Airport Liquid Hydrogen Storage Facilities

Techno-Economic Assessment

Master of Science Thesis in Collaboration with Airbus
Delft University of Technology
Faculty of Electrical Engineering, Mathematics & Computer Science

Alberto Cornel Popescu Cabo

TU Delft

AIRBUS

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by

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4839927

Supervisor:	Prof. Dr. Ir. Arvind Gangoli (Delft University of Technology)
Coach:	Ir. Marloes van Put (Airbus Netherlands)
Project Duration:	November, 2022 - Septmeber, 2023
Faculty:	Faculty of Electrical Engineering, Mathematics & Computer Science, Delft

TU Delft

Summary

The world is currently facing one of its largest challenges, namely; the phasing out of fossil fuel usage to reduce greenhouse gas emissions and curb global warming. The civil aviation industry is the second largest source of transport greenhouse gas emissions and emissions could triple by 2050 [27]. Consequently, the civil aviation industry is developing liquid hydrogen (LH_2) powered aircraft to achieve their goal of transforming into a net-zero emissions industry by 2050 [8, 96, 42, 17, 63]. This thesis focuses on tackling two of the main challenges LH_2 aviation faces: supporting infrastructure readiness and costs.

In the present research, the technologies and the corresponding levelized cost ranges of the LH_2 supply chain elements were reviewed. The review yielded that on-site LH_2 storage facilities are a key component in ensuring the supply of LH_2 for airports. Additionally, the largest knowledge gap and cost estimate uncertainty found are regarding LH_2 storage facilities. The levelised cost estimations varied by a factor greater than 200.

Consequently this thesis focuses on answering the following research question:

"How should liquid hydrogen storage facilities for airports be designed, what are the costs and how can they be reduced?"

Research on the design, operation and costs of LH_2 storage facilities was carried out via extensive literature research and expert interviews with the goal of collecting up-to-date and accurate cost estimation data. Subsequently, using the information gathered, a case study was performed of Rotterdam The Hague Airport (RTHA) in 2040.

The case study was carried out considering three main tank types, namely: trailer, cylindrical and spherical tanks. The storage facility was sized to have a capacity equal to three days' worth of peak demand (120 tonnes LH_2) based on the capacity recommendations for Jet A-1 storage and the predicted 2040 demand.

The case study involved developing a cost model that yielded the levelised cost, upfront investment and footprint of the various storage topologies. Large spherical tanks were found to be the option with the lowest levelised cost (€1.22 /kg LH_2), land usage (598 m^2) and upfront investment (M€18.1) for RTHA in 2040. Nevertheless, further considerations have to be taken into account when choosing a storage topology for other airports and storage demand levels.

A sensitivity analysis performed showed that the levelised cost has a sensitivity of -0.9 with respect to facility usage. Therefore, although larger tanks lead to lower levelised costs (even for hybrid topologies), storage facilities should be designed using modular and adaptable systems to prevent oversizing since an underused storage facility leads to a strong increase in the levelised cost.

Additionally, the sensitivity analysis yielded that the main cost drivers are the facility usage, tank CAPEX, pump CAPEX, boil off and, LH_2 cost. Therefore, the most effective ways of reducing the costs of the storage facility are: using modular and adaptable systems to prevent oversizing, developing CAPEX reduction methods such as batch production or technological improvements and lastly, implementing the recycling or usage of boil off gas.

Furthermore, the turning points between the design topologies were derived via the sensitivity analysis and are as follows. Trailer tanks should be considered for storage capacities under 30 tonnes as they offer ease of installation and usage, low upfront investment costs and high modularity. However, trailer tank storage facilities lead to higher levelised costs (around €2.14 /kg LH_2) and land usage. Nevertheless, at low levels of storage capacity, land usage should not be a constraint. Cylindrical tanks should be considered for 30-tonne to 100-tonne capacities as they offer a lower levelised cost than trailer tanks (around €1.75 /kg LH_2), lower land usage and considerable modularity to prevent oversizing. Large spherical tanks are most suited for storage capacities greater than 100 tonnes. Large spherical tanks lead to the lowest levelised cost (around €1.22 /kg LH_2), upfront investment and, land usage. At high storage demand, high modularity can be achieved with large tanks.

Concluding, this research reduced the large uncertainty regarding cost estimation for LH_2 storage facilities for airports from a factor larger than 200 to less than 20 (€0.06 /kg LH_2 - €13.75/kg LH_2 to €0.15 /kg LH_2 - €2.91/kg LH_2). Furthermore, a systematic and consistent modelling and analysis of the design, operation and cost of LH_2 storage facilities applicable to the specificities of an airport has been presented using accurate and up-to-date input data.

Acknowledgements

The last ten months I have spent performing my thesis have been the most enriching and demanding experience throughout my educational career. As this research was primarily performed and directed by myself, this has shown me the ins and outs of my strengths and weaknesses as an engineer and person. Consequently, this thesis has been a catalyst for self-reflection and improvement. Furthermore, having a deep dive at the technicalities of enabling liquid hydrogen storage at airports has been extremely exciting and I feel very proud to have contributed to the development of a sustainable future for the aviation sector.

Nevertheless, as Isaac Newton said: ”If I have seen further, it is by standing on the shoulders of giants”. Therefore, I would also like to thank all the giants who have helped and guided me throughout this challenge.

I would like to express my gratitude to Arvind Gangoli and Marloes van Put for giving me the opportunity and guidance to carry out this amazing project. I am very grateful for the time I have spent at the office with Marloes van Put. These experiences have taught me very much about work culture, etiquette and ethics, all of which have prepared me to enter the working market hereafter.

I would also like to thank all the external experts who have helped me. I would specifically like to mention two experts: Daan van Dijk and Gerhard Knol. A big thanks goes to Daan van Dijk for providing me with the necessary tools for carrying out a case study of Rotterdam The Hague Airport with a very positive and welcoming energy. I would also like to thank Gerhard Knol since he has supported me very much by openly and kindly providing me with ideas, information and contacts from the early stages of my thesis.

Lastly, I would like to thank my father. He has been a pillar throughout my education since the moment I had to learn my timetable. Much of the discipline and critical thinking skills I have are thanks to him and I would not find myself in such a privileged position without his guidance.

All in all, I feel very grateful for all the experiences and lessons the time performing my thesis has contained. However, I am sure that the future still holds many surprises and challenges, which I welcome with open arms.

Alberto Cornel Popescu Cabo
Delft, September 2023

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1 Introduction

The world is currently facing one of its largest challenges, namely; the phasing out of fossil fuel usage to reduce greenhouse gas emissions and curb global warming. The civil aviation industry contributes to around 3.8% of global CO_2 emissions and is the second largest source of transport greenhouse gas emissions [27]. Furthermore, it is predicted that emissions could triple by 2050 with respect to 2015. Consequently, the civil aviation industry is working towards transforming into a net-zero emissions industry by 2050 [17, 63].

In order for the civil aviation sector to achieve its goal, liquid hydrogen (LH_2) powered aircraft are being developed [8, 96, 42]. The usage of green LH_2 as a fuel for aircraft can reduce the global warming potential of emissions by around 90% with respect to Jet A1 aircraft [42]. However, green LH_2 powered aircraft are faced with four main challenges: the technology readiness level, safety & certification, supporting LH_2 infrastructure readiness and the costs.

This thesis tackles the issues of supporting infrastructure and cost by focusing on LH_2 storage facilities at airports and answering the following question:

"How should liquid hydrogen storage facilities for airports be designed, what are the costs and how can they be reduced?"

This report begins with chapter 2 where the reader is provided with key definitions to understand the topics discussed, the relevance of the research and its scope. Subsequently, in chapter 3, the solution methodology is explained which elaborates on the three steps taken to tackle the research question. In chapter 4, chapter 5 and chapter 6 the results of the three-step solution methodology are presented. Consequently, conclusions are drawn and the research question is answered in chapter 7. Thereafter, in chapter 8, a reflection of this research is presented alongside recommendations for further research.

2

Research Background

The goal of this chapter is to provide the reader with the necessary background information in order to understand the topics discussed, the relevance of the research and its scope. An explanation of the key definitions used is given in section 2.1. Subsequently, in section 2.2, the logic followed in order to arrive at the research question is presented. Lastly, a description of the research scope is given in section 2.3.

2.1. Key Definitions

The following concepts are key for the reader's understanding of this research:

- **Levelised cost** - The levelised cost is a measure of the lifetime costs divided by the lifetime output of a facility [65]. The costs and output that occur in a certain year throughout the lifetime of the facility must be discounted in order to be in the present value. The equation for levelised cost can be observed in Equation 2.1.

$$LC = \frac{Total\ Lifetime\ Costs}{Total\ Lifetime\ Output} = \frac{\sum_{t=0}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{O_t}{(1+r)^t}} \tag{2.1}$$

  The costs in the year "t" are composed of capital expenditures ($CAPEX_t$) and operational expenditures ($OPEX_t$). The symbol "n" represents the system lifetime. The symbol "r" represents the discount rate which is the value used in order to determine the present value of future cash flows. The symbol "O_t" is the system output in year t and is also referred to as the levelisation parameter in this research.

- **Capital expenditure (CAPEX)** - CAPEX is the cost of purchasing or improving fixed, physical, or non-consumable assets [65]. CAPEX examples include: facility construction, land or component replacement costs.

- **Operational expenditure (OPEX)** - OPEX is a recurring expense for maintaining a system, business, or product [65]. The OPEX is split into two components: the fixed OPEX and the variable OPEX [53]. Any expenditures that are constant irrespective of operation are known as fixed OPEX whereas variable OPEX fluctuates according to the operation [53]. Examples of fixed OPEX include control checks or maintenance costs. Examples of variable OPEX include energy costs.

2.2. Research Relevance

This section explains the relevance of the research question by elaborating on why LH_2 storage at airports is a critical aspect for this thesis to investigate. Firstly, an explanation of the expected LH_2 supply chain technology used for airports is elaborated upon in subsection 2.2.1. Then, a description of the complete supply chain is given in subsection 2.2.2. Subsequently, an analysis of the costs associated with the expected supply chain based on literature is performed in subsection 2.2.3 in order to explain the knowledge gaps identified which formed a basis for the research question. It is important to note that the analysis is performed based on the costs of technology commercially available today for the supply of green LH_2. Green LH_2 is produced from water electrolysis powered by a renewable energy source.

2.2.1. Airport LH_2 Supply Chain Technology Selection

The green LH_2 supply infrastructure considered is composed of four main components as seen in Figure 2.1. Each component of the supply chain has multiple technologies available.

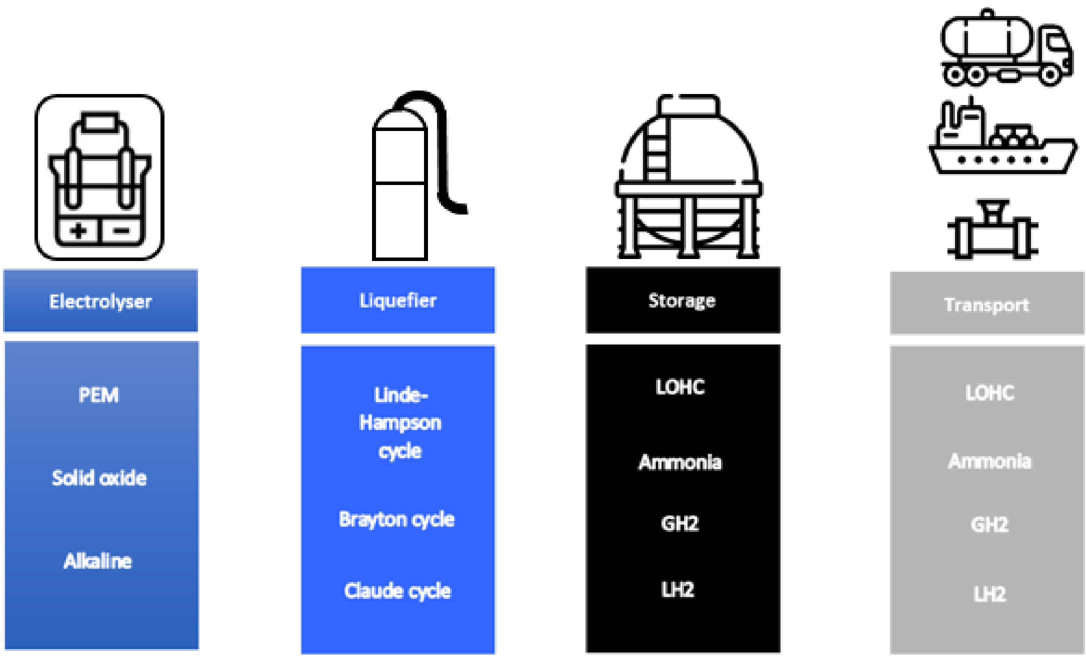

Figure 2.1: LH_2 supply chain components considered

The supply chain elements shown in Figure 2.1 are as follows:

1. The electrolyser is used to produce gaseous hydrogen (GH_2) via electrolysis from water. There are three main types of electrolysis: polymer electrolyte membrane (PEM), alkaline and solid oxide electrolysis cell (SOEC) electrolysers [38].
2. The liquefier converts GH_2 into LH_2. There are three liquefaction cycles discussed in the literature: Linde-Hampson, Brayton, and Claude cycle [9, 1, 95].
3. The storage facility acts as a buffer between supply and demand. The predominant hydrogen storage forms are: ammonia, liquid organic hydrogen carriers (LOHC), LH_2 or GH_2 [15, 5]
4. The transport method distributes hydrogen between the facilities. Hydrogen can be transported in its gaseous or liquid form as well as transformed into ammonia or absorbed into LOHCs [22, 67].

However, not all technologies are suited for supplying LH_2 to airports. There are four top-tier requirements based on literature that are used to select the expected infrastructure for delivering green LH_2 to airports:

1. **Applicable at large-scale**
   The future demand of LH_2 is estimated to be in the tens to hundreds of tonnes per day for an airport [81, 48, 25, 57]. This is comparable to the biggest current individual installed capacities of electrolysers (8.2 tonnes per day), liquefiers (30 tonnes per day) and LH_2 storage (270-ton capacity) meaning that supply needs to be large-scale [48, 31, 60, 59].
2. **Flexible**
   The infrastructure must be flexible to allow for variation in supply and demand. The supply will vary because green LH_2 is produced with renewable energy sources that depend on environmental conditions. Demand will vary due to variations in aircraft operations over time.
3. **Cost-competitive**
   The LH_2 supply must be cost-competitive as higher direct operating costs with respect to kerosene flight threaten the economic feasibility of green LH_2 flight [49].
4. **High technology readiness level**
   LH_2 supply chain technology must be applied at large scales in the coming years for LH_2 powered flight to enter the commercial aviation market by the 2030s, as aimed by Airbus and other companies [8, 96, 42]. Therefore, the technologies used must be at a technology readiness level high enough to allow for their large-scale implementation and to prevent supply interruptions due to technical issues.

Hereafter, an explanation of the supply chain technologies considered is given based on the top-tier requirements and the technology options shown in Figure 2.1.

Electrolysis

The first step of the supply chain is the production of green LH_2 via electrolysis. There are three main types of electorlysers: PEM, alkaline and SOEC [38].

Although SOEC electrolysis offers the added benefit of higher achievable efficiencies than PEM or alkaline electrolysers, the current lack of implementation, low technology readiness level and scaling of this technology means that it will not be considered further [5].

Alkaline electrolysis has benefits over PEM such as lower CAPEX, longer lifetime or higher efficiency [5, 54]. However, PEM electrolysers can produce pure H_2 between 0 % and 160 % of the nominal capacity meaning it can adapt well to changes in energy supply or hydrogen demand and produce hydrogen pure enough for aircraft fuel cells to operate on [5]. On the other hand, alkaline electrolysers have an operational range of 10 % to 110 % of their nominal capacity and produce less pure H_2 the further from nominal capacity operation. This may become a problem for aircraft fuel cells to operate on [5]. Additionally, PEM electrolysers offer the prediction of achieving equal or lower CAPEX and efficiencies than alkaline electrolysis and currently have half the land footprint of alkaline electrolysers [5, 44]. As a result, PEM electrolysis is considered a very good candidate for large-scale, flexible and low-cost hydrogen production and will be considered further [7, 90, 50].

Liquefaction

The literature generally discusses three primary designs or cycles for hydrogen liquefaction systems: Linde-Hampson, Brayton, and Claude cycle [9, 1, 95].

The Linde-Hampson cycle is one of the first cycles used to liquefy gases and is regarded as the most straightforward liquefaction technique, however, it is less efficient than other systems and is only recommended for small-scale operations hence it is not considered further [9, 40, 20, 5].

The Brayton refrigeration cycle has historically only been considered to be suitable for small-scale plants, but more recent literature has examined its potential expansion to larger-scale systems, however, it is in a low technology readiness level and is therefore not considered further [9].

The Claude cycle is advisable for large-scale applications due to lower size requirement of equipment, lower cost, higher liquefaction rates and higher efficiencies [9, 95]. A paper by Aasadnia & Mehrpooya (2018) [1] analyses large-scale LH_2 production methods and proposes 15 large-scale hydrogen liquefaction systems of which 14 employ Claude cycles [1]. Consequently, Claude-cycle-based liquefiers are considered suitable for large-scale and low-cost LH_2 supply and are considered further.

Storage

The main hydrogen storage forms are: ammonia, liquid organic hydrogen carriers (LOHC), LH_2 or GH_2 [15, 5]. Since hydrogen will be required in liquid form, approximately 12 kWh/kg of energy, which equates to 1/3 of the hydrogen's energy content is required for liquefaction [51]. This is important to consider as will become clear in the following paragraphs.

Although the technology to store ammonia is highly developed due to its wide application for the fertilizer industry, large energy losses would be incurred if hydrogen were stored as ammonia [13]. This is because converting hydrogen to ammonia consumes 10 - 15 kWh/kg of ammonia. Converting ammonia back to hydrogen consumes around 8 kWh/kg of H_2, equating in total to roughly 2/3 of hydrogen's energy content [4, 64]. The energy losses of ammonia generation, cracking and then hydrogen liquefaction translate to a conversion loss roughly equal to the energy content of hydrogen. Furthermore, converting hydrogen to ammonia requires additional equipment, land space, losses and costs [5]. Consequently, the storage of hydrogen via ammonia is not considered further.

LOHCs are oil derivatives that react reversibly with hydrogen and allow its storage and transportation under ambient conditions. The production and cracking of LOHCs also requires a lot of energy (around 11 kWh/kg, roughly 1/3 of hydrogen's energy content) in addition to the fact that the technology readiness level is considered to be in the prototype phase for large-scale applications [22, 3]. Furthermore, converting hydrogen to LOHCs requires additional equipment, land space, losses and costs [5]. Consequently, the storage of hydrogen via LOHCs is not considered further.

GH_2 storage in tanks is more expensive in comparison to LH_2 storage due to the strong structure needed to withstand high pressures [2]. Additionally, gaseous storage of hydrogen takes up around 2.7 times the volume (when stored at 300 bar) in comparison to LH_2 due to its much lower volumetric energy density [2]. LH_2 storage also has the advantage of being a mature technology as it has been implemented at large scales (hundreds of tonnes of storage per tank) since the 1960s by NASA [73]. Consequently, LH_2 storage is considered to be the most suitable option for storage in this study.

Transport

There are multiple forms of transport available. Hydrogen can be transported in its gaseous or liquid form as well as transformed into ammonia or absorbed into LOHCs [22, 67].

As explained earlier, converting hydrogen to LOHCs or ammonia requires additional equipment, land space, added energy losses and costs [5]. Consequently, the transport of hydrogen via ammonia or LOHCs is ruled out as an option for the purpose of this study.

GH_2 transport is only viable for airports if transported via pipeline where very large volumes are required as costs can drop below those of LH_2 transport [94, 5, 47, 79, 49]. Other forms of transport where the hydrogen is stored in a container (by ship or truck) are considered to be done with LH_2 due to the lower costs of storage and lower storage volumes required with respect to GH_2 [94, 5, 47, 79, 49]. Subsequently, transport via GH_2 pipelines and LH_2 storage container transport are considered the most apt as the technologies are relatively mature and low-cost and do not lead to high energy conversion losses [94, 5, 47].

2.2.2. Infrastructure Considered

Having determined the expected technologies for supplying LH_2 to airports, this subsection looks at how the supply chain topology will look as a whole.

The footprint, energy consumption and upfront investment present significant challenges to electrolysers and liquefiers being placed on-site at airports. Furthermore, there are large cost advantages associated with building large-scale electorlysers and liquefiers. Consequently, they are considered to be constructed as a part of a centralised hub but probably not on-site at airports for this study [84]. The centralised hub would serve the airport and other consumers in the area as well leading to more scaling benefits.

Nevertheless, LH_2 storage is expected to be found on-site at airports. Currently, airports generally have fuel reserves on site despite the mature nature of the aviation fuel supply chain technology [58]. On the other hand, large-scale LH_2 supply chain technology is very new. Consequently, supply chain disruptions are bound to occur such as component failure, variability in LH_2 availability or transport interruptions. Thus, LH_2 storage facilities are needed on-site to buffer for these occurrences. The backup reserve allows for security of the LH_2 supply and under typical circumstances it is not used for daily fulfilment.

Subsequently, below in Figure 2.2 one can see the infrastructure considered in this study. The magenta dotted line shows that electrolysers and liquefiers are considered to be at centralised hubs. The green dotted line shows that the LH_2 storage facility is taken to be at the airport.

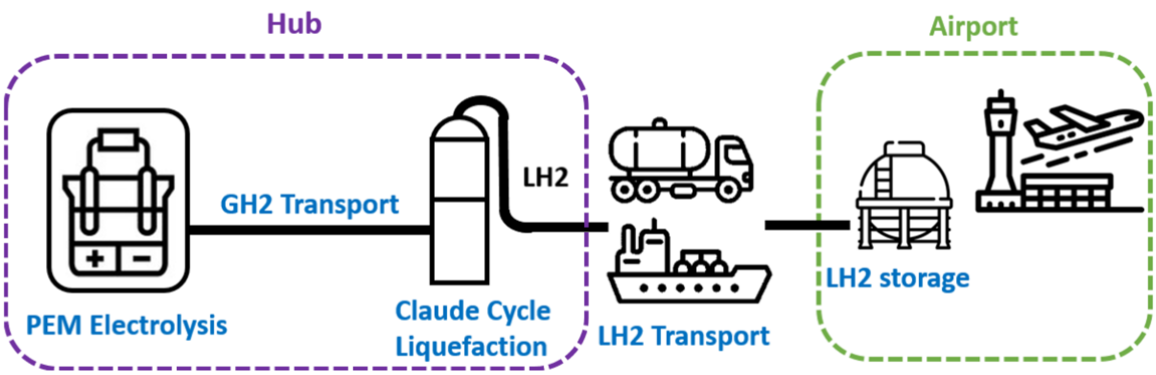

Figure 2.2: Supply chain of LH_2 for airports considered

2.2.3. Cost Analysis

This subsection presents the literature found relating to the costs of the various elements in the supply chain and evaluates the information presented by the sources. This was done with the goal of identifying a knowledge gap regarding the costs of the LH_2 supply chain for airports. The sources used in the analysis are summarised in four tables: Table 2.1, Table 2.3, Table 2.4 and Table 2.5.

PEM Electrolysis

This section presents and discusses the information obtained related to the production of hydrogen via PEM electrolysis. Based on Table 2.1, the information from each source is discussed. Subsequently, the levelised cost range is derived.

Title of source	Author	Value	Number	Units
Cost of Electrolytic Hydrogen Production with Existing Technology	Vickers et al. (2020) [89]	CAPEX Efficiency H_2 production cost (case study) H_2 production cost (external analysis)	1000 - 1500 59.7 4.00 – 6.00 2.50 – 6.80	$/kW$_{el}$ % $/ kg H_2 $ / kg H_2
Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe	Christensen (2020) [26]	Average CAPEX CAPEX range Fixed OPEX (% of CAPEX)	1671 737 – 3909 1 – 3	$/kW$_{el}$ $/kW$_{el}$ %
Green Hydrogen Cost Reduction: Scaling up electrolysers to meet the 1.5 °C climate goal	IRENA (2020) [84]	Energy requirement CAPEX Stack lifetime H_2 production cost	50 – 83 700 – 1400 50,000 – 80,000 4.50 – 5.20	kWh/kg H_2 $/kW$_{el}$ h $/ kg H_2
Future cost and performance of water electrolysis: An expert elicitation study	Schmidt et al. (2017) [80]	Stack Lifetime CAPEX	20,000 – 60,000 1860 - 2320	h €/kW$_{el}$
The Future of Hydrogen: Seizing today's opportunities	IEA (2019) [5]	Stack Lifetime CAPEX Efficiency	30,000 – 90,000 1100 - 1800 56 - 60	h $/kW$_{el}$ %

Table 2.1: PEM electrolyser data overview

The report by Vickers et al. (2020) [89] analyses the costs of PEM electrolysis based on case studies or the analysis of literature. Table 2.2 is a table presented in the report by Vickers et al. (2020) [89] summarising the input values and the levelised cost estimates for the case studies.

