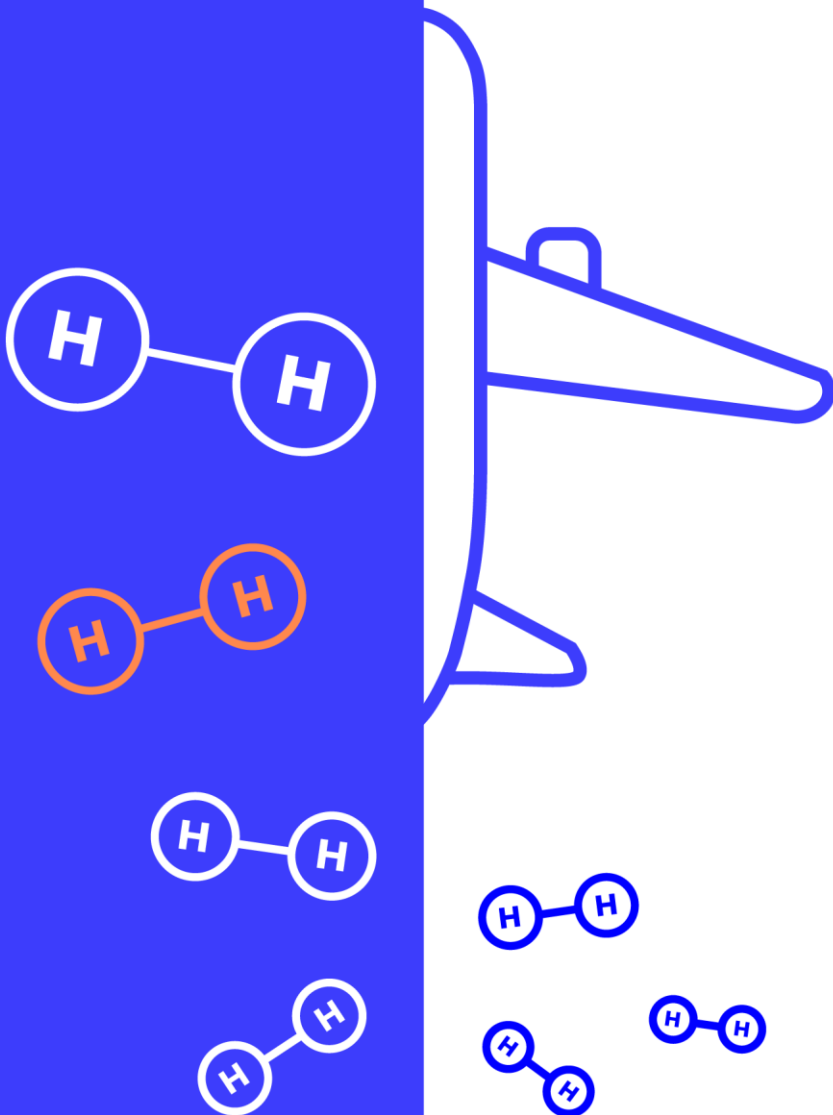


An Analysis of the Transition to Liquid Hydrogen Infrastructure for Airports

A master thesis in collaboration with the Royal Schiphol Group

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Executive Summary

The aviation industry is on the cusp of drastic change. With the threat of climate change becoming all too real, all sectors must move now to transition to more sustainable ways of operating. Aviation is no different. With this in mind, solutions are needed to decarbonize the act of flying. The use of liquid hydrogen (LH2) as an energy carrier in aviation is one of the solutions which has been put forth. The use of LH2 allows for emission free or low-emission air travel to become possible over longer distances than batteries will allow. LH2 aircraft have the potential to replace a sizable portion of the aircraft flown now, making them a very compelling new technology to look into. However, to make this a reality, a significant amount of development is still needed. Introducing such a new form of aviation requires development on all fronts, including technical, operational, legal, financial, etc. With the advent of LH2 aviation, the infrastructure required at the airport to service these aircraft will also need to change. The focus of the research performed here is this specific aspect; LH2 infrastructure at the airport.

Within this thesis report the transition to LH2 infrastructure at the airport is tackled. Specifically, how the airport can develop and adopt the infrastructure needed for LH2 supply logistics, storage, and refueling is researched. This process can be defined as a socio-technical transition in which a new niche technology (LH2 aviation infrastructure) develops to ultimately replace the incumbent regime (traditional kerosene-based fuel infrastructure). The process of gaining a deeper understanding of how this transition will look is guided by the transition management cycle. The methodological framework of this research followed certain steps of the transition management cycle for a specific case airport in order to explore this transition. The transition to LH2 infrastructure for Schiphol airport was addressed in order to gain in-context knowledge on the transition at hand. An extensive literature review was used in part to develop an initial infrastructure vision for Schiphol. Then, in an iterative manner, expert interviews were used to further develop an infrastructure vision which is expected to work best for the specific environment in which Schiphol finds itself. The opportunities and challenges which are apparent with this infrastructure vision were then defined. These previous findings, along with transition management theory, were used to develop a transition roadmap for Schiphol. The Schiphol-specific infrastructure vision and transition roadmap gave insight into this transition in a specific context and allowed for more general learnings to be gained on the nuances and factors influencing such a transition. The key parameters which determine how LH2 infrastructure will look at an airport along with a generalized transition roadmap were generated with this knowledge.

The LH2 infrastructure vision is a vision which every airport will need to create based on their specific characteristics. Regarding the supply of LH2, an airport needs to consider its geographic proximity to a transport hub; forecasted LH2 demand; and the area, natural resources, and funds available to the airport. Generally, if an airport has high LH2 demand and does not have the area, resources, and funds required to meet this demand, it will need to source LH2 elsewhere and import it. Whereas if it does have the capability to meet its demand locally, this is something which needs to be seriously considered. Storage methods will largely be based on an optimization of efficiency, required sizing, and safety. If large amounts of LH2 are to be stored and used at the airport, then a more spread-out storage strategy may allow for safety and efficiency to be optimized. At lower LH2 amounts this effect may be less and central storage can be considered. Finally, the refueling infrastructure will likely be dependent on LH2 demand, safety considerations, and the funding available. The choice of infrastructure is bound closely to the amount of LH2 which needs to be processed by the airport but is also highly dependent on whether can be done safely and cost effectively. With high LH2 demand refueling with a hydrant system may work best whereas with lower demand a bowser system may be effective. Then it is also important to consider whether refueling at the gate or at a centralized location can be done safely and efficiently. The factors stated here are important for an airport to consider in making the decision as to what infrastructure is right for them.

Envisioning the infrastructure which is most effective for a given airport to work towards is just a part of the work that is required to further this technology and progress the transition. The transition roadmap which has been developed also shows that, in addition to setting up the supply chain and developing the infrastructure, a simultaneous focus is needed regarding economic sustainability, operational development, and policy

development. Working on all different facets of the transition will be required to successfully transition to LH2 infrastructure for aviation, as is expected to be required by 2035. Currently, as was visible in the Schiphol case, most of the progress which has been made regarding LH2 aviation, and thus the knowledge, is centered around research and development parties and not the airports which will eventually need to play a central role. Leading up to 2035 it is important that airports begin to take a more active role in developing the infrastructure they will soon need to host and the many facets which accompany this. The following needs to take place:

- **Development of an LH2 supply chain** – through demand forecasting, supply vision creation, and discourse with airlines and suppliers
- **Research into LH2 aviation adoption** – by opening discourse with LH2 aircraft developers, airlines, and the market
- **Technical development** – through developing an LH2 infrastructural vision and collaborating with technology developers to work on key systems, subsystems, and components
- **Operational development** – through the development of operational procedures for the new infrastructure and the facilitation of collaboration between technology developers and safety authorities to perform safety and risk analyses
- **Development of regulatory policy** – by communicating with relevant legal authorities and facilitating collaboration between technology and operational development parties with safety authorities and policy makers
- **Ensuring financial sustainability** – by performing market research, lowering direct operating costs, allocating capital and operational expenditure costs with airlines and governing parties, and securing funding required for capital investment

These important points of focus require continual iteration as the transition develops to continually progress effectively. A focus on all of the above areas of development will allow for the eventual construction of LH2 infrastructure at the airport and the transition of LH2 aviation from a niche level to part of the aviation regime. Then, priority will become learning, improving and scaling up this first implementation of LH2 infrastructure. The same six points of focus explained above are still relevant, but instead of the emphasis being the infrastructure required for 2035, the focus must be on the further adoption of LH2 aviation, the rising LH2 demand which will come with this, and the changes to infrastructure which will be needed to make this feasible. Thus, it is important that adoption and growth is closely monitored while scaling up of the LH2 supply chain is looked into. Also the infrastructure technology and the operations and regulatory policy that go along with it need to be continually developed. And it must be ensured that this can be done in a financially sustainable way.

This research begins with the following question being asked: ***What factors will determine airport LH2 logistics infrastructure design, and what steps does an airport need to take in the socio-technical transition towards this infrastructure?*** This question is answered through the defining of the key infrastructure determining factors and the building of the generalized transition roadmap explained above. This research has thus explored this transition for airports and has started the transition to LH2 infrastructure at the airport. The next steps are to follow through with the transition management cycle by starting projects and experiments to learn as laid out in the roadmap. The specific actions which are recommended to take place immediately are:

- Improving LH2 demand forecasting models
- Developing LH2 adoption targets in line with climate goals
- Studying LH2 supply feasibility
- Developing specific technical components and subsystems for infrastructure
- Assessing safety and risks related to LH2 refueling and logistics infrastructure and the specific operations with them
- Looking into economic sustainability of LH2 aviation

1. Introduction

Aviation is changing. Not because it wants to, but because it has to, given the current environmental crisis that the world is facing. Sustainability is becoming the new normal. To keep up with the times and mounting exogenous pressures, the aviation industry must adapt. The major question then is: how? This question cannot be answered in any simple way, but within this master thesis, the aim is to contribute to the answer. The focus of this report is Liquid Hydrogen (LH2). More specifically, the infrastructure and logistic systems which will be required in order to service LH2 aircraft at an airport. LH2 aircraft without the ability to refuel at an airport are useless. In addition to that, not only one with the required infrastructure is needed, but instead a vast network of airports need an LH2 supply and LH2 infrastructure for LH2 aviation to be effective. Transitioning all or most of the worlds airports from traditional infrastructure for fossil-fuel based jet fuels to that for LH2 is a major undertaking which will take the industry many years. By the time that LH2 aircraft enter the market, for them to be adopted, they need to be usable. Thus, it is important to begin looking into the transition towards LH2 infrastructure at airports now.

This report aims to do exactly that: look into the transition to LH2 infrastructure at the airport. This transition is still in its early stages which means there is room for broad, high-level analyses of the transition process. Exploratory research into the specifics of this transition is needed to develop the first grip on the development activities that need to begin taking place. It comes back to the simple question mentioned earlier: How? How can an airport prepare itself for LH2 aircraft? Along with this question come more different questions. Some examples are the following: what type of infrastructure is needed? Is it possible to transport and store LH2 safely and efficiently? How will an airport get LH2? Research is needed to begin answering these and many more questions.

The focus of this thesis is exploratory research into the transition towards LH2 logistic infrastructure at the airport. First, in the remainder of the introduction (Chapter 1) the context of sustainable aviation will be given. In the same chapter this will be followed up by the problem definition and an explanation of the objective of this report. Chapter 2 will explain the research methodology which was followed. The third chapter is a review of relevant literature on LH2 aviation, infrastructure, and how to manage a transition. The results from following the methodological framework will be explained in detail in chapter 4. This will be followed by a discussion (chapter 5). The report will end with both a conclusion (chapter 6) and recommendations (chapter 7).

1.1. Sustainable Aviation

The modern way of life is under threat. Advancement throughout human history has brought forth great wealth and prosperity to the developed world. However, it has become apparent that the way we have gotten here is unsustainable in the long run. For one, global warming is an ever-looming threat. In 2018, the IPCC (Intergovernmental Panel on Climate Change of the United Nations) published a special report on the impacts of global warming of 1.5 °C above pre-industrial levels. In 2017, human-induced global warming has reached 1 ± 0.2 °C above pre-industrial levels and an increase of 0.2 ± 0.1 °C per decade can be expected if nothing is changed. As the global average temperature continues to increase extreme weather (heat extremes, precipitation, droughts, etc.), loss of biodiversity and ecosystems, and danger to human livelihoods continue to increase as well. The report indicates that staying below a rise of 1.5 °C is key to minimizing negative circumstances (IPCC, 2018). In addition to the significant threats from global warming, the finite nature of the world's fossil fuel supply is another threat that will eventually force a transition towards more sustainable options. 88% of global primary energy consumption is carbon-based (Dorian et al., 2006). The specific point in time when the world will run out of fossil fuels is not exactly known and is a topic of debate. There is a lot of discrepancy in the forecasts of when fossil-fuels will be depleted, but one thing is clear, this is a finite resource which can run out one day (Dorian et al., 2006) (Jaffe et al., 2011). Clearly, a socio-technical transition to more sustainable forms of energy is non-negotiable for the future.

