibbs reports a relationship with Savion Aerospace Pty Ltd that includes: board membership. The corresponding author (MR) now works at HIF EMEA GmbH, a company aiming to build and operate plants that produce synthetic fuels. The work of this paper was done while he was still employed at the DLR. The work will also be published with his affiliation under the DLR. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2024.100611.

References

[1] ICAO. 2023 Long term global aspirational goal (LTAG) for international aviation [First accessed on: 17.12.2023 - Available from: https://www.icao.int/environmental-protection/Pages/LTAG.aspx.].
[2] Fuel Cells, Hydrogen 2 Joint Undertaking. Hydrogen-powered aviation – A fact-based study of hydrogen technology, economics, and climate impact by 20502020.
[3] Greg Hemighaus, Tracy Boval, John Bacha, Barnes F, Matt Franklin, Lew Gibbs, et al. Aviation Fuels - Technical Review. 2007.
[4] Tongpun P, Wang W-C, Srinophakun P. Techno-economic analysis of renewable aviation fuel production: From farming to refinery processes. J Clean Prod 2019; 226:6–17. https://doi.org/10.1016/j.jclepro.2019.04.014.
[5] Eswaran S, Subramaniam S, Geleynse S, Brandt K, Wolcott M, Zhang X. Techno-economic analysis of catalytic hydrothermolysis pathway for jet fuel production. Renew Sustain Energy Rev 2021;151:111516. https://doi.org/10.1016/j.rser.2021.111516.
[6] Weyand J, Habermeyer F, Dietrich R-U. Process design analysis of a hybrid power-and-biomass-to-liquid process – An approach combining life cycle and techno-economic assessment. Fuel 2023;342:127763. https://doi.org/10.1016/j.fuel.2023.127763.
[7] Su-ungkavatin P, Tiruta-Barna L, Hamelin L. Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. Prog Energy Combust Sci 2023;96:101073. https://doi.org/10.1016/j.pecs.2023.101073.
[8] European Council. Initiative „ReFuelEU Aviation": Rat verabschiedet neuen Rechtsakt zur Dekarbonisierung des Luftfahrtsektors 2023. https://www.consilium.europa.eu/de/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/.
[9] IATA. Fact Sheet 2 - Sustainable Aviation Fuel: Technical Certification [First accessed on: 31.08.2023 - Available from: https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf.].
[10] Atlantic V Virgin Atlantic flies world's first 100% Sustainable Aviation Fuel flight from London Heathrow to New York JFK [press release]. 2023.
[11] Brewer GD. Aviation usage of liquid hydrogen fuel—prospects and problems. Int J Hydrogen Energy 1976;1(1):65–88. https://doi.org/10.1016/0360-3199(76)90011-2.

