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H2-powered aviation at airports – Design and economics of LH2 refueling systems

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ABSTRACT

In this paper, the broader perspective of green hydrogen (H2) supply and refueling systems for aircraft is provided as an enabling technology brick for more climate friendly, H2-powered aviation. For this, two H2 demand scenarios at exemplary airports are determined for 2050. Then, general requirements for liquid hydrogen (LH2) refueling setups in an airport environment are derived and techno-economic models for LH2 storage, liquefaction and transportation to the aircraft are designed. Finally, a cost trade-off study is undertaken for the design of the LH2 setup including LH2 refueling trucks and a LH2 pipeline and hydrant system.

It is found that for airports with less than 125 kt_{LH2} annual demand a LH2 refueling truck setup is the more economic choice. At airports with higher annual LH2 demands a LH2 pipeline & hydrant system can lead to slight cost reductions and enable safer and faster refueling. However, in all demand scenarios the refueling system costs only mark 3 to 4% of the total supply costs of LH2. The latter are dominated by the costs for green H2 produced offsite followed by the costs for liquefaction of H2 at an airport.

While cost reducing scaling effects are likely to be achieved for H2 liquefaction plants, other component capacities would already be designed at maximum capacities for medium-sized airports. Furthermore, with annual LH2 demands of 100 kt_{LH2} and more, medium and larger airports could take a special H2 hub role by 2050 dominating regional H2 consumption.

Finally, technology demonstrators are required to reduce uncertainty around major techno-economic parameters such as the investment costs for LH2 pipeline & hydrant systems.

1. Introduction

This paper is about the technological design and economics of liquid hydrogen (LH2) refueling systems at airports to enable the use of hydrogen-powered aircraft. As part of one specific supply chain setup, LH2 refueling systems are defined as the aggregates required to deliver LH2 from storage to an aircraft.

While a significant momentum can already be observed in research and development of aircraft with hydrogen (H2) propulsion, LH2 refueling systems are not available for such aircraft yet, neither does recent research properly cover this – which is briefly highlighted in the following.

H2-powered aircraft are seen as one relevant option to fully decarbonize the commercial aviation sector and thus, to reduce its total climate impact also caused by non-CO2 effects [1–5]. Of course, a CO2-neutral production of hydrogen is a basic prerequisite for this. In contrast to that, most of the global H2 production is not carbon-free and

Abbreviations: ADV, German Airports Association; AWIN, Aviation Week Intelligence Network; BRE, Bremen airport; CAPEX, Capital expenditures; CO2, Carbon dioxide; EEG, Erneuerbare-Energien-Gesetz; EIS, Entry-into-service; FINE, Framework for Integrated Energy System Assessment; FRA, Frankfurt airport; GH2, Gaseous hydrogen; H2, Hydrogen; HAM, Hamburg airport; HRS, Hydrogen refueling station; IATA, International Air Transport Association; ICCT, International Council on Clean Transportation; LAX, Los Angeles airport; LFP, Liquefaction plant; LH2, Liquid hydrogen; MILP, Mixed-integer linear programming; MTOM, Maximum take-off mass; NH3, Ammonia; PAX, Passengers; PPA, Power purchase agreement; RPK, Revenue passenger kilometers; SAF, Sustainable aviation fuels; SEC, Specific energy consumption; SP, Design switch point; TAC, Total annual costs; TEX, Total annual costs excluding energy costs.

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Nomenclature

a	Annuity payment factor
C	Cost in USD_{2020}
d	Distance in km
dp	Depreciation period in years
E_{el}	Electricity consumption in kWh_{el}
ir	Interest rate in %
m	Mass in kg
$m_{LH2,max}$	Maximum peak LH2 demand in t_{LH2}/h
$\widetilde{m}_{LH2,peak}$	LH2 demand of the peak day in a year in t_{LH2}
N	Number of installed components
p	Price in USD_{2020}/kg
r	Region
$\widehat{r}$	Second region in transport case
t_{load}	Truck loading time in h
t_{unload}	Truck unloading time in h
v_{Truck}	Average speed of truck in km/h
X	Capacity

Indices

Con	Conversion systems
H2loss	Losses of hydrogen, e.g., due to boil-off
He	Helium
i	Supply component i
OM	Operation and maintenance
Pow	Power generating or importing sources
Purgeloss	Losses for purging with He
Sto	Storage systems
Tra	Transmission / transport systems
Truck	Truck

relies on fossil fuels today [6,7]. This is why, only green hydrogen production technologies such as electrolysis fed with renewable power are considered in the following.

A further aspect is that the direct use of hydrogen for aircraft propulsion promises higher overall system energy efficiency compared to the use of synthetic kerosene, also called e-fuels [5]. This implies that on a global level less renewable energy would be required to power the aviation sector when using H2 propulsion. Consequently, established and new aerospace companies such as Airbus, ZeroAvia, Universal Hydrogen, Deutsche Aircraft are developing H2-powered aircraft or H2 propulsion technology [8–11].

On hydrogen infrastructure, larger sector-overarching and even aviation-specific projects were announced in the last years. While over 30 national hydrogen strategies were recently published by governments [12], H2 refueling infrastructures for fuel cell electric vehicles are already operated, e.g., in Germany by H2MOBILITY [13]. H2 infrastructure developments can also be observed in the aviation sector. Airbus, Groupe ADP, AirFrance-KLM Group, Paris Region and Choose Paris Region just recently initiated a hydrogen hub airport consortium that plans to work on supplying and handling H2 at airports [14].

Furthermore, several research reports can be found from academia and industry consortia on H2 aircraft and infrastructure. A recent, guiding review is presented by Hoelzen et al. [15]. While there are still many research gaps around aircraft and supply infrastructure, the bridge between both is rarely looked at: LH2 refueling systems for aircraft. Especially, the economics of such refueling systems and the potential impact on aircraft operations has not been investigated thoroughly. Previous research rather concentrated on broader overviews of a future hydrogen-powered aviation landscape [1,5,16–22], or describe LH2 refueling setups only qualitatively [4,23]. Only few very detailed technology studies were conducted in the 1970–1990s by Brewer and colleagues from NASA [24–27] as well as from Cranfield University researchers around the 2000s [28–30]. These studies provide concepts on designing LH2 fuel and refueling systems at larger airports, e.g., Chicago airport, and include detailed descriptions of H2 liquefaction units, LH2 storages, LH2 refueling trucks, cryogenic underground pipelines and dispenser units. Even a detailed modeling methodology for cryogenic LH2 pipelines was presented by Jones et al. [31].

Nevertheless, these research efforts did not consider a techno-economic optimization approach to assess the most economic LH2 refueling system setups for different airport sizes. Furthermore, they did not take into account recent developments for a global H2 economy affecting the availability of H2 technology and its economics.

Although, Hoelzen et al. [15] already found that the costs for LH2 refueling systems might not be a major cost share of the total LH2 costs at the dispenser, economics stay uncertain. Thus, it is shown that LH2 refueling systems might be a crucial enabler for large scale deployment of H2-powered aviation.

Therefore, this work aims to address the following three major research questions. First, what are the requirements for LH2 refueling systems at airports and how large are potential demands of LH2 for aircraft compared to other H2 demands around the airport? The targeted year for the following analyses is 2050, since significant adoption of H2-powered commercial aircraft might not be achieved before [1,5,32]. Second, how could a technological feasible, high-performing LH2 refueling setup at airports look like? Third, what are the economic implications of these systems and what are levers for optimization?

To answer these questions, the paper is structured as follows. In Chapter 2, the potential requirements for future LH2 refueling systems at airports are framed. Scenarios of LH2 demands at airports are derived for 2050 and compared to other H2 demands from other energy systems around airports. Thereafter, the methodological approach including the design of components and energy system modeling is introduced in Chapter 3. Results of the optimization and a sensitivity analysis are presented in Chapter 4, while conclusions, recommendations and a future research and demonstration agenda are derived in Chapter 5.

There is a parallel publication to this paper from Mangold et al. [33] which concentrates on the technological design aspects of LH2 refueling setups, the implications on aircraft turnaround and ground handling processes. It was developed in close collaboration with this work.

2. Context and requirements for LH2 aircraft refueling at airports

In this chapter, the broader context of LH2 refueling setups at airports is investigated in two steps. As a first aspect, scenarios of future LH2 demands for aircraft propulsion are calculated to provide directions on the capacities required for the refueling systems. Furthermore, this is compared to other potential H2 demands around airports to understand the role of airports potentially being H2 hubs versus other regional H2 energy systems or applications. As a second aspect, LH2 supply and refueling pathways are defined for the airport-specific use case and related requirements. Both aspects set the stage for the modeling approach in Chapter 3.

2.1. LH2 demand scenarios in aviation and role of H2 energy systems around airports

The LH2 fuel demand scenarios are calculated within three steps in this section: scope, reference and 2050 projections. Then, the resulting scenarios are used to categorize LH2 demands for aircraft with general H2 energy systems at and around airports.

Table 1
Overview of commercial aircraft segments referenced in this study.

Commercial aircraft category	**Maximum take-off mass (MTOM) of aircraft**, in tons	**Typical capacity**, in passengers (PAX)	**Exemplary aircraft**
Regional (jet and turboprop)	less than 50	20–100	ATR 42/72, DHC-8, Bae 146, CRJ-700, ERJ-135, E-175
Single-aisle	50–150	100–250	E-190, A220, A320 family, B737 family, B757
Medium widebody	150–250	200–300	A330, B767, B787
Large widebody	greater than 250	greater than 250	A340, A350, B777, B747, A380

Definition of scope for fuel demand calculations

This investigation focuses on H2-powered commercial aviation – so, regional, single-aisle, medium and larger widebody aircraft (see Table 1). In 2019, this group of airplanes accounted for approximately 99% of all commercial aircraft related CO2 emissions worldwide [5,34]. General aviation – mostly smaller aircraft flown by private pilots or business aircraft – cargo and military aircraft are not considered in the following. Neither are smaller commercial aircraft, so called commuter aircraft, with less than 20 passengers (PAX) included.

Since this work targets these larger commercial aircraft, the energy system analysis investigates the use and refueling of liquid H2. Due to the higher volumetric density of liquefied H2 compared to compressed gaseous H2 (GH2) as well as the limited available space in commercial aircraft, H2 propulsion systems will rely on LH2 as a fuel for these segments [24,28,35,36].

Reference fuel demands at three airport archetypes

Few other studies already investigated LH2 demands at specific airports by translating historic kerosene demands into equivalent fuel amounts of LH2. In the 1970s, Korycinski [27] and Brewer [24] projected that annual demands for widebody aircraft at each Chicago O'Hare Airport and San Francisco International Airport could be between 200 and 250 thousand tons (kt) of LH2 in the year 2000. Looking at refueling all aircraft at Los Angeles Airport (LAX) with LH2, Amy and Kunycky [16] calculated that around 1,400 kt_{LH2} would be required referenced as 2012 data.

Based on the large range of demand figures it becomes clear that an updated, more detailed overview of potential LH2 demands at airports is required before designing LH2 refueling and supply systems at airports. The demands determined in the following are not meant as market forecasts, but as assumption-based scenarios that provide general perspectives for the analyses undertaken in this study.

For a detailed understanding, three different airport archetypes are selected to determine potential LH2 demands from the chosen aircraft segments: smaller airports with less than 20,000, larger airports with more than 100,000 departing commercial flights per year and medium airports in between. Thus, three exemplary airports in Germany are selected due to data availability. Bremen Airport (BRE) as a smaller airport, Hamburg Airport (HAM) as a medium airport and Frankfurt-Main Airport (FRA) as a larger airport are chosen. A detailed overview of the methodology, sources and assumptions that are used for the LH2 demand scenarios can be found in Appendix A and the supplementary material.

In 2019, the calculated annual kerosene demand for commercial aircraft was 38, 366 and 4,661 kt of fossil kerosene at BRE, HAM and FRA, respectively. At smaller and medium airports, flights with regional and single-aisle aircraft account for the majority of kerosene demand with 95% at BRE and 80% at HAM. Most flights with these aircraft connect national and intra-European airports. At larger airports, which often serve as an international hub, the opposite is observed – for example, at FRA less than 20% of the kerosene demand comes from these aircraft segments. Since medium and larger widebody aircraft carry more passengers, consume more energy per kilometer and fly longer distances, these drive the high demand for fuel at the airport. At FRA around 3,000 kt of kerosene (64% of total) are calculated to be refueled for larger widebody aircraft only.

However, several studies state that true zero CO2 emission propulsion systems like H2 propulsion require larger technological breakthroughs to be an economic choice for such larger widebody aircraft by the year 2050 [1,5,22,37]. Consequently, the following analysis does not consider this larger aircraft segment and assumes that such aircraft would rather be fueled with Sustainable Aviation Fuels (SAFs) to achieve net-zero carbon emissions. If these kerosene consumptions are subtracted from the 2019 figures, considered annual fossil fuel demands at these airports are 38, 322, 1,686 kt of kerosene for BRE, HAM and FRA, respectively (Fig. 1a and second column Table 2).