	Electricity Cost ($/kWh)	Capacity Factor	System CAPEX ($/kW)	H_2 Cost ($/kg)
Grid Low	0.05	90.0%	1,500	5.13
			1,000	4.37
Grid High	0.07	90.0%	1,500	6.27
			1,000	5.50

Table 2.2: Hydrogen costs for PEM electrolysis with associated inputs of electricity cost, capacity factor, and system capital cost [89]

Table 2.2 shows how hydrogen production costs can vary between $4.37 /kg H_2 and $6.27 /kg H_2 depending on the electricity cost and CAPEX. A high-level sensitivity check shows that the hydrogen cost increases by roughly 26% as a result of the electricity price increasing by 29%

meaning electricity price has a very strong influence on the cost. If the CAPEX increases by 50%, the hydrogen price increases by 17%. This shows that CAPEX has a strong effect on the cost. CAPEX and electricity prices are also found to be the most cost-contributing components by the International Energy Agency (IEA) (2019) [5] and the International Renewable Energy Agency (IRENA) (2020) [84].

The literature study by Vickers et al. (2020) [89] found that costs ranged between \$2.50 /kg H_2 and \$6.80 /kg H_2 which is more than in the case study. The reason for the cost estimate ranges being larger in the literature study in comparison to the case study performed by Vickers et al. (2020) [89].

The CAPEX values used in the case study by Vickers et al. (2020) [89] are in line with other studies; Schmidt et al. (2017) [80] finds CAPEX values between \$1860 /kW_{el} - \$2320 /kW_{el} and Christensen (2020) [26] finds that, based on 41 different PEM electorlysers, CAPEX costs vary between \$773 /kW_{el} and \$3909 /kW_{el} with an average value of \$1671 /kW_{el}. The information presented by Christensen (2020) [26] indicates that CAPEX costs may vary a lot. The high CAPEX variance and strong influence on levelised cost may be a reason why the literature study done by Vickers et al. (2020) [89] found a larger cost range than the case study analysis. The CAPEX cost disparities may be due to the two reasons mentioned by IRENA (2020) [84]: the availability of data due to confidentiality as well as the boundaries of the cost estimates not having consistent scopes.

IRENA (2020) performs a study including a ”thorough literature review validated by consultations and a peer review with various leading manufacturers”. IRENA (2020) [84] finds that current hydrogen prices from electrolysis vary between roughly \$4.50 /kg H_2 and \$5.20 /kg H_2. The H_2 production costs stated by IRENA (2020) [84] coincide with those calculated by Vickers et al. (2020) [89].

IRENA (2020) [84] states the range of electricity required per kg of H_2: 50 kWh/kg - 83 kWh/kg as well as the stack lifetime range considered: 50,000 h - 80,000 h. The study by the IEA (2019) [5] presents stack lifetimes to range between 30,000 h - 90,000 h and Schmidt et al. (2017) [80] states a range of 20,000 h - 60,000 h. All of these ranges are close to one another however the ranges themselves are very wide meaning that they could be another cause for discrepancies in levelised cost.

The only characteristic that has a tighter range is the efficiency of electrolysis which is indicated to be between 56% - 60% by IEA (2019) [5]. The efficiency value taken by Vickers et al. (2020) [89] falls within the range of IEA (2019) [5]. This shows that efficiency discrepancies are not a cause for levelised cost estimation differences.

From the sources analysed, it can be concluded that the levelised costs for PEM electrolysis can range between \$2.50 /kg H_2 - \$6.80 /kg H_2 [89, 5]. These cost variations are due to different electricity costs, CAPEX, stack lifetime, or energy requirements for H_2 production [84, 5, 80, 26, 89]. However, the main cost contributors are electricity costs and CAPEX [5, 84].

Claude Cycle Liquefaction

This section presents and discusses the information obtained related to Claude cycle hydrogen liquefaction. Based on Table 2.3, the information from each source is discussed. Subsequently, the levelised cost range is derived.

Title of source	Author	Value	Number	Units
Current Status of Hydrogen Liquefaction Costs	Connelly et al. (2019) [29]	CAPEX	4000	\$/kg LH_2 /day
		Energy requirement	10 – 20	kWh/kg LH_2
		Lifetime	40	years
		Liquefaction cost	2.75	\$/kg LH_2
AMC's Hydrogen Future: Sustainable Air Mobility	Reiman (2009) [75]	CAPEX	1486	\$/kg LH_2 /day
		Energy requirement	12.5 - 15	kWh/kg LH_2
		Efficiency	30 - 50	%
		Liquefaction cost	1.19 - 2.00	\$/kg LH_2
Power-to-liquid hydrogen: Exergy-based evaluation of a large-scale system	Incer-Valverde (2021) [52]	Energy requirement	5.29 – 13.8	kWh/kg LH_2
		Efficiency	42.1	%
		Liquefaction cost	1.50	\$/kg LH_2
The Future of Hydrogen: Seizing today's opportunities	IEA (2019) [5]	Liquefaction cost	1.00	\$/kg LH_2

Table 2.3: Claude cycle liquefier data overview

Connelly et al. (2019) [29] published an investigation on costs of hydrogen liquefiers. Connelly et al. (2019) [29] estimated that hydrogen liquefaction costs are \$2.75 /kg LH_2 for a 27 ton per day liquefier using a CAPEX of roughly \$4000 /kg LH_2 and a lifetime of 40 years. In this analysis, the CAPEX is composed of: the plant cost, land costs, and owner's costs which include financial, engineering, permits, licensing and training costs. The energy requirement for liquefaction was given to be 10 - 20 kWh/kg LH_2 but it is unclear what exact value was used in the calculation. The energy cost used is not mentioned. Electricity and CAPEX costs were found to be the largest cost contributors as they amounted to roughly 50% and 30% of the total levelised cost, respectively.

On the other hand, Reiman (2009) [75] collected data from literature on liquefaction costs and found that the levelised cost is between 1.19 - 2.00 \$/kg LH_2. This is lower than the \$2.75 /kg LH_2 calculated by Connelly et al. (2019) [29]. The reason for the discrepancy in the levelised cost estimate could be due to the CAPEX values used since it is a strong cost contributor. The CAPEX value found by Reiman (2009) [75] is \$1486/kg /day LH_2. Reiman's (2009) [75] CAPEX value is roughly a factor three times smaller than that estimated by Connelly et al. (2019) [29]. However, other values taken such as the energy cost, lifetime or facility size are unknown and could also be the cause for discrepancies in levelised cost.

Furthermore, Incer-Valverde et al. (2021) [52] estimates a levelised cost of hydrogen liquefaction of \$1.50 /kg LH_2. Incer-Valverde et al. (2021) [52] emphasises the high sensitivity of levelised cost with respect to electricity costs. The energy use taken by Incer-Valverde et al. (2021) [52] is lower than that found by Reiman (2009) [75] (8 kWh/kg LH_2 in comparison to 12.5 - 15 kWh/kg), perhaps because it is a theoretical design larger than the liquefier considered by Reiman (2009) [75] which can lead to energy consumption benefits due to scaling [10]. Nevertheless, the levelised cost estimate of Incer-Valverde et al. (2021) [52] falls in the range of that found by Reiman (2009) [75].

Additionally, IEA (2019) [5] uses a value of \$1.00 /kg for the levelised cost of hydrogen liquefaction in their report. Details of the calculation method and values are unclear from the report or sources cited. However, the levelised cost used by IEA (2019) [5] is close to those found by Reiman (2009) [75] and Incer-Valverde et al. (2021) [52].

Overall, the sources found show that liquefaction prices range between \$1.00 /kg LH_2 - \$2.75 /kg LH_2 [29, 5, 52]. The liquefaction costs are dominated by energy costs and CAPEX [29, 52]. The cause for levelised cost estimation discrepancies seems to arise due to different CAPEX boundaries [52, 29]. However, it is difficult to pinpoint the causes for differences in levelised cost estimation as not all values used and calculation methods are documented.

LH_2 Storage

This section presents and discusses the information obtained related to LH_2 storage costs and the levelised cost range is derived. Table 2.4 shows the sources and data considered.

Title of source	Value	Number	Units	Author
Survey of the Economics of Hydrogen Technologies	CAPEX (109 – 170 tonnes) CAPEX (32.5 – 32500 tonnes) boil off (size dependant) Large storage cost (>108 t) Small daily storage costs (1t) Small monthly storage (32.5 t)	219.6 – 864.0 20.4 – 202.0 0.1 – 3 0.60 – 0.96 2.04 2.76	\$/kg LH_2 \$/kg LH_2 %/day \$/kg LH_2 \$/kg LH_2 \$/kg LH_2	NREL (1999) [47]
Projecting the levelized cost of large-scale hydrogen storage for stationary applications	Storage costs for 30 day cycle	~12.50	\$/kg LH_2	Abdin et al. 2022 [2]
H_2-powered aviation at airports - design and economics of LH_2 refuelling systems	Storage costs	0.05	\$/kg LH_2	Hoelzen et al. (2022) [48]
Liquid Hydrogen Storage: Status and Future Perspectives	CAPEX	300	€/ kg LH_2	Derking et al. (2019) [32]
Reduction in Liquid Hydrogen by Weight due to Storage in Different Sizes of Containers for Varying Period of Time	boil off (size dependant)	0.06 – 0.4	%/day	Gautamet al. (2018) [45]
Liquid hydrogen pump performance and durability testing through repeated cryogenic vessel filling to 700 bar	Loading/unloading losses	6 – 15.4	%/movement	Petitpas & Aceves (2018) [69]
Simulation of boil off losses during transfer at LH_2 based hydrogen refuelling station	Loading/unloading losses	>12	%/movement	Petitpas (2018) [68]

Table 2.4: LH_2 storage data overview

NREL (1999) [47] evaluates various hydrogen storage technologies including liquid hydrogen for stationary applications based on literature. NREL (1999) [47] estimates a levelised costs of: 0.60 - 0.96 \$/kg LH_2 for "large" storage facilities (>108 tonnes), 2.04 \$/kg LH_2 for a storage capacity of 1 ton for daily purposes, and 2.76 \$/kg LH_2 for a monthly storage facility of 32.5 tonnes. CAPEX values of 219.6 \$/kg LH_2 - 864 \$/kg LH_2 are estimated for storage facilities with a capacity between 170 tonnes - 109 tonnes, respectively. CAPEX values for capacities between 32.5 tonnes and 32,500 tonnes are given to cost between 202 \$/kg LH_2 and 20.4 \$/kg LH_2, respectively. It is important to note that the largest LH_2 storage tank has a capacity of 27 tonnes [31]. Hence, analyses of sizes much larger are very big extrapolations [31].

Due to LH_2's low boiling point (-253 ° C), it evaporates and has to be vented from storage vessels. This is referred to as Boil off losses. Boil off losses are given to be 2 % - 3 % of the tank capacity per day for "small" vessels and as small as 0.1 %/day for "large spherical" vessels according to NREL (1999) [47]. However, a quantification of the sizes for which these boil off values are applicable is not given. The data presented by NREL (1999) [47] presents large ranges for cost estimations with little explanation of the causes and insufficient data points in order to deduce correlations between cost and facility size or storage time.

A presentation by Derking et al. (2019) [32] on behalf of the Dutch cryogenics company "Cryoworld" that manufactures LH_2 storage tanks, stated that CAPEX costs are 300 €/ kg LH_2 however the storage size to which this value pertained was not given. Consequently, this source does not clarify the CAPEX values to be expected.

On the other hand, Gautam et al. 2018 [45] who performed an analysis on LH_2 losses for various supply chain layouts found per day losses of 0.4%, 0.2%, and 0.06% for 50 m^3, 100 m^3, and 20,000 m^3 LH_2 storage tanks, respectively. Gautam et al. 2018 [45] confirm that storage tank sizing has a large effect on boil off losses and slightly clarifies the boil off rates to be expected. However, no cost analysis is presented.

On the other hand, Abdin et al. 2022 [2] published a more recent study calculating the levelised cost of hydrogen storage for seven systems based on capital, operational, and decommissioning costs. It is important to note that Abdin et al. 2022 [2] includes liquefier costs for LH_2 storage. CAPEX and OPEX values are therefore larger than for LH_2 storage alone. It was not possible to understand what portion of the costs arose from the liquefier or the storage facility. This is because Abdin et al. 2022 [2] did not give the data used separately for the liquefier and LH_2 storage facilities. Furthermore, the boil off rates used are not mentioned. Nevertheless, Figure 2.3 presents the most relevant and useful information by Abdin et al. 2022 [2]; the effect of storage time on levelised cost of LH_2 storage. The red line represents LH_2 liquefaction and storage costs for different storage times.

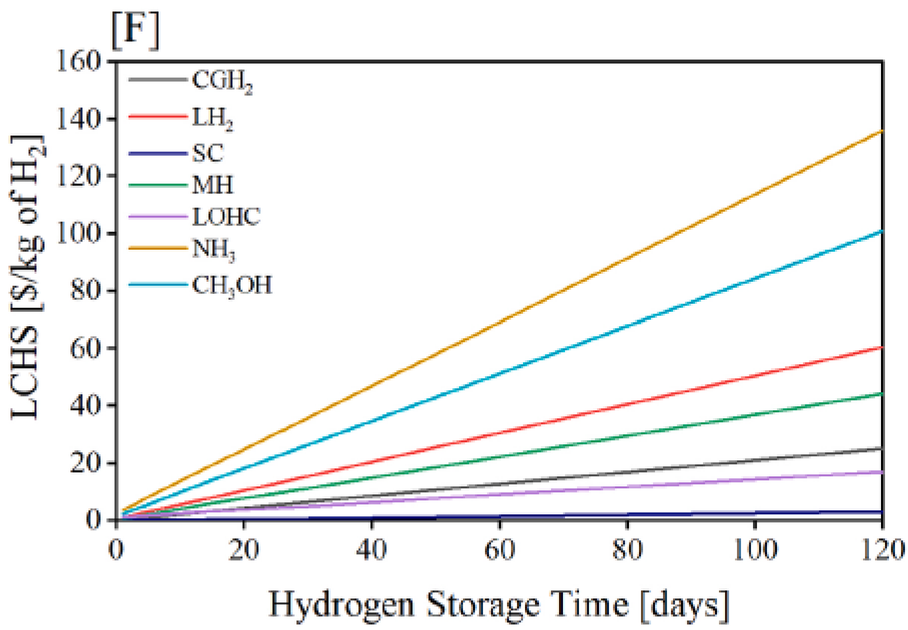

Figure 2.3: Change of levelized cost of hydrogen storage with storage time for different hydrogen storage systems [2]

From Figure 2.3 it can be seen that storage time/storage cycling varied expenses significantly. For example, storing LH_2 for 20-day cycles leads to a levelised storage and liquefaction cost of around 10.00 $/kg LH_2. However, for a 40-day cycle, the costs rise to around 20 $/kg LH_2. This high cost is because Abdin et al. 2022 [2] calculates levelised cost. So if a tank's utilization drops for the same expenditures, a much higher levelised cost is reached indicating roughly a 1:1 sensitivity.

Previous values obtained on hydrogen liquefaction costs range between $1.00 /kg LH_2 - $2.75 /kg LH_2. Consequently, depending on the storage cycling, the storage costs could be negligible or much larger than liquefaction costs when looking at Figure 2.3. A strategic reserve at an airport for events where supply is cut off may be used once every 30 days. From Figure 2.3, at a 30-day storage time, the levelised cost of LH_2 storage is around $15 /kg LH_2 including liquefaction. Taking that liquefaction costs are a maximum of $2.50 /kg LH_2, this leaves storage costs at around $12.50 /kg LH_2.

On the other hand, a study performed by Hoelzen et al. (2019) [48] which derives techno-economic models for LH_2 storage, liquefaction and transportation at airports found that storage costs are 0.05 $/kg LH_2 stored. This value is much lower than the ones found by NREL (1999) [47] and Abdin et al. 2022 [2]. Consequently, further analysis was performed in order to understand the cause of such an optimistic price estimate.

A reason for a low-cost estimate could be the calculation boundaries used by Hoelzen et al. (2019) [48] which considers tanks as the storage system in contrast to Abdin et al. 2022 [2] who evaluates costs including the storage tanks and liquefier.

Another reason for a low-cost estimate by Hoelzen et al. (2019) [48] could be the levelisation method used. Previous research presented has taken the levelisation parameter as the yearly amount of LH_2 stored in the storage facility. In other words, the levelised cost is calculated as the cost of 1 kg of LH_2 purchased from the storage facility as an independent business unit. The levelisation method used by Hoelzen et al. (2019) [48] seems to use the yearly LH_2 throughput of the airport. This method evaluates the economic impact the LH_2 storage facility has on all the LH_2 sold to aeroplanes. This method considers that the LH_2 storage facility is part of the full airport system in an economic sense.

The discrepancies found in techno-economic parameters used for LH_2 storage cost calculations between Hoelzen et al. (2019) [48] and those mentioned by Derking et al. (2019) [32] and NREL (1999) [47]) are the CAPEX values. The CAPEX values stated by Hoelzen et al. (2019) [48] range between 39 \$/kg LH_2 to 30 \$/kg LH_2 + 1,440,000 \$ whereas sources discussed earlier showed values in the range of hundreds of \$/kg LH_2 [32, 47].

Hoelzen et al. (2019) [48] presented three sources for justifying the CAPEX used.

1. The first source is by Amy & Kunycky (2019) [14] who did a study on LH_2-powered aircraft design and gave a short overview of airport infrastructure. Amy & Kunycky (2019) [14] cites Alibaba.com (a website for wholesale Chinese products) for the cost of a LH_2 storage tank. When looking at the source's description of the LH_2 tank its "working medium" is liquid oxygen, nitrogen, and argon without any mention of LH_2. Additionally, the application is labelled as "gas storage" and the name of the product is "30m3 8 bar liquid hydrogen price". Consequently, this source does not seem to be a reliable CAPEX reference.

2. The second paper cited is by Reuβ et al. (2019) [77]. This paper uses a CAPEX value of € 25 /kg LH_2 based on literature. However, when investigating the sources used by Reuβ et al. (2019) [77] only one of the sources shows a CAPEX estimation. The only paper cited giving information on CAPEX values of LH_2 storage facilities is written by Reuβ as well. The paper cited also uses the same value of € 25 /kg LH_2 and in turn cites USDOE (2015) [36]. The report by USDOE (2015) [36] provides a roadmap for improving technology for fuel cell vehicles of which part is reducing H_2 storage costs, but it is not specified whether it is in liquid or gaseous form. This report by USDOE (2015) [36] states the following goal:

   "By 2020, develop and verify onboard automotive hydrogen storage systems achieving ... a cost of \$10/kWh (\$333/kg H_2 stored)"

The cost of \$333/kg H_2 stored is not in line with the values Reuβ et al. (2019) [77] cited and neither those by Hoelzen et al. (2019) [48] but rather with those from NREL (1999) [47] and Derking et al. (2019) [32] mentioned earlier.

3. The third source used by Hoelzen et al. (2019) [48] is Gautam et al. 2018 [45] which cites NREL (1999) [47] which presents CAPEX predictions between 219.6 \$/kg LH_2 - 864.0 \$/kg LH_2 for a LH_2 storage facility with a capacity between 109 tonnes - 170 tonnes. For capacities between 32.5 tonnes and 32,500 tonnes, the CAPEX is estimated to be between 202 \$/kg LH_2 - 20.4 \$/kg LH_2, respectively.

Subsequently, it seems that data on CAPEX values for LH_2 storage facilities do not converge at tens of dollars per kilogram of LH_2 stored but rather vary by almost two orders of magnitude and could be another reason for the large spread in levelised cost estimates.

One cost aspect not taken into account in any of the cost estimations was the loading/unloading boil off losses. Petitpas (2018) [68] develops an LH_2 transfer model based on a MATLAB model previously created by NASA to simulate rocket fueling. The results of this model show that the amount of boil off losses during loading/unloading accounts for more than 12% of the amount of LH_2 transferred.

Furthermore, Petitpas & Aveces (2018) [69] performed a study testing an LH_2 pump's performance and durability for filling a cryogenic vessel with LH_2. The test results found that loading/unloading losses are between 6% and 15.4% for "representative" operations at an LH_2 refuelling station.

Additionally, Genovese et al. (2019) [46] performed an experiment evaluating the losses during hydrogen dispensing based on data from quarterly reports of a test facility. Losses were found to range between 2% - 10%.

Both the experimental and modelling results indicate that losses do occur during loading/unloading procedures that are integral to the operation of an LH_2 storage facility and hence, must be taken into account for calculating the costs of LH_2 storage.

Another aspect not considered in the literature is the differences between the three tank types available: trailer, cylindrical and spherical tanks [73]. Additionally, no information was found regarding the design of such storage facilities for airports, the respective safety measures and land usage, all of which impact the facilities' costs and topology. Land in particular tends to be a scarce resource at airports and hence plays a big role in what tank types should be used and the cost of the facility. Therefore, an understanding of land footprint requirements is paramount. Furthermore, no studies performed a comprehensive evaluation of what the cost drivers are or what the upfront investment costs may be.

To conclude, storage cost estimations seem to be inconclusive, inconsistent, and even incomplete. Sources used different system boundaries when analysing levelised storage costs. Furthermore, CAPEX values varied by orders of magnitude. Additionally, different levelisation methods were used. Subsequently, levelised cost estimations for LH_2 storage were found to vary between \$0.05 /kg LH_2 to \$12.50 /kg LH_2. All sources found did not address or consider loading/unloading losses, tank design options, land usage, cost sensitivity, upfront investment costs or the specificities pertaining to the context of an airport.

GH_2/LH_2 Transport

This section presents and discusses the information obtained related to transport costs of GH_2 and LH_2. Based on Table 2.5, the information from each source is discussed. Subsequently, the levelised cost range is derived.

Title of source	Author	Value	Number	Units
Determining the lowest-cost hydrogen delivery mode	Yang & Ogden (2007) [94]	LH_2 truck transport costs (incl. liquefaction)	1.50 – 3.50	\$/kg LH_2
		GH_2 pipeline transport costs	0.50 – 1.50	\$/kg GH_2
		GH_2 truck costs	0.50 – 3.50	\$/kg GH_2
The Future of Hydrogen: Seizing today's opportunities	IEA (2019) [5]	GH_2 pipeline transport costs	0.10 – 2.00	\$/kg GH_2
		LH_2 ship transport costs	0.90 – 1.3	\$/kg LH_2
		LH_2 truck transport costs	0.15 – 0.40	\$/kg LH_2

Table 2.5: GH_2/LH_2 transport data overview

Yang & Ogden (2007) [94] present a study modelling various hydrogen delivery mode costs depending on demand and transportation distance scenarios. They consider the cost starting from the GH_2 feed and 3 transport modes: GH_2 trucks, LH_2 trucks and GH_2 pipelines. The costs presented for the LH_2 truck transport include the liquefaction facility and its accompanying costs. Likewise, the gaseous transport costs include those of the compressor station. The paper presents Figure 2.4 describing when each transport method is the cost-optimum one for varying levels of demand and transport distance as well as the corresponding transport costs. Areas marked by G, L, and P represent conditions where transportation via GH_2 trucks, LH_2 trucks and GH_2 pipelines, respectively, is the lowest-cost option.

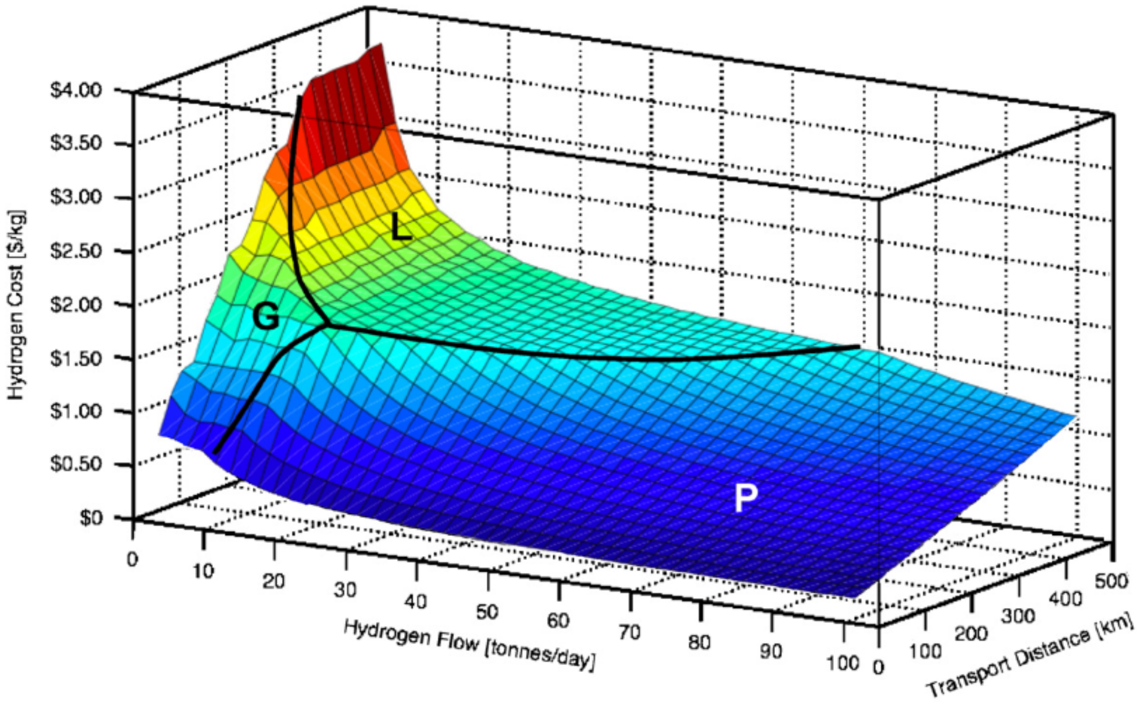

Figure 2.4: Minimum transport costs for varying demand and distance according to Yang & Ogden (2007) [94]

Figure 2.4 shows that GH_2 truck transport is only cost-effective for transport quantities below around 25 tonnes per day and under 100 km. These transport quantities are rather low compared to what is expected for airports which was found to be in the tens to hundreds of tonnes per day [48, 5]. Additionally, considering that liquefaction plants will be placed at a centralised hub and probably a considerable distance from the airport, GH_2 trucks would not be used in the supply chain.