Each industry has to deal with the transition towards increased sustainability and ultimately, carbon-neutrality. The aviation industry is no different. A major way in which the aviation industry contributes to the use of finite

resources and the bolstering of global warming is through its use of fossil fuels in the propulsion systems of their airplanes. Global aviation (including passenger, military, and freight flights) accounts for 2.5% of global CO₂ release and 1.9% of all greenhouse gasses released globally (Ritchie, 2020). In 2018 alone, over a billion tons of CO₂ were released into the atmosphere through aviation (Ritchie, 2020). To put that into perspective, this is similar to the entire CO₂ production of the entire continent of South America. In that same year (2018), South America produced 1.267 billion tons of CO₂ (Statista, 2021). Although 2.5% may seem rather small, for global sustainability goals to be reached and 1.5 °C of global warming to not be surpassed, every industry needs to do its part. The Paris Agreement includes an agreement for participating countries to halve CO₂ emissions from aircraft compared to 2005 by 2050 (ATAG Air Transport Action Group, 2020). There are only three ways the aviation industry can cut down on emissions: cut down on flying, increase aircraft efficiency, and switch to non-fossil fuel powered propulsion systems. Given the world's reliance on air travel and the simple fact that the aviation industry would collapse, this means that flying less is not a reasonable option. Thus technical solutions are required to solve the problem. Increased aircraft efficiency is a step in the right direction, but it is not the full solution. Efficiency measures have saved 11 billion tons of CO₂ since 1990, but it will not be enough to reach the 2050 goal (ATAG Air Transport Action Group, 2020) (McKinsey & Company, 2020). Therefore, the only reasonable way forward is to turn the focus towards non-fossil fuel propelled aviation.

1.1.1. Flying Sustainably

When it comes to transitioning the aviation industry towards sustainable forms of propulsion it will not come down to one specific energy carrier. Instead, the market will likely be shared by multiple different modes of sustainable aviation. The three most common sustainable alternatives to fossil fuel-based aviation are batteries, sustainable aviation fuels (SAF), and hydrogen. Each have their own positives and negatives and will therefore likely share the market with the others.

Battery-Electric Aviation

An electric aircraft powered by batteries is an attractive option since battery technology is very well known, safe, and accepted. Batteries are also already in use in other industries such as the car industry. Here they have taken over a significant portion of the market and this is only expected to increase (Ltd, 2022). Electric aircraft are also becoming more common, although not in every size and distance category. Because of the high weight to energy ratio that plagues batteries, they are not very scalable and realistic over long ranges (Hoelzen et al., 2021). Current developments have enabled small battery-electric aircraft to reach a range of up to 300 kilometers (Sripad & Viswanathan, 2021). This means that for small general aviation or commuter aircraft batteries could offer a form of completely emission-free aviation, but for most other distance and size classes they are not feasible and outmatched by other energy carriers. However, one positive aspect of batteries is that in terms of energy efficiency they are quite effective; boasting an efficiency of 75-80% (Heid et al., 2021).

Sustainable Aviation Fuels (SAF)

Blending petroleum-based jet fuel with SAF is currently a promising sustainable alternative to just traditional jet fuel. This requires no special infrastructure or equipment changes for airports or aircraft and can reduce CO₂ emissions by up to 80% (SkyNRG, 2020) (Air bp, 2019). SAF is a liquid fuel made from renewable feedstock and when burned releases the carbon captured by the biological feedstock (SkyNRG, 2020) (Air bp, 2019). There are challenges in the scalability of production and economic viability which hold it back from being a better solution than it is (McKinsey & Company, 2020). In the immediate future, its use allows for lower emissions without significant changes to the infrastructural system, but in the long term, solutions will be needed for its scalability and economic viability problems. Because it's not fully sustainable and viable as of yet, other solutions need to also be considered. This will likely be an interesting option to replace kerosene for long-range aircraft to still allow for some long-haul flights in an increasingly sustainable future since this will be much more difficult for other energy carriers to achieve (Hoelzen et al., 2021).

Hydrogen Aviation

With battery-electric aircraft only being suitable for very low-range and small aircraft and SAF being most interesting for long-range traditional aircraft, this leaves the opportunity to utilize hydrogen for short- and medium-range flights. When it comes to hydrogen aviation, liquid hydrogen is the most promising because of its potential to bring more energy aboard an aircraft within the same weight and volume when compared to its gaseous counterpart. “FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilizing fuel cell, gas turbine and hybrid systems (FlyZero, 2022).” LH2 aircraft can be operated as a fully electric aircraft using a fuel cell, with a turbine to combust the hydrogen (not electric), or in a hybrid manner. However, when hydrogen is combusted in a turbine NOx is still released meaning that this form of aviation is not completely emission-free. Short- and medium-range aircraft make up 70% of the global fleet meaning that LH2 has the potential to make up the majority of the future aviation market. Because of the large number of short- and medium-range aircraft it also means that the bulk of emissions comes from these segments making them the most attractive to convert (ATAG Air Transport Action Group, 2020) (McKinsey & Company & Clean Sky 2, 2020).

1.2. Problem Statement

As explained in the previous section, sustainable aviation is a must for the future of the industry. Sustainable aviation will not depend on one fit-for-all solution, but instead rest in a combination of multiple different technologies. Since LH2 aviation is projected to potentially end up replacing up to 70% of the current global fleet, for the goals of large international agreements like the Paris Agreement to be reached, LH2 aviation needs to be achieved (McKinsey & Company & Clean Sky 2, 2020). International agreements influence governments to enact policy and other measures to help innovation and the development of valuable technologies such as LH2 while stifling carbon-based energy systems. LH2 aircraft development is therefore a very interesting topic. As hinted to in the first part of the introduction, for LH2 aviation to be adopted by the market a number of factors need to align. The first and most obvious one is that LH2 aircraft need to be developed, tested, certified, and ultimately enter the market. As of now, LH2 aircraft developers are still in the development stage. LH2 aviation is considered achievable in the next 5 to 10 years (McKinsey & Company & Clean Sky 2, 2020).

Once purchasable, the adoption of LH2 aircraft is also dependent on the market’s willingness to adopt such aircraft into their fleet. “For short-range aircraft, which make up the bulk of emissions, the next window of opportunity is expected to be around 2030-2035 (McKinsey & Company & Clean Sky 2, 2020).” This falls quite conveniently with the point in time when LH2 aircraft are expected to enter the market. This leads to the expectation that between 2030 and 2035 and airport will need to be able to service LH2 aircraft. This means ready to operate LH2 logistic and refueling infrastructure before 2035 will likely be required at any airport which wishes to remain relevant in the transitioning aviation industry. For an airport to protect its future they will need to take liquid hydrogen seriously and begin looking into the implications that this will have. Every airport will not only need correct infrastructure, but also a sufficient hydrogen supply to meet the demand. In the longer run (around 2040 and onwards) it can be expected that airports will need to have scalable solutions to liquid hydrogen storage and refueling (McKinsey & Company et al., 2020). The focus of this research is to explore what the development and adoption of LH2 infrastructure may look like, how this can be achieved, and what the implications of this transition are.

LH2 infrastructure will need to be quite different than traditional fuel supply, storage, and refueling infrastructure. LH2 is a cryogenic liquid needing to be cooled and kept below 20 Kelvin (-253 °C), meaning that all infrastructure needs to be designed to these specifications. This leads to technical challenges which will need to be overcome. Because sustainability is of utmost importance, LH2 will need to be generated using renewable energy. Then the LH2 needs to get to the airport. At the airport LH2 needs to be safely and robustly stored. Finally LH2 needs to be refueled into an aircraft in a safe and effective way. How this entire logistic chain will look is as of yet unknown. In addition to the physical infrastructure and technical considerations, there are other aspects that need to be considered. New operating procedures and regulatory policy will need to be developed in parallel with the infrastructure for it to be adopted at the airport. In addition, ensuring LH2 aviation and the operation of infrastructure is economically sustainable for the airport and the airlines is a key

factor for success. All of these aspects are important in the transition to LH2 aviation and more specifically LH2 infrastructure at the airport and lead to extreme complexity. To reduce complexity and create a clear plan of action knowledge needs to be gained. At this point in time this is all relatively unexplored, meaning that the industry is hungry for information.

1.3. Objective

LH2 infrastructure for the aviation industry does not exist because thus far there has not yet been a demand for it. It is expected that a demand for this infrastructure will likely arise from the development towards sustainable aviation. Therefore, research into this technology has become crucial. Understanding what must be done to develop this technology further and eventually adopt it at the airport is key in taking the first steps towards making this happen. The objective of this research is thus to do exactly that; explore the transition to LH2 infrastructure at the airport.

There are a lot of different facets to the development, building, and operation of LH2 infrastructure at an airport. One main question which will need to be answered is how the infrastructure at the airport will look. However, because each airport is different this may vary dependent on a variety of factors including what is technically possible, geographic location, demand, and many more. Understanding these factors at a deeper level is key in the development of this infrastructure. Because of this, one of the central objectives of this research will be to begin developing clarity in this area. With the use of a case study (which will be explained in chapter 2 on methodology) the determinants of LH2 infrastructure design can be more clearly understood. Based on this, the factors which determine the type and design of LH2 infrastructure for an airport can be generalized and understood at a deeper level. In addition to the physical infrastructure there are a lot of elements within the greater landscape which need to align for this infrastructure to be feasible. The economics and policy related to this are central topics which also need to be understood in the transition to this infrastructure. In order to develop a better understanding of this transition a roadmap will be built highlighting the steps the airport will need to take to further develop, adopt, and scale up LH2 infrastructure. As with the design of the infrastructure, this roadmap will first be developed for a specific case which allows for a better understanding to be gained of the specifics which need to be considered in such a transition. Then, these results can be generalized to airports in general. This will result in a general roadmap which can guide an airport to the main actions which it will need to take towards LH2 infrastructure.

1.3.1. Research Question

The objective of this research has been translated to research questions in order to clarify which information is sought in this assignment. A main research question and multiple sub research questions are given here.

Main Research Question

The problem facing airports is clear. With a high likelihood, LH2 infrastructure will be needed at the airport in the future. However, how this will look and what needs to be done to get here are still questions that need to be asked. Thus, the objective of this thesis is to explore the transition towards the infrastructure which will be required to make LH2 aviation feasible. A research question which encapsulates the two main objectives of this research has been created.

What factors will determine airport LH2 logistics infrastructure design, and what steps does an airport need to take in the socio-technical transition towards this infrastructure?

Sub Research Questions

The question asked by the main research question is big and requires a lot of nuance to answer. The complexities of this transition are many and need to be considered closely. In order to make the research more manageable this research question has been split into multiple sub questions. They are the following:

1. *What is the current state-of-the-art of LH2 infrastructure technology and how can it be used at an airport?*
2. *Based on literature and expert opinion, what factors dictate airport LH2 infrastructure design?*

3. *How can the complex process of a socio-technical transition be guided most effectively?*
4. *What steps must an airport take to develop the multiple facets of a successful LH2 infrastructural system?*

2. Methodology

The aim of this research assignment is to gain a general understanding of the transition to LH2 infrastructure for refueling LH2 aircraft at an airport through the application of the transition management cycle on a case study. The transition to liquid hydrogen aviation, and more specifically the infrastructure which will be needed at an airport to service the new LH2 powered aircraft, can clearly be defined as a socio-technical transition because it involves transport, energy, technology, policy, markets, consumer practices, infrastructure, cultural meaning, and scientific knowledge (Elzen et al. 2004)(Geels, 2011). Understanding socio-technical transitions and the different principles and factors included can be done using the multi-level perspective (MLP) (Geels, 2011). A graphical representation to aid in understanding this can be seen in Figure 1. This framework can be used to establish the transition taking place and understand it's context. It is therefore important to have a clear understanding of the elements of the MLP and how they work. Transitions are multi-actor processes that occur on different levels to fulfill societal functions. The MLP is a way to “conceptualize the overall dynamic patterns in socio-technical transitions (Geels, 2011).“ Geels (2011) makes clear that transitions are nonlinear processes that result from the interplay of developments. These developments can be understood at three different analytical levels: niches, socio-technical regimes, and exogenous socio-technical landscapes. In this model, transitions are defined as a shift from one regime to another regime. The niche and landscape are concepts that are defined in relation to the regime. The regime can be seen as a system that needs to change. The niche is the development of new technologies that have the potential to grow and replace the old regime. Finally, the landscape is the external environment that influences interactions between the niches and the regime.