[12] Korycinski PF. Air terminals and liquid hydrogen commercial air transports. Int J Hydrogen Energy 1978;3(2):231–50. https://doi.org/10.1016/0360-3199(78)90021-6.
[13] Hoelzen J, Flohr M, Silberhorn D, Mangold J, Bensmann A, Hanke-Rauschenbach R. H2-powered aviation at airports – Design and economics of LH2 refueling systems. Energy Conversion Manage: X. 2022;14:100206. https://doi.org/10.1016/j.ecmx.2022.100206.
[14] Mangold J, Silberhorn D, Moebs N, Dzikus N, Hoelzen J, Zill T, et al. Refueling of LH2 Aircraft— Assessment of Turnaround Procedures and Aircraft Design Implication. Energies 2022;15(7):2475. https://doi.org/10.3390/en15072475.
[15] CORDIS. 2000 Liquid hydrogen fuelled aircraft - system analysis (CRYOPLANE) [First accessed on: 13.07.2023 - Available from: https://cordis.europa.eu/project/id/G4RD-CT-2000-00192/de.].
[16] Westenberger A. Cryoplane–Hydrogen Aircraft. H2 Expo (11 October Hamburg 2003). 2003.http://www.h2hh.de/downloads/Westenberger.pdf.
[17] Airbus. 2022 The ZEROe demonstrator has arrived [First accessed on: 13.07.2023 - Available from: https://www.airbus.com/en/newsroom/stories/2022-02-the-zeroe-demonstrator-has-arrived.].
[18] Carson L, Davis G, Versaw E, Cunnington Jr G, Daniels E. Study of methane fuel for subsonic transport aircraft. 1980. https://ntrs.nasa.gov/citations/19800024025.
[19] Eurocontrol The challenge of long-haul flight decarbonisation: When can cutting-edge energies and technologies make a difference? [press release]. 2023.
[20] Marty K. Bradley, Droney CK. Subsonic Ultra Green Aircraft Research - Phase II: N +4 Advanced Concept Development. 2012. https://ntrs.nasa.gov/api/citations/20120009038/downloads/20120009038.pdf.
[21] Jane O'Malley NP, Stephanie Searle. Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand2021.
[22] Jaramillo P, S. Kahn Ribeiro, P. Newman, S. Dhar, O.E. Diemuodeke, T. Kajino, D.S. Lee, S.B. Nugroho, X. Ou, A. Hammer Strømman, J. Whitehead. Transport. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2022.
[23] European Parliament. Renewable energy directive 2018/2001/EU. 2022.
[24] Pipitone G, Zoppi G, Pirone R, Bensaid S. Sustainable aviation fuel production using in-situ hydrogen supply via aqueous phase reforming: A techno-economic and life-cycle greenhouse gas emissions assessment. J Clean Prod 2023;418: 138141. https://www.sciencedirect.com/science/article/pii/S0959652623022990.
[25] Raab M, Körner R, Dietrich R-U. Techno-economic assessment of renewable hydrogen production and the influence of grid participation. Int J Hydrogen Energy 2022;47(63):26798–811. https://doi.org/10.1016/j.ijhydene.2022.06.038.
[26] Raab M, Dietrich R-U. Techno-economic assessment of different aviation fuel supply pathways including LH2 and LCH4 and the influence of the carbon source. Energ Conver Manage 2023;293:117483. https://doi.org/10.1016/j.enconman.2023.117483.
[27] Dray L, Schäfer AW, Grobler C, Falter C, Allroggen F, Stettler MEJ, et al. Cost and emissions pathways towards net-zero climate impacts in aviation. Nat Clim Chang 2022;12(10):956–62. https://doi.org/10.1038/s41558-022-01485-4.
[28] Gelhausen MC, Berster P, Wilken D. Airport capacity constraints and strategies for mitigation: A global perspective. Academic Press; 2019.
[29] Cirium. FLEETS ANALYZER [First accessed on: 13.07.2023 - Available from: https://www.cirium.com/solutions/fleets-analyzer/.].
[30] OAG. GLOBAL AIRLINE SCHEDULES DATA [First accessed on: 13.07.2023 - Available from: https://www.oag.com/airline-schedules-data.].
[31] Schaefer M. Development of a Forecast Model for Global Air Traffic Emissions 2012.
[32] Commission E. Flightpath 2050 – Europe's vision for aviation – Maintaining global leadership and serving society's needs. Publications Office; 2011.
[33] Withers MR, Malina R, Gilmore CK, Gibbs JM, Trigg C, Wolfe PJ, et al. Economic and environmental assessment of liquefied natural gas as a supplemental aircraft fuel. Prog Aerosp Sci 2014;66:17–36. https://ui.adsabs.harvard.edu/abs/2014PrAeS.66...17W.
[34] Troeltsch FM, Engelmann M, Scholz AE, Peter F, Kaiser J, Hornung M. Hydrogen Powered Long Haul Aircraft with Minimized Climate Impact. AIAA AVIATION 2020 FORUM.
[35] Bradley MK, Droney CK. Subsonic ultra green aircraft research phase II: N+ 4 advanced concept development. 2012. https://ntrs.nasa.gov/citations/20120009038.
[36] Rompokos P, Kissoon S, Roumeliotis I, Nalianda D, Nikolaidis T, Rolt A. Liquefied Natural Gas for Civil Aviation. Energies 2020;13(22):5925. https://doi.org/10.3390/en13225925.
[37] Atmosfair. Ergebnisse Emissionsberechnung: atmosfair; [First accessed on: 24.01.2023 - Available from: https://www.atmosfair.de/de/kompensieren/flug/.].
[38] Raymer D. Aircraft design: a conceptual approach. American Institute of Aeronautics and Astronautics, Inc.; 2012.
[39] Markish J. Valuation techniques for commercial aircraft program design. Massachusetts Institute of Technology; 2002.
[40] Brenschede A. BRouter [First accessed on: 13.06.2023 - Available from: https://brouter.de/brouter-web/.].
[41] Van der Meulen S, Grijspaardt T, Mars W, Van der Geest W, Roest-Crollius A, Kiel J. Cost figures for freight transport–final report. Panteia. 2020:1–85.
[42] VTG. Flüssiggas-Kesselwagen für tiefkalte Gase - Datenblatt VTG-Typ G91.111D [First accessed on: 13.07.2023 - Available from: https://www.vtg.de/fluessiggas-kesselwagen-fuer-tiefkalte-gase-zagkks.].