Furthermore, from Figure 2.4 LH_2 trucks appear to have a cost of around $2.00 /kg LH_2 for capacities relevant to airports (>30 tonnes/day). The cost of LH_2 truck transport is including that of the liquefaction facility. Considering that hydrogen liquefaction costs are given to be around $0.90 /kg LH_2 for a capacity of 100 t/day by Yang & Odgen (2007) [94], LH_2 truck transport must cost in the order of $ 1/kg LH_2 transported.

From Figure 2.4, GH_2 pipeline costs seem to be the lowest when transport distance and flow rate are around 100 km and 10 tonnes; $0.50 /kg H_2. GH_2 pipelines are also the low-cost option at 500 km distances and 100 tonnes/day flow rate but prices increase to around $1.00 /kg H_2. The increase in GH_2 pipeline transport cost can be attributed to the high land and pipeline CAPEX according to Yang & Odgen (2007) [94].

IEA (2019) [5] provides an assessment of hydrogen's technological, economic and political standpoint. Part of its analysis focuses on hydrogen transport as well. It divides transport options into long-distance transport: ship and pipeline in liquid form, and short-distance transport: truck and pipelines in liquid and gaseous form, respectively. Hydrogen transport costs in the form of LOHC and ammonia form are also included by IEA (2019) [5] but not analysed due to reasons mentioned in section 2.2. In Figure 2.5 and Figure 2.6 one can see the cost estimate graphs from IEA (2019) [5] for long and short-distance transport, respectively.

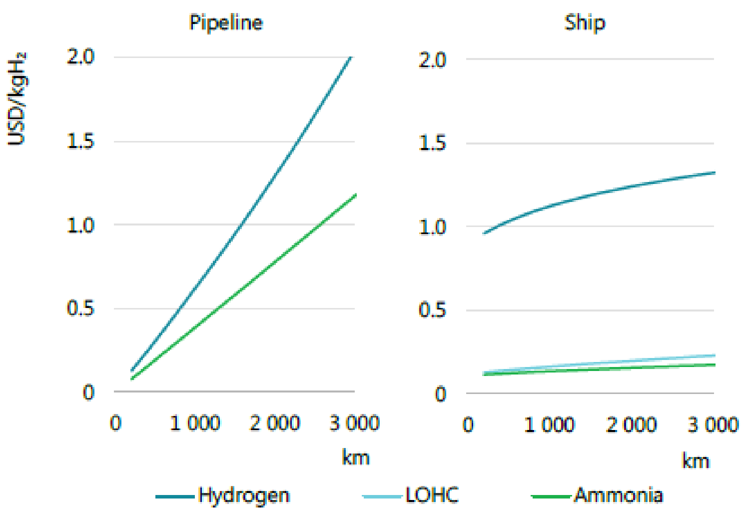

Figure 2.5: Cost of hydrogen storage and long-distance transport by GH_2 pipeline and LH_2 ship [5]

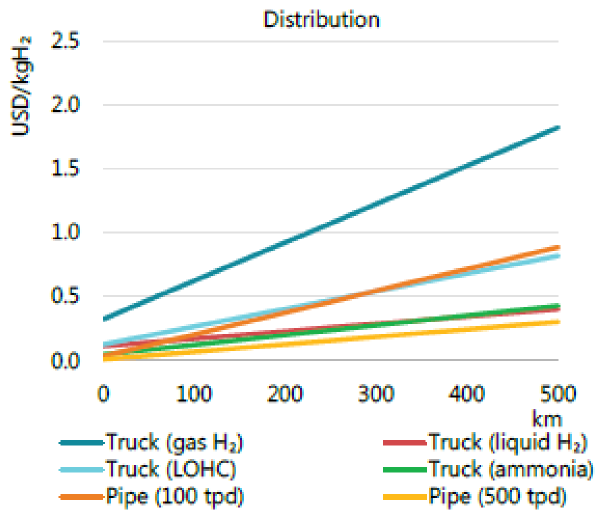

Figure 2.6: Cost of hydrogen for short distance transport [5]

Figure 2.5 presented by IEA (2019) [5] shows that costs estimated for transport of GH_2 by pipeline vary from roughly \$0.20 /kg H_2 at 300 km to \$2.00 /kg H_2 at 3000 km. Transport by ship starts at around \$0.90 /kg LH_2 for 300 km and ends at \$1.30 /kg LH_2 for 3000 km.

Yang & Odgen's (2007) [94] analysis is only comparable to IEA's (2019) [5] for short distances (up to 500km, shown in Figure 2.6). Yang & Odgen's (2007) [94] cost estimation for 500km and 70 tonnes per day via LH_2 trucks was \$2.00 /kg LH_2 (including liquefaction). IEA's (2019) [5] costs for LH_2 truck transport over 500 km was \$0.40 /kg LH_2. Hydrogen liquefaction costs are given to be around \$0.90 /kg LH_2 for a capacity of 100 t/day by Yang & Odgen (2007) [94]. Subsequently, Yang & Odgen (2007) [94] estimate LH_2 truck transport costs (excl. liquefaction) to be at around \$1.10 /kg LH_2. Discrepancies in costs calculated may arise due to a number of reasons such as CAPEX/OPEX values taken, operational assumptions, or calculation methods. However, it is difficult to pinpoint the reason for discrepancies as values taken to calculate the costs in IEA (2019) [5] are not stated.

Yang & Odgen's (2007) [94] cost estimation for 500km and 100 tonnes per day via GH_2 pipelines is \$0.50 /kg H_2 which is significantly lower than the \$0.90 /kg H_2 found by IEA (2019) [5]. GH_2 pipeline transport costs are heavily influenced by land costs (especially at low demands) which vary depending on the location [94]. Hence, this could be the core reason for the differences in estimates. Values taken to calculate the costs in IEA (2019) [5] are not explicitly stated, hence it was not possible to pinpoint the reason for discrepancies in cost estimations.

The sources presented for transport suggest that costs can vary between \$0.10 - \$2.00 /kg (L/G)H_2 [5, 94]. The costs of hydrogen transport were found to depend on the transport distance, medium and quantity [5, 94]. At high distances (< 1000 km) pipeline or ship transport is the most cost-effective, costing between \$0.10 /kg H_2 to H_2 \$2.00 /kg H_2. The higher prices are attributed to the higher transport distance. At lower distances (<500 km) LH_2 truck transport is best for quantities under roughly 100 tonnes per day however for larger quantities above around 100 tonnes per day GH_2 pipelines are most cost-effective. The lowest costs for transport are attributed to high transport capacities over short distances through GH_2 pipelines costing around \$0.10/ kg GH_2.

Research Focus

The literature review presented in subsection 2.2.3 highlights key areas that lack reliable and cohesive knowledge for an approximate cost estimate.

Although electrolysis costs may vary by a factor of three, the main causes for this are known and understood: CAPEX and electricity cost [89, 5, 84]. The same is the case for liquefaction where costs also ranged by almost a factor of three. The method for cost reduction of electrolysis and liquefaction relies on having a low-cost renewable energy supply as well as improving the technology of the systems and scaling in order to reduce the CAPEX[49].

Transport costs were found to vary by a factor of 20 mainly due to varying transport distance, medium and quantity [47, 5, 94]. Nevertheless, it became clear that transport costs can not be generalised as they strongly depend on the context of the supply chain and this strongly influences the costs.

Although electrolysis, liquefaction, and transportation all present uncertainty in sources used, numbers estimated and a variation in estimates, the biggest knowledge gaps and coherency issues were found with respect to the storage cost, resulting in by far the largest spread of the levelised cost: 0.05 \$/kg - 12.50 \$/kg, which is more than a factor of 200. Additionally, LH_2 storage sources varied greatly in what they considered as their storage facility and did not allow for a clear understanding of which part of the system caused what costs. Furthermore, different concepts were shown for the levelisation method. Sources also showed a lack of understanding and consideration of the cost, design and operation of storage facilities, especially in the context of an airport.

The differences in cost estimates for the various supply chain components considered are summarised in Figure 2.7.

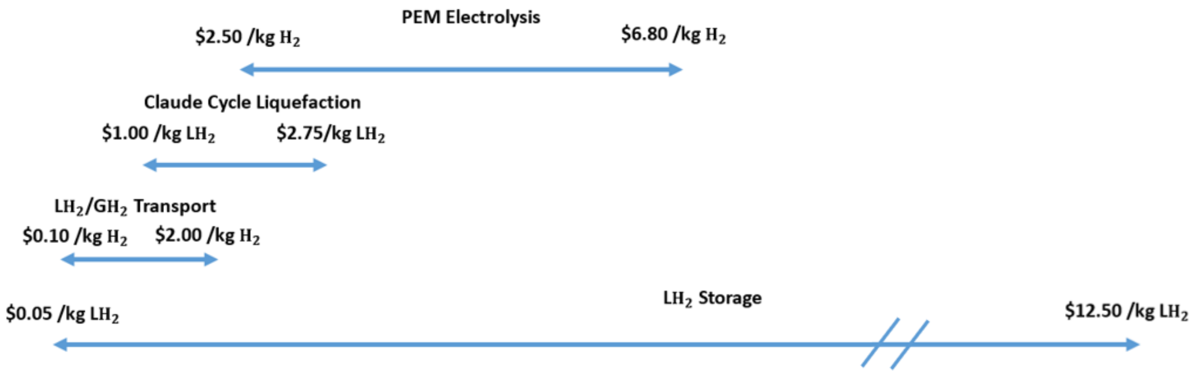

Figure 2.7: Levelised cost ranges for LH_2 supply chain components based on literature

From Figure 2.7 it is clear that the largest cost uncertainty is for LH_2 storage facilities. Furthermore, it has been identified that LH_2 storage facilities are a key element in ensuring the supply of LH_2 for airports and hence a systematic and consistent modelling and analysis of the design, operation and cost of LH_2 storage facilities applicable to the specificities of an airport is crucial.

Due to the reasons presented above, this research focuses on LH_2 storage facilities at airports. Now that the knowledge gaps have been identified, the following section translates them into a research question alongside its boundaries.

2.3. Research Scope

This subsection gives an explanation of the research question and boundaries in subsection 2.3.1 and subsection 2.3.2, respectively.

2.3.1. Research Question

This research tackles the following research question:

"How should liquid hydrogen storage facilities for airports be designed, what are the costs and how can they be reduced?"

The research question is aimed at covering the following research gaps identified in subsection 2.2.3:

1. Cost estimation using relevant cost estimation boundaries, up-to-date and accurate cost estimation data and considering various topology options
2. Understanding of the effect of the cost levelisation method used
3. Understanding of the design and operation

4. Understanding of the main cost drivers, upfront investment costs and land footprint

2.3.2. Research Boundaries

The multiple tank options available and considered are shown in Figure 2.8.

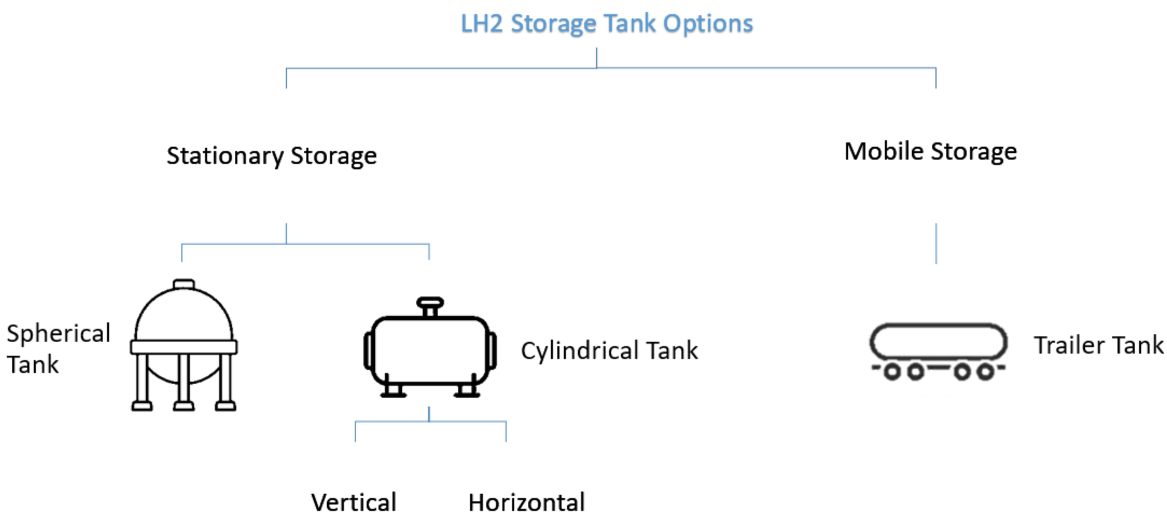

Figure 2.8: Design Options of LH_2 Storage Tanks

The tank types can be grouped into stationary tanks and mobile storage. Three different tank types are considered, namely: trailer (mobile), cylindrical (stationary) and spherical tanks (stationary). Cylindrical tanks can be placed either vertically or horizontally.

The tank type in question affects the storage components considered. Figure 2.9 gives an overview of the components considered per tank type and hence also the research boundaries.

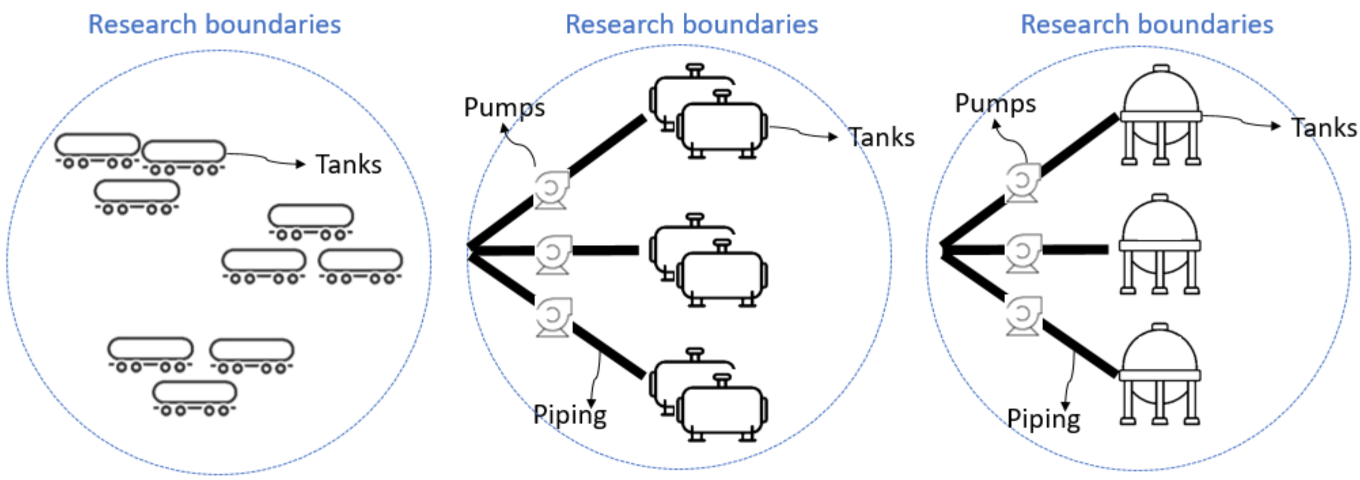

Figure 2.9: Research boundaries per tank type

The storage system for trailer tanks consists of the trailer tanks and land. For cylindrical and spherical tanks, the storage system is defined as the storage tanks, pumps, piping and land.

It is important to note that in this study two forms of levelisation methods are considered. The different levelisation methods are ways of interpreting the same absolute cost.

- The first and predominant levelisation method considered takes the yearly amount of LH_2 stored in the storage facility as the levelisation parameter. In other words, the levelised cost is calculated as the cost of 1 kg of LH_2 purchased from the storage facility as an independent ”business unit”.

- The second levelisation method considered uses the yearly LH_2 throughput of the airport as the levelisation parameter. This method evaluates the economic impact the LH_2 storage facility has on all the LH_2 sold to aeroplanes. This method considers that the LH_2 storage facility is part of the airport system in an economic sense.

Furthermore, in order to calculate the levelised cost of hydrogen storage, the CAPEX and OPEX components have to be defined.

The following CAPEX components were considered in this analysis:

- Tank
- Piping
- Pumps
- Land

The following OPEX components were considered in the analysis:

- Energy
- Fixed operation & maintenance (O&M)
- boil off losses
- Loading-unloading losses

Having defined the research scope, the methodology of how the research question is answered is described subsequently in chapter 3.

3 Methodology

This chapter explains the steps taken to cover the knowledge gaps identified and answer the research question. The solution methodology consists of three parts: information and data acquisition, case study modelling and cost estimate generalization. The three-step procedure of the solution methodology is summarised in Figure 3.1 alongside the knowledge gaps each step aims to fill.

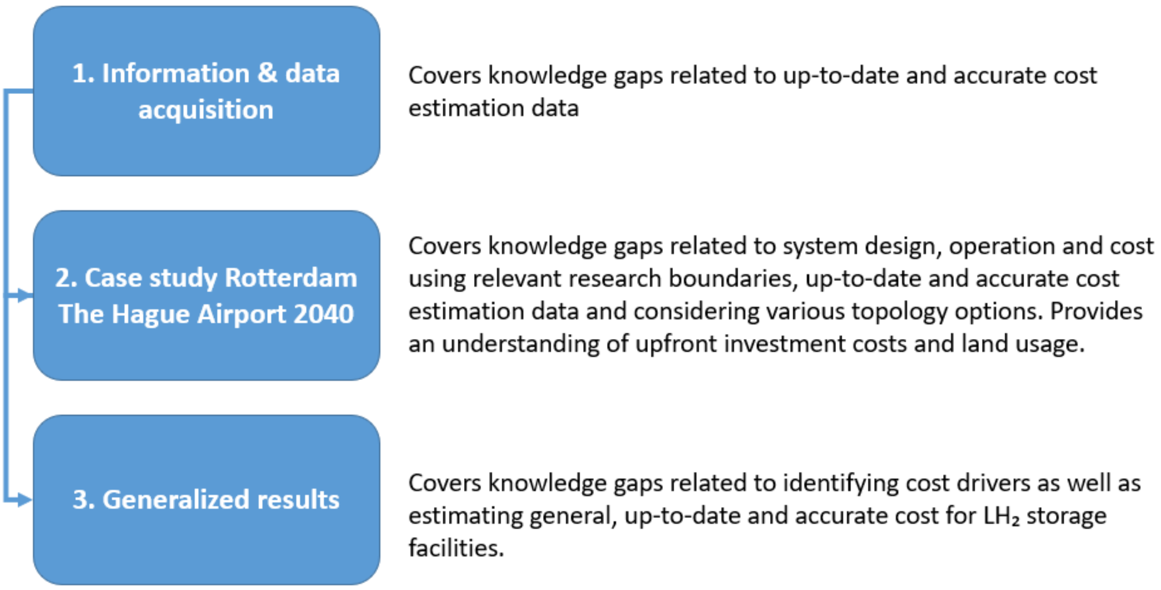

Figure 3.1: Solution methodology procedure

Part one, two and three of the solution methodology are explained in section 3.1, section 3.2 and section 3.3, respectively.

3.1. Part 1: Information & Data Acquisition

Information and data collection is necessary before an analysis can yield any worthwhile conclusions. Subsequently, this part of the solution methodology consists of collecting data needed for the following two parts of the solution method. This part of the solution method is aimed at covering knowledge gaps relating to up-to-date and accurate cost estimation data.

Two distinct information and data collection methods — a literature review and expert interviews — were employed and are presented in subsection 3.1.1 and subsection 3.1.2, respectively.

3.1.1. Literature Research Methodology

Literature research was done in order to provide a foundation of knowledge, to compare with the information given by experts and to have access to a wider range of data and information about the research topic.

A search plan was used as an algorithm that aims to find synonyms as well as related terms from the research topic's keywords to achieve more holistic research results. The following four steps are at the core of this process:

1. The first step was to define what question needs to be answered and to have it formulated in a concrete and clear manner.
2. Subsequently, the associated themes, words and synonyms were determined.
3. Next, the associated themes, words and synonyms were used in order to generate similar search queries to the original question.
4. The search queries were then used as search prompts. The results were then analysed leading to a selection of the most useful search results.

3.1.2. Interview Methodology

Interviews are paramount to this investigation due to the nature of the topic being researched. LH_2 storage facility cost data is scarcely publicly available and varies dramatically depending on the sources as shown earlier. As a result, interviews with experts in the field of LH_2 storage facilities helped rule out unrealistic cost estimates found in literature and provide further data on contemporary costs. However, interviews require the questioning to be in a consistent and documentable manner. Thus, an interview protocol was developed.

The interview methodology is comprised of three steps: pre-interview, interview and post-interview.

1. Pre-Interview

If the interaction with the specific expert was the first one, an explanation of the thesis project was provided beforehand. This was done to make sure that the expert provided information in line with the context and boundaries of the thesis during the interview. Furthermore, a document containing questions related to the expert's field of knowledge was formulated as well as a meeting plan and a presentation containing the information relevant to the meeting, all of which were sent to the interviewee beforehand.

2. Interview

The subsequent step was the interview itself which was carried out in a semi-structured manner. This meant that the order of the meeting plan was followed however the conversation was allowed to flow into relevant topics given the need to do so; such as when answers given generated follow-up questions. If the interview with the expert was the first one, a presentation of the thesis project was given. After the presentation was given, the questions sent in the email were posed and written notes were made of the answers. Notes were also made in a systematic manner on the points discussed throughout the entire interview.

3. Post-Interview

Finally the post-interview step was carried out. This consisted of reviewing the notes taken and making sure all answers were clear and thoroughly recorded. In order to validate the information gathered two methods were implemented. Firstly, the transcript of the meeting with the recorded answers was sent to the interviewee to verify that the interpretation of the responses was in line with what they intended to get across. The option of altering the answers recorded was given. Secondly, when possible, literature found on the same topic was used to cross-check answers received. If the literature showed conflicting evidence for an answer given, the interviewee was contacted in order to clarify possible causes for discrepancies.

3.2. Part 2: Case Study Rotterdam The Hague Airport 2040

Part two of the solution methodology consisted of performing a case study design of LH_2 storage facilities for Rotterdam the Hague Airport (RTHA) in 2040. The case study allowed for insight into system cost using: relevant cost estimation boundaries, up-to-date and accurate cost estimation data and considering various topology options. The case study also provided an understanding of upfront investment costs and land usage.

Firstly, an explanation of why the case study in question was chosen is given in subsection 3.2.1. Then an explanation is given of the methodology followed for the case study in subsection 3.2.2.

3.2.1. Case Study Rationale

The year 2040 was taken as this is around 5 years after many predicted commercial LH_2 aircraft flight dates [8, 96, 42]. Consequently, in 2040 it can be expected that there will be a sufficient amount of LH_2 aircraft in operation leading to the need of large scale LH_2 storage facilities [81, 48, 25, 57].

RTHA was chosen as the case study airport due to its commitment to becoming a sustainable airport, its ongoing hydrogen aviation projects, the flight profile of aircraft operating from RTHA and the responsiveness and willingness of RTHA personnel to share information.

RTHA aims to host LH_2 aviation. RTHA is also working on nine different hydrogen aviation projects in the fields of facilitating experiments on the airside (technology readiness level 6 and higher) as well as partnering in studies (technology readiness level 6 or lower). LH_2 aviation projects RTHA participates in are in the fields of LH_2 operations, refuelling, supply, storage, aircraft taxiing tests, infrastructure development, fire brigade training and commercialization [30, 97, 91].

Furthermore, RTHA is an airport that mainly hosts commercial flights in the rages of passengers and flight distance pertaining to those of predicted future LH_2 aircraft models and consequently will probably host a proportionally large amount of LH_2 flights by 2040.

Figure 3.2 and Figure 3.3 shows graphs displaying the frequency of occurrence in 2019 of the distance flown and amount of passengers in each commercial flight from RTHA, respectively.