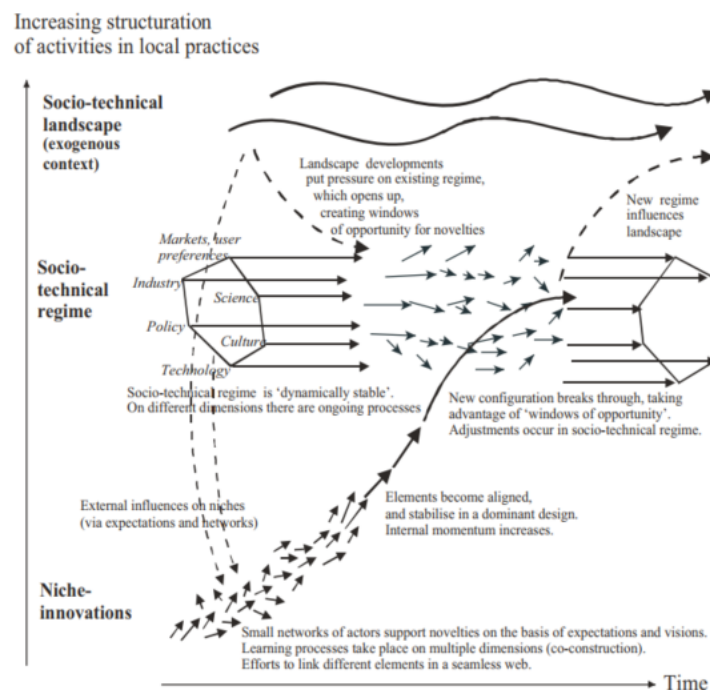


Figure 1: The multi-level perspective on transitions (Geels, 2011)

In the context of the aviation industry, and more specifically the infrastructure at the airport, the different elements of the multi-level perspective can clearly be defined. All industries, including aviation are pressured by global warming, depleting resources, and the social and political turmoil that follow them to operate more sustainably. This context is a significant part of the exogenous socio-technical landscape influencing the other two levels of the framework. The socio-technical regime then can be defined as the incumbent and proven infrastructure for fossil fuel logistic supply, storage, and refueling. Traditional aircraft use fossil fuels to efficiently move people and goods around the world in a relatively safe, affordable, and efficient manner. However, this current way of doing things uses finite resources and pollutes the world, meaning that it is not realistically sustainable in the long run. Given this, the sustainable solutions that are being developed for this

industry can be defined as different niches. As stated earlier, transitions take place at different levels. Within this research the focus will be placed specifically on the niche of infrastructure which will be needed to service LH2 aircraft at an airport. Thus the focus of this research is the transition from traditional aircraft servicing infrastructure at airports to a solution for LH2. Understanding the elements of these three levels of the framework allows for the definition of the transition at hand. LH2 infrastructure for aviation is currently a niche technology that needs to rise to take over the current incumbent (existing) socio-technical regime. Through the MLP it can be established that the development and adoption of LH2 infrastructure for aviation is a transition.

A transition as the one described above is a complex endeavor which takes a lot of time, effort, and money. Managing the successful progress of a large socio-technical transition is therefore not an easy task. Transition management is an entire field of research with the sole focus of gaining an understanding of how to manage a transition more successfully. Although each transition is unique because of its context, actors, problems, and solutions and it is therefore not possible to develop a fit-for-all solution, frameworks, principles, and guidelines which aid one in effectively steering and guiding the course of a transition are available (LOORBACH, 2010). One such framework is the transition management cycle. Originally developed in a 2007 paper by Loorbach and later improved in a 2009 paper by Rotmans and Loorbach, this framework “provide[s] the basis for managing transition in an operational sense (LOORBACH, 2010).” Figure 2 shows a basic overview of the four main steps of this cycle.

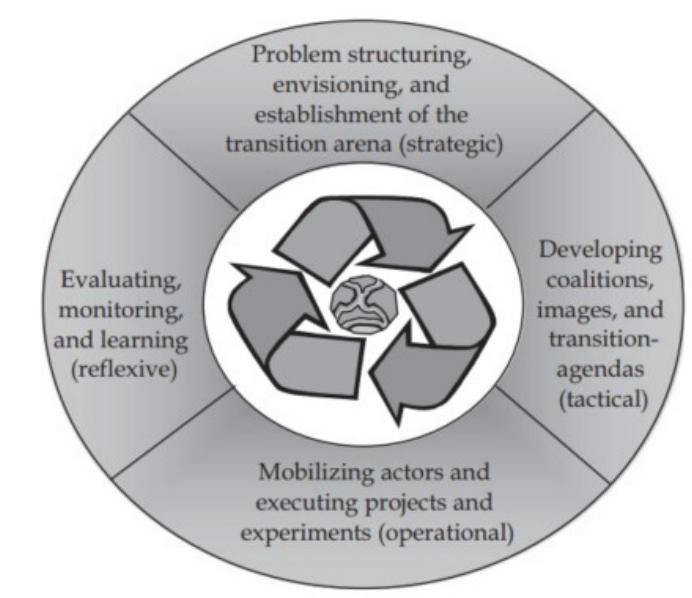


Figure 2: The transition management cycle (LOORBACH, 2010)

This basic cycle is a good starting point for what to do when managing this transition. One of the challenges with transition management is practically applying the relatively abstract rules and concepts. One way to look at transition management is as a cyclical and iterative process that continually develops on different levels of scale (Rotmans & Loorbach, 2009) (Loorbach 2007). For this research, this will be the main framework used to put transition management into practice. In order to understand the transition to LH2 infrastructure at the airport this cycle will be applied to a specific case scenario, Schiphol. More on this will be explained in section 2.1. Since this framework is cyclical and meant to be used iteratively as the transition progresses, this cycle should be run through multiple times. To guide the gathering and analysis of information for this research, a first run-through of this cycle will be performed. More specifically, the first two steps of the cycle will be performed and recommendations as to the third step of the cycle will be made. Only after actual experimentation is performed and progress is made in this sense can the fourth step of the cycle, and therefore the whole cycle be completed. This will be a task for Schiphol as the transition progresses.

The first step of the transition management cycle is that of *problem structuring, envisioning, and establishment of the transition arena*. Two specific actions will be performed to fulfil the first step of the cycle. First, **a vision for the LH2 infrastructure that will be needed at the airport will be created**. This will be done by first creating an initial vision based on literature and then iteratively building on and improving this vision through expert/stakeholder interviews. More on the gathering of data will be given in section 2.2. The aim is to have a vision for the future LH2 infrastructure at the airport which is based on the state of the art of current knowledge on LH2 infrastructure technology and the context in which it will need to be built. Then, using this infrastructure vision, the specific **opportunities and challenges that become apparent from it will be identified**. This will help understand what risks need to be mitigated and which chances there are to capitalize on. With the completion of these two processes, the first step of the transition management cycle will be considered mostly complete since additional structure will have been given to the problem and a solution has been envisioned. The first understanding of what transition arenas are needed will also begin to become clear, but more clarity for this specific element will come when the next step is taken. Such overlap between steps is considered acceptable during this process since continual adjustment and flexibility are key in complex transitions and this model accounts for that (Rotmans & Loorbach, 2009). These steps are displayed in a logical sequence, but in reality, many often take place in parallel or in a different order.

As stated earlier, a transition takes place at different levels of scale. Thus, within the transition management cycle the concept of different governance activities which can take place at these different levels of scale is clearly addressed. As can be seen in Figure 2, each step of the cycle is denoted with the words strategic, tactical, operational, and reflexive. This is in reference to the different scale levels at which governance/management activities can take place as explained in the 2013 paper by Loorbach and Wijsman. The activities of the first step of the cycle should focus on the strategic. These are *activities at the level of societal systems and looking at a long time horizon. Related to structuring complex societal problems*. As is clear from the practical steps which will be taken in this research for the first step of the cycle explained above, a focus here will indeed be broader and more general. The focus is on envisioning how the system as a whole could work on a long time horizon (past 2050). The idea is to bring structure to the problem in the form of a likely solution.

The second step of the transition management cycle is to *develop coalitions, images, and transition agendas*. In a sense, the focus here is to develop a process for niche innovation through identifying collaboration that needs to take place and actions that need to be performed. In order to do this, **a transition roadmap will be created that highlights the practical actions and collaboration that need to be taken to reach the earlier created infrastructure vision**. Thus a clear agenda will have been set, an image of future development is created, and coalitions have been identified. In order to make a more effective transition roadmap, **additional theory from transition management, complexity management, and stakeholder management literature will be carefully considered**. This **roadmap will be validated through further discussion with select experts in the field**. In this way, the developed agenda can already begin to be scrutinized by relevant parties which can help improve aspects of the roadmap. The finalized roadmap will mark the completion of the second step of the transition management cycle and also give practical steps that can be taken to *mobilize actors and execute projects and experiments* (step 3 of the transition management cycle).

The practical actions explained here for the second step of the cycle are on the tactical scale level. The tactical level focuses more on *activities at the level of subsystems related to system structures (institutions, regulations, infrastructure, etc..)*. Within the to be developed roadmap the different aspects of this transition and different subsystems will be highlighted more. These are important elements which need to be considered at the tactical level. Then, with the second step of the transition management cycle done and step 3 and 4 to be continued after this research the operational and reflexive activities respectively will take place. Operational governance activities are *activities related to short-term and everyday decisions*. Thus, as was explained, these are activities related to experimentation and executing projects which come forth from the roadmap. These activities are much more specific and short term. Then, finally reflexive activities *related to the evaluation of the existing situation*. Thus, here it is important to learn from the development thus far (from the previous three steps of the cycle) and use this to evaluate and feed into a new iteration of the cycle.

All of the previous steps have been performed for the specific transition to LH2 infrastructure which will need to take place at Schiphol. The creating of infrastructure visions and the roadmap are therefore specific to Schiphol's case. From this, a significant amount can be learned about how this transition process will need to go for all airports. The final step of this paper's methodology will consist of **generalizing from the learnings for Schiphol specifically**. This final step will take place outside of the transition management cycle but will result in the finalization of the process to reach the final aim of this research assignment and answer the main research question.

The previous few paragraphs explain how the methodology of this research assignment follows the majority of the first iteration of the process management cycle. Each step of this cycle is achieved through the completion of one or more specific actions. To give additional clarity that text cannot give, in Figure 3 the methodological process of this research can be seen in a more visual manner. As can be seen the first methodological steps of the assignment correspond with the first step of the transition management cycle, steps 3 and 4 of the methodology correspond mostly with the second step of the transition management cycle. Then, step 5 of this research's methodology partly corresponds with step 3 of the transition management cycle. The final step of the research methodology leaves the transition management cycle behind, but results in the answering of the research question and completion of the main aim of this assignment.

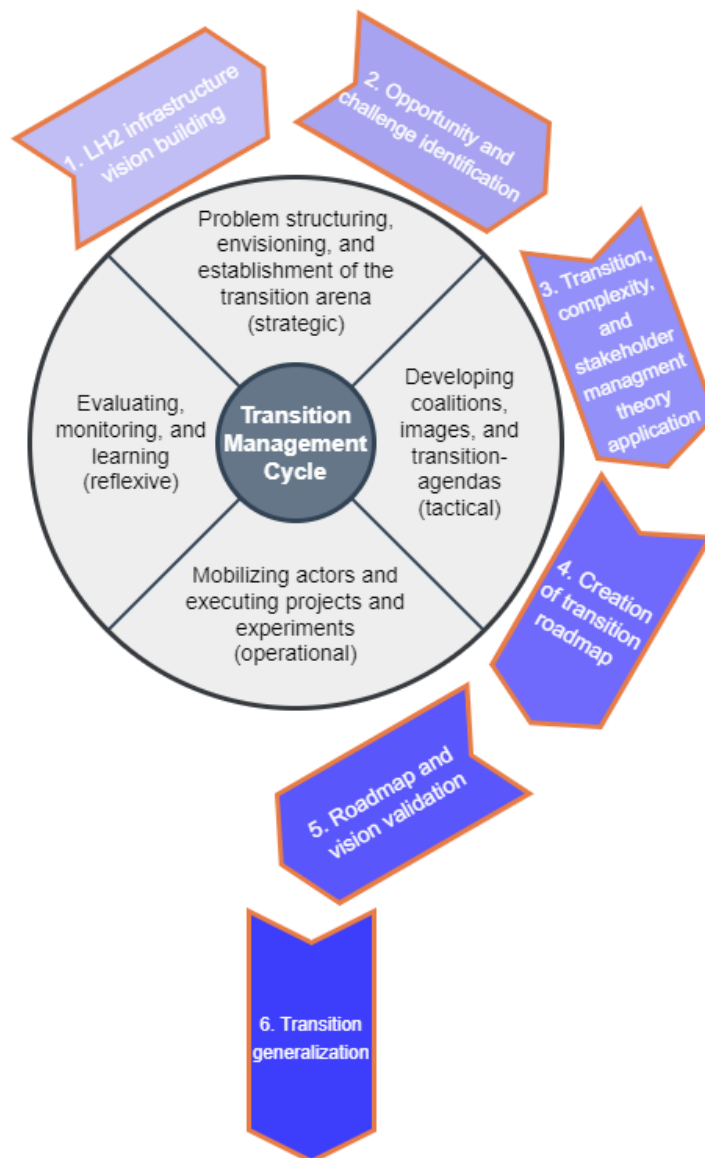


Figure 3: Methodological framework of the research assignment

2.1. Case Study

How the socio-technical transition to an aviation sector where liquid hydrogen is one of the major (if not ‘the’ major) propulsion technologies will go, comes down to many factors which will be explored. Much of how this transition takes place relies on the actions of the major actors that work to develop the technology and policies and take steps to adopt them. Understanding and predicting their individual actions and interactions with each other is a crucial part of making this transition as smooth and efficient as possible. Social science can aid in understanding the interactions and relationships between actors in this industry. Within the social sciences, case studies can deliver effective exemplars which lead to a strengthening of the scientific discipline (Flyvbjerg, 2006). Thus, utilizing a case study to better understand the practicalities of the transition at hand adds a significant amount of value.