Besides the total annual fuel demand, Fig. 1b and 1c highlight another important design requirement for refueling systems at airports. These show the variation of fuel demand over an average day and over the months of a year for the example of Hamburg Airport in 2019 [38,39]. Like at most German airports a night curfew restricts aircraft operation which can be seen in Fig. 1b. Furthermore, aircraft departures peak in the morning and evening times. Considering a whole year, April to October are busier months with around 10% higher air traffic (departures) than in the colder months November to February with 15% less traffic compared to the annual average. Even though the exact

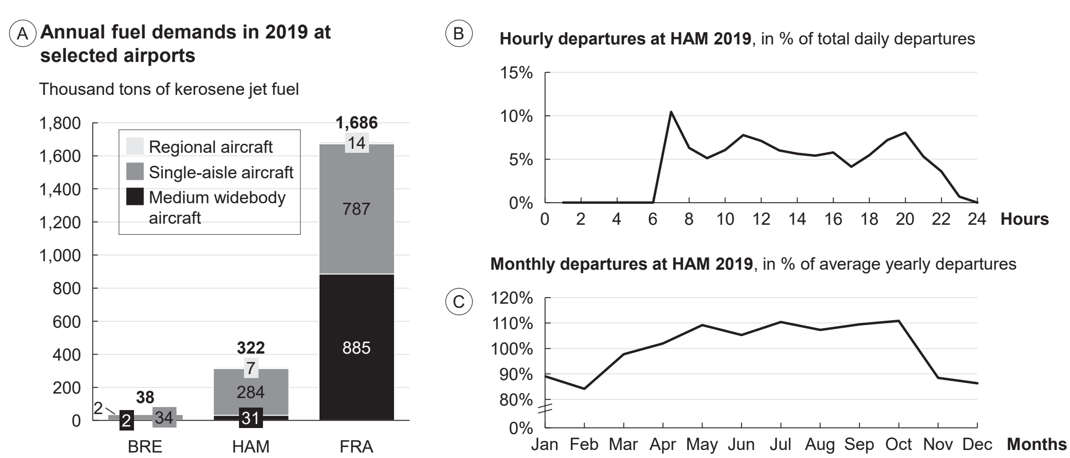

Fig. 1. a) Considered annual fossil kerosene fuel demand in 2019 at three German airports without larger widebody aircraft, b) average daily aircraft departures at HAM in 2019 [39], c) monthly aircraft departures at HAM in 2019 [38].

Table 2
Calculated annual fuel demands for 2019 at selected airports and 2050 demand scenarios – all excluding large widebody aircraft.

Airport (Example)	**Considered total fuel demand 2019**, in t of kerosene	**Converted total fuel demand 2019**, in t of LH2-equivalent	**Projected total fuel demand 2050**, in t of LH2-equivalent	**Base case scenario: LH2 demand 2050**, in t per year	**Ambitious case scenario: LH2 demand 2050**, in t per year
Smaller (Bremen)	38,467	15,463	20,722	9,949	17,416
Medium (Hamburg)	321,722	130,235	175,505	80,600	142,390
Larger (Frankfurt)	1,686,052	698,330	987,668	317,375	565,206

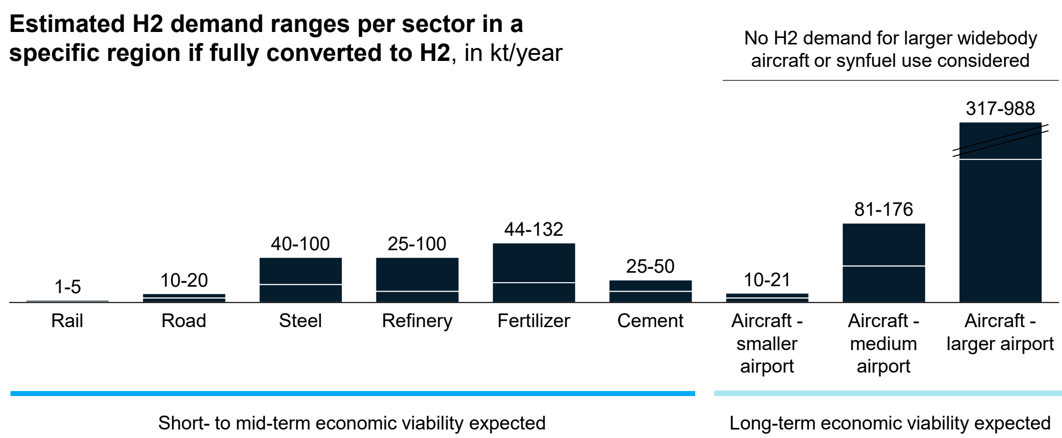

Fig. 2. Annual H2 demand ranges for different sectors at a specific region and their projected economic viability based on [7,12] – specific region defined as a generic location (e.g., city, industry park) where these sectors are placed; due to economic uncertainty and highly varying demand sizes inputs from other sectors such as power services [48], building heating [43,44] or maritime [49,50] are not shown.

distribution of air traffic will certainly differ for each airport depending on the type of airlines and flight destinations at the airport, similar phenomena are assumed for all airport types in this study.

To enable aircraft refueling with LH2 in seasonal but also daily peak times the design of a fuel system at an airport has to cover such fluctuations accordingly, further details will be discussed in Chapter 3.

After the calculation of fossil kerosene demands in 2019, the figures are converted into LH2-equivalent fuel demands based on energy conversion factors also reflecting a change of specific energy consumption (SEC) per aircraft segment (see Appendix A). The results excluding larger widebody aircraft are shown in the third column of Table 2. Based on these assumptions including the fuel demands and number of flights at the specific airports, flights with regional aircraft would consume on average 0.25 t_{LH2}, with a single-aisle aircraft 1.8 t_{LH2} and a medium widebody aircraft 16 t_{LH2}. Further detail can be found in the Supplementary Material.

2050 fuel demand scenarios

In the next step, aircraft fuel demands are projected until 2050. Despite the current, temporally, drastic decrease of air traffic due to the COVID health crisis, a strong growth is forecasted for the aviation sector over the next decades [40–42]. Airport specific results are displayed in the column “Projected total fuel demand 2050” in Table 2. These reflect air traffic growth projections that lead to an overall increase of total fuel consumption as well as aviation efficiency improvements that decrease the specific energy demands per aircraft (see Appendix A).

Furthermore, two different deployment scenarios of H2-powered aircraft are used to project the demand of LH2 for 2050. This will be used to derive the demand context for LH2 refueling setups at airports. Both scenarios consider a future in which H2-powered aircraft will be techno-economically feasible, but with different progressive assumptions. In the base case scenario, deployment of H2-powered aircraft will start to scale between 2040 and 2050. In the ambitious scenario, this deployment will already reach larger H2 fleet delivery rates in the late 2030 s (details provided in Appendix A).

The 2050-scenarios show clear differences between the magnitudes of LH2 demands at airports depending on their size (fifth and sixth column of Table 2). This is now discussed and set into context to other H2 applications.

LH2 at airports and their role in an overarching H2 energy system

At a smaller airport like BRE the 2050-projections indicate an annual LH2 demand of 10 to 17 kt_{LH2} (27 to 48 t_{LH2} daily) depending on the base and ambitious case scenario assumptions.

This amount of LH2 is in a similar order of magnitude such as projected demands for H2-powered road applications in regions with higher mobility demands. As highlighted by Ueckerdt et al. [43] and Staffell et al. [44], H2-powered heavy-duty vehicles might be an economically viable decarburization option compared to other alternatives such as battery-electric vehicles. One H2 refueling station (HRS) for such larger vehicles might have an average daily consumption of 2.5 tons of H2 [45]. Hence, in a region with around 10 to 20 HRS a similar H2 consumption (10 to 20 kt_{H2}) would result than for aircraft at BRE in 2050 (Fig. 2).

For H2-powered rail applications, H2 demands at rail HRS are in a similar size. At Bremervoerde, Germany, a HRS with a daily capacity of 1.6 t_{H2} was already installed for trains [46]. However, the amount of required HRS in a specific region is significantly lower for rail applications [47]. Hence, regional H2 demands from trains are assumed to be lower than for road applications.

The LH2 demand scenarios for aircraft at medium sized airports such as HAM are calculated to be around 81 to 142 kt_{LH2} in 2050. This equals 46 to 81% of a theoretically maximum LH2 fuel consumption for aircraft in that year – similar to the results at BRE. Reason for this effect at BRE and HAM is that at both airports most flights are assumed to be operated with regional and single-aisle aircraft; both segments that are

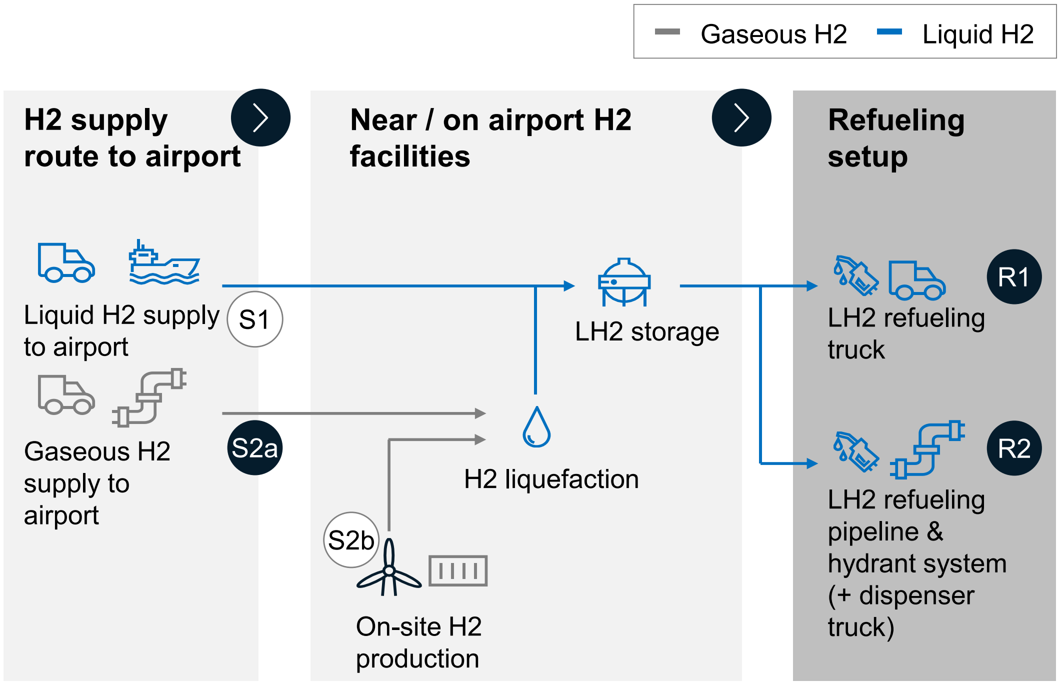

Fig. 3. Topologies for H2 supply routes and LH2 refueling setups at airports.

predestined for the potential deployment of H2 propulsion [5].

For comparison, industrial applications are or might be operated with H2. Today, grey H2 is used as a feedstock in fertilizer plants producing ammonia and in refineries for, e.g., hydrocracking. Furthermore, steel, iron and cement plants are being discussed to use green H2 as a new feedstock for decarbonizing these heavy carbon emitting sectors [7,12].

In Germany, 40 million tons of steel were produced in 20 steel plants in 2019 [51]. Assuming a future green H2 consumption for one ton of steel production of 20 to 50 kg_{H2} [52–54], an average plant would require around 40 to 100 kt_{H2} per year.

Similar H2 consumption figures are calculated for refineries and ammonia production. Refineries with an annual capacity of 5 to 10 million tons crude oil input would require 25 to 100 kt_{H2}/a assuming a H2 demand of 5 to 10 kg per ton of crude oil input [53]. A fertilizer plant with an output of 250 to 750 kt of ammonia (NH3) [55] and a H2 consumption of 176 kg_{H2} per ton of NH3 [53] would also consume a similar demand with 44 to 132 kt_{H2} per year.

These values show that potential LH2 demands at medium airports could become as large as the H2 demand of larger industrial plants operated with H2. In a specific region, such an airport could already take the role of a H2 hub in a broader, surrounding H2 energy system. In that case, the H2 hub is the central and very large consumer of H2 for which dedicated H2 supply could be designed. Other H2 applications around such a hub might then benefit from potentially lower supply costs due to economies of scale.

At larger airports like FRA the LH2 demand scenarios result in 317 to 565 kt_{LH2} in 2050. In this case, only 32 to 57% of the total equivalent fuel demand, excluding larger widebody aircraft, would be substituted by H2-powered aircraft. Including the fuel demand of larger widebody aircraft this share decreases to 10 to 17% only.

While the LH2 demand is rather low compared to the total fuel demand at FRA in 2050, it is already 2 to 4 times larger than the largest fertilizer plant assumed above (Fig. 2). Moreover, this also shows significant potential of increasing demands in the decades thereafter, given that the fleet penetration of H2 aircraft could increase further. Consequently, the role of such a large airport in a specific region might trump all other H2 consumptions from other sectors around the airport. However, there are less than 100 larger airports worldwide extracted from [56], as defined in this work, that might take such a special role in regional H2 energy systems.

Next to the insight that LH2 demands at airports could become dominant in some regions two additional trends can be observed.

First, most other sectors might feed GH2 and not LH2 such as the aviation sector. So, cost synergies for LH2 sub-systems might be limited. LH2 is discussed in the heavy-duty road and maritime sector or for general transportation of H2 over longer distances only [44,57]. Consequently, the design of such LH2 supply and refueling systems at airports could take a unique role in a future hydrogen economy.

Second, based on economic viability analyzed in [12] and [7] the introduction of the discussed other H2 applications might happen until 2030 already (short- to mid-term horizon), while larger scale deployment might take longer than 2035 in the aviation sector [1,5]. This could mean that the installation of general H2 fuel infrastructure might take place without considering the aviation use case.

All in all, as a context for designing LH2 refueling systems at airports it becomes clear that demands could reach large orders of scale by 2050. Nevertheless, for the design of such systems the whole context of H2 infrastructure around airports has to be considered. Since other sectors might require a H2 supply infrastructure already one decade earlier than needed for larger commercial aircraft, synergies or resource conflicts should always be investigated before deploying LH2 systems at airports.

2.2. Refueling topologies and setups for LH2 at airports

LH2 as a fuel for aircraft is projected to be sourced by various hydrogen fuel supply routes that are discussed in the following and shown in Fig. 3. Since the target of introducing H2-powered aviation is to achieve true zero CO2 emissions, only green H2 supply chains are considered.

As a start, there are several H2 supply routes to an airport. If H2 is produced off-site of the airport, it can be transported in its liquid or gaseous form. Transport modes for LH2 could be trucks, rail, vessels or pipeline systems (S1 in Fig. 3) or for GH2 it could also be trucks or a pipeline (S2a) [26,58,59]. In these routes, H2 production via electrolysis plants powered by renewable energy are placed at a central location off-site the H2 demand side (airport) [60]. This could be located in the same country, but also farther away on other continents to make use of favorable, low-cost conditions for renewable energy supply [15,17].