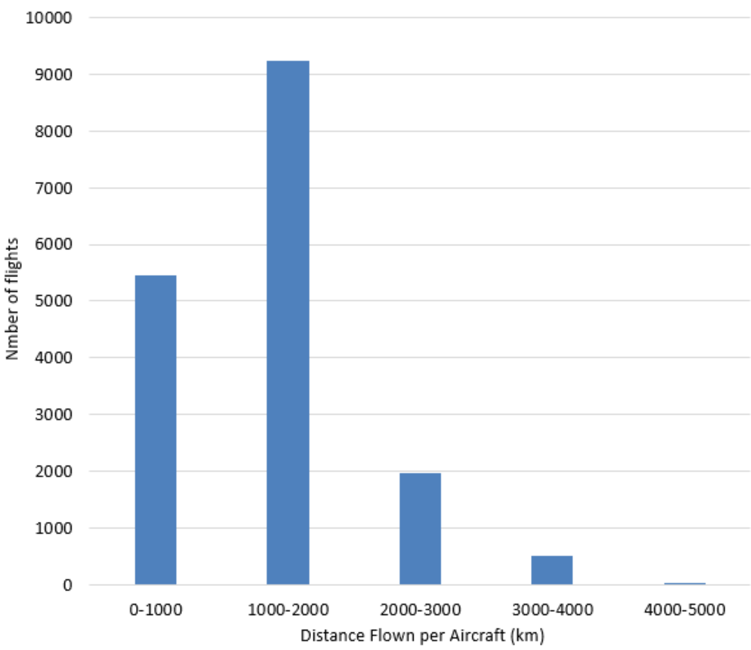

Figure 3.2: Frequency of distance flown per commercial flight in 2019 from RTHA

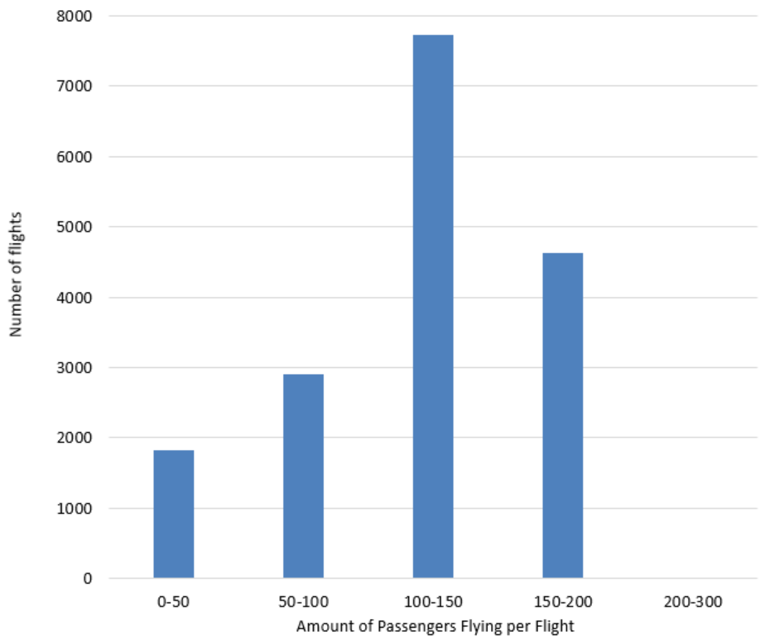

Figure 3.3: Frequency of number of passengers per commercial flight in 2019 from RTHA

It can be seen from Figure 3.2 that only 0.02% of flights traveled distances over 4000 km and 85.5% of flights traveled distances under 2000 km. It can be seen from Figure 3.3 that only 0.08% of flights carried more than 200 passengers. This is similar to the characteristics of LH_2 powered aircraft planned to be developed as seen later.

In Table 3.1 one can see a collection of data regarding future LH_2 powered commercial aviation aircraft timelines from Airbus ZEROe, Flyzero and ZeroAvia which are developing said aeroplanes with the respective maximum ranges and passenger capacities.

Model	Max Pax	Max Range (km)	Engine type	Source
Airbus ZEROe: first commercial flight in 2035				[8]
Turborop	<100	>1852	Turboprop	
Blended-wing body	<200	>3704	Turbofan	
Turbofan	<200	>3704	Turbofan	
Flyzero: first commercial flight in early 2030s				[42]
Regional	75	1482	Turboprop	
Narrowbody	179	4445	Turbofan	
Midsize	280	10650	Turbofan	
ZeroAvia: first commercial flight in 2025-2040				[96]
Turboprop, 2025	19	556	Turboprop	
Turboprop, 2027	80	1852	Turboprop	
Turbofan, 2029	200	3704	Turbofan	
Turbofan, 2032	200	5556	Turbofan	
Blended wing body, 2040	>200	9260	Turbofan	

Table 3.1: Predicted LH_2 commercial aeroplane models to be released, per company

Below in Figure 3.4 and Figure 3.5 one can see the data from Table 3.1 summarised.

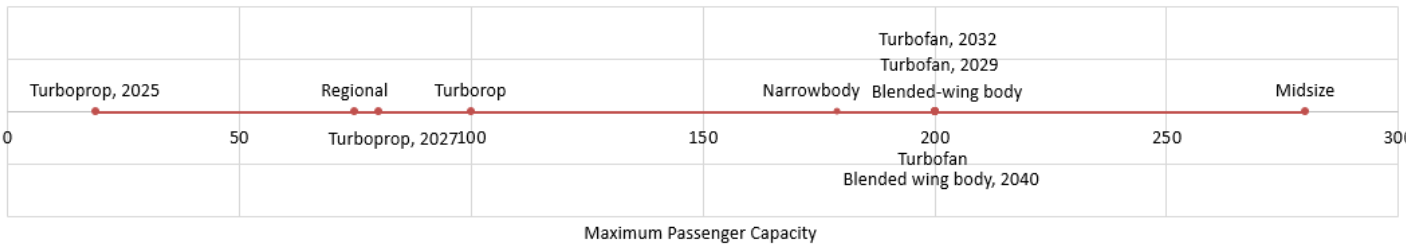

Figure 3.4: Maximum passengers per LH_2 aircraft model [8, 42, 96]

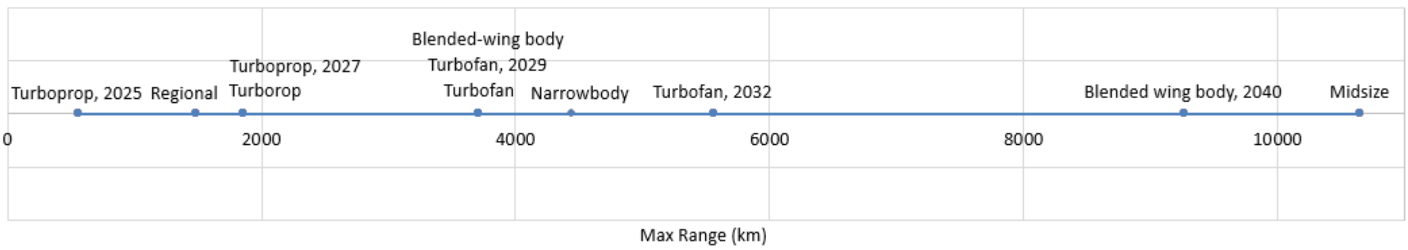

Figure 3.5: Maximum range per LH_2 aircraft model [8, 42, 96]

The majority of LH_2 aircraft are predicted to carry 20 to 200 passengers and have a maximum range between 500 km - 5500 km. Consequently, it is apparent from the predicted LH_2 aircraft models that a large portion of the flights at RTHA could be LH_2 powered in the future; flights of less than 2000km and 200 passengers. Therefore, it is also necessary for RTHA to plan their future hydrogen infrastructure, including LH_2 storage facilities.

3.2.2. Techno Economic Assessment Methodology

Having decided on the case study airport, part two of the solution methodology involves performing an analysis of the costs of LH_2 storage facilities. This is done via a techno-economic assessment (TEA). This TEA was composed of three different steps based on the book by Murthy et al. (2022) [65] on systems analysis for sustainability: infrastructure design and operation, infrastructure sizing and cost modelling. These steps are elaborated upon subsequently.

1. Infrastructure Design & Operation

The first step entails defining all components involved in the process of storing LH_2 and how the process is carried out. This was achieved by firstly studying how Jet A-1 storage is performed now and then adjusting the current design and operation methods to the storage of LH_2. These adjustments were made via the consideration of the nature of the two fuel types and regulations or recommendations on the storage of LH_2.

2. Facility Sizing

Next, the equipment involved was sized considering RTHA's predicted storage demand. The necessary storage capacity was determined via the method described in the paper "Guidance on Airport Fuel Storage Capacity" by the International Air Transport Association (IATA) [58]. This method was designed for storing Jet A-1 however it was adapted in this thesis to the needs of storing LH_2. The IATA process was comprised of the following steps:

a The first step involved determining the airport storage purposes from a list of options presented by IATA (e.g. cover for supply disruptions or demand-supply mismatch).

b The second step consisted of deriving a list of quantifiable requirements based on the airport's storage facility purposes identified in step I.

c Then the individual storage requirements were quantified.

d Lastly, the storage capacity was calculated by applying a recommendation by IATA. Namely, the storage size required is 85% of the sum of the storage sizes needed for the individual requirements, which were identified in step three.

The most important quantifiable requirements that were chosen are as follows:

I *To act as a buffer for supply interruptions via quantifying the need for a strategic reserve*

The storage facility should be able to act as a buffer for events that lead to the temporary reduction or interruption of supply. These events include but are not limited to: supply chain component failure, variability in LH_2 production or transport interruptions.

II *To allow for maintenance and inspection via quantifying the type, duration and impact of inspection*

Maintenance and inspection may lead to the temporary inoperability of components and hence the system must allow for this.

III *To allow for system failures via quantifying the type, duration and impact of failures*

System failures may lead to the inoperability of components and hence the system must allow for the fact that some storage capacity may be unavailable for operation due to failures.

3. Cost Modeling

This step aimed at identifying which costs were taken into account and how they were calculated. Three cost elements had to be defined, namely: the levelised cost equation, the CAPEX equations and the OPEX equations. The equations were then used as inputs for the cost model.

Next, a cost model was generated in Python using the cost equations defined and input data collected. Consequently, the upfront investment, levelised costs and land footprint were calculated per topology option.

3.3. Part 3: Generalized Results

Part three of the solution methodology is aimed at generating results that are not bound to the specificities of the case study airport. Three analyses were carried out are are explained subsequently.

3.3.1. Comparison of Levelisation Method

The cost model was used in order to understand the changes in outcomes between the two levelisation methods. Understanding the differences between the levelisation methods and their outcomes showed whether the results and conclusions derived are comparable or not. This was achieved by running the cost model for the two levelisation methods and analysing the outcomes.

3.3.2. Sensitivity Analysis

Using the cost model developed in step two of the solution methodology, a sensitivity analysis was performed. The sensitivity analysis aimed at:

- Identifying the main cost drivers
- Presenting recommendations for cost reduction methods
- Identifying tipping points between the various LH_2 storage facility design typologies

The sensitivity analysis was performed by varying the following key input parameters of the model and observing their effects on the levelised cost of hydrogen storage:

- Storage capacity
- Usage
- Tank number
- CAPEX (tank, pump, pipe, land)
- Boil off
- LH_2 cost
- Loading/unloading losses
- Fixed OPEX

The sensitivity analysis was performed by taking the input parameters and increasing one value at a time by 10%. Thereafter, the effects on the levelised cost of hydrogen storage were observed and noted. The sensitivity was calculated by the percentage change in the levelised cost of hydrogen storage by the percentage change in the input parameter.

3.3.3. Topology Transition

Using the tipping points identified and the cost model, an analysis was performed of how the levelised costs change when transitioning from one storage topology to another as demand for storage increases while also considering hybrid system topologies with more than one tank type.

Now that the solution methodology has been elaborated upon, the three subsequent chapters will discuss the outcomes of each part of the solution method.

4

Information & Data Acquisition

This chapter presents the outcomes of the first part of the solution methodology. The purpose of part one of the solution method was to gather information and data to create a cost analysis of LH_2 storage facilities. Information and data was collected on the following topics:

- General Jet A-1 storage facility information:
  - Facility components
  - Tank design
  - Operational procedures
  - Maintenance, inspection and safety practices
- Comparison of fuel characteristics and effects on the design of storage facilities
- General LH_2 storage facility information:
  - Facility components
  - Tank design
  - Operational procedures
  - Maintenance, inspection and safety practices
  - Loading/unloading losses
  - Fill level range
  - LH_2 cost
  - Electricity cost
  - Land cost
  - Storage capacity
- Characteristics per LH_2 tank type:
  - Capacity/ capacity range possible
  - Lifetime
  - CAPEX
  - Fixed O&M costs
  - boil off
  - Failure rates
- Characteristics of LH_2 pumps:
  - Capacity
  - Lifetime
  - CAPEX
  - Fixed O&M costs
  - Energy consumption
  - Failure rates
- Characteristics of LH_2 pipes:
  - Capacity
  - Piping length per tank
  - Lifetime
  - CAPEX
  - Fixed O&M costs
  - Failure rates

In order to gather data on the above topics, Table 4.1 shows the experts interviewed that lead to input data and information. The respective hyperlink letters are used hereafter to indicate what information was obtained from which expert.

Interviewee	**Position**	**Company**	**Hyperlink letter**
Gerhard Knol	Product Manager	Cryoworld	[A]
Thomas Jordan	Head of Hydrogen Department	Karlsruhe Institute of Technology	[B]
Benjamin Schaerer	Head of Instrumentation, Reliability and Hydrogen Production	Air Liquide	[C]
Johan Alblas	Operations Manager BNL	Shell Aviation	[D]
Daan van Dijk	Innovator	Rotterdam The Hague Airport	[E]
Julian Klaaßen	Environmental Engineer	Hamburg Airport	[F]
Ronald Dekker	Owner	Demaco	[G]

Table 4.1: Table of experts interviewed

The tables shown in Appendix A contain the data gathered and their respective sources. The data and information gathered are used in the following chapters.

5 Case Study Rotterdam The Hague Airport 2040

This chapter presents a case study design and cost estimation of LH_2 storage facilities for RTHA based on the estimated demand in 2040. The purpose of the case study is to cover knowledge gaps relating to design, operation and cost using: relevant cost estimation boundaries, up-to-date and accurate cost estimation data and considering various topology options. Furthermore, this chapter provides estimates of upfront investment costs and land usage.

This chapter is structured as per the three steps described in chapter 3 for a techno-economic assessment. Firstly, the infrastructure design and operation of the LH_2 storage facility is determined in section 5.1. Then, the facility is sized in section 5.2. Lastly, the cost modelling is performed in section 5.3.

5.1. Infrastructure Design & Operation

In this subsection, the infrastructure design and operation of LH_2 storage facilities are derived. Firstly, the current Jet A-1 topology, design and operation is described in subsection 5.1.1. Then, a comparison between Jet A-1 and LH_2 fuel characteristics is made in subsection 5.1.2 after which the future LH_2 storage infrastructure design and operation is derived subsection 5.1.3.

5.1.1. Current Jet A-1 Storage Infrastructure Design & Operation

In this subsection, a description of the components, tank design, operation and respective maintenance, inspection and safety practices are given for the current Jet A-1 storage facility at RTHA.

Components:
RTHA currently uses trailer tanks which entails a truck trailer containing Jet A-1 fuel [D] [E]. A total of six parking lots are available at RTHA of which five can be used for storage trailers and one for the refuelling truck [E]. Each trailer contains 42 m^3 of Jet A-1 fuel [D]. This equates to 168 tonnes of Jet A-1 which is roughly 1 day's worth of peak demand. The main limiting factor mentioned on storage capacity for airports is land availability, however, RTHA has spare land [F] [E].

Tank Design:
Jet A-1 tanks are made of stainless steel, aluminium, or steel with an epoxy lining [33]. Storage tanks include a manual water drain valve with frost protection [33]. Furthermore, jet fuel tanks have venting for both routine and emergency situations due to expansion of the fuel or vacuum created when the tank is emptied [33, 21]. Heater probes are installed to prevent water that has contaminated the fuel from freezing [19]. Standard identification signs on the tanks and piping are also present [78]. In Figure 5.1 one can see an example of large Jet A-1 storage tanks.

Figure 5.1: Jet A-1 storage tanks [82]

Trailer tanks are used at RTHA. Figure 5.2 shows an example of a trailer tank.

Figure 5.2: Jet A-1 trailer tank [18]

Operation:
The Jet A-1 storage process at RTHA is reflected in Figure 5.3. The grey and blue tanks represent empty and full tanks, respectively.

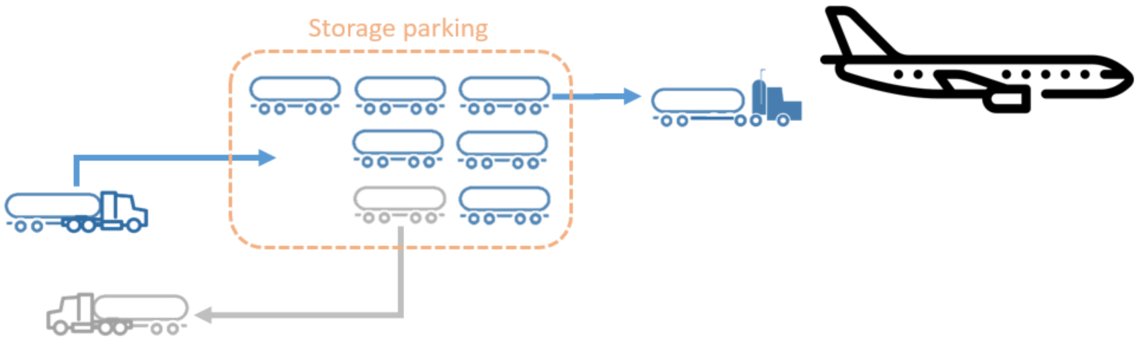

Figure 5.3: RTHA Jet A-1 storage process [D] [E]

The JET A-1 storage steps reflected in Figure 5.3 are as follows:

1. Full Jet A-1 tank trailers are brought to RTHA by transport trucks.
2. The transport trucks deposit the trailers at a dedicated storage location at the entry to the airport.
3. The empty trailers - which are found at the same location as the recently deposited full ones - are picked up by the transport trucks and taken away.
4. The trailers containing fuel are picked up by a refueling truck for the airport which includes a refueling unit to fill aircraft up with Jet A-1.
5. Once the trailer tank is emptied, it is taken away by one of the arriving trailer transport trucks.

Tanks are filled up to 90% of their maximum capacity to allow for expansion of the fuel [19, 34]. Deliveries are made 24 hours per day and a maximum of six to seven trailers were needed in 2019 in one day [D] [E]. If the trailer loads are enough to last more than a day, they act as a storage tank until they are used up after which they are taken away [D] [E].

Maintenance, Inspection & Safety:
According to Avfuel (a global supplier of aviation fuel services) and the Federal Aviation Administration of the USA, the maintenance, inspection and safety tasks mentioned in Table 5.1 are carried out for Jet A-1 fuel storage facilities.

Activity	Process
Daily maintenance & inspection	Sumping - opening of a valve at the bottom of the tank which releases contaminants due to fuel pressure Check for fuel leaks
Weekly maintenance & inspection	Jet fuel needs to be pumped through a filtration system Fuel sample inspection Visual inspections to make sure all safety equipment is functioning
Monthly maintenance & inspection	Valves, refuelling equipment and filters checked for contaminants and functionality
Quarterly maintenance & inspection	Emergency fuel shutdown system functionality check Alarm functionality check
Yearly maintenance & inspection	Visual inspection of storage tank interiors Calibration of measuring devices Filter change Vent check Water defence check by injecting water into storage tank

Table 5.1: Jet A-1 storage maintenance and control check procedures [19, 33]

The safety regulations also stipulate the following. Absorbent materials should be available on-site in case of fuel leaks [19]. Atmospheres Explosibles (ATEX) zones are used for the storage of Jet A-1 meaning that certain equipment is not able to be used within certain distances of the fuel storage tanks [D]. From personal observations, fuel storage trailers at RTHA were spaced roughly 3 meters apart and 5 meters from the nearest office with no physical barriers in between.

5.1.2. Comparison of Fuel Characteristics

In Table 5.2 one can see a comparison of the key characteristics of Jet A-1 and LH_2 and their respective implications on the storage of LH_2.

Property	Jet A-1	LH_2	Implications
Density (kg/m3)	840	71	11.8 times lighter molecule leading to more volume needed for storage of LH_2 and higher diffusivity
Gravimetric Energy Density (MJ/kg)	43.1	142	3.3 times less mass needed for same energy content LH_2 the same amount of energy
Volumetric Energy Density (MJ/m^3)	36204	10082	3.6 more volume for same energy content LH_2 the same amount of energy

Property	Jet A-1	LH_2	Implications
Boiling Point (C)	167-266	-253	Danger of H_2 frostbite, high H_2 boil off rate, material embrittlement unlike with Jet A-1
Flammability Limits (%)	0.6-4.7	4-75	High likelihood of H_2 fire, but higher concentration required to start it than Jet A-1
Min. ignition energy (mJ)	0.25	0.02	High likelihood of H_2 fire with weak sparks
Burning velocity (cm/s)	18	265-325	A H_2 fire would burn out faster than a kerosene one leading to a lower duration of fire
Buoyancy	Pools on the floor	14x lighter than air, rises at 20 m/s	Gaseous H_2 disperses faster than Jet A-1. Hence, propper venting allows for quick dispersion of leakages and lower risk
Sensory Properties	Light amber liquid, petroleum odour, toxic, chemical taste	Colourless, odourless, tasteless and nontoxic	Harder to detect H_2 spills/leakages
Self Ignition Temp (C)	210	585	Harder to ignite H_2 with pure heat
Fire heat radiative fraction	30-40%	10-20%	H_2 fires could be less destructive, as they radiate less heat
Flame colour	Yellow flame	Almost invisible blue flame	It is more difficult to detect H_2 flames

Table 5.2: Selected properties of Jet A-1 fuel compared to liquefied hydrogen [70, 82, 11, 41]

From Table 5.2 it can be seen that there are important differences between Jet A1 fuel and LH_2 which impact the storage characteristics. The three main characteristics of storing LH_2 were derived and are discussed below.

1. LH_2 Storage Technology

The following technological considerations are needed for storing LH_2:

- **Thermal insulation technology:** Highly insulating technology is required due to LH_2's low boiling temperature which is not the case for kerosene [98]. The boiling temperate of hydrogen (-253 C) requires the use of multilayer vacuum insulating technology [98].

- **Material technology:** materials used for liquid hydrogen storage must adhere to a number of unique specifications: resistance to (hydrogen) embrittlement, thermal robustness, as well as fire and heat resistance [98, 85]. Stainless steel or aluminium alloys are typically used for LH_2 storage tanks [66].

- **Boil off control:** LH_2's low boiling point also leads to the need for a boil off management system to prevent overpressures in the LH_2 tank.

2. LH_2 Storage Footprint

Although the gravimetric energy density of LH_2 is 3.3 times higher than that of Jet A-1, its much lower density leads to a 3.6 times lower volumetric energy density in comparison to Jet A-1. Consequently, a 3.6 times larger storage volume is required for LH_2 in comparison to Jet-A1 for the same energy content. This is important to consider as land availability at airports may be low and hence land usage may be a limiting factor when it comes to LH_2 storage facilities.

3. LH_2 Storage Safety Considerations

Specific safety measures need to be implemented for LH_2 storage due to the following reasons:

- **Fires:** Since liquid hydrogen has relatively small molecules, low density and a low boiling point, it evaporates and leaks very easily. This increases the size of the combustible cloud but lowers the localised concentration of hydrogen in the air and the duration of a potential threat. Thus, it is essential to avoid leaks and to allow for very good venting in all areas where leakage can occur. This way leaked hydrogen can disperse quickly such that the ignition conditions are not reached and explosions are avoided.

- **LH_2 tank contamination:** The possibility for a hydrogen tank to become contaminated with air is a significant issue when handling LH_2. It must be noted that oxygen liquefies at 90 K and freezes at 55 K whereas hydrogen liquefies at a temperature of 20 K. Thus, oxygen or air can solidify when in contact with LH_2. If these leaks pass through seals and valves, they may deteriorate over time and allow more hydrogen gas to escape, resulting in fuel loss and safety risks. Consequently, the regular monitoring of seals and valves is very important to prevent contamination.

- **Air pollution with hydrogen:** Air pollution with hydrogen may also be dangerous, particularly in enclosed spaces. Hydrogen leakages can result in air condensation, a shortage of oxygen for humans to breathe, and flames [73]. Human contact with cryogenic hydrogen must be avoided as it can generate serious injuries by extreme frostbite. Hence, it is important to have good ventilation and protection for workers to avoid frostbite.

5.1.3. Future LH_2 Storage Infrastructure Design & Operation

Having defined the current Jet A-1 storage topology as well as the differences between Jet A-1 and LH_2 fuel characteristics, the future LH_2 storage topology, design and operation are presented hereafter.

It is important to note that there are three tank types available. The storage topology, design and operation are affected by the tank type in question. In Figure 5.4 one can see a diagram representing the tank options.