In this research specifically, Schiphol’s transition towards the facilitation of liquid hydrogen aviation is studied. This constitutes a case study of a one-of-a-kind scenario that will give information on both the transition for Schiphol and many other airports which will need to do the same. This example will allow for theories on transition management to be applied to a real case to gain increased practical, in-context know-how on these context-independent theories. Case studies can be seen as weak in a scientific sense because they are so specific. But in the case of studying human interactions (through social sciences), it is very difficult to create predictive theories, which means that concrete context-dependent knowledge is very valuable (Flyvbjerg, 2006). In a 2006 paper by Flyvbjerg, he states that although within a case study there is a sample size of only one, a case study can still be central to scientific development via generalization as a supplement to other methods if the case study is strategically chosen. He continues that extreme, critical, or paradigmatic cases are favorable for generalization. The case at Schiphol has elements of all of these. Since it is a large hub airport, the transition it must go through is rather extreme but also critical since it gives information on how other large hub airports could transition. This case could also potentially be paradigmatic since it has the chance to highlight general characteristics of how such transitions will look for all other airports. Thus, choosing to learn about the socio-technical transition in this field through a case study at Schiphol will be both a practically and educationally valuable endeavor that will allow for generalized knowledge on the transition of any airport to liquid hydrogen infrastructure to emerge.

2.2. Gathering Data

To reach any valuable conclusion through analysis, first relevant data needs to be gathered. To strengthen the data utilized to develop a transition process for the transition to liquid hydrogen, two different data gathering techniques have been used: literature review and expert interviews. Each data gathering technique has then been used to find multiple pieces of relevant information that all add to the overall story being told. There are two broad types of information relevant to this research on which data is gathered. The first is information on the LH2 aviation transition including information on the LH2 aviation niche, the incumbent fossil fuel aviation regime, and the exogenous socio-technical landscape factors influencing the transition. The second type is a theoretical basis for managing the transition including frameworks, guidelines, and theory on transition, complexity and stakeholder management. Regarding the theoretical basis on transition management, only literature review is used to gather data. To gather information on the LH2 aviation transition both an extensive literature review and expert interviews are used.

2.2.1. Literature Review

Literature is the main form of information gathering that has been done to establish a solid foundation of theory on transition, complexity, and stakeholder management. These are fields of research on which extensive peer-reviewed research is available. From this research a number of frameworks (including the MLP and transition management cycle which have been discussed earlier in this chapter) and guidelines which are key to the effective management of the complex transition at hand are collected. This information will be used in step 3 of this research’s methodological framework. This will aid in the development of a realistic and valuable transition roadmap in step 4 of the framework.

The basis of data used on the LH2 aviation transition comes from peer-reviewed literature, articles from reputable sources, and large-scale industry reports. There are a number of industry reports that give great

information which relevant to the transition studied in this research coming from incumbents to the aviation industry and experienced consulting and research parties. Because of the newfound increased relevance of a transition towards LH2 aviation, these reports are all very recent. Multiple reports are from 2022, and others are only a year or two older than that. Thus, the information in there is very up-to-date and relevant to the research. This is key since the niche is growing and developing quickly, meaning that older information could already be outdated after only a few years. The topics of these reports range from the technology for LH2 aviation and the infrastructure around it to general sustainable aviation research to relevant projects. These reports give a solid foundation when it comes to the LH2 aviation transition information desired, but often are not in-depth enough on specific topics to be used alone. Thus, additional information on specific topics key to the feasibility and management of this transition is supplemented where possible through peer-reviewed research papers and articles from reputable sources. These papers and articles often focus on specific technical details of the transition such as, for example, electrolysis or the economics of LH2 flight. This adds a lot of valuable depth where needed. This information will be key in the first step of this research's methodological framework. The first iteration of the infrastructure vision will be created using this data. Also, the general knowledge gained on LH2 aviation and infrastructure will aid in the work done in steps 2 and 4 of the methodological framework.

However, it will not be possible to complete step 1 of the framework based on literature review alone. Due to the cutting-edge nature of many of the elements key to this transition, additional information that is not reasonably collectible through literature review (such as information specific to the case) is needed. Thus, experts and stakeholders relevant to the case studied are interviewed.

2.2.2. Expert/Stakeholder Interviews

To complete step 1 of the methodological framework by further iterating on the infrastructure vision created from the information gathered through literature review, extra information is gathered via interviewing. The information gained from the initial set of interviews will also be utilized in steps 2 and 6 of the methodology. A second round of interviews will be performed to validate the roadmap. The new information gained here will be used in steps 5 and 6 of the methodology.

As established, the research being conducted has elements of social sciences since the actors/companies involved are run by humans and inherently interact in social ways. Given this, the way in which data is collected on the transition at hand is of key importance to the success of the study. As supplementation to the utilization of existing literature, extensive use of interviews is made to gain a significant amount of information on liquid hydrogen infrastructure technology and the industry that will need to further develop and adopt this technology. The fact that this transition is partly based on social interactions between actors means that a flexible data collection tool is needed. Qualitative data will be much more prominent than quantitative data. In a 2014 review on using interviews for data collection by Alshenqeeti, it is stated that "interviewing is expected to broaden the scope of understanding investigated phenomena, as it is a more naturalistic and less structured data collection tool (Alshenqeeti, 2014)." This broader, less structured way to gather data is crucial in order to capture the nuance of the transition process researched here. Since interviews are interactive, the interviewer has the ability to press for additional clarity in answers and delve into emerging topics (Alshenqeeti, 2014). This type of freedom will be important to learn more about the complexities of the research topic. However, given the fact that interviews are less structured and require the interviewer to be active, a clear protocol needs to be established.

The chosen style of interviewing is a semi-structured interview meaning that the questions are predetermined, but flexibility in the flow of the conversation is accepted and the interviewer can probe or ask for further clarification (Alshenqeeti, 2014) (Griffiee, 2005). Before each interview, a set of questions based on scenarios derived from existing literature will be prepared. This gives the interview a clear structure and goal. However, because of the complexities of the socio-technical environment in which this transition takes place, during the interview, the interviewer has the freedom to delve into certain topics that come up if they are deemed valuable to the research. Each interview will be uniquely prepared for the specific actor/expert being interviewed. Each actor/expert has a different set of expertise and influence; thus the focus will be placed on

these to gain the most amount of value from the limited time. The respondents are selected based on a three-step process. First, from the literature, a base understanding of the transition that needs to take place is built up and scenarios unique to Schiphol are crafted. Then, based on the scenarios, parties in the Dutch aviation industry that will be crucial to such a transition scenario for Schiphol are selected. Finally, at every company selected to be important, contact is made with a representative that has an understanding of the topics at hand. The interview is then conducted with this representative.

To clarify, two separate rounds of interviewing will be conducted. The first round of interviews will be focused on iteratively improving the infrastructure vision which was created based on information gathered through literature review (step 1 of the methodological framework). Because of the novelty of liquid hydrogen technology in aviation, during each interview a brief presentation will be given on the most recent infrastructure vision iteration and any other pertinent information. In this way, the respondent can give relevant comments on the infrastructure vision based on their expertise. With the fact that the respondent now knows more information pertinent to their position in this transition in mind, questions related to their position are asked in a semi-structured manner. As stated, the semi-structured nature allows the interviewer more freedom to go deeper into key topics or new concepts that come up during the interview. To ensure that information is not lost during the interview, it will be recorded which will allow for later transcription and analysis. During the interview, the interviewer will pay attention to making the interview flow naturally from one topic to another, listening attentively, speaking as little as is needed, and seeking specifics (Alshenqeeti, 2014). The data gained from the interviews is then used each time to create a new iteration of the infrastructure vision. This process is repeated until all planned interviews are done and a final infrastructure vision is completed. The second set of interviews will be conducted to validate the roadmap and infrastructure vision created during this research. These interviews are done in a less structured way. During the meeting the results for which validation is required are presented and afterwards the respondent gives feedback in the form of an open discussion. Information from this interview/meeting is written down and used to improve the roadmap and infrastructure vision.

2.3. Data Analysis

The interviews will result in a lot of raw data in the form of words, but this needs to be interpreted before it can be valuable to the research (Griffiee, 2005). A large amount of data will be reduced using an interview analysis strategy highlighted in the 2005 article by Griffiee on interview data collection. He explains that one strategy is to prepare hypotheses for each question beforehand which will allow for quicker analysis of the answers of the respondent by the interviewer afterward. In this research the hypothesis prepared before an interview will be the earlier iteration of the infrastructure vision. In a sense this is a hypothesis for how the infrastructure could reasonably look which will be tested against the expertise of the respondent. This method will be used to make sense of the expected complexity of the answers given during the interview. From there, the data collected can be used in the further analysis of the research project.

Throughout the execution of the methodological framework of this research data will be used in different ways. Each step requires information input in order to be completed and this information comes partly from the conclusion of the previous step and partly from the data collected via literature review and interviewing. An overview of the information used for each step of this research's methodological framework is as follows: The first step consists of iteratively building an LH2 infrastructure vision for Schiphol. Literature review data is used for the first iteration and then the interviews are used to further iterate on this concept resulting in a final infrastructure vision built from both types of data. Then, using the infrastructure vision as a starting point, the opportunities and challenges will be identified in the second step. Information from the literature review and interviews will also aid in this step. The third step it to analyze theory on transition, complexity, and stakeholder management from the literature relative to the case transition. The fourth step consists of building a transition roadmap with as inputs the results from the previous three steps of the methodological framework. Step 5 tests the roadmap from step 4 in a set of interviews. Then, all of the information from the previous 5 steps and the literature and interviews is used to finally complete step 6.

Data from interviews is sometimes criticized because people might not say what they think/are unwilling to discuss what they know, might not have the information required, or may be unable to state their position in a clear way (Flinders, 1997). However, validation can remedy some of these weak points (Griffiee, 2005). Two validation techniques which are highlighted in the earlier mentioned 2005 paper by Griffiee will be utilized to strengthen the data gathered from interviews. The process of reinterviewing can be used to validate interview answers. Instead of traditional reinterviewing, a modified version will be done. After each interview, the interview transcript will be sent to the respondent in order to allow them to correct interpretations of the interviewer and/or add additional information that did not come up during the interview. This is a formal check of the information in the transcript to further ensure the respondent's views. Also, the first versions of the Schiphol-specific roadmap and the infrastructure visions (which are some of the main results of the methodological process) which have been created using interview data as a major input, will be validated further. This is highlighted in the fifth step of the methodological framework. Instead of reinterviewing the exact same respondents as in the earlier phase of interviews, instead new people have been chosen. This is to reduce self-bias from the validation process since the earlier respondents had contributed to the formation of the exact roadmap that is being validated.

3. Literature Review

The previous chapter introduced the methodology with which the final objective will be achieved, and the research questions will be answered. This methodology requires the input of a significant amount of data. A large portion of this data comes from the aggregation of a large amount of literature on a variety of topics. The aim of this chapter is to give an overview of the information that has been obtained from researching this wide array of papers, reports, articles, and book sections. As explained previously, there are two main sets of information that needed to be gathered from the literature. The first is a theoretical basis on how to manage a transition such as the one researched here. The first section of this chapter (3.1.) will give an overview of the three different management fields that are considered. The second type of information from literature is on the many different important aspects of the transition toward LH2 aviation. The second (3.2.), third (3.3.), fourth (3.4.), and fifth (3.5.) sections of this chapter are all dedicated to this. The basics of LH2 aviation, how LH2 infrastructure could look at the airport, how LH2 supply logistics to the airport could look, and the effect time will have on these elements are all discussed respectively.