If H2 is produced on-site or nearby the airport (S2b), transportation of GH2 is not required necessarily. In both supply pathways S2a and S2b, GH2 is liquefied at or in the near of an airport. After the liquefaction of H2 or if H2 is already delivered in its liquid form, LH2 is stored in tanks at or near the airport. These LH2 storage facilities are mainly required to buffer daily and seasonal fluctuations in fuel demands (see Fig. 1b and 1c), but also to ensure LH2 supply reliability over several days – in case, the supply chain is disrupted by other events.

There are currently two major LH2 refueling pathways discussed to distribute LH2 from the LH2 storages to the aircraft [4,5]: LH2 refueling trucks (R1) or a LH2 pipeline & hydrant system (R2).

While the use of LH2 refueling trucks enables a more flexible deployment option, these would contribute to increasing traffic on airport aprons. The investment per refueling truck is rather limited and the number of required trucks can be adjusted flexibly to the demand of LH2 at airports (more details in Chapter 3 and 4). However, the LH2 loading volume of one refueling truck is limited and space for a larger fleet of these could be rare at airports.

In addition to that, increased safety and potentially faster aircraft refueling and hence, faster turnaround times are the reasons why, LH2 refueling pipelines & hydrant systems are seen as an alternative. These systems could be built underneath the airport apron and accessed through a hydrant at each aircraft stand. In comparison to the deployment of refueling trucks, the installation of a pipeline & hydrant refueling system comes with high upfront expenses and a longer lifetime over several decades. Thus, the dimensioning of this system – and hence, its costs – are not as flexible to adjust as with refueling trucks. Similar considerations are also taken into account at airports for the design of current kerosene refueling systems [61,62].

For both refueling setups, a dispensing unit is required for the refueling procedure to connect the pipeline or the LH2 tank on the refueling truck to the LH2 storage on-board the aircraft [24,28]. Furthermore, such dispenser systems can function as purging unit to "wash" out the LH2 refueling hoses from other gases before refueling with cryogenic LH2 (more details in parallel publication [33]). This dispensing unit can be integrated onto the refueling truck. For pipelines a dispensing truck is operated between aircraft stands to connect the hydrant and the LH2 aircraft tank.

Since the focus of the following analyses lies on the design choices for different LH2 refueling setups at airports (R1 and R2), only one supply pathway is chosen for detailed investigation.

It is assumed that GH2 supply (S2a) is available through pipelines at the discussed airports in these 2050 scenarios. This is seen as a realistic assumption for the selected European airports, because retrofitting and installation of a European hydrogen pipeline system is already discussed [63,64]. This also means that H2 production via electrolysis is not further considered in detail. Comprehensive studies on H2 supply routes for airports are subject for future publications.

In addition to the techno-economic design optimization of the LH2 refueling system, three side aspects have to be kept in mind.

First, availability of space to place additional refueling systems at airports is often very limited, especially at larger airports [62]. Consequently, the design of LH2 refueling systems has to reflect, if these can be placed at a specific space on the airport or on land nearby the airport.

Second, the responsible operator of refueling systems has to be determined to be able to allocate the costs for LH2 refueling operations correctly. Most fuel infrastructures at airports are not operated by the airport managing company, but by third parties such as oil & gas companies. This is often organized with concessions granted by the airport company for longer time periods (e.g., decades) [65]. Accordingly, refueling infrastructure and operating costs are often included in the fuel price paid by the aircraft operator and not as a separate fee or levy paid to the airport [61,66].

Third, airport infrastructure and operation of aircraft is highly regulated to ensure safe operations [67]. That is why it is likely that the design of LH2 systems at airports and LH2 refueling procedures will have to comply with high safety standards that are also applied to kerosene infrastructure. Several hydrogen component-specific standards can already found in the SEVESO [68], the ATEX directives [69] and the directive 2010/75/EU on industrial emissions [70]. These include general comments on plant safety, occupational safety, consumer protection, construction law, traffic law, environmental law, insurance law and energy industry law, but nothing specifically applicable to an aviation context. Also no safety zone radius and other distances are specified.

Only a withdrawn ISO-certification is found from 2004 [71] that is looking at processes required to handle H2-powered aircraft. However, no insights are provided on potential safety and certification requirements.

In the parallel publication from Mangold et al. [33], study results do not indicate that safety standards for LH2 refueling should be different to current kerosene standards. Additionally, the modeling of new turnaround processes with LH2 showed that turnaround times and gate designs might be unchanged compared to kerosene handling.

3. Modeling a hydrogen refueling infrastructure at airports

In this chapter, the modeling approach of LH2 energy systems at airports is shown in three steps. First, an overview of the selected approach and model is provided. Second, the individual components of the energy system including their techno-economic assumptions are discussed. Third, a generic airport design is created to ensure that airport requirements and constraints are reflected in the model.

3.1. Modeling framework for LH2 energy systems at airports

The energy system is modeled to investigate the functional relationships of the previously described supply chain and refueling setups (Fig. 3) as well as the resulting supply costs of LH2.

For this study, the open-source FINE framework [53] is modified for the context of LH2 refueling systems. It uses a mixed-integer linear programming (MILP) approach for optimization. The adjusted model structure needed for the following analyses will be outlined briefly.

In detail, different components (source, conversion, storage, transmission, sink) as illustrated below are described in the energy system. These are spatially and temporally resolved – hence, each component can be sized accordingly and geospatial contexts are reflected by using different locations, while considering technical constraints [53].

For the modeling of LH2 refueling systems at airports all relevant components are characterized, commodities (such as H2, electricity and purging gases) are defined and the geographic allocation of fuel processing and storage farms, transportation and refueling at the aircraft gates is determined, see Sections 3.2 and 3.3.

The overarching objective of the energy system optimization is to minimize total annual costs (TAC, C_{TAC}) in Eq. (1.1):.

$$C_{\mathrm{TAC}} = \sum_{pow \in Pow} \sum_{r \in R} C_{\mathrm{TAC},r,pow} + \sum_{con \in Con} \sum_{r \in R} C_{\mathrm{TAC},r,con} + \sum_{sto \in Sto} \sum_{r \in R} C_{\mathrm{TAC},r,sto} + \frac{1}{2} \sum_{tra \in Tra} \sum_{\hat{r} \in R} \sum_{\hat{r} \in R} C_{\mathrm{TAC},r,\hat{r},tra} \tag{1.1}$$

Table 3
Techno-economic parameters for LFPs in 2050 based on [58,87–89].

Component	Capacity X_{con} in t_{LH2} per day (tpd)	Specific CAPEX in Mn USD_{2020} per capacity (tpd)	Depreciation period dp_{con} in years	Specific energy demand $E_{el,con}$ in kWh_{el} per kg_{LH2}	Annual O&M costs $C_{OM,con}$ in % of total CAPEX	Specific losses $m_{H2loss,con}$ per kg_{H2} feed
Small LFP	24–96	$1.6\ X_{con} + 45.8$	20	9	4	1.65%
Medium LFP	96–192	$1.2\ X_{con} + 87.4$		7.5		
Large LFP	192–312	$0.96\ X_{con} + 127$		6.68		
Extra-large LFP	312–864	$0.73\ X_{con} + 197$		6.1		

The TACs are calculated by adding all specific TACs of power generating or importing sources (pow), conversion systems (con), storages (sto) and transmission components between two locations (tra). The index r describes the region in which the components are located, $\hat{r}$ is used to represent the respective second location during a transport between two locations. Since the costs for the transport component in the model framework are divided between two locations and finally summed up, the cost split is calculated using a factor of 0.5.

In this study, electricity and H2 production are not considered in detail. Hence, only costs for sourcing such commodities are included in the TAC calculation for conversion, storage and transmission components. The total annual costs C_{TAC} for each component i consist of the total annual costs excluding energy costs (TEX, C_{TEX}), the energy costs for H2 consumptionC_{H2}, for H2 lossesC_{H2loss}, for electricityC_{El}, for purge gas $C_{Purgeloss}$ and for trucking C_{Truck} (Eq. 1.2–1.8):.

$$C_{TAC,i} = C_{TEX,i} + C_{H2,i} + C_{H2loss,i} + C_{Eel,i} + C_{Purgeloss,i} + C_{Truck,i} \tag{1.2}$$

$$\text{with} \quad C_{H2,i} = m_{H2,i} \cdot p_{H2}$$

$$C_{H2loss,i} = m_{H2loss,i} \cdot p_{H2} \tag{1.4}$$

$$C_{Eel,i} = E_{el,i} \cdot p_{Eel} \tag{1.5}$$

$$C_{Purgeloss,i} = m_{He,i} \cdot p_{He} \tag{1.6}$$

$$C_{Truck,i} = p_{Truck} \cdot d_{r,\hat{r},tra} \tag{1.7}$$

$$m_{H2,i}, m_{H2loss,i}, E_{el,i}, m_{He,i} \in \mathbb{R}_{\geq 0} \tag{1.8}$$

The total annual costs excluding energy costs C_{TEX} for each component class are derived in Eq. 1.9–1.13 with the investment costs C_{CAPEX}, number of installed components N, an annuity payment factor a and an annual cost share for operation and maintenance costs C_{OM}. Costs for transmission components are provided per km length, so the distance d between two locations is reflected. Interest rates ir used to calculate annuity payment factors are assumed to be 6% for all components. The individual depreciation periods dp are shown in Section 3.2.

$$C_{TEX,r,con} = C_{CAPEX,con} \cdot N_{r,con} \cdot \left(a_{con} + C_{OM,con}\right) \tag{1.9}$$

$$C_{TEX,r,sto} = C_{CAPEX,sto} \cdot N_{r,sto} \cdot \left(a_{sto} + C_{OM,sto}\right) \tag{1.10}$$

$$C_{TEX,r,\hat{r},tra} = C_{CAPEX,tra} \cdot N_{r,\hat{r},tra} \cdot d_{r,\hat{r},tra} \left(a_{tra} + C_{OM,tra}\right) \tag{1.11}$$

$$\text{with} \quad N_{r,con} \in \mathbb{R}_{\geq 0}, N_{r,sto} \in \mathbb{Z}_{\geq 0}, N_{r,\hat{r},tra} \in \{0, 1\}$$

$$a_i = \frac{(1 + ir)^{dp_i} \cdot ir}{(1 + ir)^{dp_i} - 1} \tag{1.13}$$

For the temporal abstraction, which is required due to the time dependent demand profile introduced in Section 3.2, hourly time steps are used. Furthermore, main constraints are determined to ensure a balanced energy system at every time step and that each sub-system is designed according to its technological feasibility limits. These constraints are explained in detail in [53].

All cost-specific parameters are given in United States Dollars for the year 2020 (USD_{2020}). An exchange rate of 1.2 is chosen for EURO to USD calculations [72]. Thus, pre-2020 inflation is adjusted in USD based on data from [73].

Next to the optimization function and major constraints, the LH2 supply pathway has to be described in more detail – used components and commodities are introduced in the following.

3.2. Techno-economic descriptions of components

In this section, assumptions for the techno-economic parameters are derived for all relevant components. Since the LH2 demands in 2050 are investigated, parameters are also projected for this year.

Commodities

First, the three commodity sources H2, E_{el} and He (from Eq. 1.2–1.8) are described.

Green GH2 is fed into the LH2 refueling system at the airport via a GH2 pipeline (S2a in Fig. 3). The feeding costs are highly variable and come with large uncertainties as shown by Hoelzen et al. [15]. Currently, the supply of green GH2 is still limited because there is no established market, but this will change by 2050 according to [64]. In this work, it is assumed that green GH2 can be sourced for $p_{H2} = 1.80\ USD_{2020}/kg_{H2}$ in 2050 taken from [5,15]. Only the sourcing price is considered, costs for electrolysis are not considered separately.

Electricity is required to power aggregates such as the liquefaction plant and pumps in the LH2 refueling setups. Like for the GH2 production, it is assumed that renewable electricity is used to reach minimized climate impact. Even though renewable electricity costs highly depend on geographical factors (sun radiation, wind velocities etc.), a constant cost of $p_{Eel} = 50\ USD_{2020}/MWh_{el}$ is assumed based on [59,74,75]. Special levies, e.g., Erneuerbare-Energien-Gesetz (EEG) in Germany, or higher grid fees are not considered in this 2050 projection.

The use of purging gas is assumed to be required for the preparation of the refueling equipment before the actual LH2 refueling can be conducted. Further details can be found in the description of the refueling components and in the parallel publication by Mangold et al. [33]. Hence, Helium is chosen as purging gas with average costs of around$p_{He} = 17.5\ USD_{2020}/kg_{He}$ [76].

Price fluctuations or limitations in availability are not considered for the commodity sources. It is assumed that long-term contracts for GH2 feed and storage facilities for purging gas at the airport would enable a sourcing strategy to minimize such costs. Thus, renewable electricity might be sourced through individual power purchase agreements (PPA) to ensure best and constant electricity costs.

Liquefaction of H2

Second, the conversion of GH2 to LH2 with a hydrogen liquefaction plant (LFP) using green electricity is regarded. The general liquefaction process is divided into different stages of cooling, compression and expansion in order to achieve the boiling point of H2 at around 20 K [77–83].

There are different process designs for hydrogen liquefaction available – in large-scale industrial applications, the Claude process and helium Brayton cycles are used in particular. Although the investment

Table 4
Techno-economic parameters for LH2 storage based on [16,59,93,96].

Component	Capacity X_{sto} in t_{LH2} stored	Specific CAPEX in USD_{2020} per kg_{LH2} stored	Depreciation period dp_{sto} in years	Specific energy demand $E_{el,sto}$ in kWh_{el} per kg_{LH2}	Annual O&M costs $C_{OM,sto}$ in % of total CAPEX	Specific losses $m_{H2loss,sto}$ per kg_{LH2} stored
Small storage	20–100	39 X_{sto}	20	Not applicable – passive cooling	2	0.1%
Medium storage	100–250	$33.6X_{sto}$ + 540,000				0.07%
Large storage	250–550	30 X_{sto} + 1,440,000				0.035%
Backup storage	3 $\cdot\widetilde{m}_{LH2,peak}$	see above[a]				0.035–0.1%[a]

[a] Depending on storage size.