[43] wascosa. Kesselwagen [First accessed on: 13.07.2023 - Available from: https://www.wascosa.ch/de/wagenpark/kesselwagen.].
[44] "Verfondern K. Safety consideration on liquid hydrogen. Germany: ; Forschungszentrum Juelich GmbH Institut fuer Energieforschung (IEF) Sicherheitsforschung und Reaktortechnik (IEF-6); 2008. Medium: ED; Size: 178 pages p.
[45] Amos WA. Costs of storing and transporting hydrogen. National Renewable Energy Lab.(NREL), Golden, CO (United States); 1999.
[46] mobile.de. Search for new tank trailers 2023 [First accessed on: 13.07.2023 - Available from: www.mobile.de.].
[47] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Appl Energy 2017;200:290–302. https://doi.org/10.1016/j.apenergy.2017.05.050.
[48] Mariani F, Gonzalez D, Ribas X. Cost analysis of LNG refuelling stations. Studija Brussels: European Commision: FP7 LNG Blue Corridors, LNG BC D. 2016; 3.
[49] DIE GÜTERBAHNEN. 4 Promille - Empfohlene maximale Steigung für neu gebaute Schienenstrecken [First accessed on: 14.07.2023 - Available from: https://die-gueterbahnen.com/news/zahl-des-tages/4.html.].
[50] Luftfahrtmagazin. 2012 Neue Kerosin-Pipeline am Frankfurter Flughafen [First accessed on: 20.07.2023 - Available from: https://www.luftfahrtmagazin.de/aviation/zivile-luftfahrt/neue-kerosin-pipeline-am-frankfurter-flughafen-181567.html.].
[51] MarineTraffic. 2023 Global Ship Tracking Intelligence [First accessed on: 12.06.2023 - Available from: https://www.marinetraffic.com/en/ais/home/centerx:8.470/centery:50.024/zoom:14.].
[52] Streta. 2023 Inland tankbarge [First accessed on: 12.06.2023 - Available from: https://stetra.de/en/fleet/inland-tankbarge/.].
[53] Ship Technology. 2014 LNG Greenstream Tanker [First accessed on: 27.03.2024 - Available from: https://www.ship-technology.com/projects/lng-greenstream-tanker/.].
[54] Kawasaki. 2019 World's First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-free Society [First accessed on: 21.07.2023 - Available from: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487.].
[55] Hekkenberg RG, editor A building cost estimation method for inland ships. European inland waterway navigation conference Budapest, Hungary; 2014.
[56] IGU. 2023 2022 WORLD LNG REPORT [First accessed on: 21.07.2023 - Available from: https://www.igu.org/resources/world-lng-report-2022/.].
[57] Skytanking. Verhalten bei Störfällen [First accessed on: 14.07.2023 - Available from: https://www.skytanking.com/fileadmin/user_upload/downloads/Skytanking_Munich_Oeffentl-Info-11-Verhalten-bei-Stoerfaellen_de_01.pdf.].
[58] Walter. D. 2021 Aiwanger wirbt für grünes Kerosin in Bayern - „dem Flugkunden das schlechte Gewissen nehmen" [First accessed on: 04.07.2023 - Available from: https://www.merkur.de/lokales/erding/flughafen-muenchen-ort60188/flughafen-muenchen-kerosingruen-oeko-aiwanger-passagiere-gewissen-91060762.html.].
[59] Woods DR. Rules of thumb in engineering practice. John Wiley & Sons; 2007.
[60] Baker. LNG Storage Tank Cost Analysis. Interiorgas. 2013. https://www.interiorgas.com/wpdm-package/lng-storage-tank-cost-analysis/.
[61] Peters MS, Timmerhaus KD, West RE. Plant design and economics for chemical engineers. McGraw-Hill New York; 2003.
[62] Hromadka M, Cíger A. Hydrant refueling system as an optimisation of aircraft refuelling. Transport Problems. 2015;10. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-0269da72-0918-4697-b410-a83b9532107e/c/Hromadka.pdf.
[63] Fraport. Facts and figures [First accessed on: 14.07.2023 - Available from: https://www.fraport.com/en/our-group/about-us/facts—figures.html.].
[64] International Airport Review. 2021 Sustainable aviation fuel to be used at Munich Airport from June 2021 [First accessed on: 02.08.2023 - Available from: https://www.internationalairportreview.com/news/158439/sustainable-aviation-fuel-munich-airport/.].
[65] Stolzenburg K, Berstad D, Decker L, Elliott A, Haberstroh C, Hatto C, et al., editors. Efficient liquefaction of hydrogen: results of the IDEALHY project. Proceedings of the XXth Energie—Symposium, Stralsund, Germany; 2013.
[66] Raab M, Maier S, Dietrich R-U. Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media. Int J Hydrogen Energy 2021;46(21):11956–68. https://doi.org/10.1016/j.ijhydene.2020.12.213.
[67] Songhurst B. LNG plant cost reduction 2014–18. 2018. https://ora.ox.ac.uk/objects/uuid:f5bebe7f-1559-47ad-a80a-018ab9d78061.
[68] Fuchte J, Nagel B, Gollnick V. Twin Aisle for Short Range Operations - An Economically Attractive Alternative? 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference.
[69] Swoodoo. Billige Flüge und Billigflüge suchen und buchen [First accessed on: 13.06.2023 - Available from: https://www.swoodoo.com/.].
[70] IATA. 2023 Jet Fuel Price Monitor [First accessed on: 26.01.2023 - Available from: https://www.iata.org/en/publications/economics/fuel-monitor/.].
[71] Cardella U, Decker L, Sundberg J, Klein H. Process optimization for large-scale hydrogen liquefaction. Int J Hydrogen Energy 2017;42(17):12339–54. http://www.sciencedirect.com/science/article/pii/S0360319917311746.
[72] Al-Breiki M, Bicer Y. Liquified hydrogen vs. liquified renewable methane: Evaluating energy consumption and infrastructure for sustainable fuels. Fuel 2023; 350(128779). https://www.sciencedirect.com/science/article/pii/S0016236123013923.
[73] Proesmans P-J, Vos R, editors. Comparison of future aviation fuels to minimize the climate impact of commercial aircraft. AIAA Aviation 2022 Forum; 2022.