3.1. Management Theoretical Basis

The goal of this section is to gain an understanding of transition management, complexity management, and stakeholder management. Through extensive literature review, these fields of research and the valuable topics they cover have been explored. Here the key takeaways and applicable theories are summarized so that they can later be applied to the transition tackled in this paper. This section will focus on the relevant theoretical basis without applying it yet. In subsequent chapters, the theory highlighted here will be used to identify challenges and opportunities within this transition, derive management techniques, build a Schiphol-specific transition roadmap, and ultimately develop a transition process for airports looking to a future with liquid hydrogen aviation.

3.1.1. Transition Management

Although difficult, change is one of the constant truths of life. Change needs to take place constantly at every different level to ensure improvement and the ability to overcome new problems. Much of the change that is observed in life is incremental, however, occasionally, radical change has to occur. At a macro or societal level radical change comes in the form of a transition. The need for a transition arises from a persistent/wicked problem that can only be overcome through structural, systemic changes (Loorbach & Wijsman, 2013). System failures lead to these persistent problems; thus these systems need to be changed through a transition. A transition works through the coevolution of the economic, cultural, technological, ecological, and institutional aspects of a societal system (Rotmans & Loorbach, 2009). The main goal of a transition is to overcome the persistent problems facing society by removing/changing the incumbent socio-technical regime and the systems which failed in the first place. This is then replaced with a new emergent structure (or niche) which consists of agents that deviate from the previous regime (Rotmans & Loorbach, 2009) (Lamberg et al., 2008). In this way, the persistent problems facing a society that cannot be overcome by the existing regime can be tackled by the emerging niche which is designed to handle these problems. Transitions can be seen as a shift from one dynamic equilibrium to another (Loorbach & Wijsman, 2013).

There are a number of concepts in the transition management literature that can aid in the practical application of the transition management cycle as discussed in chapter 2. Firstly, in a 2015 paper by Kamp and Vanheule the concept of strategic niche management is discussed. This is “a theoretical framework that can be used to study the sociotechnical dynamics and factors within a niche around new innovation (Kamp & Vanheule, 2015).” Thus, the elements of the transition management cycle that refer to the proliferation and strengthening of the niche level can be supported by this framework. In this paper, three niche processes that are dynamically interrelated with each other are discussed. They are the following:

1. *Shaping and voicing of expectations* → Expectations of future success that are robust (shared by multiple actors), specific (give guidance), and have a high quality (validated based on ongoing experiments) make it easier for participants to join the niche by investing effort, money, and time.

2. *Network formation* → It is important to build an actor-network that is comprised of a heterogeneous group of actors with different interests and roles, and which are also aligned (having visions, expectations, and strategies in line with the niche development) in order to sustain niche development.
3. *Learning processes* → The relevant technological aspects, markets and other characteristics of a niche development need to be articulated through the learning process and shared among actors. Both first-order learning (about the innovation's effectiveness in achieving pre-defined goals) and second-order learning (about the underlying norms and values related to a new technology) are important in niche development.

As stated, these three processes are dynamically interrelated meaning that they need to be performed together as they have impacts on each other. A focus on these niche processes can aid in most steps of the transition management cycle. The shaping and voicing of expectations relates to the first step of the cycle where envisioning and structuring of the problem takes place. Network formation relates to the second step where coalitions must be formed. Then, the final step of the transition management cycle also connects to the learning processes discussed here.

Secondly, Geels et al. (2017) zooms out a bit and looks at 3 mutually reinforcing processes that stimulate socio-technical transitions. These processes add some critical elements that need to be taken into account when going through the transition management cycle. They are the following:

1. *Increasing momentum of niche innovations* → This can be done by aligning multiple innovations and systems and by providing societal and business support.
2. *Weakening existing systems* → By phasing out existing technologies the incumbent socio-technical regime can be made unstable.
3. *Strengthening exogenous pressures* → Here the focus is on generating landscape pressures that support the transition from the current socio-technical regime to the new niche. An example of this is the implementation of new policy.

These processes strengthen the overall transition process and need to be considered important additions to the transition management cycle. The transition management cycle does not focus on the actual practicalities of a transition, thus an understanding of the processes discussed here is valuable. The first process on increasing the momentum of niche innovations is supported by the three niche processes discussed before this. The second and third reinforcing processes paint a more complete picture of the transition process.

It can clearly be seen that the transition management cycle and the other frameworks that reinforce the process of successfully managing a transition are complex in their own right. But this in a sense mirrors transitions themselves because they are complex and long-term processes comprising of multiple actors (Geels, 2011). Managing a successful transition is difficult due to the many stakeholders involved and the inherent complexity that is apparent in all facets of a transition (including in the network of stakeholders). Thus, how to deal with and manage both complexity and stakeholder networks are of key concern. Transition management theory incorporates this to a certain extent. However, due to the great complexity of the transition towards LH2 aviation and the environment in which this transition takes place, it is relevant to take a more specific look at how to manage complexity. The study of complex systems theory is used to gain better insights into the dynamics of societal systems so that transitions can be managed better (Rotmans & Loorbach, 2009).

3.1.2. Complexity Management

Overarching societal systems and the structures within these systems can be defined as complex. This is largely due to the intricate relationships that these systems have with the environment, the dynamism of this environment they are part of, and the sheer size of the system. Having a deeper understanding of complex systems and how to manage them allows for more effective application of the transition management theory laid out above. As explained by Rotmans and Loorbach (2009), a complex system can be defined as an open system that interacts with its environment and constantly evolves and unfolds over time. They contain many diverse components which interact non-linearly. These interactions also lead to feedback loops with negative

(damping) or positive (amplifying) effects. Prior states of the complex system also influence future states. This is a concept called path dependence. Complex adaptive systems are a form of complex systems that are able to adjust to changes in their environment due to select features (Rotmans & Loorbach, 2009). One such feature is coevolution, or the ability to change together with its environment due to interaction and feedback loops with the environment. Also, the process of self-organization means that internal systems of complex adaptive systems increase in complexity without being guided or managed by an outside force. During this process, emergence leads to new structures, patterns, and properties to arise (Rotmans & Loorbach, 2009).

The complexity of an airport itself is already high. With the added complexity that comes from the greater socio-technical transition of the landscape in which the aviation industry takes place, much can become obscure and uncertain. Managing such a complex system thus requires a great deal of understanding of how complex systems work and can best be influenced. Management of a complex (adaptive) system can be defined as influencing the process of change of the system from one state to another (Rotmans & Loorbach, 2009). Basically, ensuring that the transition goes according to plan. Rotmans & Loorbach lay out a set of guidelines for this process in their 2009 paper. Here they explain five basic principles that need to be kept in mind:

1. *Management at the system level is important* → At the system level adverse effects of implemented changes can be more clearly seen. This also implies that management at different levels of complexity is key to identifying all emergent properties of the transition.
2. *The status (performance) of the system determines the way it is managed* → insights into how the system works is an essential precondition for management.
3. *Objectives should be flexible and adjustable at the system level* → This refers to the idea that complexity and fixed objectives interfere with each other. Flexibility in objectives allows for more ability to react to changes inside and outside of the system.
4. *Managing a complex, adaptive system means using disequilibria rather than equilibriums* → Periods of nonequilibrium offer opportunities to direct the system towards a desirable direction.
5. *Creating space for agents to build up alternative regimes is crucial for innovation* → this refers to the idea that new emergent structures need to take over from the incumbent structures that led to the system failures which caused the persistent problems that need to be solved. Resources need to be given to stimulate the emergent structures.

These principles will play a key role in managing the complexities that are inherent to the transition at hand. In order to successfully manage a transition, complexity needs to be dealt with, meaning that techniques such as these are crucial. How they can be implemented and applied to the transition of an airport to liquid hydrogen infrastructure will be looked into in a subsequent chapter.

As stated earlier, stakeholders and their relation to a transition is another aspect which can increase the complexity of a transition. Managing the complex stakeholder networks that are often seen in the large systems that are going through a transition is thus another way to reduce complexity and better manage a transition. The transition towards LH2 aviation takes place in an environment with a large number of very interconnected stakeholders. Because of this, in order to practically implement transition and complexity management theory, stakeholder management also needs to be looked at specifically and understood more deeply.

3.1.3. Stakeholder Management

Behind all of the elements that are required to make an airport run are stakeholders that need to work together to ensure that the airport functions. In addition “For a liquid hydrogen fuelled aircraft to be successful it is essential to understand the impacts on stakeholders, including airports, airlines and air navigation service providers (FlyZero, Postma-Kurlanc, et al., 2022).” There is a great degree of complexity that comes from the network of stakeholders central to the operation of the airport. This network of stakeholders is inherent to the complexity of the airport system and can make organizational transitions much less predictable (Lamberg et al., 2008). Also, in a technological transition, the capabilities of a company to access new technological opportunities depends on its role and position in the innovator network and market (Riccaboni & Moliterni,

2009). Interconnectedness with a wide variety of stakeholders is thus very important. In a 2008 paper by Lamberg et al. the value of stakeholder management is further explained. When transitions take place within systems, and specifically, within organizations, the reformulations of structures engage and concern various organizational stakeholders. It is very important to clarify the role of stakeholders before and during organizational transitions. “An organization cannot survive in the long run unless it provides fair treatment to its key stakeholders (Lamberg et al., 2008).” To understand an organization's environment the stakeholders and their rights, obligations, interests, and power need to be understood because they are a critical precondition for making successful managerial decisions. Therefore the relationships with the stakeholders, or the “explicit and implicit agreement[s] of mutually acknowledged rights and obligations to achieve mutual benefit or prevent some harm”, need to be clearly understood (Lamberg et al., 2008). Because decisions during radical transitions involve many different stakeholders, firms face a dilemma. Varied responses can be expected from different stakeholders that have different interests, viewpoints, and levels of power. This causes the making of decisions to once again become increasingly complex and makes stakeholder management crucial for a successful transition.

An important aspect of stakeholder management in a transition discussed by Lamberg et al. (2008) is path dependence. They argue that the determinants of stakeholder mobilization needs to partially focus on the organization-stakeholder relationships and its impact. Thus, to understand stakeholder dynamics, the topic of path dependence and what it means for a firm is of utmost importance. As shown earlier in the section on complexity, this is a concept that can increase complexity greatly. Path dependence can be defined as is the tendency of institutions or technologies to become committed to develop in certain ways as a result of their structural properties of their beliefs and values (Greener, 2019). Current and future states depend on the path of previous states (Rotmans & Loorbach, 2009). However Lamberg et al. (2008) identify four elements that typify a process as path dependent. They are the following:

1. *Dependence on initial conditions* → Previous relationships with stakeholders determine the initial conditions of the process, can shape the process direction, and limit alternative directions.
2. *Web of commitments* → A firm's previous contractual agreements (position in the institutional matrix) can constrain and affect organizational transitions.
3. *Network effect* → The greater the number of contractual linkages between and among stakeholders, the greater the complexity and unpredictability of the stakeholder network.
4. *Event sequence* → The sequence and nature of managerial decisions of a firm have an important role in the organizational transitions proceedings.

Lamberg et al. (2008) conclude with a set of prescriptions to analyze stakeholder linkages in strategic initiatives. They are the following:

1. Because of the importance of path dependence, all stakeholders which can lead to “a vicious cycle of demands, threats and sanctions” because of their contractual position, should be involved in the initial negotiations.
2. In order to reduce information asymmetry-related incentive conflicts, an unbiased party must transparently deal with the financial impacts of deal contingencies.
3. Explicit strategies for harnessing opportunism should mitigate its use, especially if the initiative creates organizational discontinuity.
4. When deciding whether to initiate a change process or not, the complex multi-party negotiations and the risk of an uncontrolled conflict escalating that are inherent to such a change should not be seen as a hurdle to overcome, but instead as a decision-making variable (just like profitability, value, etc.).

These prescriptions give some valuable insights into how a company, such as an airport, should handle its stakeholder relations, especially during the sustainability transitions that they are entering. It is clear that coping with the complexity of sustainability problems requires inter-organizational collaboration (Loorbach & Wijsman, 2013). If clear strategies regarding stakeholder relations are adopted, potentially some of the complexity that comes with it can be reduced. However, due to the large number of interconnections within the average stakeholder network of an airport and the constant evolutions and interactions with its environment, there will always remain a level of complexity that requires additional management to deal with

(Rotmans & Loorbach, 2009). In subsequent chapters a deeper look into the proposed stakeholder management strategy for Schiphol and airports in general during the transition to liquid hydrogen aviation will be given.