Table 5
Techno-economic parameters for cryogenic pump systems based on [87,98].

Component	Capacity $X_{tra,pump}$ in t_{LH2} pumped per h	Specific CAPEX in USD_{2020} per capacity (t_{LH2}/h)	Depreciation period $dp_{tra,pump}$ in years	Specific energy demand $E_{el,tra,pump}$ in kWh_{el} per kg_{LH2}	Annual O&M costs $C_{OM,tra,pump}$ in % of total CAPEX	Specific losses $m_{H2loss,tra,pump}$ per kg_{LH2} feed
Cryopump	1.2 $\cdot m_{LH2,max}$	256,300	10	0.1	3	0%

costs for the Claude process exceeds those of the Brayton cycle, the Claude process provides a significantly higher process efficiency, which results in lower operating costs. Since the demand scales for the aviation use are rather large and would profit from lower operating costs, the Claude process is chosen for this work [84].

The theoretic minimal physical liquefaction work for H2 is 3.92 kWh/kg_{H2} [85]. However, in real industrial applications losses occur in heat exchangers, pumps, compressors, expanders, air-coolers, separators and mixers [86]. Depending on economies of scale, specific energy consumptions (SEC) and relative costs decrease with larger plant capacities. CAPEX are calculated with the specific CAPEX multiplied with the capacity X_{con}. All parameters including O&M cost, depreciation periods and H2 losses are presented in Table 3.

LH2 storage

Third, the LH2 storage that is required as a buffer and as a backup for supply reliability in the LH2 supply route is discussed.

The buffer storage is placed after the LFP and before the refueling route via truck or pipeline. It enables a more flexible and constant operation of the LFP, since the storage is used to balance out temporal fluctuations in the LH2 demand profile. Hence, the LFP can be operated in its optimum load setting.

The backup storage ensures supply reliability of LH2 at the airport. Today, fuel supply at airports have to be stable for several days. In this study, a storage capacity of LH2 for three days of the LH2 demand of the peak day in a year $\widetilde{m}_{LH2,peak}$ are set as reserve capacity and its fill level should not fall under 90% in normal operation which is in accordance with findings in [4,5]. Consequently, the backup storages are not used for daily fulfilment under normal conditions.

A spherical or cylindrical shape ensures optimized surface-to-volume ratio of LH2 storages and therefore reduced heat input from the outside [26,90], while vacuum-insulated double walls prevent heat transfer by convection [91,92]. However, H2 losses cannot be fully prevented due to spontaneous conversion of the two isomeric forms of H2 (*ortho*-to-*para*-conversion) [78,79]. The resulting vaporized H2 must be vented off the storage to avoid overpressures.

Nevertheless, daily losses of large storage facilities (see Table 4) are comparatively low [77,79,93,94] and resulting costs for losses are potentially lower than the costs for additional active cooling systems [95]. Thus, due to the expected high usage and fluctuation of LH2 in tanks in an airport environment, it is assumed that the constant LH2 flows also limit losses.

Table 4 displays all relevant techno-economic parameters for LH2 storages including similar economies of scale effects like for the LFP.

LH2 refueling route

Forth, the transport of LH2 between the fuel farm and aircraft stands can be realized by either LH2 refueling trucks or a LH2 pipeline and hydrant system as described in Section 2.2. In addition to that, this study considers two cryogenic pump (cryopump) systems that are required for both setups to generate the flow of LH2 for transmission.

There are different types of cryopumps available, but most have not yet reached commercial maturity for large scale applications. Hence, data availability on techno-economics is very limited. Further research is needed especially to achieve high flow rates that might be required in the investigated airport context [87,97]. For the analysis, it is assumed that these technology challenges can be overcome by 2050.

The first pump system is used to either fill the LH2 trucks at the LH2 storages or to create the required mass flow to feed the LH2 pipelines, depending on which option is chosen. Another pump system is required for the fuel flows when refueling the aircraft. In this model, trucks have an additional cryopump on board, while the LH2 pipeline & hydrant system includes a mobile dispenser unit (truck and cryopump system). As a simplification, it is assumed that both pump systems have the same capacities. Moreover, the costs of a sub-cooling unit for the LH2 prior to refueling as described in [33] is assumed to be dealt with the pump system costs.

All techno-economic parameters required to describe the cryopump systems can be found in Table 5 including a linear CAPEX calculation based on the required maximum pump capacity depending on the peak demand per hour $m_{LH2,max}$ (see section "demand profile") and a safety factor of 1.2. The use of the safety factor ensures that the cryopumps do not become a bottleneck in supplying LH2 to aircraft in peak demand times.

The first refueling setup uses refueling truck systems; parameters are provided in Table 6. One LH2 refueling truck system is defined as a tractor, an insulated cryogenic LH2 tank mounted on a trailer and a small purging gas storage including a dispenser unit. The usable capacity of the LH2 tank is assumed to be 4 t_{LH2} in total, 4% additional capacity remains permanently in the tank to keep it cool. These storage tanks are built and isolated similarly as the large storage tanks [58]. Since a small amount of LH2 has to stay in these tanks at all times to keep the tanks cool (called ullage), H2 losses are considered for this (Table 6). The refueling truck systems are detailed out in the parallel paper [33].

The refueling trucks are parked and fueled at the central fuel farm and drive via the apron to the aircraft for refueling. The following assumptions are made according to [58,59,99–103]:.

- Average speed of a truck at the airport is v_{truck} = 25 km/h

Table 6
Techno-economic parameters for dispenser and LH2 refueling trucks based on [24,58,71,90,100–102].

Component	Capacity $X_{tra,truck}$ in t_{LH2} stored	Specific CAPEX in USD_{2020} per truck	Depreciation period $dp_{tra,truck}$ in years	Specific energy cost p_{Truck}	Annual O&M costs $C_{OM,tra,truck}$ in % of total CAPEX	Specific losses $m_{H2loss,tra,truck}$ per kg_{H2} feed
LH2 dispenser truck	No storage	90,000	12	Not considered	3	Not applicable
LH2 refueling truck	4	90,000 for truck + 550,000 for LH2 trailer		0.35 USD_{2020} per km		0% while driving, 1% for loading and unloading process

Table 7
Techno-economic parameters for LH2 pipeline & hydrant system based on [24,31,58,105,106].

Component	Capacity $X_{tra,pipe}$ in transported t_{LH2}/h	Specific CAPEX in Mn USD_{2020}	Depreciation period $dp_{tra,pipe}$ in years	Specific energy demand in kWh_{el} per kg_{LH2}	Annual O&M costs $C_{OM,tra,pipe}$ in % of total CAPEX	Specific losses $m_{H2loss,tra,pipe}$ per kg_{H2} feed and km length
LH2 pipeline	$X_{tra,pipe} = \begin{cases} 72, m_{LH2,max} < 72 \\ m_{LH2,max}, m_{LH2,max} \geq 72 \end{cases}$	$\frac{5}{72} * X_{tra,pipe} * 2d$	40	Not applicable	3	0.175%

- Truck loading time from the LH2 storage at the fuel farm takes on average 30 min taking into account the maximum available cryopump capacity used ($t_{load} = 0.5$ h)
- Unloading time is on average 30 min, consisting of time given for the attachment and detachment of the refueling couplings, the flushing and cooling processes, and the refueling itself ($t_{unload} = 0.083$ h + 0.083 h + 0.33 h)
- For peak demand hours: In the event that several small aircraft have to be refueled simultaneously, there must always be a minimum number of trucks installed to manage parallel refueling operations
- Moreover, 350 $kUSD_{2020}$ of fixed costs are accounted for a fueling and maintenance building, if refueling trucks are used.

The second LH2 refueling setup uses a pipeline system with hydrants for refueling at the gates – analogue to existing kerosene pipeline & hydrant systems. Relevant techno-economic parameters are displayed in Table 7.

Within the pipeline system, LH2 is constantly available, which allows larger outputs of LH2 at the airport gates. The double-walled LH2 pipelines are designed with a minimum diameter of 254 mm in order to reduce friction inside the pipes for smaller diameters, while a maximum flowrate of 20 kg_{LH2}/s, so 72 t_{LH2}/h is permitted for this diameter setting [24]. This minimum diameter size seems reasonable in the airport context according to [35] and [36] – further details on LH2 flowrates can be found in the parallel publication [33].

For a reliable operation and to avoid two phase flows of hydrogen in the pipeline, it is recommended to design the pipeline as a three-phase system as described by [24,104]. A primary LH2 supply loop, a spare loop for redundancy (supply reliability), and a collection loop for GH2 are installed together in one pipeline bundle. The pipeline has a circular design in order to ensure a steady LH2 flow and requires an inlet and outlet from the storage tank. This circulation, driven by the pump at the storage, prevents high heating at periods of low demands, so low flow rates [24].

Furthermore, the pipeline should be as accessible as possible and only run underground in direct aircraft taxi areas or at gates to allow easier access in case of maintenance or malfunction. In order to be able to constantly monitor damages to the pipeline, methods of monitoring the vacuum should be established [24,71].

To connect the LH2 pipeline with the aircraft, the mobile dispensing units mentioned above are used at the pipeline hydrants, see also Table 6 for parameters. In the calculation, costs for an extra personnel handling the dispensing unit and refueling process are considered, if the pipeline & hydrant setup is chosen.

Details around the purging process and requirements are described in the parallel publication [33]. It has to be noted that this study assumes the use of already commercialized Johnston type couplings that require purging. This is seen as a conservative assumption, since the development of a clean-break coupling - that would not require purging and hence save costs - might be accomplished by 2050. Consequently, helium as a purging gas is used when connecting aircraft LH2 tank to the refueling hose. The used helium evacuates the free space of oxygen and other gases to prevent damages potentially caused by frozen gases. It is assumed that 1 kg_{He} per refueling of 1 t_{LH2} is consumed for purging which cannot be recycled.

LH2 demand profile

A time dependent demand profile is used as an input for the model to simulate the LH2 demand for aircraft by each time step. This is used in the model for the optimized sizing of each component.

Based on the findings for demand fluctuations shown in Fig. 1, it is assumed that the hourly demands fluctuate between 100 and 120% of the base demand profile due to different peak flight hours (see Fig. 1b). Furthermore, annual fluctuations also have to be reflected due to seasonal differences (vacation periods and other effects [107]). Hence, an additional 10% upward deviation in the hourly maximum LH2 demand $m_{LH2,max}$ is assumed, while the total annual demand remains the same (see Fig. 1c). Consequently, the installed capacities of pipelines, trucks and cryopumps are designed accordingly.

The backup storage is only affected by the annual demand fluctuations to have sufficient supply reserves during peak days in case the supply is interrupted. So, $\widetilde{m}_{LH2,peak}$ is calculated based on the average daily demand adding 10% for the LH2 demand on a peak day in a year.

Finally, to reduce computing times calculating for 8,760 unique time steps (one year), a time series aggregation module is used to form clusters of typical periods. This reduces the total number of time steps within the optimization while keeping the error small. For 12 representative days the error accounts for less than 2% [108].

3.3. Generic airport model

As a last major aspect of the modeling approach, a generic airport design is determined to reflect an exemplary geospatial placing of future LH2 refueling systems at airports.

Most medium and larger airports have several terminals with aircraft gates which are sometimes distinguished by domestic or intra-EU flights and (non-EU) international flights. For a clearer perspective on the general setup of LH2 refueling systems, the modeling only focuses on

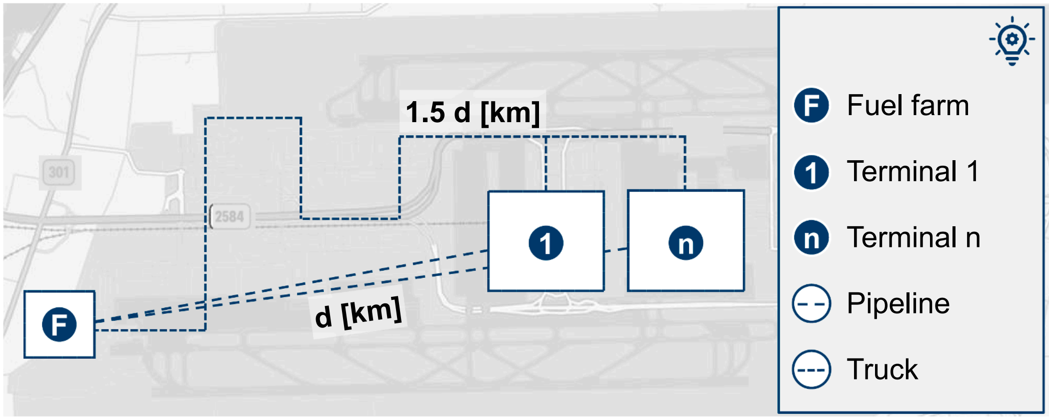

Fig. 4. Generic airport design used in this study shown for an exemplary airport layout, illustration based on [110].