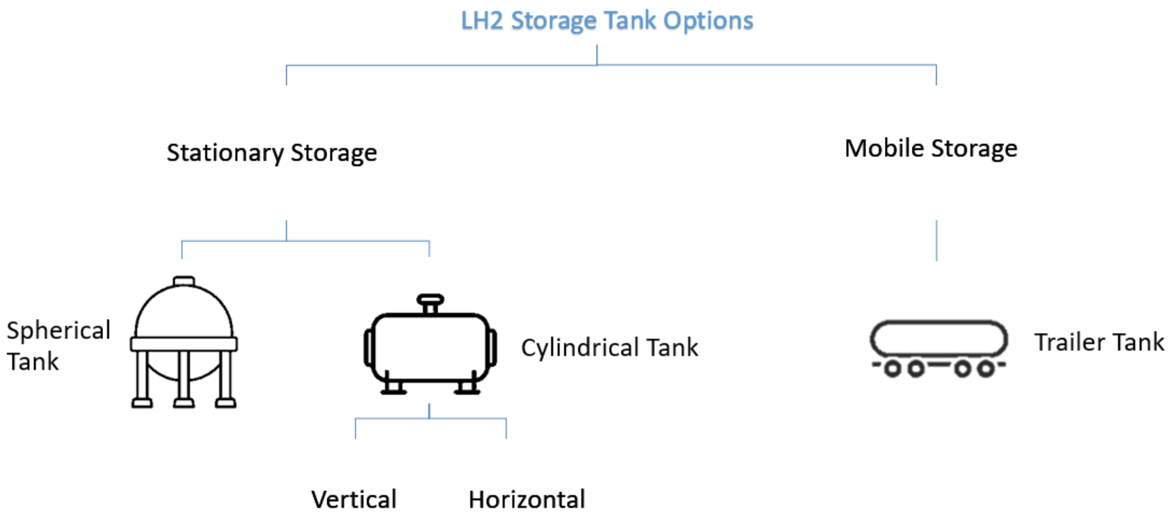

Figure 5.4: Design Options of LH_2 Storage Tanks

Components:

The components considered in LH_2 storage system depend on the storage tank type in question. A trailer tank storage system is considered to consist of trailer storage tanks and land. No pumps are included in the system as these are found at the location where the trailer tank is filled or on the refuelling truck at the airport. When it comes to cylindrical or spherical tank systems, four components are considered: the tanks, piping, pumps and land.

Tank Design:

Double-walled multi-layer-vacuum-insulated (MLVI) storage tanks are used in order to maintain cryogenic temperatures in the tank [A] [C].

At atmospheric pressure, one litre of liquid hydrogen will require 845 litres of space to vaporise. Consequently, the boil-off of even a small amount of LH_2 can quickly generate significant pressure in the tank. Therefore, pressure sensors and relief valves are installed in hydrogen storage tanks to prevent overpressure, which if left unchecked, could cause the vessel to fail [70]. Another component that provides protection in case of failure is rupture discs which are used as a failure mechanism in case of the failure of the pressure relief valves [C]. Valves are also used in the filling process of the tank to prevent flow in the wrong direction [C].

Furthermore, level and pressure sensors are used to measure the liquid level and pressure in the tank in order to remain in the operating ranges [C] [A]. The tank operates between 5% to 95% of its maximum capacity [C] [A].

Operation:

Depending on the tank type selected, the operation of storing LH_2 differs. The operation of LH_2 trailer tanks is the same as that of Jet A-1 (described in subsection 5.1.1). The process is depicted in Figure 5.5.

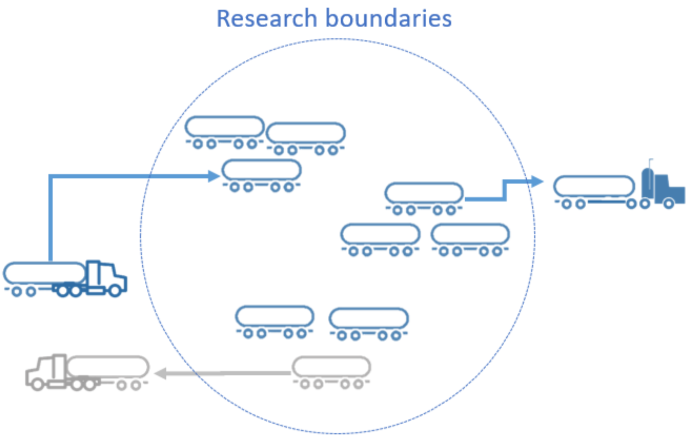

Figure 5.5: LH_2 trailer tank operation

The operation of cylindrical and spherical tank topologies is depicted in Figure 5.6 and Figure 5.7, respectively.

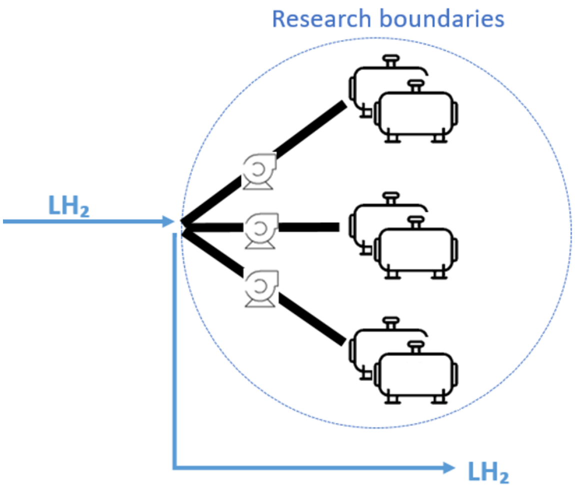

Figure 5.6: Cylindrical tank operation

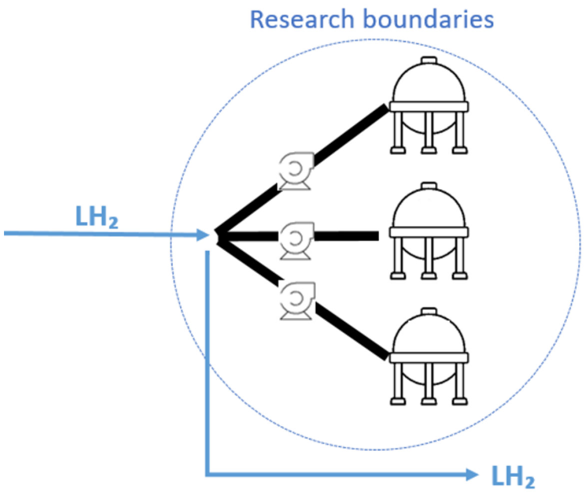

Figure 5.7: Spherical tank operatio

Figure 5.6 and Figure 5.7 show how the incoming source of hydrogen is pumped into the LH_2 storage tanks by cryogenic pumps. When LH_2 is required from the storage facility, it is pumped out of the tanks.

Maintenance, Inspection & Safety:

For the inspection and maintenance activities of LH_2 storage facilities, papers by the European Industrial Gases Association (EIGA) and the International Organization for Standardization (ISO) were used in accordance with Dr. Thomas Jordan's (KIT) recommendations [B].

Table 5.3 shows the maintenance, inspection and safety practices that are performed at LH_2 storage facilities for safe operation:

Activity	Process	Frequency	Source
Periodic control check	Involves an exterior visual inspection of the vessel and its components, checking the functionality of the valves, conducting leak tests under operational settings, and evaluating any alterations to the operational circumstances surrounding the installation. Analysis of the vacuum between the inner and outer jackets.	5 years	ISO - Cryogenic vessels - Static vacuum insulated vessels - Part 2 [83] EIGA- Periodic inspection of static cryogenic vessels [16]
Visual inspection	The exterior jacket, support structure, exposed pipes, and controls should all be visually inspected Before usage, vessel lifting lugs should be checked for rust and deterioration.	year	EIGA- Periodic inspection of static cryogenic vessels [16]
Health monitoring	Monitoring of the level of vacuum in the vacuum chamber, the evaporation rate of cryogenic liquid or the rate of pressure rise of the inner tank	monitoring	EIGA- Periodic inspection of static cryogenic vessels [16]
Maintenance & inspection during filling	To make sure the vacuum between the inner vessel and outer jacket is intact, the vessel and its components must undergo an external visual examination (looking for anomalous icing on the tank's surface, gas venting from a vacuum protection device and continuously venting relief valves). Purging the fill hose is necessary. The relevant measurement apparatus must be in excellent working order and, when necessary, within the calibration window. Before filling, if there is no residual pressure in the vessel, it should be purged to get rid of any potential pollutants.	During filling	ISO - Cryogenic vessels - Static vacuum insulated vessels - Part 2 [83]

Table 5.3: Maintenance, inspection and safety practices for LH_2 storage

From Table 5.3 it can be seen how numerous checks are carried out periodically to cover for some of the previously identified safety issues.

To tackle issues relating to higher flammability, leakage detection or leakage impact on the environment, safety distances are taken. In Table 5.4 one can see the safety distances taken between LH_2 storage tanks based on ISO, EIGA and Air Products recommendations [83, 16, 71].

Vessel capacity (tonnes)	Safety distance (m)
< 5	3
5 - 20	5
20 - 50	7
>50	10

Table 5.4: Safety distances between LH_2 storage tanks [83, 16, 71]

Now that the future LH_2 storage infrastructure design and operation is defined, the following step of the techno-economic analysis is elaborated upon subsequently.

5.2. Facility Sizing

In this subsection, the storage system is sized. The storage tanks, pumps and piping are sized in subsection 5.2.1, subsection 5.2.2 and subsection 5.2.3, respectively.

5.2.1. Tank Sizing

As mentioned previously in chapter 3, three main requirements had to be satisfied in order to size the storage in accordance with IATA's method [58]. The three quantifiable requirements were satisfied as follows:

I ***To act as a buffer for supply interruptions via quantifying the need for a strategic reserve***

The need for strategic reserve was taken to be 3 days' worth of peak daily demand. This was chosen in line with the case studies performed in IATA's paper on "Guidance on Airport Fuel Storage Capacity" and Hoelzen et al. (2022) [48]. Furthermore, this storage capacity was recommended by experts [E] [F].

The strategic reserve has the task of acting as a buffer for events that lead to the temporary reduction or interruption of supply. These events include but are not limited to: supply chain component failure, variability in LH_2 production or transport interruptions.

In order to quantify the 3 days' worth of peak daily demand and hence the capacity of the strategic reserve, the demand profile had to be determined on a daily scale in 2040. The demand prediction was based on flight data for commercial aviation in 2019 from RTHA as it was the most recent non-COVID data available. The methodology for the demand prediction is explained in Appendix B. The daily peak demand of RTHA in 2040 was found to be 40 tonnes of LH_2 which leads to a 120-tonne storage capacity for this requirement.

II ***To allow for maintenance and inspection via quantifying the type, duration and impact of inspection***

Earlier, Table 5.3 was presented which summarises the maintenance, inspection and safety practices for LH_2 storage. There are four activities that are performed at different time intervals: "Periodic Inspection", "Visual Inspection", "Health Monitoring" and "Maintenance and Inspection During Filling".

The first is the ”Periodic Inspection” which requires a downtime of 1 week for the storage tank and is performed every 5 years [A]. The ”Visual Inspection” does not require any downtime as it only consists of visually observing for defects on the outside of the tank. ”Health monitoring” only involves checking measuring devices and hence no downtime is attributed. Lastly, there is ”Maintenance and Inspection During Filling” which requires checks and purging of the tank and piping however does not lead to the downtime of the tank itself.

Subsequently, a downtime of 1 week per tank every 5 years is taken. It is assumed that tank maintenance is performed on only 1 tank at a time. Consequently, one tank is taken as redundancy which undergoes graceful degradation during the planned maintenance and inspection task.

III ***To allow for system failures via quantifying the type, duration and impact of failures***

EIGA members collect data regarding failure rates and inspection outcomes of cryogenic vessels and found the following [16]. In Europe, there are over 60,000 cryogenic containers in operation, some of which date back to the 1960s. The data gathered includes the annual interior inspection and deconstruction of a number of vessels to check for any potential failure mechanisms. None have ever been found. Consequently, EIGA implies that unexpected failure rates are low for LH_2 tanks and recommends that no interior inspection is required of tanks and that the aforementioned safety practices, maintenance and control check methods are sufficient to ensure the safe operation of cryogenic vessels.

A paper by Psara (2014) [72] estimated failure frequencies of large-scale LH_2 storage systems. The failure analysis was performed using the component failure data associated with each of the identified failure modes via a failure tree analysis. The following failure rates were presented per failure mode:

- Instantaneous release of hydrogen (4.9 $\cdot 10^{-6}$ occurrences/year)
- Continuous release of hydrogen in the liquid phase (8.3 $\cdot 10^{-5}$ occurrences/year)
- Continuous release of hydrogen in the vapour phase (3.5 $\cdot 10^{-5}$ occurrences/year)

The sum of all failure probabilities estimated by Psara (2014) [72] ranges in the order of 10^{-4} occurrences per year. This confirms the low failure probability implied by EIGA [16]

A report by the Health and Safety Executive in Great Britain included data on failure rates of double-walled cryogenic vessels and also estimated a total failure rate in the order of 10^{-4} for a combination of different hydrogen leakages and outcomes of the leakages.

From the failure rates shown above, and the information given by EIGA, it can be concluded that tanks are unlikely to experience failures throughout their lifetime if the proper maintenance and inspection are carried out. Consequently, one tank is taken as redundancy which undergoes graceful degradation during failure.

By quantifying the storage necessities for each of the requirements it is concluded that:

- Requirement I calls for 3 days' worth of peak demand as a strategic reserve which equates to 120 tonnes of LH_2
- Requirement II calls for one additional tank for covering maintenance and inspection, but no extra capacity
- Requirement III calls for one additional tank to cover possible failure, but no extra capacity

Since only one requirement yielded a necessary storage capacity, no further calculation is needed to find the total storage capacity. As a result, the capacity required for the storage of LH_2 at RTHA in 2040 is concluded to be 120 tonnes with a minimum number of three tanks.

Having determined the tank capacity and redundancy, next, the pumps and the piping are sized.

5.2.2. Pump Sizing

Pumps were sized based on the requirement that a trailer must be fully unloaded every 30 minutes. Assuming it takes 30 minutes to connect/disconnect and 30 minutes to load/unload a trailer, two 8-tonne/hr pumps are needed in order to satisfy the requirement.

Furthermore, cryogenic pump failure rates are seen to occur frequently according to literature. A paper on "Selected Component Failure Rate Values from Fusion Safety Assessment Tasks" by Cadwallader (1998) [24] gives the failure rates for cryogenic pumps. The failure rates can be seen in Table 5.5.

Failure mode	**Frequency (/year)**
Failure to operate	0.0175
Leakage of cryogen into vacuum chamber	0.175
Casing leak	0.005
Total failure probability	0.1977

Table 5.5: Cryogenic pump failure rates [24]

Table 5.5 indicates that the total probability of failure is 0.1977 per year. Although the probability of leakage into the environment (casing leakage) is low, Table 5.5 and expert opinion indicates that there is a high downtime associated with cryogenic pumps [A].

According to the data presented in Table 5.5 there are around two cases of failure expected to occur over the 10-year lifetime of a cryogenic pump, which are most likely leakages of LH_2 into the vacuum chamber. This failure mode can be mitigated by the use of vacuum pumps which expel contaminants in the vacuum chamber [86]. Vacuum pumps do not require the halting of operation of the system.

On the other hand, ”failure to operate” and ”casing leakage” do require downtime. The remaining two failure modes are expected to have a joint failure probability of 0.0225 times per year which amounts to a 22.5% probability throughout the pump’s lifetime.

Due to the relatively high pump failure rate, an extra pump is considered for redundancy. Consequently, three pumps are considered in the storage system.

5.2.3. Pipe Sizing

LH_2 piping has a very low failure rate and downtime [G]. This information is backed up by Cadwallader (2010) [23] that analyses failure rates of cryogenic vacuum piping. The failure rates found are in the order of 10^{-6} / (yr · m). As a result, piping with a capacity of 8 tonnes/hr is taken without any redundancy.

Having defined the infrastructure design and operation as well as sized all the components, a system overview is given hereafter for the various topologies.

5.2.4. System Overview

In Table 5.6 one can see a summary of the outcomes of the storage facility sizing.

Component	**Size**	**Redundancy**
Tanks	120 tonnes	minimum 3 tanks
Pumps	24 tonnes/hr	3 x 8 tonnes/hr pumps
Piping	8 tonnes/hr	None

Table 5.6: Storage facility sizing outcomes

In Figure 5.8 one can see schematics of the storage facilities for the three different tank types.

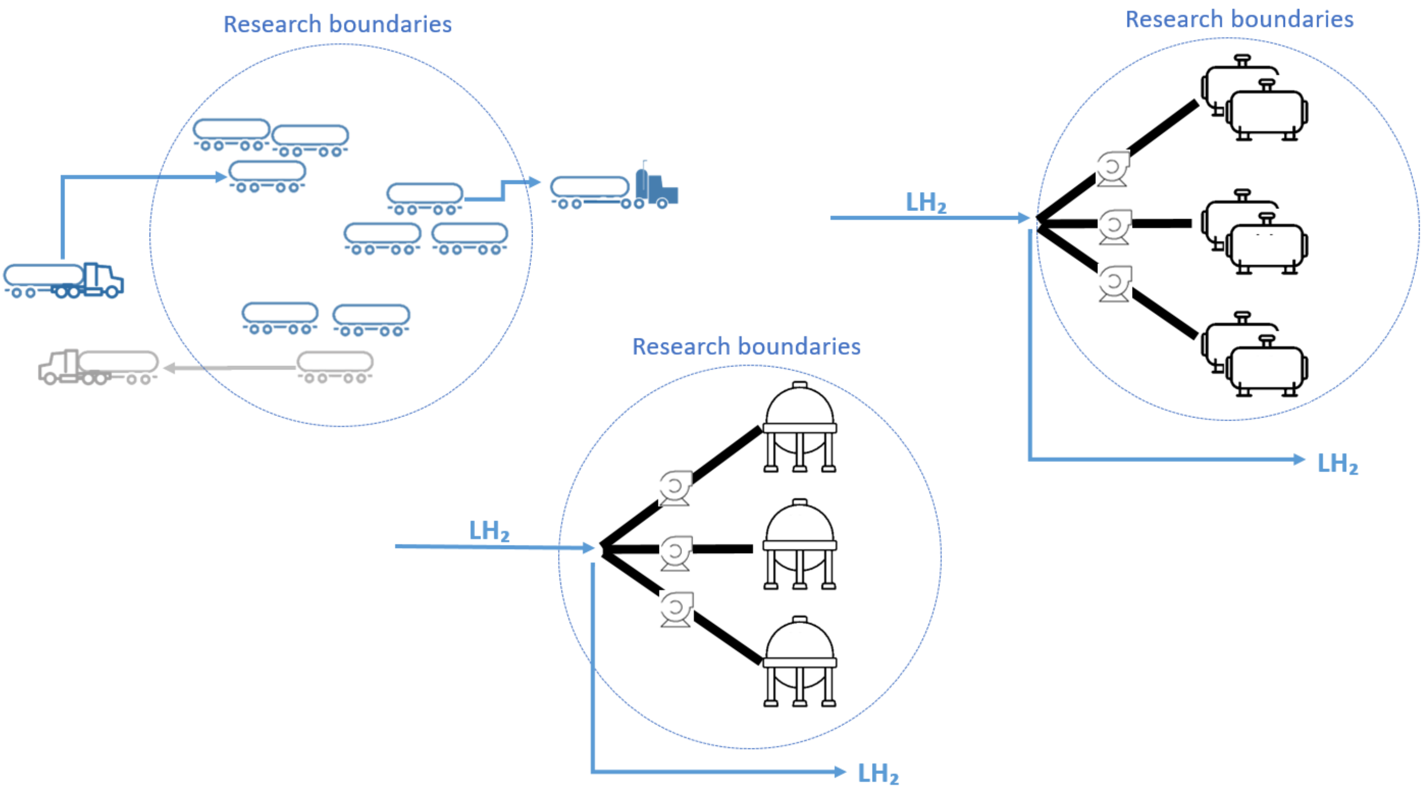

Figure 5.8: Storage topology per tank type

Now that the first two steps of the techno-economic assessment have been performed, the next subsection discusses the last step.

5.3. Cost Modeling

This section presents the cost modelling. Firstly, the input data for the model is given in subsection 5.3.1, then the equations of the cost model are presented in subsection 5.3.2 after which the model outputs are shown in subsection 5.3.3.

5.3.1. Input Data

The input data used for calculating the costs of LH_2 storage at RTHA in 2040 is summarised in the subsequent tables including the respective sources used. The individual values obtained from each of the experts and papers can be found in Appendix A. The values in the subsequent tables are the maximum likelihood values based on the data obtained, discussions with experts and the knowledge gained from the analysis. Later, input values pertaining to the ranges of data collected are also considered for the analysis.

General Parameters

Table 5.7 shows general input parameters required for the cost calculation.

Characteristic	Unit	Value	Source
Loading/unloading losses	% of amount transferred	5	Genovese et al. (2019) [46], Petitpas & Aveces (2018) [69], Petitpas (2018) [68]
Fill level range	%	5 - 95	Knol (Cryoworld) [A]
LH_2 cost	2.5	€/kg LH_2	subsection 2.2.3
Electricity cost	0.05	€/kWh	IRENA (2021)[6]
Land cost	500	€/m^2	Funda [43]
Storage capacity	120	ton LH_2	chapter 5
Usage	times fully unloaded / year	12	-
Discount rate	-	0.06	Hoelzen et al. (2022) [48]
Scaling factor exponent	-	0.6	Tribe & Alpine (1986) [87], Murthy (2022) [65]

Table 5.7: General LH_2 storage data used

It was assumed that the usage of the storage facility equates to twelve times fully unloaded per year. The effects of altering this parameter are evaluated later.

Trailer Tank Parameters

Table 5.8 shows specific input parameters for trailer tanks.

Characteristic	Unit	Value	Source
Capacity	tonnes LH_2	4	USDOE (2016) [35], Rutten (2022) [79], NAPKIN (2022) [57]
Lifetime	years	40	USDOE (2016) [35], Thomas Jordan (KIT) [B], Knol (Cryoworld) [A]
CAPEX	€/kg LH_2	170	USDOE (2016) [35], Reddi et al. (2015) [74]
Fixed O&M costs	% of CAPEX / year	4	Hoelzen et al. (2022) [48]
boil off	%/day	0.8	Al Ghafri et al. (2022) [10], Gautam et al. (2018) [45], Knol (Cryoworld) [A]

Table 5.8: LH_2 trailer tank data used

Trailer tanks have the highest CAPEX and boil off rates of the three tank options due to their small size and higher surface area to volume ratio.

Cylindrical Tank parameters

Table 5.9 shows specific input parameters for cylindrical tanks.

Characteristic	Unit	Value	Source
Capacity	tonnes LH_2	< 10 (vertical)	Knol (Cryoworld) [A], Linde (2020) [39], Kiwa (2022) [56]
		< 16.8 (horizontal)	FuelCellsWorks (2022) [93], Ministry of Infrastructure and Water Management (2015) [12]
Lifetime	years	40	Thomas Jordan (KIT) [B], Knol (Cryoworld) [A]
CAPEX	€/kg LH_2	130	Schaerer (Air Liquide) [C], Knol (Cryoworld)
Fixed O&M costs	% of CAPEX / year	1	Knol (Cryoworld) [A], Kennedy et al. (2019) [55], Hoelzen et al. (2022) [48]
Boil off	%/day	0.3	Schaerer (Air Liquide) [C]

Table 5.9: LH_2 cylindrical tank data used

The capacity limitations for vertical and horizontal cylindrical tanks are due to the following reasons. Cylindrical tanks can only be placed vertically up to sizes of roughly 10 tonnes due to the scaling of structural loads with size. Beyond a certain size, the loads become too large for the structure to handle and hence an upper limit is considered.

Horizontal cylindrical tanks can be up to 16.8 tonnes as this is the size limitation for being transportable by road. Beyond this size, the tanks have to be manufactured on-site which leads to added costs due to installation complexity and lack of the possibility for volume production.

Cylindrical tanks generally tend to have a lower CAPEX and boil off than trailer tanks as they are larger leading to scaling benefits and lower surface area to volume ratios.

Spherical Tank Parameters

Table 5.10 shows specific input parameters for spherical tanks.

Characteristic	Unit	Value	Source
Capacity	tonnes LH_2	>38.2 tonnes	Demaco (2021) [31]
Lifetime	years	40	Thomas Jordan (KIT) [B], Knol (Cryoworld) [A]
CAPEX	€/kg LH_2	50	Ratnakar et al. (2021) [73], USDOE (2016) [35]
Fixed O&M costs	% of CAPEX / year	1	Knol (Cryoworld) [A], Kennedy et al. (2019) [55], Hoelzen et al. (2022) [48]
Boil off	%/day	0.05	NREL (1999) [47], Ratnakar (2021) [73]

Table 5.10: LH_2 spherical tank data used

In theory, spherical tanks can be manufactured in a wide range of sizes. The smallest spherical tank found was 38.2 tonnes and hence only capacities larger than this were considered. Spherical tanks installed tend to be the largest available and hence the reference CAPEX and boil off values are the lowest of the three tank types. Spherical tanks have to be manufactured on-site as their shape and size prevent them from being transported by road [A].

Pump Parameters

Table 5.11 shows specific input parameters for pumps costs.

Characteristic	Unit	Value	Source
Capacity	kg/h	3 x 8000	section 5.2
Lifetime	Years	10	USDOE (2016) [35], Reuß et al. (2017) [76]
CAPEX	€/kg/h	300	USDOE (2008) [37], Hoelzen et al. (2022) [48]
Fixed O&M costs	%	3	Reuß et al. (2017) [76]
Energy consumption	kWh/kg	0.5	USDOE (2016) [35], Reuß et al. (2017) [76]

Table 5.11: LH_2 pump data used

Pipe Parameters

Table 5.12 shows specific input parameters for pipe costs.

Characteristic	Unit	Value	Source
Capacity	kg/h	8000	section 5.2

Characteristic	Unit	Value	Source
Lifetime	years	25	Dekker (Demaco) [G]
CAPEX	€/m	0.224 x flow rate (kg/h) + 950.32	Knol (Cryoworld) [A]
Fixed O&M costs	%	0	Dekker (Demaco) [G]
Piping length per tank	m	20	-

Table 5.12: LH_2 pipe data used

A piping length per tank of 20 m per tank was assumed.