3.2. Liquid Hydrogen Aviation

William Lee Jolly (2020) has written a comprehensive article on Hydrogen for Britannica which gives a good introduction to the element that has recently been touted as the solution to all of the world's climate issues. Hydrogen is the most abundant element in the universe at three times more abundant than helium (the second most widely occurring element). It can be found in large quantities in the earth's oceans, ice packs, rivers, lakes, and atmosphere in the form of water. Because hydrogen is most commonly found bonded to oxygen to form water (H_2O) it needs to first be split from the oxygen atom to get pure H_2 . At ambient temperatures on earth hydrogen, when not bonded with anything else, it will be in its gaseous form (GH_2). This gas is colorless, odorless, tasteless, and flammable. Electrolysis is needed to split hydrogen from the oxygen in water to generate gaseous hydrogen. Typically, commercial electrolyzers take approximately 48 - 53 kWh to produce one kg of GH_2 (Hodges et al., 2022) (Antweiler, 2020). However, recent research does show that it may be possible to generate hydrogen at only 40.4 kWh/kg of hydrogen, reaching up to 98% efficiency (Hodges et al., 2022)(Antweiler, 2020). Nonetheless, even with improvements in electrolysis efficiency, there is still a high demand for energy if one wishes to produce hydrogen.

One of the reasons that hydrogen has so much potential is because of its high energy-to-weight ratio of approximately 120 MJ/kg (Slanger, 2022). This converts to approximately 33.6 kWh of usable energy per kg of hydrogen. Compared to kerosene (which is the primary fuel for all jet engines) which has 42.8 MJ/kg (or 11.9 kWh/kg) of energy, it can be seen that the energy-to-weight ratio is nearly three times higher for hydrogen (Deutscher Luft- und Raumfahrtkongress et al., 2009) (Marconi, 2004). However, although the energy-to-weight ratio is good, the volumetric energy density of hydrogen is where it struggles to keep up with more traditional fuels such as kerosene. In its gaseous form (GH_2), one kg of hydrogen has a volume of 11 m³ at normal atmospheric pressure (0 bar) (Air Liquide Energies, 2017) (Demaco Holland B.V., 2022). This means that it is about 11 times lighter than the air we breathe. This equates to a density of 0.09 kg/m³. To put this into perspective, aircraft kerosene has a density of roughly 800 kg/m³ (Air BP, 2000). Because of the lower density, although the energy-to-weight ratio is good, a larger amount of volume will still be needed to store the same amount of energy using hydrogen as with kerosene. This large volume of GH_2 will still be comparatively lighter for the same amount of energy storage though. When GH_2 is stored at higher pressures, this problem is slightly helped. Typically GH_2 is stored at up to 700 bar. Then the density is 42 kg/m³ (Demaco Holland B.V., 2022). This problem is further helped when hydrogen is stored in liquid form, resulting in a density is 71 kg/m³ (Air Liquide Energies, 2017) (Demaco Holland B.V., 2022). In its liquid form the energy density is ultimately a quarter of kerosene meaning that for an aircraft to have the same amount of energy in fuel it needs significantly more storage space (FlyZero, Postma-Kurlanc, et al., 2022).

The improvements in energy density that come with liquid hydrogen also bring some challenges. Hydrogen is liquid below -253°C or 20 kelvin (Jolly, 2020). If energy enters the LH2 and heats it to above this temperature it reaches its boiling point and returns to its gaseous state. If this is in an enclosed location, immense pressure can build up quickly since in its gaseous state it is naturally roughly 800 times more voluminous than liquid (FlyZero, Postma-Kurlanc, et al., 2022) (Air Liquide Energies, 2017). Thus, to ensure that the LH2 stays in a conditioned environment, heavily insulated tanks need to be used to store it. In addition, energy is needed to liquefy hydrogen. An analysis of the current state of the art showed that the specific energy consumption of liquefaction is between 5 to 8 kWh/kg of LH2 but can also be up to between 10 and 20 kWh/kg of LH2 (Yin & Ju, 2019)(Connelly et al., 2019). A theoretical minimum of 2.88 kWh/kg was also discussed (Connelly et al., 2019). This is added on top of the energy needed to make the GH_2 itself. Thus, making one kg of LH2 requires an input of water and likely 53 to 73 kWh/kg (with a theoretical low of about 45 kWh/kg). In addition to that, before the LH2 can be used to generate energy, it needs to be transported to the use location (in this case an aircraft). At that use location the hydrogen then needs to be stored until it can be used by either a fuel cell or a combustion motor to generate energy that can be used. Over the total life cycle, the efficiency of hydrogen as a fuel source is often about 30 to 40% due to the losses from electrolysis, liquefaction,

transport/storage, and utilization (Heid et al., 2021) (Aziz et al., 2019). Hydrogen is not a fuel that can be taken from the environment such as fossil fuels, but instead more similar to a battery. Hydrogen is a way to store energy so that it can be used later. Compared to a traditional battery which has a life cycle efficiency of roughly 75 to 80%, hydrogen is much less efficient (Heid et al., 2021). However, this is where the high energy to weight ratio of hydrogen (33.6 kWh/kg) comes into play. Because it is significantly higher than that of batteries. Lithium-ion batteries (which are the best battery for aviation because of they have the highest energy density) only have an energy density up to 260 Wh/kg (NASA Spinoff, 2019) (Cloud, 2020) (Sripad & Viswanathan, 2021).

3.2.1. Basic LH2 Aircraft Design Principles

In recent years, hydrogen has become a central part of the solutions to reduce pollution, reduce carbon emissions, and stop climate change. In the aviation industry, this is no different. As established in the introduction, hydrogen does have great potential if used in the right way. Due to the significantly higher energy density of hydrogen when it is stored in a liquid state, the potential of LH2 in aviation is much more than its gaseous counterpart. Although hydrogen is gaseous at ambient temperatures, the high pressure it would need to be stored at to allow for any reasonable amount of hydrogen to be brought on board a plane means that the tank needs to be very thick and reinforced. This results in a tank that's significantly heavier than the fuel that it is carrying (Hyfindr, 2022). The heavy, reinforced, high-pressure GH2 tanks are a particular issue in the aviation industry since the weight of the aircraft cannot exceed certain limits. This makes it very difficult to exceed a range of 1000 km when flying using a GH2 storage method (SYSTEMIQ, 2022). LH2 tanks are significantly lighter than their GH2 counterparts (McKinsey & Company & Clean Sky 2, 2020). Using LH2 however, comes with its own challenges because of the cryogenic temperatures that it needs to be stored at. The storage tank needs to be extremely well insulated against radiation, convection and conduction to ensure minimal heat/energy enters the system (Cryoworld et al., 2019). Storage tanks of this nature are traditionally insulated using a vacuum insulation system (Demaco Holland B.V., 2022b) (Swanger, 2022). A vacuum insulated tank works simply by having an inner tank in which the cryogenic liquid is stored, and an outer tank around it for the vacuum. Between the two tanks, a vacuum is made to ensure air does not transfer energy to the inner tank. Minimal connections are used between the tanks and these connections are made using a low thermally conductive material. Also, to reduce thermal radiation from adding energy to the system, radiation shielding is applied to the inner tank (Demaco Holland B.V., 2022b) (Cryoworld et al., 2019). In addition to the insulation measures, the tank must also be outfitted with advanced ventilation systems to ensure that in the event that insulation is lost, the rapid pressure buildup from the LH2 boiling off, can be released in a safe efficient manner (Rivard et al., 2019)(FlyZero, Postma-Kurlanc, et al., 2022). In addition to emergency situations, the ventilation system will also be required to balance the pressure in the tank during normal operation.

The LH2 aircraft needs to be able to take the stored LH2 and utilize it to generate power and thrust to propel itself forward. This can be done in two ways: a hydrogen fuel cell connected to an electric motor or a hydrogen combustion engine (SYSTEMIQ, 2022) (McKinsey & Company & Clean Sky 2, 2020). Figure 4 shows a basic overview of both of these systems. Both systems require hydrogen in its gaseous state, so the hydrogen needs to boil off and be reheated before it is usable. Heating the hydrogen is done by heat exchanging equipment after it exits the tank. When hydrogen combustion is used, NO_x and water vapor are the only byproducts, thus eliminating CO₂ and soot (SYSTEMIQ, 2022). The hydrogen is burned in a gas turbine similar to how jet fuel is used today. The combustion of hydrogen with oxygen does not produce CO₂, however, it can produce dangerously high levels of nitrogen oxides (NO_x) (Clean Energy Group, 2021). This also has a greenhouse effect, meaning that hydrogen combustion is also not the solution for fully emission-free aviation (Lammel & Graßl, 1995). However, it could reduce climate impact in flight by 50 to 75 percent (McKinsey & Company et al., 2020). A fuel cell on the other hand creates electricity purely through a chemical process that results in only water vapor. This means that there is no CO₂, soot, or NO_x pollution (SYSTEMIQ, 2022). Thus, fuel cell propulsion systems have a higher potential to reduce climate impact than combustion (McKinsey & Company & Clean Sky 2, 2020). The electricity generated can then be used to power electric motors for propulsion. For shorter-range aircraft a fuel cell system is applicable, but for longer flights a combustion-based system is expected to be needed (SYSTEMIQ, 2022) (Hoelzen et al., 2021).

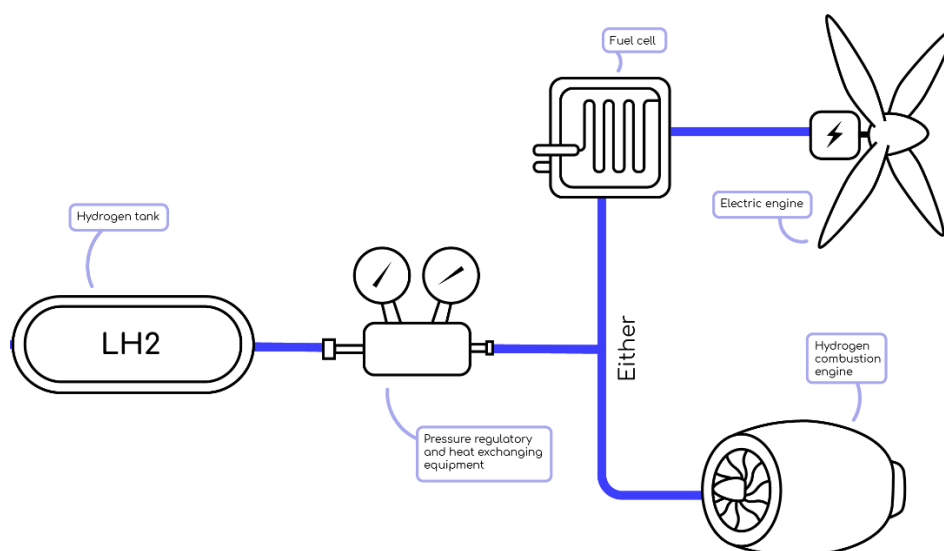


Figure 4: Basic layout of an LH2 propulsion system

However, using hydrogen as a fuel requires the ability to work with it safely. This can be a challenge since many of its properties lend it to being a potentially dangerous substance. Hydrogen is colorless and odorless in its gaseous state and when it burns the flame is also nearly invisible making it very hard to detect (FlyZero, Postma-Kurlanc, et al., 2022). The use of hydrogen sensors inside an aircraft will be an important measure to notify of any leaks and hazards. At a 4% mix with air, hydrogen becomes flammable, and at 18% it becomes an explosion hazard (SYSTEMIQ, 2022) (Hydrogen Association, n.d.). It takes just 0.02 MJ of energy to ignite the hydrogen in such a situation (FlyZero, Postma-Kurlanc, et al., 2022). These factors make it extremely hazardous in an enclosed area. Luckily, because of how light it is, when outside the hydrogen quickly dissipates. In addition, hydrogen does not light easily from pure heat. A self-ignition temperature of 585°C makes hydrogen much harder to ignite in that way than kerosene with a self-ignition temperature of 210°C (FlyZero, Postma-Kurlanc, et al., 2022). Also, if a fire is burning, things close by but not in the flame will be damaged much less because the fire heat radiative fraction is only 10-20% (much lower than the 30-40% of kerosene) (FlyZero, Postma-Kurlanc, et al., 2022).