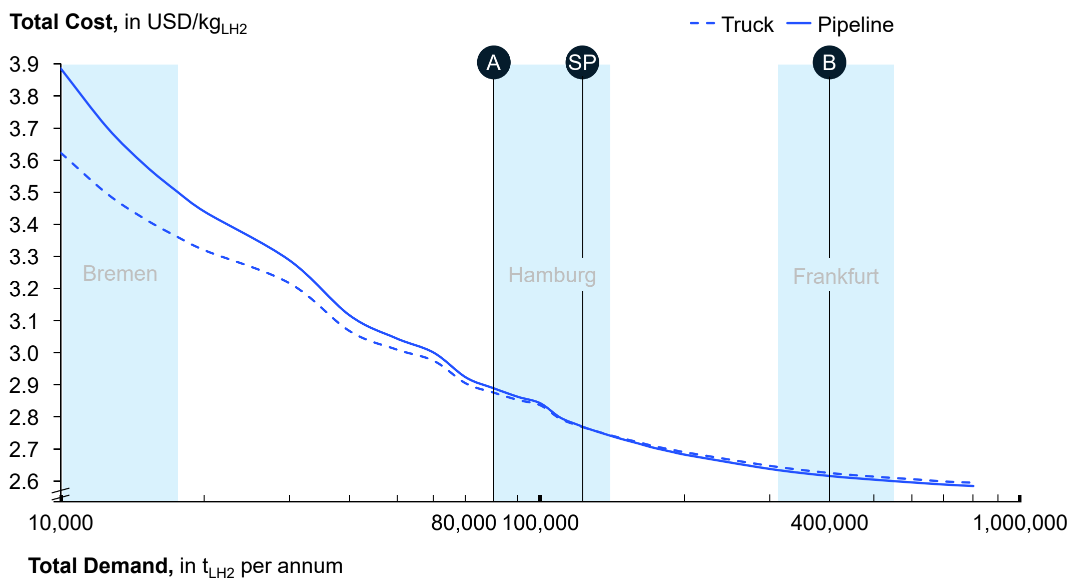

Fig. 5. Total costs of LH2 at the dispenser with truck (dotted blue line) and pipeline & hydrant refueling (continuous blue line) in 2050; demand scenarios for three exemplary German airports shown as shapes; points of interest highlighted: SP referring to the design switch point, A and B for detailed techno-economic analysis in Section 4.1.

one terminal which could be used as a blueprint for other terminals as well. To reflect different sizes of airports variable demands are investigated.

For safety reasons and since space at the terminals and gates is very limited, fuel farms are typically farther away from the terminals. They are often located as a central fuel farm with fuel storages, loading facilities of trucks or the connection to a pipeline & hydrant system. In some cases, these farms are even outside of the airport area but close by [109].

The distance between the LH2 fuel farm and the aircraft stands is highly variable. Here, a standard case of 3 km average direct distance between the fuel farm and the central point of the terminal is taken. This is assumed to be an average distance on German medium to large sized airports, tested through measurements on maps of airports (see Fig. 4) [110].

For an underground LH2 pipeline & hydrant system this is also the distance for the transmission. For LH2 refueling trucks, which are parked when not needed and loaded at the fuel farm, it is assumed that due to different routing on the airport apron that on average the transmission distance *d* is longer by a factor of 1.5.

4. Results and discussion

In this chapter, the results of optimizing the design of LH2 refueling systems at a generic airport setting with variable total demands are shown. The main design decision considered is the choice for one of the outlined refueling setups, which will be discussed in Section 4.1. Then, a sensitivity analysis is used to identify the main techno-economic parameters that influence the optimized design of these LH2 refueling setups. Last, implications for the specific airports described in Chapter 2 are derived based on the modeling insights.

4.1. LH2 costs at the dispenser

In a first step, the design optimization is run for both LH2 refueling setups separately. The calculated LH2 costs at the dispenser including the GH2 feed costs for a demand between 10,000 to 800,000 t_{LH2} per annum in 2050 are presented in Fig. 5 with a logarithmic scale.

The results underline that refueling costs decrease by nearly 30% with larger LH2 demands for both refueling setups from 3.6 to 3.9 to 2.6 USD_{2020}/kg_{LH2}. Considering the optimization, a design switch point (SP) for the given techno-economic assumptions can be identified. For an annual demand below 125,000 t_{LH2} LH2 truck refueling (15 trucks in

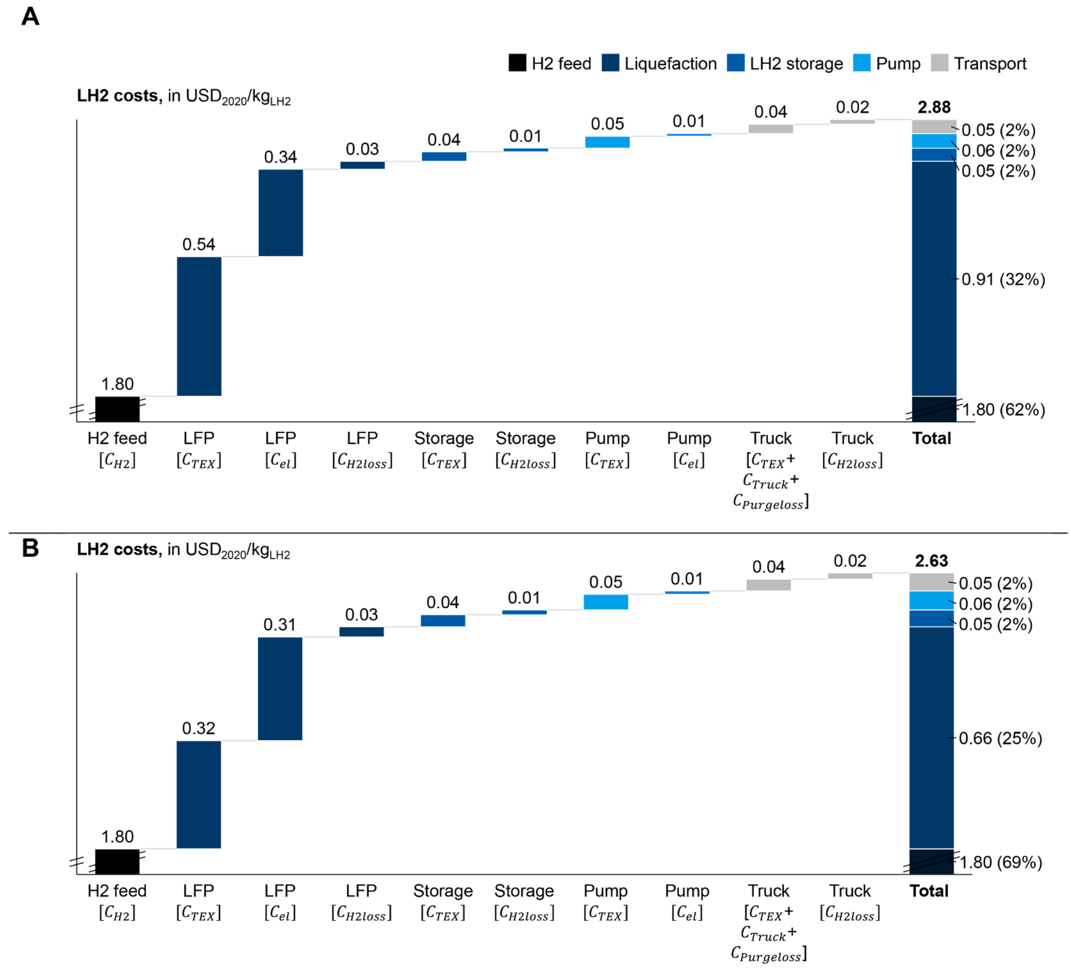

Fig. 6. Cost breakdown for LH2 truck refueling system – Fig. 6a: at 80 kt_{LH2}/a (point A in Fig. 5), Fig. 6b: at 400 kt_{LH2}/a (point B in Fig. 5).

use) is the more economic setup. Above that demand, pipeline & hydrant refueling is slightly less expensive by 0.01 to 0.02 USD_{2020}/kg_{LH2}. Consequently, the optimization for the energy systems' total annual costs follows the course of the lowest LH2 supply costs as described.

As a next step, detailed cost breakdowns are analyzed for demand point A at 80 kt_{LH2}/a and B at 400 kt_{LH2}/a (both highlighted in Fig. 5) – first, for the LH2 truck refueling in detail and then, highlighting differences only for the design of LH2 pipeline & hydrant systems.

Results for LH2 truck refueling system

Fig. 6a and 6b show the cost split for LH2 at the dispenser caused by each supply and refueling component. Further details can be found in Table B1 in the Appendix.

The cost figures underline that the supply costs for GH2, C_{H2}, (point A: 62%, point B: 69%) and the TAC for the LFP (A: 32%, B: 25%) are the main drivers for the total LH2 costs at the dispenser – in total accounting for 94% of total costs in both demand points.

Investigating the costs caused by the different aggregates in detail (from LFP, LH2 storages cryopumps to trucks) several trends can be observed.

For the LFP, cost scaling effects are identified as the main driver for a cost reduction of 41% between demand point A and B from 0.54 to 0.32 USD_{2020}/kg_{LH2} – see also "step-wise" cost reductions in Fig. 5. These economies of scale are caused by lower relative CAPEX per capacity for a larger LFP and due to a lower specific energy consumption (SEC). However, energy savings in design point B are rather limited, since the LFP in point A is already designed with a lower SEC for large capacities (Table B1 for further details). Hence, the costs for electricity only decrease by 9% from 0.34 to 0.31 USD_{2020}/kg_{LH2}. Larger relative energy savings can be observed, if the design in point B is compared to design points for demands below point A, when medium or even small LFP are selected.

Due to limited data availability on H2 losses in LFP of different scales, all plant sizes are assumed to have the same loss rate of 1.65% per kg_{H2feed} (Table 3). Consequently, the cost share for H2 losses in the LFP stays constant for all demand settings.

The total costs for the fuel reserve and buffer storage systems including costs for H2 losses contribute to the total LH2 costs by 2% only, so 0.05 USD_{2020}/kg_{LH2}. With a total capacity of around 800 t_{LH2} the LH2 storages serving for fuel reserves are already built using the largest available capacities including economies of scale effects (parameters in Table 4). Additionally, specific H2 boil-off losses do not differ significantly between both demand points. This is why relative cost reductions are very limited for the storage costs comparing point A and B.

The two cryopump systems, used for filling the truck and refueling the aircraft, are sized according to peak demands per hour. Both together cause similar costs compared to the storage TAC – costs for electricity and TEX result in 0.06 USD_{2020}/kg_{LH2}. Since a linear model is used to determine the CAPEX and the SEC is constant for all pump designs, the cost shares are same for all demand points. Nevertheless, it has to be highlighted that the techno-economic assumptions for cryopump systems are highly uncertain, since there is a lack of data and no larger installation examples are found (see Section 3.2).

For the LH2 truck refueling pathway, 10 trucks are installed in point A and 49 in point B to serve all H2-powered aircraft, also in peak

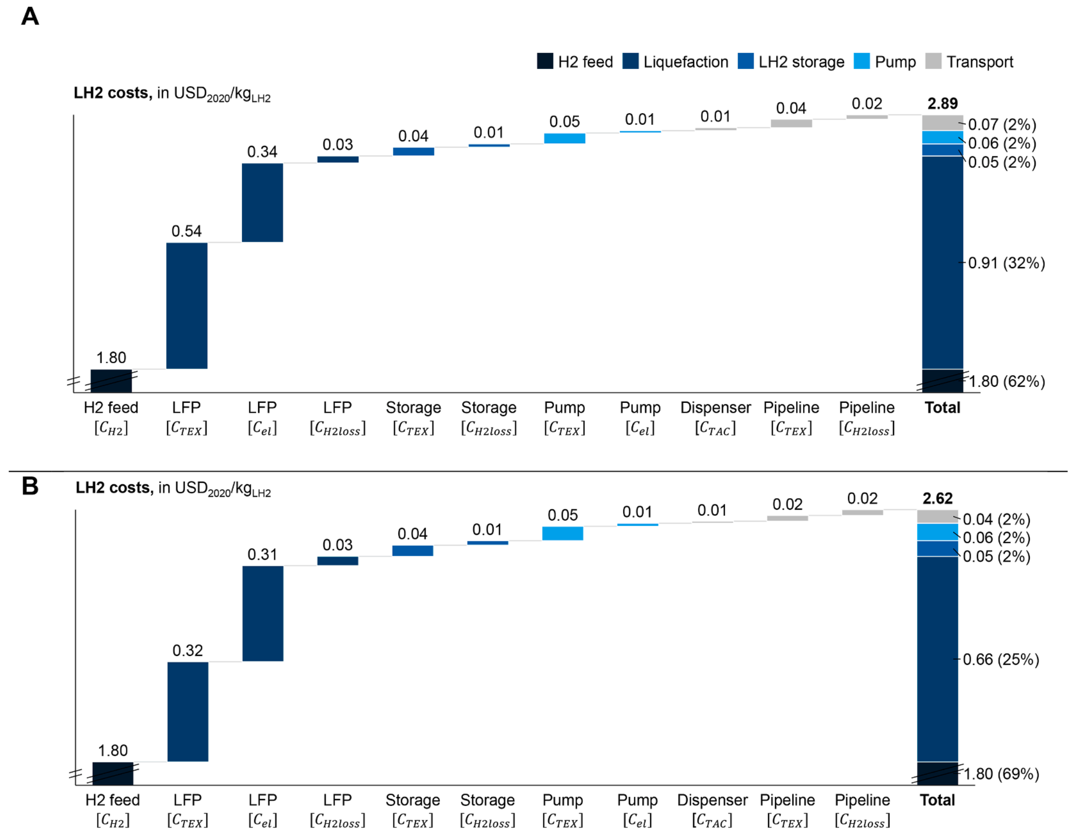

Fig. 7. Cost breakdown for LH2 pipeline & hydrant system – Fig. 7a: at 80 kt_{LH2}/a (point A in Fig. 5), Fig. 7b: at 400 kt_{LH2}/a (point B in Fig. 5).