5.3.2. Cost Equations

Having given an overview of the input data used, this subsection presents the cost equations derived in order to evaluate the costs of the various storage topologies for RTHA.

Levelised Cost

In Equation 5.1 one can see the equation used to calculate the levelised cost of hydrogen storage.

$$LCHS = \frac{CAPEX_0 + \sum_{t=0}^{n} \frac{OPEX_t + CAPEX_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{m_{LH_2}}{(1+r)^t}} \quad (5.1)$$

Where:

- $CAPEX_0$ represents the capital expenditures in year zero and hence they do not need to be discounted. The breakdown of $CAPEX_0$ is as follows:

$$CAPEX_0 = CAPEX_{tanks} + CAPEX_{piping} + CAPEX_{pumps} + CAPEX_{land} \quad (5.2)$$

  $CAPEX_0$ is represented in Equation 5.2 by the sum of the tank ($CAPEX_{tanks}$), piping ($CAPEX_{piping}$), pump ($CAPEX_{pumps}$) and land ($CAPEX_{land}$) capital expenditures.
- $OPEX_t$ represents the operational expenditures in year t. The breakdown of $OPEX_t$ is as follows:

$$OPEX_t = Energy_t + Fixed\ O\&M_t + BO_t + L/U_t \quad (5.3)$$

  $OPEX_t$ is represented in Equation 5.3 by the sum of energy ($Energy_t$), fixed O&M ($Fixed\ O\&M_t$), boil off (BO_t) and loading/unloading losses (L/U_t) operational expenditures.
- $CAPEX_t$ represents the capital expenditures carried out in year t which need to be discounted. The breakdown of $CAPEX_t$ is as follows:

$$CAPEX_t = CAPEX_{piping} + CAPEX_{pumps} \quad (5.4)$$

As shown in subsection 5.3.1, the tank lifetime is 40 years, consequently, the pumps and pipes need to be replaced as their lifetimes are 10 and and 25 years, respectively. Hence, the capital expenditures in the 10th and 25th year need to be discounted and $CAPEX_t$ is composed of the piping ($CAPEX_{piping}$) and pump ($CAPEX_{pumps}$) capital expenditures as shown in Equation 5.4.

An explanation of the equations derived for the sub-components of the $CAPEX_0$, $OPEX_t$ and $CAPEX_t$ equations is given in Appendix C.

5.3.3. Cost Calculation

Using the input data and model, the costs of LH_2 storage could be calculated. It must be noted that during the analysis it was found that the costs are the lowest for the largest tank size possible. This is shown later in subsection 6.2.2. Consequently, the tank sizes analysed are the largest sizes feasible that still respect the minimum number of three tanks and other limitations mentioned previously.

The levelised cost ranges for the three storage topologies are presented in Figure 5.9. The bar chart was generated using the data ranges derived from experts and literature sown in Appendix A. The black lines mark the levelised cost values pertaining to the maximum likelihood input data values presented earlier in this subsection. The levelisation method used is the facility usage (considering the storage facility as an independent business unit).

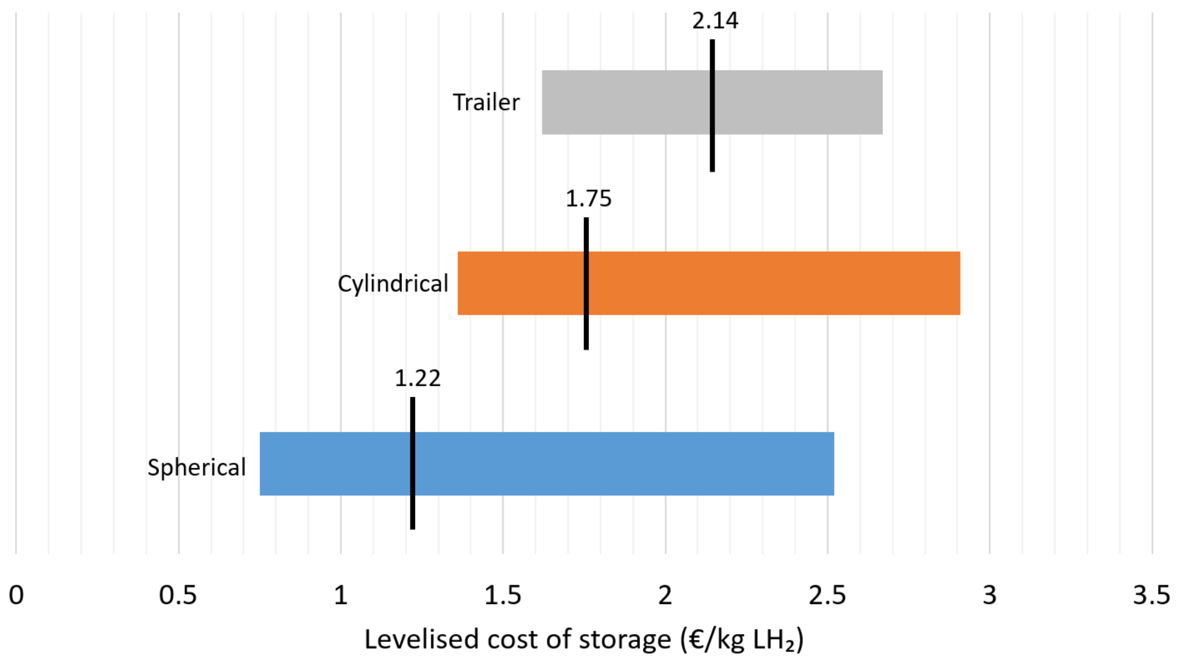

Figure 5.9: Levelised cost of storage range per tank topology

Figure 5.9 shows that the cost range of LH_2 storage is between 0.75 to 2.91 €/ kg LH_2. It is notable that the levelised cost per topology varies by almost 100% when considering the maximum likelihood input values. Consequently, it is important to understand what storage topology is being considered when estimating the levelised cost of storage, unlike done previously in the literature.

Figure 5.9 also shows that the largest cost uncertainty is found with spherical storage tanks. This is because the least concise data could be found on this tank type since there are very few constructed due to their relatively larger size and complexity. The tightest range found was for trailer tanks. This was because the most concise data found through experts and literature was for this tank type as trailer tanks have been more widely implemented due to their relatively smaller size and simplicity. Furthermore, piping and pumps were not included in the trailer tank system, hence those uncertainties did not add to the overall cost variance, which was not the case for cylindrical and spherical tank system cost estimates.

Furthermore, Figure 5.10 shows how the levelised cost and land usage change depending on the storage system topology.

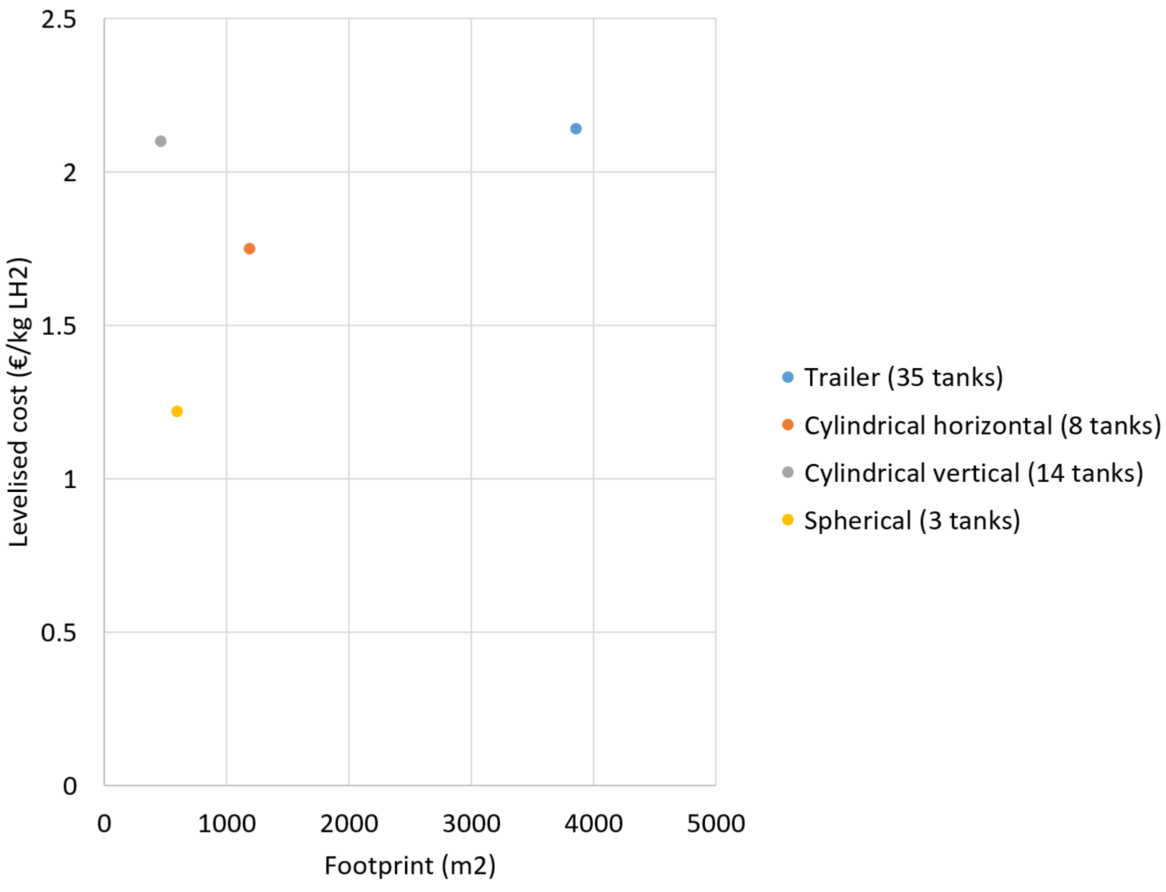

Figure 5.10: Levelised cost and land footprint for the various storage system topologies

From Figure 5.10 it is visible that the lowest levelised cost and footprint corresponds to the lowest tank number or largest tank configuration, namely, spherical tanks. Nevertheless, the land available for LH_2 facilities at RTHA is 79450 m^2 [E]. So in the case of RTHA, land constraints are not an issue for any of the tank topologies.

Furthermore, Figure 5.11 shows the upfront investment required per tank topology for the 120-tonne storage capacity.

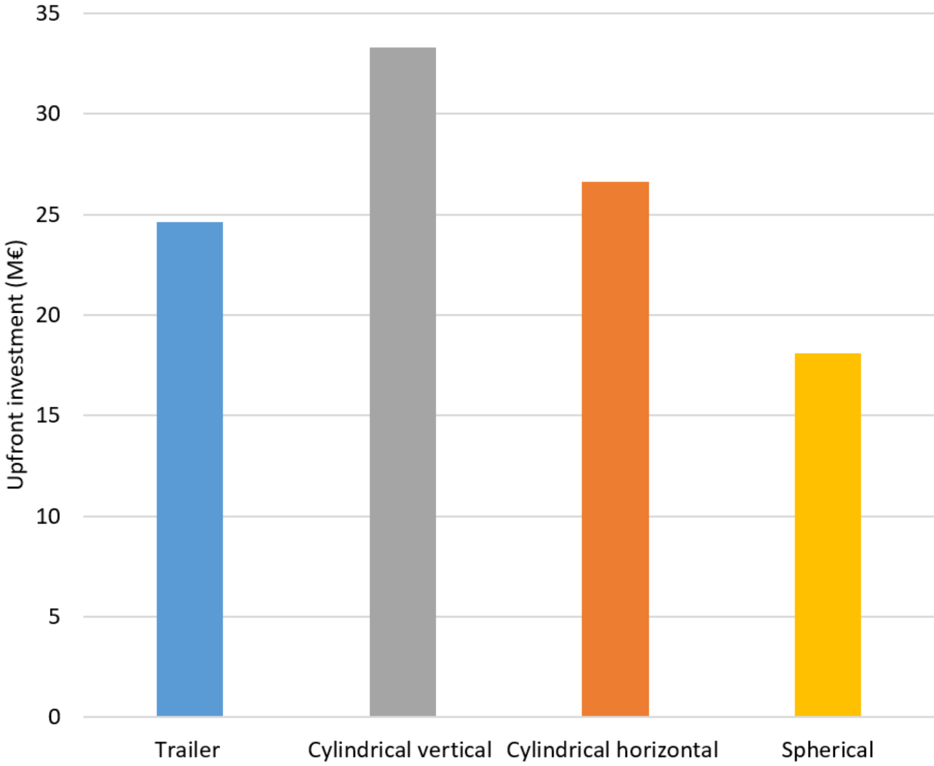

Figure 5.11: Upfront investment costs per system topology for a 120-tonne storage capacity

Despite trailer tanks having the largest levelised cost of the three options, from Figure 5.11 it can be seen that the upfront investment required is the second lowest. This is because trailer tanks do not require the construction of pumps or piping. This also leads to a more simple system procurement, installation and O&M.

In the case of spherical tanks, the upfront investment is the lowest despite the pump and piping system as the tank size is very large which leads to a low tank CAPEX due to scaling benefits. This indicates that having large tanks reduces the upfront investment costs and can compensate for the added cost of the pump and piping system.

Large spherical tanks are the most recommendable option for RTHA in 2040 since they yielded the low cost (€1.22 /kg LH_2), land usage (598 m^2) and upfront investment (M€18.1). Nevertheless, further considerations have to be taken into account when choosing a storage topology for other airports and storage demand levels. Consequently, the following elements have to be considered to see what their effects are on the storage costs and topology choice:

- The effects of using different levelisation methods

- The sensitivity of input parameters
- How storage topologies change with storage demand

Therefore, these topics will be analysed in the following chapter.

Although it is out of the scope of this research, a high-level comparison was made between Jet A-1 and LH_2 trailer storage costs using the cost model and adapting it to Jet A-1 storage. The CAPEX of Jet A-1 trailer tanks was found to be around €1/kg Jet A-1 [61]. The calculation was performed for a 400-tonne Jet A-1 system which contains the same amount of energy as a 120-tonne LH_2 storage system. A levelised cost of €0.04 /kg Jet A-1 (€0.13 / 3.3 kg Jet A-1 for the same energy content as 1 kg LH_2) and an upfront investment of M€2.8 was calculated. This shows that levelised costs of Jet-A1 storage are almost two orders of magnitude lower than that of LH_2 and the upfront investment costs are almost one order of magnitude lower for Jet A-1 storage with respect to LH_2 storage. This indicates that the transition to LH_2 storage will require higher costs unless developments are made in order to reduce the LH_2 storage costs. Therefore, the cost reduction methods for LH_2 storage looked at in the following chapter are very relevant.

Summarizing, this chapter has covered knowledge gaps by providing insights into the design, operation and sizing of LH_2 storage for airports. Additionally, the levelised costs of LH_2 storage facilities have been calculated. Upfront investment costs and land usage have also been quantified for RTHA considering the 2040 demand scenario. All of this has been done using accurate and up-to-date cost data for LH_2 storage facilities and given per topology option.

6

Generalized Results

Part three of the solution is aimed at generating generalized results applicable to airports beyond the case study. At the end of this chapter, knowledge gaps will be covered relating to: the effects of the levelisation method, what the main cost drivers and cost reduction techniques are as well as what general LH_2 storage facility cost estimations for airports are.

In section 6.1 the cost model is used in order to understand how the levelised costs change if another cost calculation method is taken. Subsequently, a sensitivity analysis is presented in section 6.2. The sensitivity analysis identifies the cost drivers, cost reduction methods and turning points in design topology. Lastly, in section 6.3 an analysis is presented of the levelised costs when transitioning from one storage topology to another as demand for storage changes.

6.1. Comparison of Levelisation Method

Different levelisation methods are ways of interpreting the same absolute cost. In this section, two levelisation methods are compared and the effects of taking different levelisation methods are explained. The two levelisation methods considered are as follows:

1. So far, the levelised cost has been calculated by taking the yearly amount of LH_2 stored in the storage facility as the levelisation parameter. In other words, the levelised cost is calculated as the cost of 1 kg of LH_2 purchased from the storage facility as an independent business unit. The levelisation parameter used is 1440 tonnes of LH_2 per year pertaining to an equivalent of 12 times fully unloaded per year.
2. The second method considered distributes the storage facility costs over the total amount of fuel sold to the aircraft. This method evaluates the economic impact the LH_2 storage facility has on all the LH_2 sold to aeroplanes. This method considers that the LH_2 storage facility is part of the full airport system in an economic sense. The levelisation parameter

used is 7894 tonnes of LH_2 per year pertaining to the predicted LH_2 demand of RTHA in 2040.

Below in Figure 6.1, one can see a comparison of the levelised cost of hydrogen storage when considering the two levelisation methods.

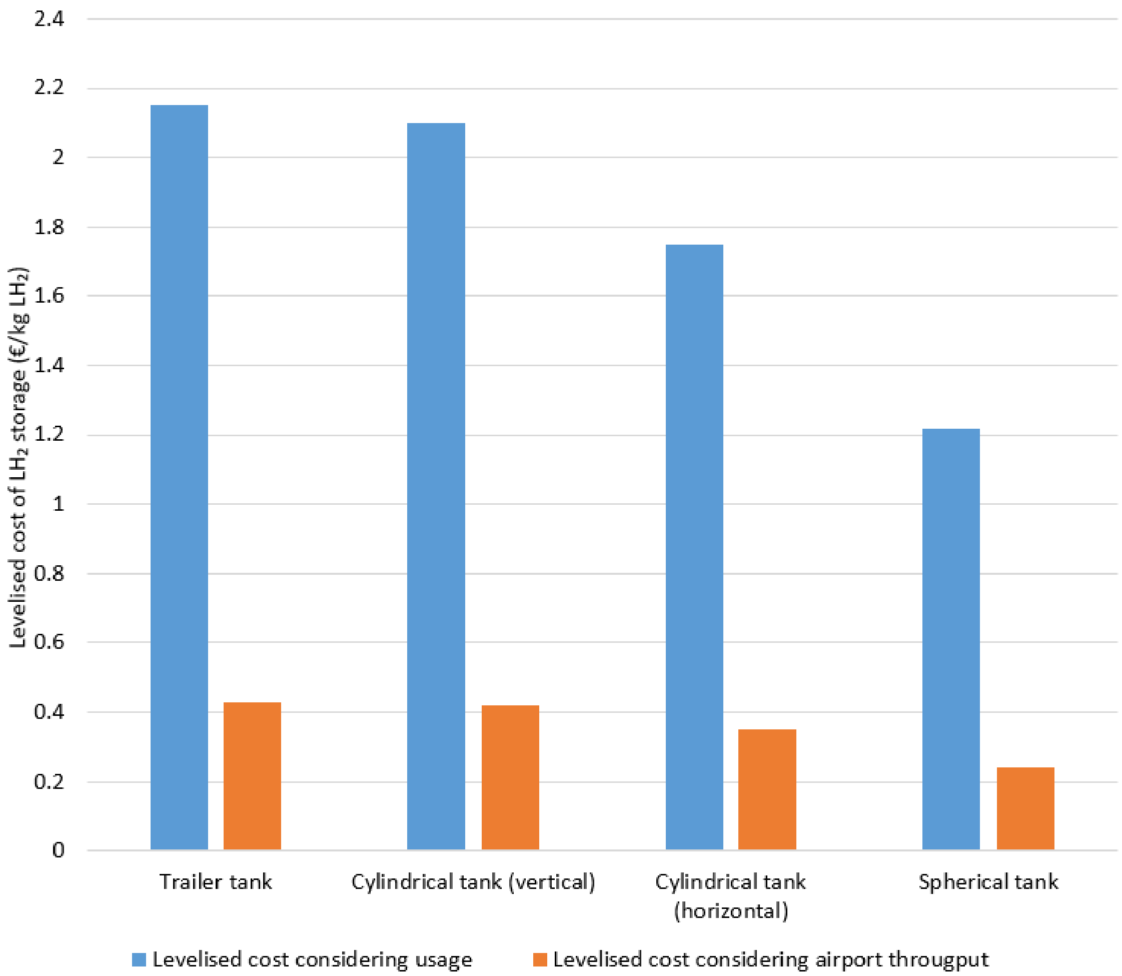

Figure 6.1: comparison of the levelised cost of hydrogen storage when considering the two levelisation methods

Figure 6.1 shows that the levelised cost of LH_2 storage drops significantly when considering the throughput of the airport instead of the usage of the storage facility as the levelisation parameter. This is because the same costs are now being divided by a larger levelisation parameter.

Figure 6.1 also confirms that a reason for large cost estimate variances found in literature could be the levelisation method used. Furthermore, Figure 6.1 shows that two levelised cost estimations using different levelisation methods can not be compared.

It must be noted that the second levelisation method considered does not change the relative costs between the topologies considered. This indicates that conclusions derived for one levelisation method are also valid for the other.

6.2. Sensitivity Analysis

In this section, a sensitivity analysis of the levelised cost of storage is performed. The goal of the sensitivity analysis is to identify the: cost drivers, cost reduction methods and turning points in design topology. The cost drivers and reduction methods are described in subsection 6.2.1 after which the turning points in design topology are elaborated upon in subsection 6.2.2.

6.2.1. Cost Drivers & Reduction Methods

The cost drivers and reduction methods were identified via a sensitivity analysis that revealed the most influential input parameters on the levelised cost. Figure 6.2 summarises the outcomes of the sensitivity analysis.

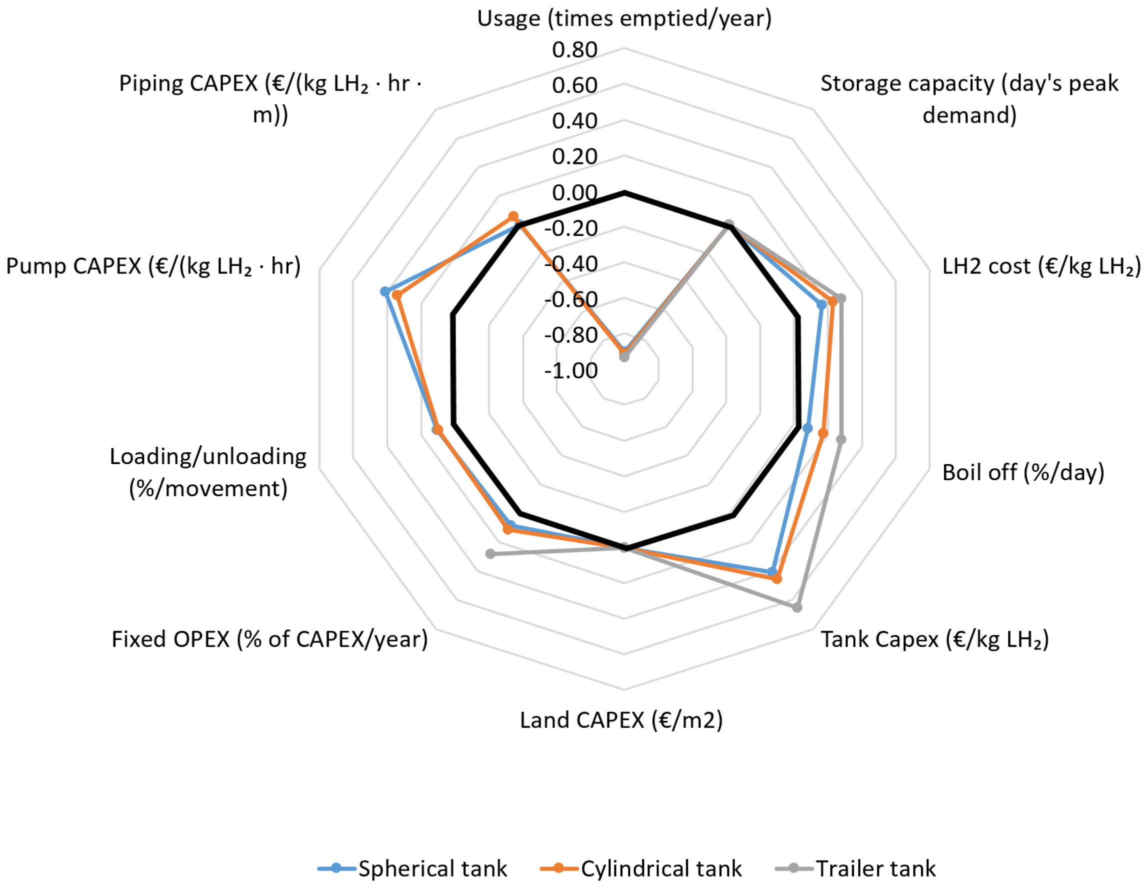

Figure 6.2: Sensitivity of input parameters

In Figure 6.2, each vertex represents the sensitivity of the levelised cost with respect to an input parameter. The thick black line represents the zero sensitivity level, anything above the black line represents positive sensitivity and anything below a negative sensitivity. Positive sensitivity indicates that for an increase in an input parameter the levelised cost increases, the opposite is true for a negative sensitivity. The sensitivities of the trailer, cylindrical and spherical tank topologies are shown by the grey, orange and blue lines, respectively.

Figure 6.2 shows that the three most influential parameters on the levelised cost are the facility usage, the tank and pump CAPEX and the boil off or LH_2 costs.

From Figure 6.2 it can be seen that the levelised cost is most sensitive to the usage of the storage facility. The sensitivity of -0.9 means that if the storage is used at 50% capacity, the levelised cost increases by 90%. Consequently, large tank systems can become very expensive if not used at full capacity. Large tank systems are prone to be oversized at the time of installation. Consequently, a modular system is recommendable as it can be adapted better to demand evolution and finally be more cost-effective.