[74] Barke A, Thies C, Melo SP, Cerdas F, Herrmann C, Spengler TS. Maintenance, repair, and overhaul of aircraft with novel propulsion concepts – Analysis of environmental and economic impacts. Procedia CIRP. 2023;116:221–6. https://doi.org/10.1016/j.procir.2023.02.038.

[75] Svensson F, Hasselrot A, Moldanova J. Reduced environmental impact by lowered cruise altitude for liquid hydrogen-fuelled aircraft. Aerosp Sci Technol 2004;8(4):307–20. https://www.sciencedirect.com/science/article/pii/S127096380400015X.

[76] Sand M, Skeie RB, Sandstad M, Krishnan S, Myhre G, Bryant H, et al. A multi-model assessment of the global warming potential of hydrogen. Commun Earth Environ 2023;4(1):203. https://doi.org/10.1038/s43247-023-00857-8.

[77] Nojoumi H, Dincer I, Naterer GF. Greenhouse gas emissions assessment of hydrogen and kerosene-fueled aircraft propulsion. Int J Hydrogen Energy 2009;34(3):1363–9. https://www.sciencedirect.com/science/article/pii/S0360319908015048.

[78] Yahyaoui M. The use of LNG as aviation fuel: combustion and emission. In: 13th International Energy Conversion Engineering Conference; 2015. p. 3730.