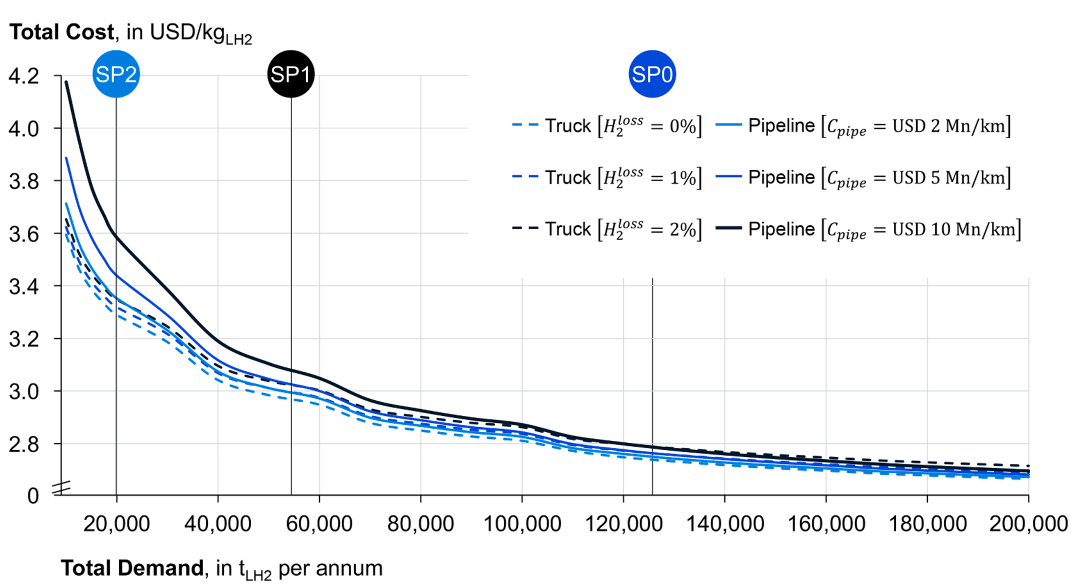

Fig. 8. Variation of main techno-economic parameters for LH2 truck and pipeline & hydrant refueling for annual LH2 demands between 10 and 200 kt_{LH2}.

demand times. The total truck refueling costs of 0.06 USD_{2020}/kg_{LH2} are very similar in both demand points, because there are only rather low fixed costs for the fueling building and the amount of installed trucks varies with the total LH2 demands. This means that the truck TEX and costs for H2 losses per kg_{LH2} stay nearly constant and only depend on the utilization of the lastly added truck when demands increase.

H2 losses occur for each loading and unloading of the refueling trucks. These are 40% lower compared to the losses in the LFP, but still cause a third of the transmission costs with 0.02 USD_{2020}/kg_{LH2}. It has to be noted that there would also be the possibility of reusing the evaporated H2 in a circular use. In this case, the captured GH2 could be liquefied again and used for refueling aircraft, or it could be reacted in a fuel cell to feed the LFP and other components and thus to reduce their electricity demands.

Even though the integrated dispenser unit on the truck consumes relatively expensive helium for purging, the amount and thus, the related costs per kg_{LH2} refueled are insignificant with less than 1% compared to the truck TEX in both demand points. Similar cost values are calculated for the truck fuel costs. Consequently, both energy costs are not shown as a separate bar in Fig. 6.

While relative costs for refueling via the truck setup do not increase for larger LH2 demands, space for parking and in general on the apron might be limited for such trucks at capacity constraint airports. This implies that for larger demands such as in point B the use of refueling trucks might be challenging. Especially, if there is still a kerosene refueling infrastructure in place to refuel larger widebody aircraft or the ones not replaced by H2-powered versions yet.

In total, around 3% of the GH2 feed to the airport is lost in both demand settings, which is caused by the LFP, storages and truck un-/loading. Furthermore, renewable electricity is sourced to operate the LFP and cryopumps – since electrolysis is considered to be off-site, its energy demands are not considered. Both, LFP and cryopumps, consume 560 GWh_{el} and 2,651 GWh_{el} of renewable electricity in point A and B per annum, respectively. If a wind park would be installed for supply, 56 (A) and 261 (B) wind turbines with a power rating of 5 MW_{el} and 2,000 annual full load hours would be required. Such a wind park would require another large area in proximity to the airport or a stable, dedicated grid connection, which might be challenging at some airports.

Regarding the CAPEX for the total LH2 energy system without the electrolysis or GH2 transport (see Table B1), the LFP causes 87% (A) and 81% (B) of these, while the other aggregates only account for a minor share. The investment for an airport with demands comparable to point B reaches a significant scale with a total of 1,255 Mn USD_{2020}. For smaller airports (below demand point A) the installation of a LFP might cause too high investment / financing needs. In that case, off-site LH2 supply could be a more competitive choice, e.g., if a larger LFP is already operated in the region for other LH2 applications leading to lower costs (S1 in Fig. 3).

Results for refueling pipeline & hydrant system

When installing a LH2 energy system with a cryogenic pipeline & hydrant refueling setup, similar cost scaling effects occur for the LFP, storages and pumps comparing demand points A and B as described for truck setups (see Fig. 7a, 7b and Table B2). Consequently, only differences for this specific setup are analyzed in the following.

As part of the LH2 pipeline & hydrant system, separate mobile dispenser units are installed. These cause similar costs of 0.01 USD_{2020}/kg_{LH2} in every demand point. Reason for this is the underlying "fixed" cost structure which is comparable to the cost effects described for the LH2 refueling trucks. Scaling effects do not occur for dispensing units, since their number increases linearly with the LH2 demand with constant relative operational costs.

Nevertheless, cost scaling effects can be achieved with increased utilization of the pipeline, for which a minimum installation capacity and thus, pipeline diameter is required. In this study, the CAPEX for the installation of the pipeline system are assumed to be independent of the pipeline diameters, causing higher costs for a system with low LH2 utilization. Another reason is that smaller pipeline diameters would lead to higher friction of LH2 in the pipes and hence, to higher losses [24,31]. Due to this modeling approach, the pipeline utilization is below 40% in demand point A, which increases total LH2 costs at the dispenser significantly. In demand point B, the LH2 flow through the pipeline system increases so that a utilization of 90% is reached and larger diameters for the pipeline have to be used. Hence, the pipeline TAC decrease from 0.04 to 0.02 USD_{2020}/kg_{LH2}.

Given the selected modeling design, H2 losses are determined not in dependence of the pipeline utilization but of the pipeline length. This is deemed a reasonable assumption, because the pipeline is designed as a loop with a steady LH2 flow that ensures to keep the fluid cold and H2 losses low (even in case of lower utilization). Over the short distance of two times three kilometers, this effect leads to about 1% of H2 losses per kg_{LH2} transported through the pipeline. So, H2 losses and their costs are comparable with the refueling truck design for such short distances – 0.02 USD_{2020}/kg_{LH2} in both design points.

While renewable energy and investment requirements for the LFP, storages and cryopumps are similar to the refueling truck setup, the investment costs for the pipeline & hydrant setup differ to the truck setup (Table B2). With 31 Mn USD_{2020} in point A and 55 Mn USD_{2020} in point B the investment for this system is larger than for LH2 refueling trucks by a factor of 4.4 and 1.6, respectively. Despite the high investment, the annualized costs for the pipeline & hydrant setup are lower for higher demands (point B) especially due to the longer expected lifetime of 40 years – LH2 refueling trucks are expected to be economically useable for 12 years only [98].

Given the set of assumptions made in Chapter 3, the optimization of both LH2 refueling systems clarifies that for lower annual LH2 demands (point A) refueling setup costs are around 20% less expensive with refueling trucks with 0.05 USD_{2020}/kg_{LH2} compared to 0.07 USD_{2020}/kg_{LH2} with a pipeline & hydrant system. This is mainly caused by the high CAPEX as well as the operations and maintenance costs for the latter. For larger annual LH2 demands with a better utilization of the pipeline (point B), it becomes competitive with 0.05 USD_{2020}/kg_{LH2} compared to 0.05 USD_{2020}/kg_{LH2} for refueling trucks. Nevertheless, in all cases both refueling setups only account for 2% of the total LH2 costs at the dispenser. The results underline the findings from [5,15] and indicate that the pure economics of LH2 refueling systems are not a main hurdle for the deployment of H2-powered aviation.

4.2. Sensitivity analysis of main techno-economic parameters

In the previous section, a design switch point (see "SP" in Fig. 5, now referred to as "SP0" in Fig. 8) was identified, beyond which LH2 pipeline & hydrant refueling setups are economically more favorable than the use of refueling trucks. However, the assumptions made for the year 2050 in these calculations come with high uncertainties due to the very long-term projection period and since reliable data is not available. In addition to that, most of these components have never been built in large quantities or capacities before.

A sensitivity analysis is conducted in this section to test the results with different techno-economic inputs. First, this is done with the focus on the choice of the refueling setup. Second, change of costs for liquefaction and the GH2 feed are also discussed briefly.

Several techno-economic factors were varied as part of this study. In the following, only the two main factors are discussed that were found to influence the choice of the refueling setup most. On the one hand, this is the H2 loss factor for truck refueling, which could potentially be influenced by developing new couplings and H2 recovery systems for loading and unloading the truck storage [33]. Boil-off losses while driving the refueling trucks in the airport context for several kilometers are less likely to occur. On the other hand, the CAPEX for pipeline & hydrant systems depend on future development and research progress as well as larger production capacities (leading to economies of scale and learning rates) of cryogenic pipelines. Today most installed LH2 pipelines are used in space or laboratory contexts [33]. Therefore, different properties and often less frequent usage lead to not fully comparable techno-economic parameters for this system, if applied to the aviation setup.

Fig. 8 emphasizes the large range of resulting design switch points depending on the variation of these two factors. In general, similar cost trends can be observed for all parameter variations with increasing LH2 demands and the total costs do not differ largely.

If the H2 losses of realized refueling truck systems would increase to 2%, the annual demand for the design switch point decreases to around 55 kt_{LH2}/a (SP1). On top of this and assuming a most favorable case for the pipeline system with reduced CAPEX to 2 Mn USD_{2020}/km, the design switch point would even decrease to 20 kt_{LH2}/a (SP2). So, under certain conditions a pipeline could already become the more economical choice even for smaller airports.

However, the technical challenges of constructing and operating such a LH2 pipeline system should also be considered, which might overweigh the savings of 0.01–0.02 USD_{2020}/kg_{LH2} compared to the more flexible solution of using refueling trucks. In addition to that, the sensitivity analysis with these two selected factors also shows that a truck variant with 0% H2 loss is always less costly than any of the pipeline systems considered – even for very large annual LH2 demands.

Insights for another parameter, the transmission distance, are briefly given. It is found that a longer distance favors the use of LH2 trucks and leads to a shift of the design switch point to higher annual LH2 demands. On the one side, trucks have a factor 1.5 longer distances and therefore consume more time for driving between a fuel farm and a refueling stand. On the other side, the H2 losses remain stable for trucks, while the H2 losses for pipelines depend on the length of the pipelines. Furthermore, CAPEX for refueling trucks have a lower relative increase than for pipeline systems.

Overall, it can be stated that a decision between the two LH2 refueling setups can rarely be made on a pure economic basis. Rather safety aspects, space constraints or existing know-how at the airports have to be considered for the design choice of LH2 refueling systems.

Lastly, cost changes to the GH2 feed price or the TAC of the LFP have the highest total impact on the LH2 price delivered to the aircraft, since the sum of both accounts for 94% of the total costs. Depending on the demand point chosen, a variation of the GH2 price by +50% to 2.70 USD/kg_{GH2} causes an increase of the total costs by 32% in point A and 35% in point B. In comparison to that, a variation of the CAPEX of the LFP by +50% leads to an 9% (A) and 6% (B) increase of LH2 costs, while the same variation of the LFP energy consumption results in similar cost increases. Future studies should consider the optimization potential for other supply setups, e.g., S1 and S2b in Fig. 2 or the effect on infrastructure costs when bundling several H2 applications at and around the airport. The latter might lead to more economic conditions, e.g., through larger scales of LFP.

4.3. *Specific recommendations for the selected three airports*

As already indicated in Fig. 5, the implications of the energy system optimization for the three airports examined in Chapter 2 are discussed briefly in the following.

Smaller airport: Bremen

At a smaller airport such as Bremen (BRE) with a demand of 10–20 kt_{LH2}/a, the LH2 truck refueling setup would be the most economic choice. Since space might not be as constrained as at larger airports, distances between the fuel farm and the aircraft gates are potentially shorter than the assumed 3 km in the generic airport design. So, shorter driving times for LH2 refueling trucks could lead to a higher utilization and less trucks might be required.

The largest challenge could be to achieve competitive LH2 refueling costs at such airports depending on the market access to a GH2 feed for 1.80 USD_{2020}/kg_{H2} or LH2 for around 2.7 to 3.3 USD_{2020}/kg_{LH2}. The airport might not be the largest hydrogen use case in the region, because H2 demands are comparable to the H2 road sector (Fig. 3). Consequently, there is a need that other large H2 applications, e.g., for industry feedstock, drive cost reductions of H2 production. This could allow airports like BRE access to a H2 market with similar cost conditions as assumed in this study. Otherwise, and highly depending on good conditions for renewable energy supply [15], the installation of electrolysis plants on-site or near the airport could also be an alternative to reach such cost figures. For detailed insights, a broader analysis will be required on H2 supply chains for such smaller airports in future studies.

Medium airport: Hamburg

For a medium-sized airport, such as Hamburg with a potential demand of 80–150 kt_{LH2}/a, the economic choice of the refueling setup is not as certain as the demand is around the design switch point (SP0) at 125 kt_{LH2}/a. It highly depends on the techno-economic assumptions taken and hence, the development of the economics of such LH2 systems in the next decades (Section 4.2).

Nevertheless, the absolute LH2 costs at the dispenser might only vary by few cents in these demand scales which might increase the importance of other design criteria for choosing the best fitting refueling setup. A truck setup is a less complex system to operate compared to the LH2 pipeline & hydrant system (Section 4.1). In addition to that, operational procedures might not be impacted too much by refueling trucks: since most flights at this medium-sized airport are short-range flights with LH2 fuel demands below the max. transport capacity of a refueling truck (4 t_{LH2}), typical refueling and ground handling times might be realized.

The analysis also shows that the installation of a LFP at or close to the airport could be an economic choice, if a low-cost LH2 feed is not available. Cost scaling effects for the LFP can already be reached in demand settings of medium-sized airports and hence, result in competitive costs for liquefying H2 – potentially even selling LH2 to other markets nearby.