The levelised cost of storage is also relatively sensitive to the tank and pump CAPEX as shown in Figure 6.2. The high sensitivity indicates that a CAPEX reduction will significantly influence the costs of storage. CAPEX can be reduced for example via batch production, volume scaling and technology improvements.

Figure 6.2 shows that the levelised cost can also be notably affected by the boil off or LH_2 costs. This indicates that costs can be reduced by using integrated refrigeration cycles or using boil off gas for other purposes in order to reduce hydrogen losses. These systems could also benefit the environment because hydrogen can contribute to global warming since it prolongs the lifetime of methane, reduces the concentration of ozone in the high stratosphere, and raises the concentration of water vapour [88].

Subsequently, from the sensitivity analysis it is clear that the main cost drivers are the facility usage, the tank and pump CAPEX, and the boil off. Furthermore, the most effective ways of reducing the costs of the storage facility are: using modular adaptable systems to prevent oversizing, developing CAPEX reduction methods such as batch production or technological improvements and lastly, implementing the recycling or usage of boil off gas.

6.2.2. Topology Turning Points

The turning points in design topology for trailer tanks, cylindrical tanks and spherical tanks are subsequently explained.

Trailer Tanks

For storage facilities of up to around 30 tonnes trailer tanks should be considered. This is because they have low upfront investment, high adaptability and simple implementation. At these sizes of storage, land usage is not considered to be a problem.

In Figure 6.3, the levelised cost of a cylindrical tank system for varying individual tank sizes is shown by the red line. The green dot represents the levelised cost of a trailer tank system.

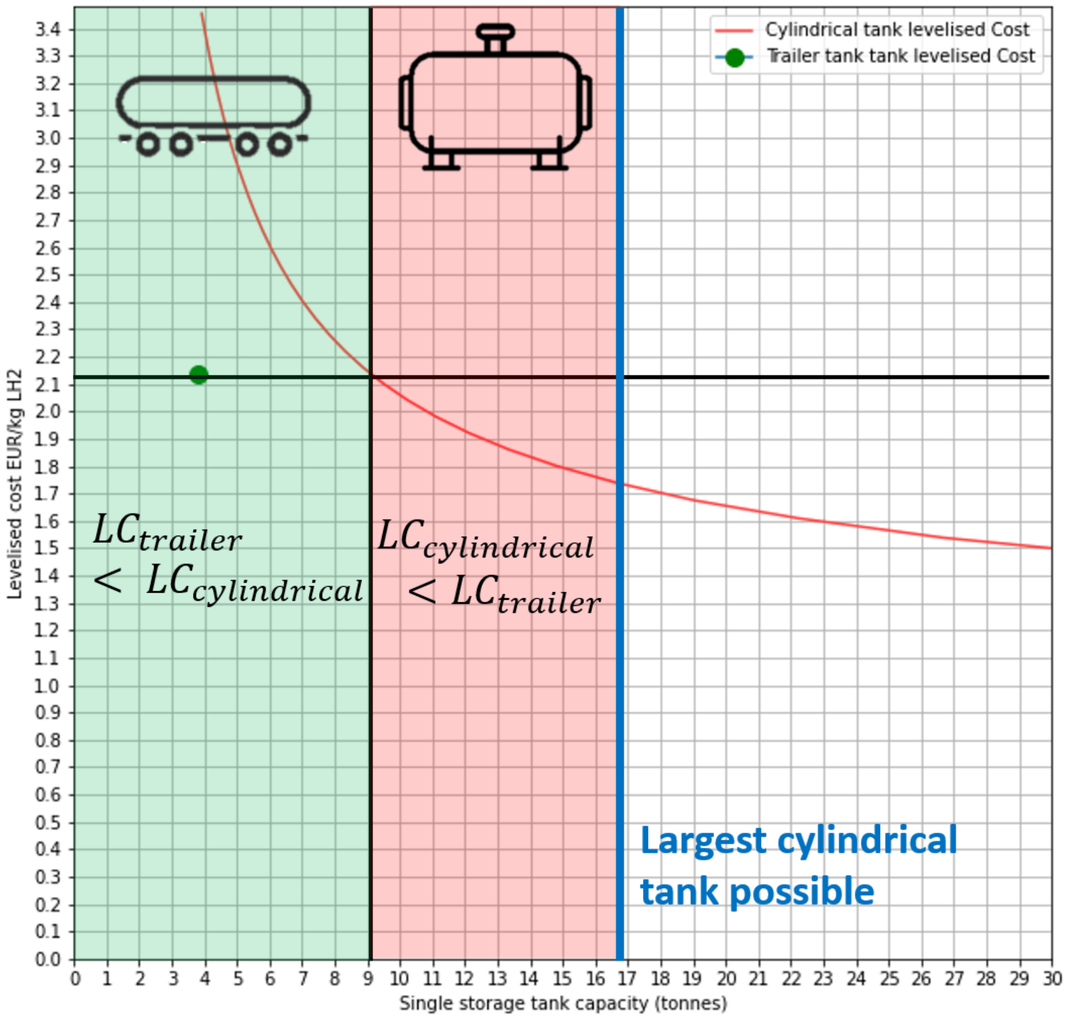

Figure 6.3: Levelised cost of hydrogen storage for a cylindrical tank system for different individual cylindrical tank capacities

The red line shows how the levelised costs drop for systems using larger tanks. At a cylindrical tank capacity of 9 tonnes, the levelised cost of the cylindrical tank system drops below that of the trailer tank. Since a tank system must include at least three tanks as identified in chapter 5, this equates to a 27-tonne system where using cylindrical tanks begins to have a lower levelised cost and hence should be considered instead. Consequently, from a levelised cost point of view, cylindrical tank systems become more advantageous than trailer tanks for 30-tonne systems or larger.

Cylindrical Tanks

For storage facilities greater than approximately 30 tonnes, cylindrical tanks should be considered as they have a decreased levelised cost and land usage compared to trailer tanks.

Cylindrical tanks offer reasonable adaptability and a higher ease of installation with respect to spherical tanks.

From Figure 6.3 it can be seen that as the size of the cylindrical tanks increases, the levelised cost decreases from €2.14/kg LH_2 down to €1.75/kg LH_2 (marked by the second vertical blue line). This levelised cost corresponds to the maximum reference size of road transportable tanks of 16.8 tonnes and also the lowest levelised cost for cylindrical tank systems when considering the upper limit in size.

Spherical Tanks

Figure 6.4 shows how the levelised cost of spherical tanks changes depending on individual tank capacity in comparison to the levelised cost of the largest cylindrical tank possible.

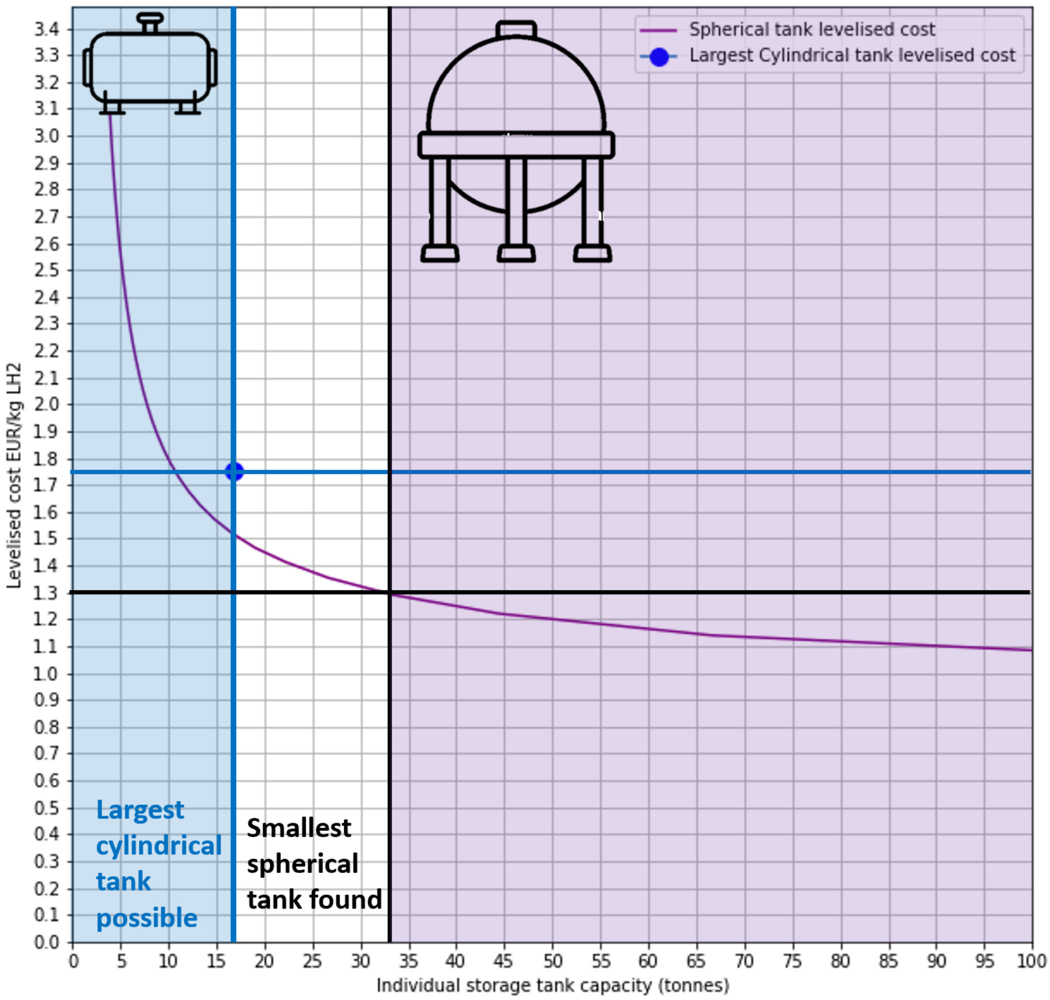

Figure 6.4: Levelised cost of hydrogen for different individual spherical tank capacities

From Figure 6.4, at storage capacities of 100 tonnes, three 33-tonne spherical tanks could be installed which are roughly twice the size of the largest cylindrical tanks and around the same size of the smallest spherical tanks found in the literature [31]. Consequently, Figure 6.4 shows that going from a cylindrical tank system (16.8 tonnes per tank) to a spherical tank system (33 tonnes per tank) leads to a levelised cost reduction from €1.75/kg LH_2 to €1.3 LH_2, respectively, and is a recommendable transition point.

At high storage capacities (>100 tonnes), adaptability begins to become less of an issue for large tanks as more can be fit into the system, allowing for high levels of redundancy and reduced levelised costs. Consequently, large spherical tanks should be considered.

Figure 6.5 summarizes the turning points in design topology derived.

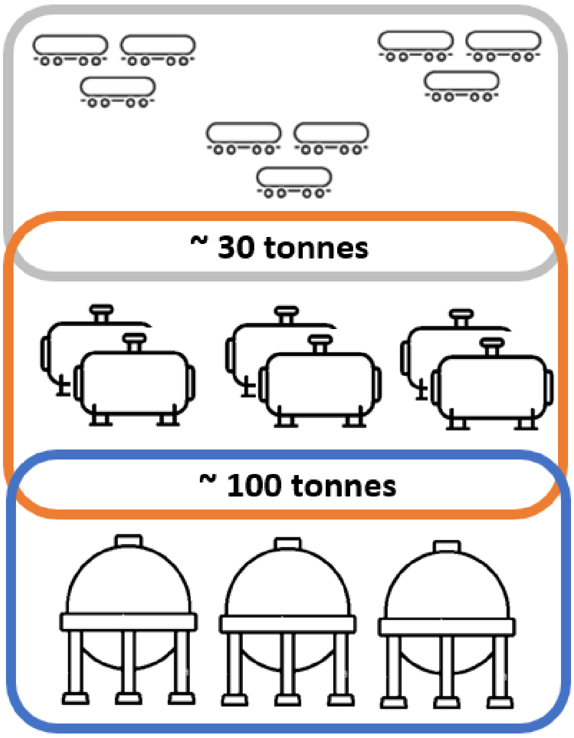

Figure 6.5: Topology turning points

6.3. Topology Transition Costs

Using the maximum likelihood input data, the cost model previously developed and the turning points identified, Figure 6.6 was generated which shows the levelised costs of a system transitioning between design topologies for increasing storage demand.

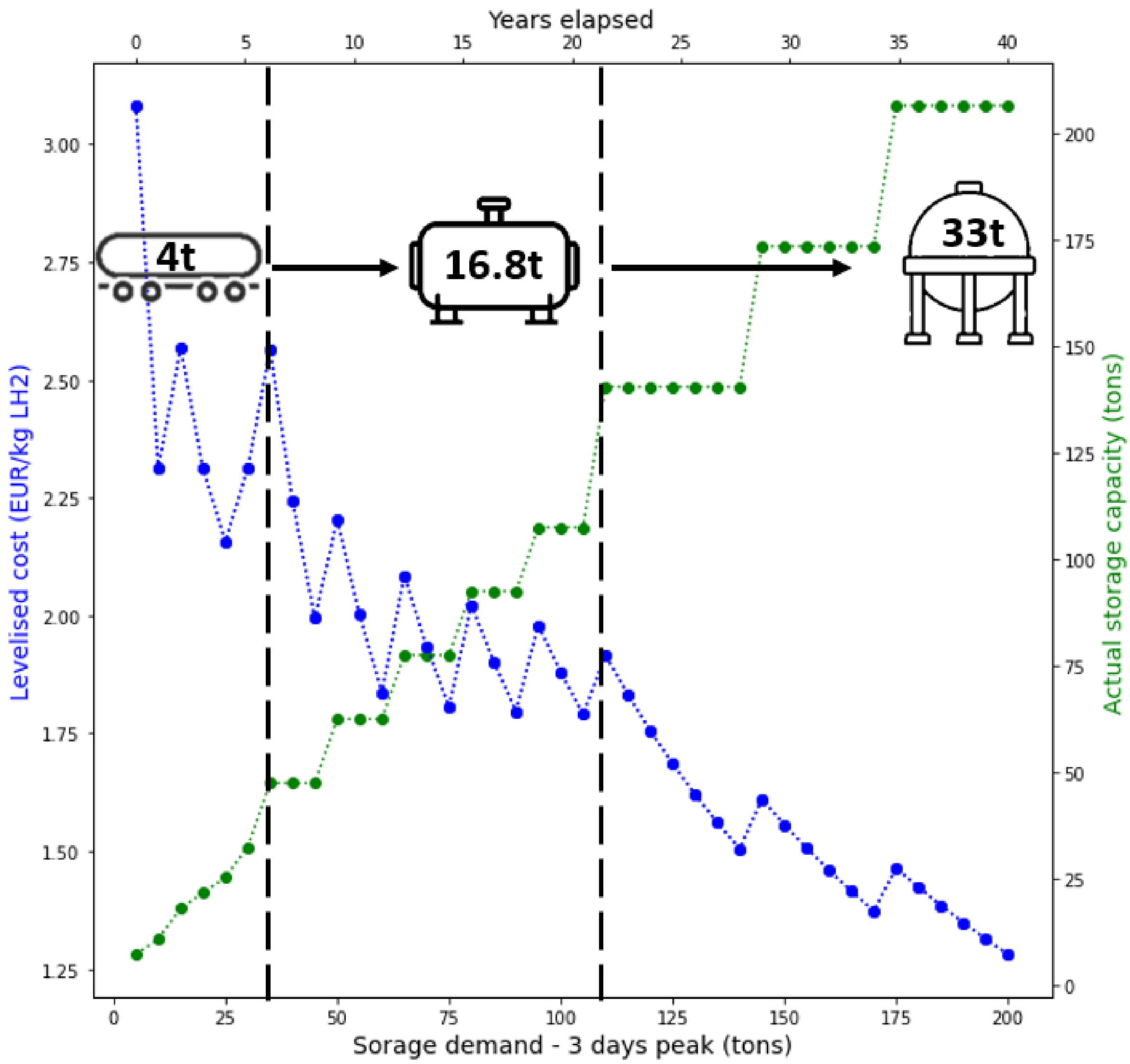

Figure 6.6: Levelised cost of hydrogen storage for varying storage demand and actual storage capacity

In Figure 6.6, each point represents a five-tonne increment per year starting at a five-tonne storage demand. Each trailer, cylindrical and spherical tank added were of 4, 16.8 and 33 tonnes capacity, respectively. It is important to note that the costs were calculated considering that the smaller tank system is progressively replaced by the larger tank system as storage demand increases. Tanks that are removed from the system are considered not to lose any value and the CAPEX of the old tank is replaced by that of the new tank being added.

Figure 6.6 shows how when transitioning from a small tank system to a large tank system, the levelised costs on average decrease. Hence, even when considering hybrid systems, having larger tanks is the most cost-effective.

However, spikes of levelised costs are also observable. This is because each time a new tank is added an oversizing can potentially occur as the added capacity is higher than the instantaneous storage demand increase. As the storage demand increases further, the storage overcapacity is reduced and the levelised cost is reduced until the next storage capacity increment occurs and the process repeats itself. The levelised cost spikes show once more the importance of having a modular system that can adapt well to changes in storage demand while keeping oversizing at a minimum.

Consequently, this chapter has identified: the effects of using different cost levelisation methods, the cost drivers and reduction methods, turning points in design topology as well as the costs of a dynamic storage system progressing between storage topologies. Furthermore, this chapter has presented levelised cost estimations for various cases applicable to a range of storage demands and hence airports. As a result, the subsequent chapter discusses the conclusions of this research.

7 Conclusion

This thesis began with a broad review of the LH_2 supply chain in order to identify knowledge gaps that need to be filled to facilitate the transition towards a sustainable civil aviation industry powered by LH_2 aircraft. From existing literature, it became apparent that LH_2 storage facilities are an important element in ensuring the supply of LH_2 for airports and that the largest knowledge gap and cost estimate uncertainty found in the supply chain was regarding LH_2 storage facilities. Additionally, a systematic and consistent modelling and analysis of the cost of LH_2 storage facilities applicable to the specificities of an airport was found to be missing in the literature. This led to the following research question:

"How should liquid hydrogen storage facilities for airports be designed, what are the costs and how can they be reduced?"

After collecting data from research papers, performing expert interviews, carrying out a case study and finally modelling costs and closing information gaps identified, the following outcomes were generated in order to cover the three parts of the research question.

1. How should liquid hydrogen storage facilities for airports be designed?

Due to LH_2's low boiling point, highly insulating tank technology is required in addition to a boil off management system to prevent overpressures in the tank. Much larger storage volumes are required due to LH_2's lower volumetric energy density which may lead to land availability issues. New safety considerations have to be taken into account due to the cryogenic temperatures, low density of hydrogen and low leakage/flame detectability.

This study concludes that three main tank types are well suited to cover a wide range of storage facility capacities, namely: trailer tanks, cylindrical tanks and spherical tanks. Each tank type drives the design topology and operation of the storage facility.

Trailer tanks should be considered for storage capacities under 30 tonnes as they offer ease of installation and usage, low upfront investment costs and high modularity. However, trailer tank storage facilities lead to higher levelised costs (around €2.14 /kg LH_2) and land usage. Nevertheless, at low levels of storage capacity, land usage should not be a constraint. Cylindrical tanks should be considered for 30-tonne to 100-tonne capacities as they offer a lower levelised cost than trailer tanks (around €1.75 /kg LH_2), lower land usage and considerable modularity to prevent oversizing. Large spherical tanks are most suited for storage capacities greater than 100 tonnes. Large spherical tanks lead to the lowest levelised cost (around €1.22 /kg LH_2), upfront investment and, land usage. At high storage demand, high modularity can be achieved with large tanks.

Larger tanks were found to lead to lower levelised costs, even when considering hybrid tank systems. However, storage facilities should be designed using modular and adaptable systems to prevent oversizing since an underused storage facility leads to a strong increase in the levelised cost.

Furthermore, airports should size the storage facilities to have a capacity equal to three days' worth of peak demand based on the capacity recommendations for Jet A-1 storage. In order to ensure redundancy in case of maintenance or component failure, a minimum number of three storage tanks arranged in three strings with each string equipped with a pump is recommended.

2. What are the cost of liquid hydrogen storage facilities for airports?

The levelised costs for each storage topology varied as shown in Figure 7.1 based on the ranges of input data collected.

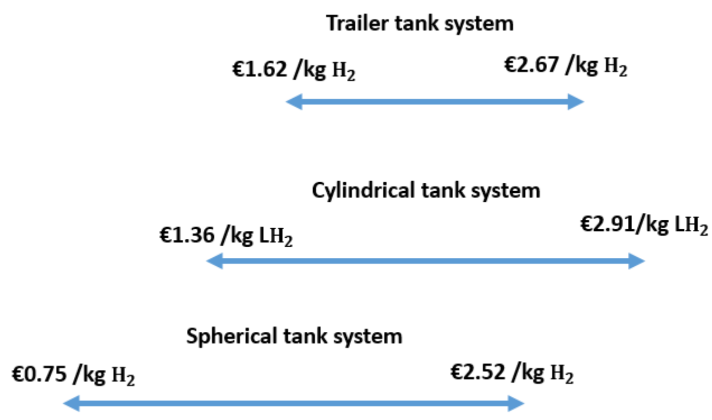

Figure 7.1: Levelised cost of storage range per tank topology based on facility usage

Figure 7.1 shows that the storage topology has a large effect on the levelised costs of the storage facility and hence must be taken into account, unlike previously done in the literature.

Figure 7.2 shows how the present work reduces the large cost range found in the literature. Please note that the data previously collected in United States dollars has been converted to euros using the current exchange rate ($ 1 - €0.93) for comparative purposes.

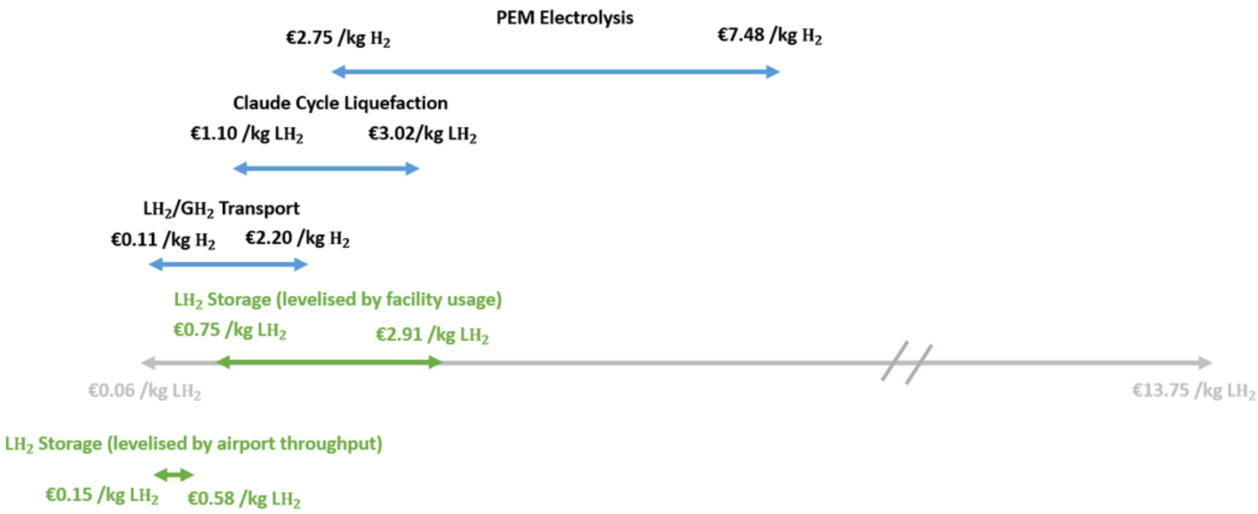

Figure 7.2: Updated levelised cost ranges for LH_2 supply chain components

From Figure 7.2, it is clear that having consistent levelisation methods is needed to be able to compare cost estimates.

3. How can the costs of liquid hydrogen storage facilities for airports be reduced?

The sensitivity analysis revealed that the main cost drivers are the facility usage, tank CAPEX, pump CAPEX, boil off and LH_2 costs. Subsequently, the most effective ways of reducing the costs of the storage facility are: using modular adaptable systems to prevent oversizing, developing CAPEX reduction methods such as batch production or technological improvements and lastly, implementing the recycling or usage of boil off gas.

8 Recommendations

In this chapter, the research is reflected upon and consequently, recommendations are given for future research which aims at further investigating LH_2 storage facilities for airports.

In this research, the facility sizing was taken to be three days worth the peak daily demand. This is based on the requirement for Jet A-1 strategic reserves. The LH_2 supply chain maturity is much lower and will be lower for some time with respect to that of Jet A-1. Hence, a different storage sizing may be needed. Consequently, it is recommended that future research evaluates the degree of backup storage required taking into account the specificities of supplying LH_2. This way storage facilities can also be more accurately sized leading to a lower probability of under/oversized facilities causing a lack of fuel supply or oversized facilities causing very high costs, respectively.

Future research should investigate how changes in production methods or technology could help reduce the CAPEX as it was found to be a main cost driver. More specifically, an investigation into standardization and mass production of tanks could be highly beneficial to the cost reduction of LH_2 storage.

It must be noted that the cost data used is based on today's technology and component characteristics. In the future, the cost model inputs might need to be revised in case the parameters of the different components change significantly.