3.2.2. Proposed LH2 Aircraft Designs

Due to the characteristics of hydrogen explained above, it will likely not be the most suitable fuel source for all different types of aircraft sizes and ranges. Earlier, in the introduction, the niche that LH2 aviation fills within the array of sustainable aviation methods was mentioned. The lower energy to volume ratio of LH2 compared to kerosene and the sustainable counterpart SAF means that long-range (and potentially medium-range) aircraft will for the foreseeable future not be able to fly using hydrogen without giving up significant amounts of room and becoming economically unfeasible. On the other end of the spectrum, LH2 aviation may not be the most optimal for commuter and very short-range regional flights because of its low lifetime efficiency compared to that of batteries. The short-range (and potentially regional and medium-range) flight segments are the most optimal to be flown by LH2 aircraft (Air Transport Action Group, 2020).

This is further supported by a number of proposed LH2 aircraft designs from the literature. Multiple different parties have attempted to size aircraft based on current and future expected technological capabilities in order to see what type of aircraft are possible using liquid hydrogen. Table 1 is a list of proposed aircraft concepts from different sources. The type, size (in PAX), max range, typical mission range, LH2 fuel requirement for the max and typical missions, and the estimated entry into service (EIS) are all shown.

Table 1: Relevant technical specifications of multiple proposed LH2 aircraft designs

Proposed LH2 Aircraft Specs								
Aircraft Classification	Aircraft Type	Aircraft PAX	Max Aircraft Range (km)	Typical Mission Aircraft Range (km)	Block LH2 Mass Design Mission (kg)	Block LH2 Mass Typical Mission (kg)	EIS	Source
Regional	LH2 turboprop	70	1220-1420	400	1,190	269	2035	(Mukhopadhaya & Rutherford, 2022)
Short-range	LH2 narrowbody	165	2800-3440	1500	5050	2230	2035	[(Mukhopadhaya & Rutherford, 2022)
Regional/short-range	Fuel cell/hybrid	180	1500	800	2023	1154	2035	(Hoelzen et al., 2021)
Short-range/medium-range	combustion/hybrid	290	4000	2000	11208	5531	2035	(Hoelzen et al., 2021)
Regional	Regional	75	1500	700	877	470	-	(FlyZero & Debney, 2022)
Mid-range	Narrowbody	180	4400	1600	3283	1241	-	(FlyZero & Debney, 2022)
Long-range	Midsize	279	10600	6800	15151	9677	-	(FlyZero & Debney, 2022)

What can be clearly seen from the different proposed LH2 aircraft in Table 1 is that the majority of these aircraft indeed have ranges that fulfill the regional to short-range aircraft market. A few of these could potentially venture into the medium-range market. There is one proposed aircraft that has a much higher range which may suggest that in larger aircraft that are designed for carrying a large amount of fuel a higher range may be achievable. However, this is an outlier and seems to be an exception. Nonetheless, these proposed aircraft largely support the suggested market share that LH2 aviation will be able to capture. Now the key is to successfully develop such theoretical concepts into actual aircraft.

3.2.3. Current Developments

LH2 aviation, as it is explained above, does not exist as of yet. The application of LH2 technology in an aircraft is still in development. There are, however, many parties that are working on tackling this very issue right now. These parties understand that if hydrogen is going to be one of the solutions to the problems that the aviation industry is facing, the first step is to develop aircraft that can fly on LH2. Because of its more widespread acceptance and utilization, storing hydrogen in its gaseous state is often one of the first steps that parties take in the process of development. A prominent example and global frontrunner when it comes to GH2 aviation is ZeroAvia. This party has developed and flown a 2-person aircraft on GH2 in previous years (ZeroAvia, 2022). By 2024 they hope to have a 19-seater aircraft that can fly very short-range flights on GH2 (ZeroAvia, 2022). In the future, they will be working to develop larger-scale LH2 aircraft. By 2030 they aim to have a 100 to 200-seater aircraft that can travel 3700 km and by 2040 they wish to extend that range to 9200 km for an aircraft that will have over 200 seats (ZeroAvia, 2022). Incumbents to the market also see the future potential of this innovation and are working hard to develop in this field. Airbus revealed the ZEROe project in 2020 in which they hope to develop the world's first zero-emission commercial aircraft by 2035 using hydrogen propulsion (Airbus, 2021). Three concepts including a turbofan, turboprop, and blended-wing body aircraft are being developed to use modified gas turbine engines and LH2 fuel. Soon testing will begin with a skylab in order to gain valuable information (Airbus, 2022).

In the Netherlands there are also a number of parties and initiatives working on advancing LH2 aviation. The TU Delft is a university with one of the best renowned aerospace programs in the world (TU Delft in International Rankings, n.d.) (Aerospace Engineering in Top Five Global QS Subject Ranking, 2020). There, projects such as the Flying V and AeroDelft are working towards developing aircraft technologies which will aid in the proliferation of LH2 aviation (AeroDelft, 2022) (Piesing, 2022). Also, the European commission has

awarded 25 million euros in funding to a consortium called TULIPS (Royal NLR - Netherlands Aerospace Centre, 2021). 29 parties, led by Dutch airport Schiphol and involving other Dutch parties such as the Royal Netherlands Aerospace Center, are working to tackle many of aviation's sustainability challenges. One of those things is the use of LH2 in aviation. Recently, another big announcement came from the Netherlands when the party known as HAPSS (Hydrogen Aircraft Powertrain and Storage System) announced plans to develop the world's first large passenger aircraft to be powered by green LH2 (Veenstra, 2022). This public-private partnership between 17 companies including Fokker, the Dutch government, and many others hopes to use the 383 million euros that were allocated to them to bring 6 40-80 seat LH2 aircraft that will be able to fly from the Netherlands to London in 2028. But in addition to these examples of Dutch and International developments, there are many more parties looking into every aspect of this transition. Everything from the large-scale implementation to the exact sciences of improving fuel cells and other key components are being researched and invested in.

3.2.4. Timeline Estimates

These developments and their individual timelines begin to paint a picture of when the technology required to make LH2 aviation at a large scale possible. It is important here to understand that there is a difference between the technology being ready at a technical level and the aircraft entering into service. After the first functional proof of concept LH2 aircraft are developed, there is still a long certification process that needs to take place (Air Transport Action Group, 2020) (McKinsey & Company & Clean Sky 2, 2020). To ensure safe air travel the aviation industry has a high degree of scrutiny when it comes to the certification of new aircraft. This can be expected to be even greater when it comes to aircraft which fly using such new technologies. A number of years will be needed to ensure that these aircraft are up to the high standards and can operate safely. A large portion of this process will only be able to take place after the first working aircraft are developed. In addition to the length of this entire process, another aspect needs to be considered, entry into the market. When an airline purchases a number of new aircraft, they intend to use these assets for a certain amount of time, often about 30 years (How Are Planes Decommissioned, and How Much Value Can Be Salvaged From Their Parts?, 2022). If they do not, then they will have lost money on this purchase which is logically bad business practice. Only once a number of an airline's aircraft are going to be retired, they will need new aircraft to replace them. Only at this point, they will consider purchasing LH2 aircraft if they are a proven technology with sufficient infrastructure. These factors equate to the rollout and adoption of LH2 aircraft by the market being a process that will take quite some time.

Estimating the time the development, certification, and entry into market of this technology will take is an important factor in the development of the infrastructure around it. Although it is impossible to know at this point in time when this will come exactly, a rough estimate as to the expectations can be made based on the timelines of the parties working on development and industry experience with previous new technologies. Regarding technology development and the eventual certification of these aircraft, the literature and the projects currently show a range of expected timespans from roughly 2022. The lower end is about 5 to 6 years (McKinsey & Company & Clean Sky 2, 2020) (Veenstra, 2022). The longest estimates are at about 20 years (FlyZero, Cole, et al., 2022). But many estimates are around 10 years (Air Transport Action Group, 2020) (McKinsey & Company & Clean Sky 2, 2020). These rough estimates are also supported by the estimated entry into service of the proposed aircraft concepts shown above. Multiple of them could be feasibly developed and certified by 2035. These ± 10 years come from the further development of elements of the technology, aircraft development (5 to 10 years) and certification (3 to 5 years) (McKinsey & Company & Clean Sky 2, 2020) (SYSTEMIQ, 2022). Potentially the first aircraft will begin to enter the market around the late 2020s (like HAPSS) and more will follow into the 2030s. Likely, as time goes on more and more aircraft developers will begin to make LH2 aircraft of different sizes available.

Estimating when the market will be ready to adopt the LH2 aircraft is based on the speed with which the logistic infrastructure around LH2 aircraft develops and when airlines wish to purchase new aircraft. Because the focus of this report is on the development of LH2 infrastructure to ensure that these aircraft can be serviced, once they enter the market, this element will not be seen as a determinant for the timeline, but instead a variable of it that needs to change depending on the other parameters. Thus, the entry into market

will be based on when airlines will want to purchase new aircraft. This is hard to know for sure and will likely be dependent on when previous aircraft types that could be replaced by LH2 aircraft were developed and purchased by airlines. However, estimates show that a large window of opportunity for short-range aircraft is expected to be around 2030 to 2035 (McKinsey & Company & Clean Sky 2, 2020). Given this lines up very well with the estimated point where the first certified LH2 aircraft will be expected to enter the market. This means that based on current estimates, an airport will want LH2 logistic and refueling infrastructure to be ready to operate somewhere between 2030 and 2035 (Air Transport Action Group, 2020).

3.2.5. Economics

One of the central questions to whether LH2 aviation will be feasible is its economic sustainability. As with any industry, ultimately the market will decide whether a change is accepted or not. If an airline or airport is not able to make any money with LH2 aviation, then a transition to LH2 is unlikely without additional government support. In a 2021 paper, Hoelzen et al. take an in-depth look at hydrogen aviation from the financial point of view. Here the direct operating costs (DOC) of a short and medium range kerosene aircraft are compared to estimated DOCs for LH2 aircraft. The DOC is a metric showing yearly costs of operating an H2 aircraft and is the sum of capital investments, maintenance, crew, air traffic control fees, airport fees, and energy costs. At this point in time when the transition is still in early stages, these calculations are still based on a significant number of assumptions and estimates and result in a large range. However, such calculations give an initial sign of what can be expected. DOC for the short-range aircraft were shown to range from a decrease of 1% to an increase of 77% and the DOC for the medium-range aircraft could at best stay the same and at worst increase 112%. Thus on average DOC could end up being between 1 and 2 times the DOC of standard kerosene aircraft.

The significantly increased DOC of LH2 aviation is an important factor for its financial feasibility. “Overall, it is shown that the economy of H2 aviation highly depends on the availability of low-cost, green liquid hydrogen (LH2) supply infrastructure (Hoelzen et al., 2021).” Thus, reducing the DOC will largely depend on the ability to produce and transport LH2 in the most cost-effective way. These high costs come from the extensive supply chain which is needed to ultimately get LH2 into an aircraft. The price of LH2 is built up from the need for renewable energy, an electrolysis plant, a liquefaction plant, storage facilities (along the supply chain), transportation, and on airport refueling equipment (Hoelzen et al., 2021). Thus reducing DOC of LH2 aviation can be done most effectively by targeting the production and transport of LH2. Specifically, because of the high energy requirements electrolysis is expected to be the largest contributor to LH2 costs. Apart from reducing fuel prices, an additional avenue which can be used to reduce direct operating costs is government support through subsidies, incentives, tax breaks, etc. However, this is something which will be highly dependent on the climate goals and capabilities of local governments. Then, any DOC increases which cannot be reduced will likely end up being borne by the customer.

3.3. Liquid Hydrogen Infrastructure – At the Airport

With the potential rise of LH2 as an energy carrier in aviation growing ever closer airports will need to adjust their infrastructure in line with the changing fuel demand. LH2 aviation will not appear overnight, instead, its market share will build up over time. Whether there is relatively low or high demand, as may be expected early on or later in this transition respectively, one thing is clear: airports will need adequate infrastructure to service and refuel LH2 aircraft. If this technology gets adopted by the industry and an airport is not ready, then this will mean they get left behind. Thus, it is of utmost importance to understand what capabilities an airport needs once LH2 aircraft want to arrive and depart from there. The main capability an airport needs is to refuel an LH2 aircraft with LH2. The basic process of getting LH2 into the fuel tank of an aircraft consists of three infrastructural elements: 1. LH2 supply, 2. LH2 storage, 3. LH2 Refueling (Hoelzen et al., 2021). An airport that is missing just one of these elements will not be able to service an LH2 aircraft. Each of these three infrastructural subsystems consists of multiple components making them in themselves quite complex. In addition to the three major infrastructural subsystems themselves, there are many (less tangible) things needed to support the system, such as adequate rules and regulations, safety protocols, experienced personnel, etc. Reconfiguring airport operations, scaling this technology, and optimizing refueling practices are all major challenges that will require significant planning and development to overcome (McKinsey &

Company & Clean Sky 2, 2020). However, in general “there seem to be no fundamental technical constraints that would prevent implementation, if planned and addressed in a timely manner (McKinsey & Company & Clean Sky 2, 2020).” In this section, an overview of the current literature on the LH2 infrastructural requirements of an airport will be given. The focus here will be on the refueling and storage infrastructure. After this, a deep dive into the LH2 supply piece of the puzzle is added. Understanding how the technology niche works is crucial in effectively managing the socio-technical transition.