Larger airport: Frankfurt

For a larger airport such as Frankfurt (FRA) design criteria other than economics could be especially important. In the 2050 scenarios, more than 50 trucks would need to be installed at the airport to fulfil all required refueling operations for H2-powered single-aisle and medium widebody aircraft only. At an airport like FRA that is capacity constraint this might lead to significant shortage in space and congestions on the apron and for loading the refueling trucks.

Moreover, it must be considered that the current assumptions are based on a demand of around 300–600 kt_{LH2}/a. If all single-aisle, medium and potentially even some larger widebody aircraft are switched to LH2 as a fuel, demand could grow to significantly over 1,000 kt_{LH2}/a. In this case, the installation of a more performing LH2 pipeline & hydrant setup might outweigh its complexity. It could prevent traffic congestions as well as more complex refueling procedures with more than one truck for larger aircraft (fuel demands above 4 t_{LH2}).

In addition to the refueling setup, the space requirements for the fuel tanks storing more than 4,500 t_{LH2} (design point B) would be significant. Considering that the largest demonstrated LH2 storage takes around 3,000 m^2 of space storing 850,000 gallon (270 t_{LH2}) as built at NASA site in Kennedy Space Center, more than 16 of such facilities would be needed at FRA [95]. This would require additional space at an already space constraint airport.

In summary, the design choices of LH2 refueling setups are clearer for smaller airports – LH2 refueling trucks might be the dominant choice. For larger airports, LH2 refueling pathways might be a major challenge in the future due to space or safety aspects. Techno-economic uncertainties remain and airport-specific test facilities will be required to further investigate optimized LH2 refueling setups. In addition, the H2 supply to the airports remains a subject of future analysis to ensure competitive GH2 or LH2 feed prices.

5. Conclusions and outlook

The study finds that LH2 demands for aircraft propulsion use could be significant at medium and larger airports. With approximately 80–150 kt_{LH2} per annum (medium airports) and 300–600 kt_{LH2} p.a. (larger airports) these airports could become central H2 consumption hubs compared to other H2 demanding sectors in 2050. In case fleet penetration rates would increase continuously after 2050 and potentially also larger widebody aircraft would be powered by H2 propulsion, these LH2 demand scenarios would be even larger.

For the fuel supply and LH2 refueling infrastructure at airports these demand scenarios and the techno-economic system optimization led to three main findings.

(1) A reliable and low-cost green H2 supply is required as it has the largest impact (60–70% of total LH2 costs) on economically competitive H2-powered aviation. In this work, GH2 supply costs via pipeline were assumed to cost 1.80 USD_{2020}/kg_{H2} in 2050 –

depending on the geography and availability of renewable energy this might be challenging to achieve for all airports.

(2) It can be concluded that LH2 refueling systems (LH2 transmission and cryopumps) could cause total annual costs as low as 0.10 to 0.13 USD_{2020}/kg_{LH2} only, so 3 to 4% of the total LH2 costs. In contrast to that, with 0.66 to 0.91 USD_{2020}/kg_{LH2} the costs for liquefaction of H2 would make the largest portion of H2 infrastructure costs at airports with off-site GH2 supply. Thus, CAPEX for such liquefaction plants could be more than one billion USD_{2020} at larger airports with a demand of 400 kt_{LH2}/a and greater. In comparison, investments for a LH2 pipeline & hydrant system including dispenser trucks and cryopumps would be less expensive by a factor of approx. 8 with 125 Mn USD_{2020}.

(3) The design choice of LH2 refueling systems for LH2 pipeline & hydrant systems versus LH2 refueling trucks might not fully depend on their economics. Even though the deployment of a LH2 pipeline & hydrant transmission system might save 0.01 USD_{2020}/kg_{LH2} for airports with LH2 demands significantly above a design switch point of 125 kt_{LH2}/a, also other criteria play a role. Less traffic and reduced potential for human error (driving such trucks) could increase safety of LH2 handling at airports, when using pipelines instead of refueling trucks. Especially for highly space constraint airports, the avoidance of further traffic on the apron might be more critical than enabling slightly more economic refueling pathways. Furthermore, it was shown in a sensitivity analysis that the economics for the switch point still depend on several techno-economic factors leading to a large variety of best economic scenarios. Therefore, the exact cost figures for the choice of the most competitive LH2 refueling setup are still highly uncertain and will depend on the future development of each techno-economic factor.

Only for smaller airports like Bremen LH2 refueling trucks will certainly be a more practical and economic choice for operation – expected demands were determined to be below 20 kt_{LH2}/a in 2050. However, in that case the consumption of LH2 at smaller airports would probably not take a dominant role in the region the airport is located at. Consequently, low H2 supply costs and investment might be more challenging for these airports, especially in the transition phase towards fully deployed H2-powered aviation. It will then be crucial to achieve synergies in H2 supply with other sectors close to the airport to gain higher bargaining power or utilization of own assets for realizing low green H2 costs.

Furthermore, it was shown that H2-powered aviation at medium and larger airports might lead to new roles of H2 energy systems around airports – however, the deployment of LH2 in aviation might be the latest realized application compared to other sectors. Hence, there is large potential for further design studies looking into the role of existing versus new H2 supply infrastructures to and around airports (H2 hubs). Optimization potential could include merging large H2 demands in a region around the airport to achieve cost scaling effects of systems such as liquefaction plant. Designing such systems for the aviation and also other sectors would increase utilization and might lead to synergies. This could be even more of interest in the transition towards a full scale H2-powered aviation. Thus, seasonal fluctuations in air traffic demand (Fig. 1c) will always affect the costs of most LH2 systems at airports that have to be sized for peak demands. In times of lower demand from aircraft propulsion these LH2 supply capacities could be utilized by other systems in such non-peak times and thus lower the supply costs.

For aircraft operators the following implications are derived. Finding fuel infrastructure providers for low-cost H2 supply will be a key enabler for competitive operational costs with H2-powered aviation. As Hoelzen et al. [15] already concluded, LH2 supply costs could be a main economic obstacle for the introduction of H2-powered aviation. In this work, only costs for the LH2 aggregates are investigated, while GH2 supply costs are kept constant. The resulting LH2 fuel costs would be around 3.50 USD_{2020}/kg_{LH2} at a smaller airport (BRE) and 2.60 USD_{2020}/kg_{LH2} at a larger airport (FRA). This would be comparable to an increase of the kerosene price (base is 0.60 $USD_{2020}/kg_{kerosene}$) of 110% or 56%, respectively. Translated into a carbon tax, paid on top of the kerosene price, this equals 210 or 110 USD_{2020}/t_{CO2} for BRE and FRA. However, it has to be noted that assuming constant kerosene costs until 2050 comes with a high uncertainty.

Besides the reported implications also the limitations of this work are reflected. Linear models were used for all LH2 components to ease the computation of optimizing LH2 refueling systems. For very detailed engineering of each system, non-linear relations should be reflected. Moreover, the allocation of LH2 demands over several terminals and aircraft gates were aggregated in this optimization. Hence, more detailed constraints on refueling and transmission times as well as distances were not considered.

Moreover, this research only targeted one out of three potential supply structures for airports (Fig. 3). This is why further analyses looking into more centralized, even internationalized, or fully decentralized, on-site supply infrastructures should be of high interest for more certain results on H2 supply costs.

All in all, the analyses highlight the clear need for technology demonstration and development of components applicable for the use in cryogenic fuel systems. Only then, more realistic techno-economic parameters and even more detailed design studies can be conducted to determine optimized refueling system setups. First prototypes and demonstrators would especially be required for the test of cryogenic pipelines & hydrants as well as for LH2 refueling trucks and dispenser units. Refueling rates, H2 losses and other energy consumptions, CAPEX & scaling effects and safety aspects such as leak detection, fail safe mechanisms and predictive maintenance features should be further looked into.

Since H2 losses were identified as a main techno-economic factor for LH2 refueling trucks, further modeling and testing of minimizing these losses and designing a more circular use should be a priority for LH2 systems at airports. Therefore, a techno-economic evaluation of different options for reusing GH2, e.g., for electrification or feeding GH2 back into the liquefaction loop, would help to identify the most economic and practicable solutions for such circular uses.

Declaration of Competing Interest

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

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Appendix A. On LH2 demand projections at exemplary airports

In this part, the approach, sources and assumptions for projecting LH2 demands for aircraft propulsion at airports in 2050 are explained. All calculations and detailed results can be found in the supplementary material.

Four steps are taken to derive the LH2 demand scenarios for four different aircraft size segments presented in Chapter 2:

1. The kerosene demand for aircraft propulsion is calculated for the reference year 2019 at three exemplary airports. These airports are meant to be archetypes for smaller, medium and larger airport sizes.

2. Based on the results, traffic growth projections reflecting the impact of the COVID health crisis are used to determine potential fuel demands at these airports from 2019 to 2050.
3. The development of aircraft fleet from 2019 to 2050 is projected in a next step. This enables the calculation of the share H2-powered aircraft might have of all flights at the selected airports in 2050. Two different introduction scenarios for the introduction of H2-powered aircraft are used to reflect more and less progressive assumptions.
4. Finally, LH2 demand projections at these airports are calculated based on the kerosene forecast, the share of H2-powered aircraft in each aircraft category and energy conversion factors.

The underlying methodology and assumptions are detailed out in the following.

Kerosene baseline 2019

In this step, historic air traffic data is used to derive the kerosene demand at three selected airports that represent smaller, medium and larger archetypes of airports. As reference year 2019 is selected to have an undistorted view of traffic data without any influences of the COVID health crisis.

The German Airports Association (ADV) publishes monthly and annual air traffic reports including number of passengers and movements at German airports [38]. Since this data is not reported by the defined aircraft segments used in this study but by length of the flights (national, international), these are translated accordingly. Therefore, it is assumed that national flights are flown with regional and single-aisle, international-European flights with single-aisle and medium widebody and international-non-European flights with medium and large widebody aircraft. Thus, the assumptions for the relative splits of the aircraft segments in each flight category are derived from company reports such as from Frankfurt Airport [107] and flight profiles from Flightradar24 [111]. These splits can be very specific for the region that is focused on in this work. In countries with very high air traffic demand on short routes (e.g., China) also widebody aircraft could be used for national, short-range flights [34].

Based on average passenger (PAX) capacities per aircraft segment from [5] and load factors (here load factors reported for flights departing or arriving in Europe are used) from [112] the number of passengers are translated into aircraft departures per each segment.

Then, average flight distances that are assumed to be specific to the size of airport are determined from ICCT average traffic data [34] and reported flight profiles [111].

In a final calculation step, the total flight kilometers flown per aircraft segment are multiplied by reported average kerosene consumption data (kg kerosene per aircraft km) from the European Environment Agency [113] to derive total kerosene demands in 2019 at the selected airports – shown in Fig. 1 and Table 2.

Kerosene forecast 2050

Since the projection of future LH2 demands in 2050 is targeted in this work, air traffic growth projections are used to calculate a kerosene demand forecast as a reference.

As part of the WeCare project of the German Aerospace Center air traffic growth forecasts were developed [114]. In a recent publication from Grewe et al. [115] these were used to model climate impact from aviation over the next 30 years. Their publication including all relevant data sets is used in this work to forecast air traffic growth in terms of global revenue passenger kilometers (RPK) and the annual improvement of aircraft efficiency over the global fleet. In addition to that, a recent market forecast from the International Air Transport Association (IATA) is incorporated to reflect the different growth perspectives between domestic and international aviation [40]. It is assumed that domestic air traffic growth affects regional and single-aisle aircraft segments and international air traffic growth the widebody segments. Thus, the IATA report also provides insights on the effects of the COVID health crisis on air traffic demand, which are built into this forecast by assuming no air traffic growth between 2020 and 2023. Compared to an average annual growth rate of air traffic between 2020 and 2050 of 3.7% without the COVID-“shock”, the calculated average growth rate in this work is 3.0% per annum. So, the used air traffic projections for the next 10 to 30 years are 16% lower than a projection without a COVID-“shock”, which might be a more conservative estimation but is in line with a forecast by Embraer [116].

Last, the kerosene demand from 2019 to 2050 is projected for the three different airports taking the kerosene baseline for 2019 and applying the air traffic growth rates and efficiency changes discussed. Results are shown in Table 2 and the supplementary material.

Aircraft fleet forecast and H2-powered aircraft scenarios

Next, a forecast is determined for the selected commercial aircraft fleets from 2019 to 2050 for each aircraft segment. This is required to calculate potential penetration scenarios of H2-powered aircraft in relation to the total fleet and new aircraft deliveries.

As a starting point the global existing fleet of active and temporary parked aircraft in the four segments is determined using data available on the open source data base Airfleets.net [117]. The fleet numbers are cross-checked with the Commercial Aircraft Market Analysis from Aviation Week Intelligence Network (AWIN) [118] and used as a reference for 2019.

The development of the commercial aircraft fleet and aircraft deliveries is taken from market forecasts published by Boeing [41], Airbus [119] and Embraer [116]. Since Boeing’s and Embraer’s market analysis already mention COVID effects, their projected annual fleet growth from 2019 to 2029 and 2039 as well as total aircraft delivery units are used for this modeling. Furthermore, the growth rates were extrapolated to 2050, since no contradictory indicators or forecasts are available for that time period.

To account for less deliveries and more retirements of aircraft due to COVID effects the fleet projection from 2019 to 2024 is adjusted to fit reported market data from AWIN for 2020 and 2021 [118].

In a second part, two different scenarios for the market introduction of H2-powered aircraft are derived and the resulting penetration in relation of the total aircraft fleet is calculated. Therefore, assumptions for three main parameters are determined for each aircraft segment: the entry-into-service (EIS) year, the time for full manufacturing ramp-up – when an aircraft manufacturer would be able to fully utilize their production with H2-powered aircraft – and the take-rate. The latter describes the quota of H2 aircraft that are sold to airlines or lessors compared to all aircraft deliveries including non-H2 aircraft.