Lastly, a recommendation presented for cost reduction was implementing boil off recycling systems or the usage of boil off gas for secondary purposes. Additionally, due to hydrogen's global warming potential, it is paramount that boil off is not emitted into the atmosphere. Consequently, a thorough evaluation of the various options, their impact on system costs and their integration into airport infrastructure is recommendable.

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A

Data Collected

Characteristic	Unit	Value	Comment	Source
Load/unload losses	%	2 - 10	Based on experimental data	Genovese et al. (2019) [46]
		6 – 15.4	Based on LH_2 pump performance test for refuelling	Petitpas & Aveces (2018) [69]
		>12	Based on NASA model to simulate rocket fuelling	Petitpas (2018) [68]
Fill level range	%	5 - 95	% of total capacity used	Knol (Cryoworld) [A]

Table A.1: General LH_2 storage tank data collected

Characteristic	Unit	Value	Comment	Source
Capacity	tonnes	4.5		USDOE (2016) [35]
		4		Rutten (2022) [79], NAPKIN (2022) [57]
Lifetime	years	30		USDOE (2016) [35]
		30 - 50	Lifetime of tanks can reach even over 50 years, 30 years is a conservative estimate	Thomas Jordan (KIT) [B]
		~ 30		Knol (Cryoworld) [A]
CAPEX	$/kg L$H_2$	190		USDOE (2016) [35]
		167		Reddi et al. (2015) [74]
Fixed O&M costs	% of CAPEX / year	3		Hoelzen et al. (2022) [48]
Boil-off	%/day	0.4	For a 50 m^3 tank (3.5 tonnes)	Al Ghafri et al. (2022) [10], Gautam et al. (2018) [45]
		0.8	Higher due to added on-board piping and components	Knol (Cryoworld)

Table A.2: LH_2 trailer storage tank data collected

Characteristic	Unit	Value	Comment	Source
Capacity	tonnes	< 16.8	238 m3 cylindrical tank seen carried by road transport in India	FuelCellsWorks (2022) [93]
		<7.1	If placed vertically the size cannot be larger than 100 m3	Knol (Cryoworld) [A], Linde (2020) [39]
		< 10.6	150 m3 vertical tank design presented	Kiwa (2022) [56]
	m	<25.25	Maximum allowable length to be carried by trailer trucks on road in the EU including the truck	Ministry of Infrastructure and Water Management (2015) [12]
Lifetime	years	30 - 50	Lifetime of tanks can reach even over 50 years, 30 years is a conservative estimate	Thomas Jordan (KIT) [B]
		~ 30		Knol (Cryoworld) [A]
CAPEX	€/kg LH_2	196	Horizontal cylindrical tank, double walled and MLVI for the space industry, 360 m^3	Schaerer (Air Liquide) [C]
		130	Horizontal cylindrical tank, double walled and MLVI, 150 m^3	Knol (Cryoworld) [A]

Characteristic	Unit	Value	Comment	Source
Fixed O&M costs	%	0.5	Percentage of CAPEX per year. Rough estimation	Knol (Cryoworld) [A]
		2 – 4		Kennedy et al. (2019) [55]
		2		Hoelzen et al. (2022) [48]
Boil-off	%/day	0.3	Horizontal cylindrical tank, double-walled, MLVI for the space industry, 360 m^3	Schaerer (Air Liquide)[C]

Table A.3: LH_2 cylindrical storage tank data collected

Characteristic	Unit	Value	Comment	Source
Capacity	tonnes	227.2		Ratnakar et al. (2021) [73]
		248.5		USDOE (2016) [35]
		177.5		Mandra (2021) [62]
		38.2		Demaco (2021) [31]
Lifetime	years	30 - 50	Lifetime of tanks can reach even over 50 years, 30 years is a conservative estimate	Thomas Jordan (KIT) [B]
		~ 30		Knol (Cryoworld) [A]
CAPEX	\$/kg LH_2	88	Double-walled vacuum-perlite insulated spherical tank at NASA built in 1960s, 3200 m^3	Ratnakar et al. (2021) [73]
		27	Theoretical price calculated by United States Department of Energy. 3500 m^3. Technology is unknown.	USDOE (2016) [35]
Fixed O&M costs	%	0.5	Percentage of CAPEX per year. Rough estimation	Knol (Cryoworld) [A]
		2 – 4	Percentage of CAPEX per year	Kennedy et al. (2019) [55]
		2	Percentage of CAPEX per year	Hoelzen et al. (2022) [48]
Boil-off	%/day	0.1	For “large” spherical tanks	NREL (1999) [47]
		0.03 – 0.05	Estimate for 3200 m^3 tank	Ratnakar (2021) [73]

Table A.4: LH_2 spherical storage tank data collected

Characteristic	Unit	Value	Comment	Source
Lifetime	years	10		USDOE (2016) [35], Reuß et al. (2017) [76]
Specific CAPEX	$/kg/h	567.1 x + 11565	Linear cost relationship where x is the output of the pump in kg/h. Based on cost data for various pump models	USDOE (2008) [37]
		256	Based on a combination of studies	Hoelzen et al. (2022)
Fixed O&M costs	%	3		Reuß et al. (2017) [76]
Energy consumption	kWh/kg	0.6		USDOE (2016) [35]
		0.1		Reuß et al. (2017) [76]

Table A.5: LH_2 pump data collected

Characteristic	Unit	Value	Comment	Source
Lifetime	years	25		Dekker (Demaco) [G]
CAPEX	€/m	0.224 x flow rate (kg/h) + 950.32	For an internal pipe diameter of 50 mm and 1m/s flow speed, the cost was given as €1400/m. For 80mm cost was given as roughly 1.5 times higher.	Knol (Cryoworld) [A]
Fixed O&M costs	%	0		Dekker (Demaco) [G]

Table A.6: LH_2 pipe data collected

B

LH_2 Demand Prediction RTHA 2040

Predicting the demand of RTHA in 2040 consists of three main steps: determining the degree of LH_2 aircraft adoption in 2040, converting the current Jet A-1 fuel consumption into the equivalent amount of LH_2 and lastly, extrapolating the demand to 2040. These three steps and their respective results are subsequently explained.

1. **LH_2 aircraft adoption**
   The first step involves determining which part of the current fuel consumption would be LH_2. In Table B.1 one can see the sources used to determine the degree of LH_2 fuel consumption in 2040.

Title of source	**Method**	**LH_2 penetration**	**Author**
"Hydrogen Consumption at Airports"	Munich airport is used as a case study. Flights flying less than 1000 nautical miles assumed to be LH_2 powered. Different scenarios considered depending on ramp-up of aircraft market penetration and aircraft life.	Munich (48 million pax /yr): 20% – 30.95% in 2050	Schmidt (2022) [81]
"H_2-powered aviation at airports – design and economics of LH_2 Refueling Systems"	Demand prediction made for Bremen, Hamburg and Frankfurt. Fuel demand scenarios generated based on entry into service, ramp-up of aircraft manufacturing and take-rate.	Bremen (0.63 million pax /yr): 48% - 84% in 2050 Hamburg (13.8 million pax /yr): 46% - 81% in 2050 Frankfurt (48 million pax /yr): 32% - 56% in 2050	Hoelzen et al. (2022) [48]
"Making Zero-carbon Emission Flight a Reality in the UK"	Based on three LH_2 aircraft models entering the market between 2025 – 2040. Three scenarios generated per airport based on different average annual growth rates of annual movements.	Inverness (1 million pax /yr): 8% - 40% in 2040 London city (5 million pax /yr): 8% - 28% in 2040 Heathrow (19.4 million pax /yr): 8% - 18% in 2040	NAPKIN (2022) [57]

Table B.1: Sources and interviews used to determine level of LH_2 fuel consumption in 2040 at RTHA

The method of predicting LH_2 fuel penetration used by Schmidt (2022) [81], Hoelzen et al. (2022) [48] and NAPKIN (2022) [57] was based on what portion of the fleet could be LH_2 powered in a case study airport by comparing the current flight profiles of aircraft to possible future LH_2 aircraft models. The different rates of market penetration, aircraft manufacturing ramp-up rates, aircraft life or growth rates of aircraft markets were used in order to find the degree of LH_2 aircraft penetration.

Considering that RTHA hosts around 2 million passengers per year and is an international airport hosting flight profiles within the design specifications of future LH_2 aircraft models, it was considered that the LH_2 fuel penetration would be similar to that estimated for Inverness or Bremen airport in 2040. Consequently, 30% of fuel consumed (by energy content) was taken to be LH_2 at RTHA in 2040.

2. **Equivalent LH_2 fuel amount**
   Having determined the degree of LH_2 fuel consumption, the second step involves converting the Jet A-1 fuel consumption into the equivalent LH_2 amount. This was done by using the commercial aviation fuel demand of RTHA in 2019. This was carried out with the following steps:

   (a) The energy content of the Jet A-1 fuel tanked into aircraft is calculated by multiplying the amount of fuel by the energy density of Jet A-1:

   $$E_{Jet\ A-1} = m_{Jet\ A-1} \cdot U_{Jet\ A-1} \tag{B.1}$$

   (b) Then the energy content of the Jet A-1 fuel is converted into the equivalent mass of H_2 by dividing the Jet A-1 fuel energy content by the energy density of H_2:

   $$m_{H_2} = \frac{E_{Jet\ A-1}}{U_{H_2}} \tag{B.2}$$

   (c) Subsequently, corrections are made for differences in energy consumption between Jet A-1 and LH_2 powered aeroplanes based on the report by Westenberger (2007) [92].

   The changes in energy consumption given by Westenberger (2007) [92] were used to calculate the corrected equivalent amount of LH_2. This was done by multiplying the LH_2 amount calculated in step 2 with the percentage increase in energy consumption:

   $$m_{LH_2\ corrected} = m_{LH_2} \cdot (1 + \delta E) \tag{B.3}$$

   Figure B.1 shows the data provided by Westenberger (2007) on changes in energy consumption between Jet A-1 and LH_2 powered aeroplanes.

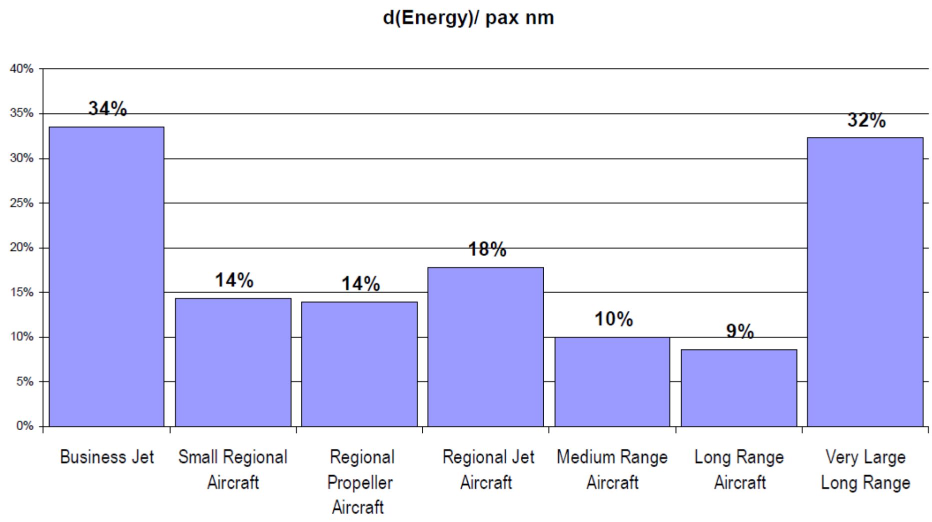

Figure B.1: Change of energy consumption for H_2 fuelled aircraft [92]

Since RTHA's commercial aviation entails mainly small regional aircraft to medium /long-range aircraft, an increase in efficiency of 14% was assumed for all commercial aircraft. The values used in the calculations are summarised in Table B.2 alongside their respective sources.

Parameter	Units	Value	Source
Specific Energy Jet A-1	MJ/kg	43.1	[82]
Specific Energy H_2	MJ/kg	142	[11]
Energy Consumption Increase	%	14	[92]

Table B.2: Parameters used in Equivalent LH_2 Mass Calculation from RTHA Jet A-1 Fuel Demand

3. **Fuel demand extrapolation**
The third step involves determining the growth rate of flights at the airports in order to predict the demand in 2040. A growth rate of 2.7% per annum was taken based on Statista's data for global airline fuel consumption [28]. The 2.7% was calculated by taking an average of the growth rate in fuel consumption for pre-COVID years, namely, between 2005 and 2019.

Consequently, by using the growth rate of 2.7% per annum in fuel consumption, the predicted demand of LH_2 in 2040 could be calculated on a daily scale. This demand profile can be seen in Figure B.2. Each data point represents the demand on a certain day of the year.

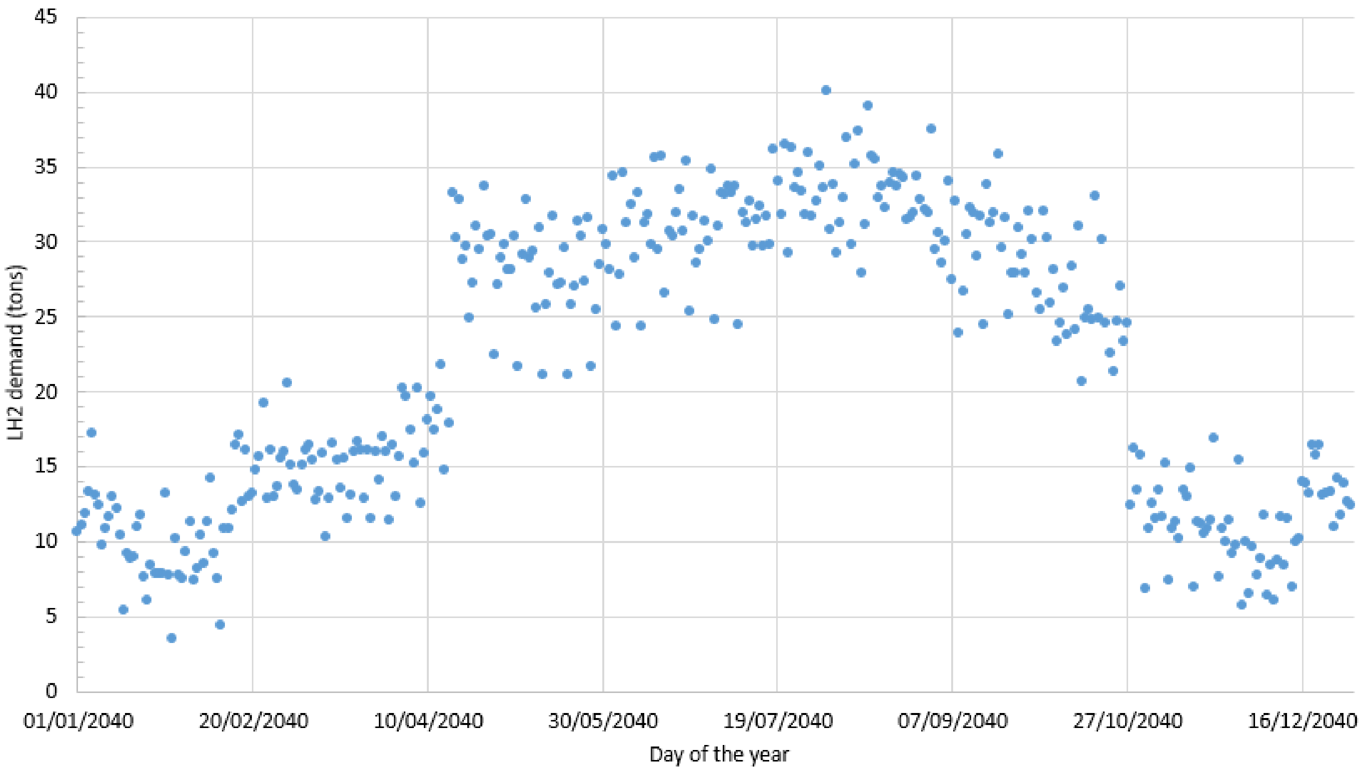

Figure B.2: Predicted LH_2 Demand at RTHA in 2040 for Commercial Aviation

From Figure B.2 it can be seen that the peak daily demand is 40 tonnes of LH_2. Furthermore, this prediction yields a total annual demand in 2040 of 7984 tonnes of LH_2.

C
Cost Equations

The cost model was generated for a known storage capacity. Hence, Equation C.1 shows the relation between tank number (n), individual tank storage capacity (c) and total storage capacity (c_{total}) is valid and is used subsequently.

$$n = \frac{c_{total}}{c} \tag{C.1}$$

Tank CAPEX

The equation used to calculate the capital expenditure of tanks is shown in Equation C.2.

$$CAPEX_{tanks} = CAPEX_{ref} \cdot S_{CAPEX} \cdot c \tag{C.2}$$

$CAPEX_{tanks}$ is calculated by multiplying the reference specific tank CAPEX ($CAPEX_{ref}$, €/kg LH_2) with the scaling parameter (S_{CAPEX}, -) and the total capacity required (c, kg).

The scaling parameter (S_{CAPEX}, -) used was based on the book on techno-economic assessments by Murthy (2022) [65]. In the book, it is stated that in order to scale CAPEX values for equipment, the Equation C.3 should be used.

$$S_{CAPEX_{tanks}} = (\frac{New\ capacity}{Original\ capacity})^{exp} \tag{C.3}$$

The exponent of the power law equation shown above is given to vary between 0.6 and 0.7 for engineering equipment as stated by Murthy (2022) [65]. Tribe & Alpine (1986) [87] states in an article on scale economies that 0.6 is taken for storage tanks. Subsequently, 0.6 was taken in this study as the exponent for the cost power law.

As indicated in Equation C.2, a specific CAPEX reference is needed in order to calculate the new CAPEX. For this, Table C.1 shows the two reference tanks that were taken based on information given by experts and online on the latest tank designs. Since trailer tanks are only considered to be 4 tonnes, no scaling was needed.

Tank type	Dimension (m)	Volume (m3)	Capacity (kg)	CAPEX (€/kg LH_2)	Sources
Cylindrical	Length = 21, diameter = 4	247	17,500	130	Knol (Cryoworld) [A], Schaerer (Air Liquide) [C]
Spherical	Diameter = 18m	3200	227,000	50	Ratnakar et al. (2021) [73], USDOE (2016) [35]

Table C.1: Reference tank data used for CAPEX scaling

Pump CAPEX

Equation C.4 was used to calculate the CAPEX for the pumps.

$$CAPEX_{pumps} = CAPEX_{specific} \cdot c_{pump} \tag{C.4}$$

Equation C.4 is calculated by multiplying the specific capacity ($CAPEX_{specific}$, €/kg/hr) by the desired pump system capacity (c_{pump}, kg/hr).

Pipe CAPEX

Equation C.5 shows the equation used to calculate the piping CAPEX.

$$CAPEX_{piping} = (0.224 \cdot c_{pipe} + 950.32) \cdot l_{ref} \cdot n \tag{C.5}$$

The piping costs were calculated by multiplying the cost per unit length ($0.224 \cdot c_{pipe} + 950.32$, €/m) by the reference length per tank (l_{ref}, m) of piping and the number of tanks (n, -).

Land CAPEX

The overarching land CAPEX equation is Equation C.6.

$$CAPEX_{land} = Cost_{land} \cdot FP \cdot n \tag{C.6}$$

The land CAPEX is calculated by multiplying the land costs ($Cost_{land}$, €/m^2) by the footprint per tank (FP, m^2) and the number of tanks (n, -). The subsequent equations show how the footprint of a tank was calculated.

The main challenge for calculating the land cost was to find an expression that calculated the change in footprint (FP, m^2) of a tank as the size of the tank changed.

It was assumed that the same ratio length:diameter (L:D) for cylindrical tanks (or a perfect spherical shape in the case of spherical tanks) was maintained, independent of the tank size. This assumption was used to derive the new tank dimensions and the footprint if the capacity is changed, based on the reference tanks. The reference sizes taken are shown earlier in Table C.1. No size scaling was needed for trailer tanks as they were taken to be only one size. The method used to determine the tank footprint is as follows.

All tanks in a system are taken to be the same size. Therefore, the volume of an individual tank is given by the total storage capacity (c_{total}, kg) divided by the number of tanks (n, -) and multiplied by the density of liquid hydrogen (ρ_{LH_2}, kg/m^3) as shown in Equation C.7.

$$Volume_{tank} = \frac{c_{total}}{n \cdot \rho_{LH_2}} \tag{C.7}$$

In the case of a cylindrical tank, the volume of the reference tank is expressed in Equation C.8, with L_{ref} and D_{ref} being the reference length and diameter.

$$Volume_{ref\ cylindrical} = (L_{ref} - D_{ref}) \cdot \pi \cdot \frac{D^2_{ref}}{4} + 4 \cdot \pi \cdot \frac{D^3_{ref}}{3 \cdot 8} \tag{C.8}$$

If the tank size increases but maintains the same L:D ratio, both L and D increase by the same amount, namely the factor named x in Equation C.9.

$$Volume_{new\ cylindrical} = (L_{ref} \cdot x - D_{ref} \cdot x) \cdot \pi \cdot \frac{(D_{ref} \cdot x)^2}{4} + 4 \cdot \pi \cdot \frac{(D_{ref} \cdot x)^3}{3 \cdot 8} \tag{C.9}$$

Furthermore, Equation C.9 is also equal to the following, where n_{new} is known:

$$Volume_{new\ cylindrical} = \frac{c_{total}}{n_{new} \cdot \rho_{LH_2}} \tag{C.10}$$

Subsequently, Equation C.8, Equation C.9 and Equation C.10 can be combined and re-arranged for x as seen in Equation C.11 and as a result x can be calculated.

$$x = (\frac{c_{total}}{n_{new} * \rho_{LH_2} * Volume_{ref}})^{\frac{1}{3}} \tag{C.11}$$

Since now x can be calculated, the new L and D can be computed and hence the new footprint can be calculated. The equation used to calculate the footprint of a horizontal and vertical cylindrical tank can be seen in Equation C.12 and Equation C.13, respectively. SD represents the safety distance. The footprint was approximated to a rectangle or a square for the horizontal or vertical tank and spherical tanks, respectively.

$$FP_{horizontal\ cylindrical} = (L_{ref} \cdot x + SD/2) \cdot (D_{ref} \cdot x + SD/2) \tag{C.12}$$

$$FP_{vertical\ cylindrical\ /spherical} = (D_{ref} \cdot x + SD/2)^2 \tag{C.13}$$

Once the scaled footprint of an individual tank was known, Equation C.6 could be calculated. The same methodology was applied for the spherical tank footprint calculation.

Energy OPEX

Equation C.14 shows the equation used for calculating the energy costs in year t.

$$Energy_t = E \cdot LH_{2stored} \cdot Cost_{energy} \tag{C.14}$$

Energy costs were calculated by multiplying the energy consumption of the pump (E, kWh/kg LH_2) by the amount of LH_2 stored in a year ($LH_{2stored}$, kg) and the energy costs ($Cost_{energy}$, €/kWh).

Fixed O&M OPEX

Equation C.15 shows the equation used to calculate the fixed O&M costs in year t.

$$Fixed\ OM_t = Fixed\ O\&M \cdot CAPEX \tag{C.15}$$

The fixed O&M costs were calculated by multiplying the fixed O&M as a percentage of the CAPEX ($Fixed\ O\&M$, %) by the CAPEX calculated earlier ($CAPEX$, €).

Boil Off OPEX

The overarching equation for calculating the boil off (BO) costs is Equation C.16.

$$BO_t = BO_{ref} \cdot scaling_{BO} \cdot Cost_{LH_2} \cdot c \cdot 365 \tag{C.16}$$

Boil off costs are calculated by multiplying the reference boil off rate (BO_{ref},%/day) by a scaling factor ($scaling_{BO}$, -), the cost per kg of LH_2 ($Cost_{LH_2}$, €/kg LH_2), the storage capacity (c, kg) and the number of days in a year (365).

Table C.2 shows the reference boil off values taken for the tanks and their respective dimensions, capacities and volumes.

Tank type	Dimension (m)	Volume (m3)	Capacity (kg)	Boil off (%/day)	Source
Cylindrical	Length = 21, diameter = 4	247	17,500	0.3	Schaerer (Air Liquide)
Spherical	Diameter = 18m	3200	227,000	0.05	Ratnakar et al. (2021)

Table C.2: Boil off reference tanks

Having the reference tank characteristics, now the scaling parameter ($scaling_{BO}$) could be determined. This was done based on the fact that heat influx is proportional to the surface-area-to-volume ratio of an object. Subsequently, also the LH_2 boil off is proportional to this ratio. As a result, the scaling factor involved finding an expression for the new divided by the old surface-area-to-volume ratio. Earlier, a method was described for finding new tank dimensions based on the scaling factor x. This same method could be applied in order to calculate the new dimensions of the scaled tanks and hence their surface-area-to-volume ratios and therefore the scaling factor for finding the adjusted boil off rate. No scaling was needed for the trailer tanks.

Loading/Unloading Losses

The equation used to calculate the costs of the loading/unloading losses is shown Equation C.17.

$$L/U_t = L/U \cdot LH2_{stored} \cdot Cost_{LH_2} \tag{C.17}$$

The loading/unloading losses were calculated by multiplying the % losses per load/unload (L/U, %) by the amount of LH_2 stored ($LH2_{stored}$, kg) and the cost of LH_2 per kg ($Cost_{LH_2}$, €/kg).