As a base case it is assumed that H2-powered regional aircraft will be available from 2030 on. Manufacturers would reach full production capacity of regional aircraft by 2034 and 80% of these new delivered aircraft would be equipped with H2 propulsion. Assumptions for all segments are shown in Table A1. In general, these reflect a scenario

Table A1
Assumptions for fleet projection of H2-powered aircraft – base case.

Aircraft segment	**Entry-into-service (EIS) year**	**Time for full manufacturing ramp-up**, in years	**Take-rate of H2 aircraft vs. all aircraft deliveries in segment**
Regional (jet and turboprop)	2030	4	80%
Single-aisle	2035	5	67%
Medium widebody	2040	6	50%
Large widebody	greater than 2050	n/a	n/a

Table A2
Assumptions for fleet projection of H2-powered aircraft – ambitious case.

Aircraft segment	Entry-into-service (EIS) year	Time for full manufacturing ramp-up, in years	Take-rate of H2 aircraft vs. all aircraft deliveries in segment
Regional (jet and turboprop)	2028	2	100%
Single-aisle	2033	3	100%
Medium widebody	2038	4	67%
Large widebody	greater than 2050	n/a	n/a

which already counts on the introduction of H2-powered aircraft and that major technological and economic barriers can be overcome. While regional and single-aisle aircraft would be a viable purchase option for operators, H2-powered medium-range aircraft do not play a larger role in the total aircraft fleet by 2050 mainly due to late EIS and long manufacturing ramp-up times. Here, other decarbonized options such as synthetic fuels would be a main option for such aircraft operators in this scenario at least until 2050 as also highlighted by [1,5].

In a significantly more progressive scenario, called ambitious case, a radical transition to true zero emission aircraft concepts is assumed. This could be caused by regulation limiting emissions and emission-related climate effects or by the introduction of very high emission taxes. Furthermore, this scenario reflects that H2 propulsion could be the dominant true zero propulsion option for regional and single-aisle aircraft – only commuter aircraft with less than 20 PAX, which are not considered in this study, might be powered by battery-electric propulsion. In such a scenario, a LH2 supply and refueling infrastructure would be available at all airports and also medium widebody aircraft would be available for purchase in the late 2030 s to early 2040 s. All assumptions are summarized in Table A2.

As shown in both tables and explained in Chapter 2, an EIS of a large widebody aircraft powered by H2 propulsion is not assumed to happen before 2050.

The resulting H2 aircraft fleet penetrations are displayed in Fig. A1a for the base case and Fig. A1b for the ambitious case scenario. These clearly show that the share of H2 aircraft is relatively low in a base case scenario in 2050. Only in the regional and single-aisle segments, fleet shares of 50% or more would be achieved. Since larger widebody aircraft that account for a major share of emissions from commercial aviation would not be powered by H2 propulsion, H2 aircraft would be still a "minority" compared to other aircraft at larger airports. This is also in accordance with a statement from Airbus saying that traditional aircraft concepts will be dominating until 2050 [32].

It is important to highlight that more conservative scenarios with lower adoption rates of H2 aircraft could also be likely. However, these were not further considered for this energy system design study. Nevertheless, readers could derive their own scenarios with the help of the supplementary material and see resulting LH2 refueling costs in Fig. 5 where a broad range of LH2 demands are investigated.

LH2 demand projections

Based on the kerosene demand projections 2019–2050 and the fleet penetration scenarios of H2-powered aircraft the resulting LH2 demands at the selected airports are calculated. Therefore, the equivalent energy demand of H2-powered aircraft compared to kerosene powered aircraft is determined for each aircraft segment. Based on relative changes of the specific energy consumptions (SEC) of H2 aircraft and the different gravimetric energy densities of the fuels (H2 with 33.3 kWh/kg, kerosene with 12 kWh/kg lower heating values) LH2 fuel substitution factors are derived, see Table A3. Changes of aircraft efficiencies for single-aisle and medium widebody aircraft are taken from [15] – for large widebody aircraft from [5]. Since the regional aircraft segment comprises of jet and turboprop aircraft, a synthesis is taken from [5] with an decrease of SEC for turboprop and from [120] with an increase of SEC for jet variants.

Table A3
Efficiency factors for novel H2-powered compared to kerosene-powered aircraft used to calculate LH2 demand scenarios.

Commercial aircraft category	Relative change of specific energy consumption for H2-powered aircraft vs. kerosene reference	Resulting calculation factor for substitution, kg LH2 per substituted kg kerosene	Sources
Regional (jet and turboprop)	~0%	0.36	Seeckt and Scholz [120] and Clean Sky JU and FCH JU [5]
Single-aisle	+12%	0.40	Hoelzen et al. [15]
Medium widebody	+18%	0.42	Hoelzen et al. [15]
Large widebody	+42%	0.51	Clean Sky JU and FCH JU [5]

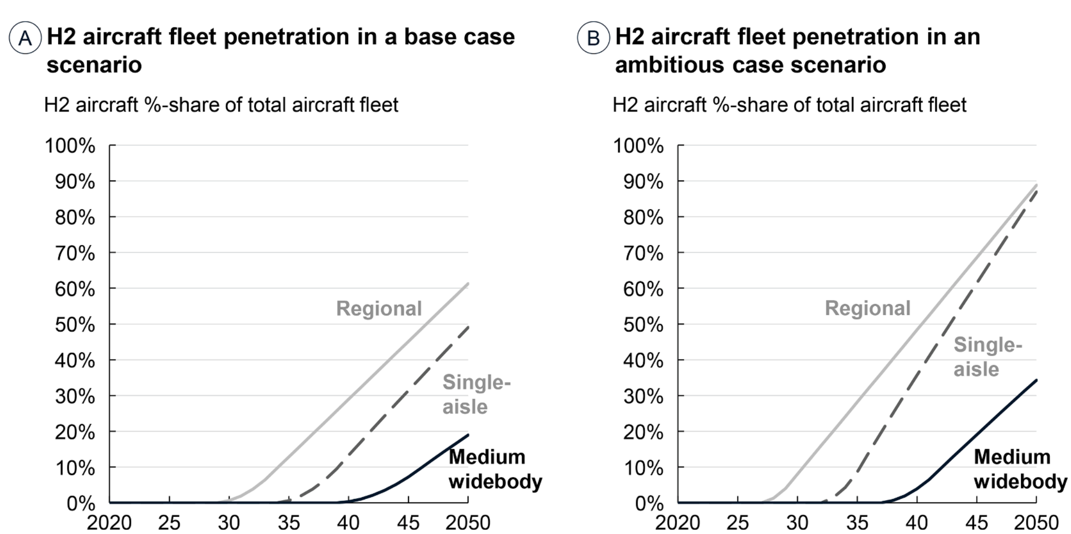

Fig. A1. Assumption-based H2 aircraft fleet penetration until 2050 in a) a base case and b) an ambitious case scenario.

The resulting LH2 demands at the three selected airports are shown in Fig. A2a-c. Since large widebody aircraft are not assumed to be powered by H2 propulsion in 2050, the total LH2-equivalent fuel demand at the airports does not consider this segment.

Appendix B. on results for LH2 refueling systems

The detailed design of the LH2 refueling systems in demand point A and B from Chapter 4 are shown in Table B1 (truck refueling) and Table B2 (pipeline & hydrant refueling). These include the design capacities, resulting costs and losses.

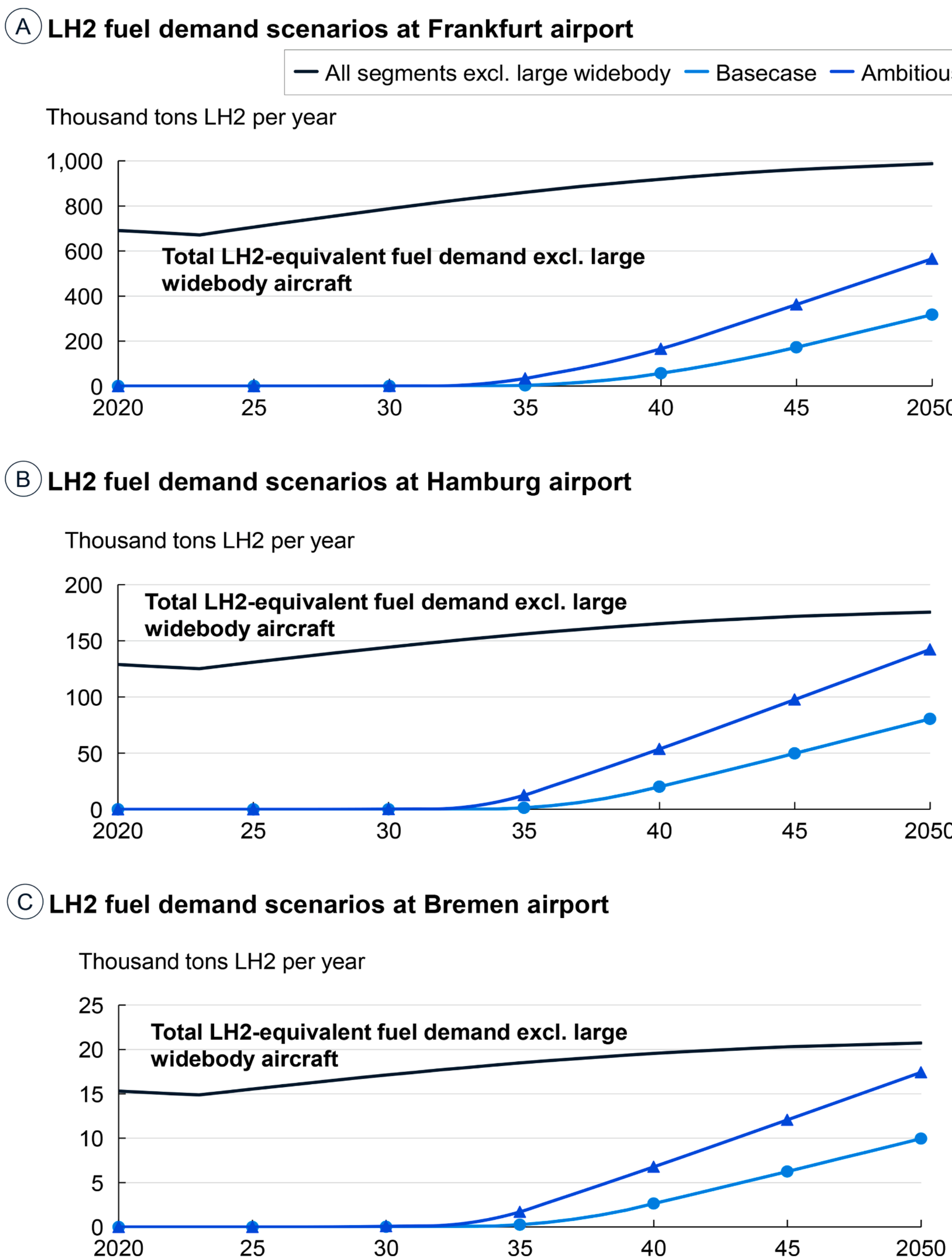

Fig. A2. Calculated annual LH2 fuel demand scenarios at a) Frankfurt airport (FRA), b) Hamburg airport (HAM), c) Bremen airport (BRE).

Table B1
LH2 refueling system setup and investment costs for selected point A (Fig. 6a) and point B (Fig. 6b) for LH2 truck refueling.

Feeds and sub-systems / aggregates	Annual amounts & max. capacity	Resulting costs in Mn USD_{2020}	Annual losses in t_{LH2}	Annual amounts & max. capacity	Resulting costs in Mn USD_{2020}	Annual losses in t_{LH2}
Demand point A: 80 kt_{LH2}/a				**Demand point B: 400 kt_{LH2}/a**		
Hydrogen feed	82,791 t_{H2}	149	–	413,940 t_{H2}	745	–
Electricity feed	560 GWh	28	–	2,651 GWh	128	–
Liquefaction	222 tpd (large LFP)	341[a]	1,344	1,118 tpd (x-large LFP)	1,018[a]	6,719
Fuel reserve storage	796 t_{LH2}	24[a]	640[b]	3,978 t_{LH2}	119[a]	3,180[b]
Buffer storage	103 t_{LH2}	4[a]		475 t_{LH2}	16[a]	
2 cryopump systems	27 t_{LH2} per hour (tph)	14[a]	–	137 tph	70[a]	–
LH2 truck	10 trucks	7[a]	808	49 trucks	32[a]	4,040

[a] Total investment costs – not including annuity payment factor / depreciation period[b] Losses for both fuel reserve and buffer storage.

Table B2
LH2 refueling system setup and investment costs for selected point A (Fig. 7a) and point B (Fig. 7b) for LH2 pipeline & hydrant systems.

Feeds and sub-systems / aggregates	Annual amounts & max. capacity	Resulting costs in Mn USD_{2020}	Annual losses in t_{LH2}	Annual amounts & max. capacity	Resulting costs in Mn USD_{2020}	Annual losses in t_{LH2}
	Demand point A: 80 kt_{LH2}/a			**Demand point B: 400 kt_{LH2}/a**		
Hydrogen feed	82,834 t_{LH2}	149	–	414,149 t_{LH2}	745	–
Electricity feed	560 GWh	28	–	2,565 GWh	128	–
Liquefaction	223 tpd (large LFP)	341[a]	1,344	1,118 tpd (x-large LFP)	1,018[a]	6,722
Fuel reserve storage	796 t_{LH2}	24[a]	642[b]	3,978 t_{LH2}	119[a]	3,182[b]
Buffer storage	103 t_{LH2}	4[a]		477 t_{LH2}	16[a]	
2 cryopump systems	27 tph	14[a]	–	137 tph	70[a]	–
LH2 pipeline & hydrant	72 tph (minimum)	31[a]	848	123 tph	55[a]	4,244

[a] Total investment costs – not including annuity payment factor / depreciation period.
[b] Losses for both fuel reserve and buffer storage.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2022.100206.

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