3.3.1. Refueling

Understanding the LH2 infrastructure that is required to refuel an LH2 aircraft requires a look into each element of the system. In a scenario where an aircraft has landed at an airport and needs to be refueled the system that makes direct contact with the aircraft is the refueling infrastructure. The system for refueling can differ depending on the demand of the airport, operational factors, and the willingness to invest in infrastructure. From the literature and current developments, the following three options for refueling are clear (McKinsey & Company & Clean Sky 2, 2020)(FlyZero, Postma-Kurlanc, et al., 2022)(Hoelzen et al., 2021):

1. LH2 Bowser Trucks
2. LH2 Hydrant System
3. Radically innovative refueling technology

When which of these options is most logical and what that means for the airport is very relevant to successful decision making. In addition, the current Technology Readiness Levels (TRL) of each system is assessed to give an indication as to the development left and the technical difficulty. Figure 5 explains the TRLs:

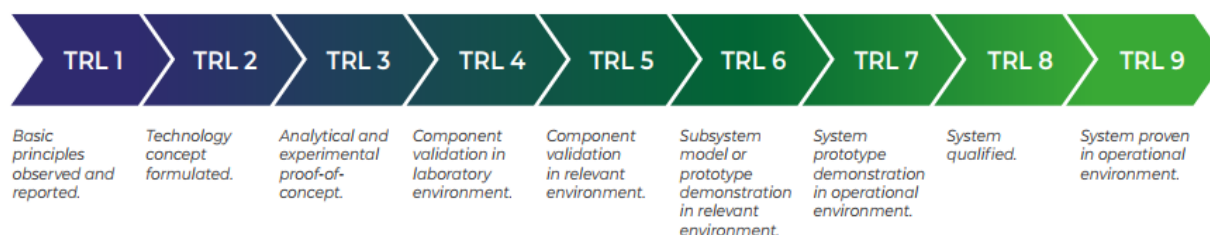


Figure 5: TRL level explanatory chart (FlyZero, Postma-Kurlanc, et al., 2022)

LH2 Bowser Trucks

It is expected that early in the adoption process when an airport only services a small number of LH2 aircraft that fly only certain routes, a very low amount of LH2 will be required. Then, a bowser (refueling truck) system may be employed (FlyZero, Postma-Kurlanc, et al., 2022) (McKinsey & Company & Clean Sky 2, 2020). A simplistic representation of this process can be seen in Figure 6. When using such a system, the bowser truck takes fuel from the airside storage location to the aircraft and refuels directly into the aircraft. Because of the possibility to only purchase a select number of bowser trucks, the capital expenditures are expected to be significantly lower than building other forms of refueling infrastructure (FlyZero, Postma-Kurlanc, et al., 2022)(McKinsey & Company & Clean Sky 2, 2020). In a 2022 FlyZero Report on Hydrogen Infrastructure and Operations, how such a refueling method would work is considered. The bowser trucks will need to be insulated similarly to other LH2 storage tanks to ensure proper conditioning and reduce losses. In addition to the insulation, it is expected that these trucks will need to be bigger than traditional kerosene refueling trucks because of the lower energy density of LH2 (compared to kerosene). Even when considering this, it is expected that the number of bowser trucks required could be up to double the number needed for kerosene or synfuel (McKinsey & Company & Clean Sky 2, 2020). Any LH2 aircraft that uses fuel cells requires a high level of purity of the hydrogen that it consumes (VSL, 2020) (Stolten et al., 2016). To ensure that purity is maintained when refueling, the bowser trucks will also need to carry helium to purge the refueling lines (FlyZero, Postma-Kurlanc, et al., 2022).

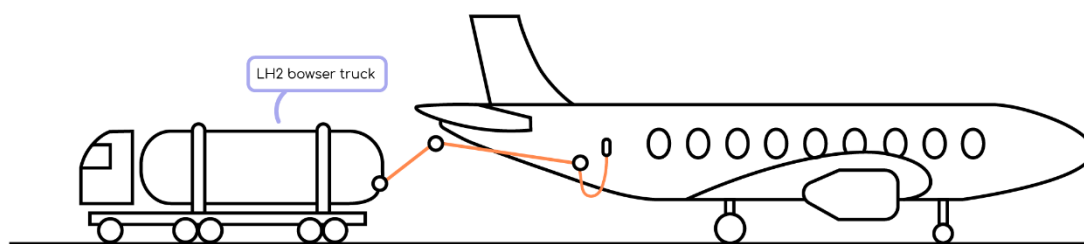


Figure 6: Refueling via LH2 bowser truck

These factors mean that LH2 bowser trucks are significantly different than traditional refueling trucks and thus will need to be specially designed for their purpose. Both manually operated or automatically operated versions are on the table, however, both do not exist yet. The technology for manually operated LH2 bowser trucks is estimated to be at a TRL of 3 to 4 and the TRL of the automated counterpart is only estimated at 1 to 2 (FlyZero, Postma-Kurlanc, et al., 2022). Although these scores are quite low, they are significantly influenced by the fact that no party has invested development time in them yet. However, once a standardized design has been made and certified, this can be implemented on a global scale. Once implemented they do “require a different training and a safety assurance framework for operations, but these are manageable challenges to overcome (McKinsey & Company & Clean Sky 2, 2020).” Using LH2 bowser trucks to refuel aircraft is an option that will be attractive for any airport that has low demand and does not wish to invest a significant amount of money in other refueling infrastructure. However, as adoption rises and LH2 demand increases, using bowser trucks for refueling has its limitations because it adds a significant amount of airside logistics and traffic (McKinsey & Company & Clean Sky 2, 2020) (FlyZero, Postma-Kurlanc, et al., 2022).

LH2 Hydrant System

With high LH2 demand comes the requirement to have a refueling system that can meet that demand. An LH2 hydrant refueling system is a likely candidate to meet that demand. This system is shown in Figure 7. A hydrant system employs a cryogenic pipeline to transport LH2 from storage tanks to the aircraft stand (FlyZero, Postma-Kurlanc, et al., 2022). From there, a vehicle outfitted with mobile refueling equipment connects the hydrant to the aircraft’s LH2 tanks to begin the refueling procedure (FlyZero, Postma-Kurlanc, et al., 2022). Since the transportation of LH2 from the storage tanks to the aircraft stand is automated via underground cryogenic pipelines, a significantly higher number of aircraft could be serviced while reducing logistics clutter at the airport (which would also improve safety conditions) (FlyZero, Postma-Kurlanc, et al., 2022) (McKinsey & Company & Clean Sky 2, 2020). However, an LH2 hydrant system is expected to require significantly higher capital expenditure (FlyZero, Postma-Kurlanc, et al., 2022). Early estimates show such a system costing up to five times more than the traditional kerosene counterpart (McKinsey & Company & Clean Sky 2, 2020). Although it may be necessary when LH2 aircraft adoption is significantly scaled up, early in the transition an LH2 hydrant system is likely cost-technically infeasible for most airports. The 2022 FlyZero Report on Hydrogen Infrastructure and Operations also researched how an LH2 hydrant system would feasibly work. There are two significant differences with a traditional hydrant system. Firstly, the entire system needs to be conditioned to maintain liquid hydrogen at or below $-253\text{ }^{\circ}\text{C}$. This means all of the storage and pipes need to be insulated and designed to handle the little bit of boil-off that will inevitably occur. Secondly, regular pumping systems need to be avoided since they add energy to the system which increases the hydrogen boil-off.

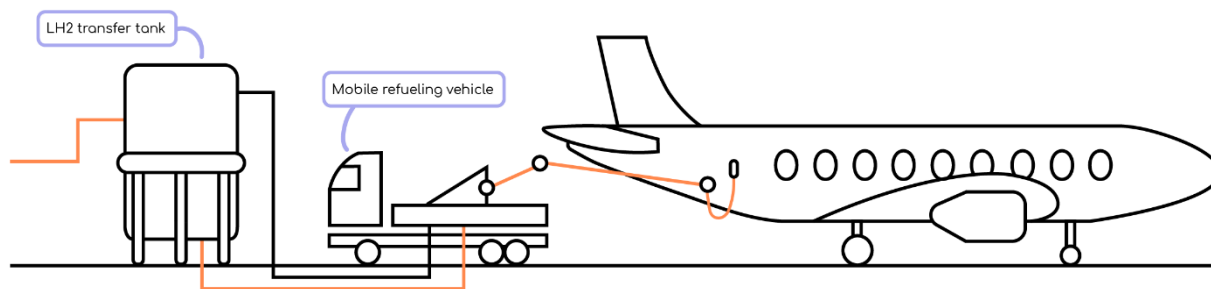


Figure 7: Refueling via LH2 hydrant system

There are a few different ways in which an LH2 hydrant system could be achieved which are outlined by FlyZero (2022). Regarding the piping, either a vacuum insulated pipe or a solid insulation pipe could be used. The industry standard for cryogenic pipelines is using a vacuum insulation (Demaco Holland B.V., 2022a). Cryogenic piping is already used in various applications, however, at an airport large distances will need to be traversed. Depending on the application, a TRL of 5 to 9 can be given (FlyZero, Postma-Kurlanc, et al., 2022). This same FlyZero report explains that the way that hydrogen is moved around the airport could be in two different ways. A cryogenic hydrogen gas pipeline system would allow the LH2 to heat up just enough to turn back to gas in order to make it easier to transport. Then at the aircraft stand the GH2 is liquefied before entering the aircraft. Another option is to build a looped hydrant system in which LH2 constantly flows to reduce boil-off. Regardless, hydrogen will likely need to be moved using a pressure differential between the storage tank and the receiving tank. To achieve this the storage tank is pressurized using the warming of LH2 which would boil off and turn to GH2 which expands to 845 times the size and applies pressure to the LH2 (FlyZero, Postma-Kurlanc, et al., 2022). A second return pipe can deal with the gas boil-off and bring it to a location where it can be reliquefied. At an airport this would occur on a continuous basis to multiple different aircraft stands. It is expected that there would be more aircraft stands than LH2 storage tanks which makes this process a little more complicated. Intermediate transfer tanks located at each stand is a way to solve this issue. This technology is not new, but tanks suitable for airport use do not exist making the TRL level rather low (2-3) (FlyZero, Postma-Kurlanc, et al., 2022).

How such a system is designed naturally comes with a lot of choices. Some of the choices that would need to be made include sizing of the transfer tanks based on the expected aircraft to be serviced at each stand and whether the hydrant system will be above or below ground. Naturally, the capital expenditures to install a hydrant system are significant, but they can differ based on the design decisions (McKinsey & Company & Clean Sky 2, 2020) (FlyZero, Postma-Kurlanc, et al., 2022). Another thing to consider is that due to the characteristics of hydrogen and fuel cell systems, the mobile refueling vehicles connecting the hydrant to the aircraft will also need to be outfitted with purging equipment. This means that these types of vehicle also need to be specially designed for this purpose. Similarly to the bowser trucks, the TRL level is estimated at a 1 to 2 currently because no such vehicle has been developed yet, although the technology is feasible with current techniques (FlyZero, Postma-Kurlanc, et al., 2022).

Radically Innovative Refueling Technology

The previous two methods of refueling are LH2-modified versions of traditional refueling technologies. However, due to the very different properties of LH2, it is reasonable to believe that other methods could be just as good if not better at achieving a safe, efficient, and cost-effective refueling process. One such idea is to build LH2 aircraft which use replaceable hydrogen tanks (or pods) which simply need to be switched out when the aircraft wishes to refuel. A representation of this process can be seen in Figure 8. Universal Hydrogen, a startup looking to address aviation's challenge of decarbonizing, is developing this technology. Instead of solely focusing on aircraft design, they focus on the entire logistic chain (Universal Hydrogen, 2022) (Universal Hydrogen, 2022b). The concept is relatively simple, instead of refueling into a permanent tank in the aircraft, the entire empty tank can be replaced by a full tank. Likely instead of one large tank, it would be in the form of multiple pods. However, this makes the system more modular and standardizable. Empty pods

can be transported back to a production and distribution center where they are refilled. Currently, the company is still quite new (founded in 2020) and working on GH2 systems, however there are plans to look into LH2 pods which would work in a similar way (Blain, 2021) (Marcaillou, 2022). If successful, this type of technology could lessen or solve some of the issues that are apparent with refueling LH2 aircraft. Turnaround times could be lowered significantly by requiring less time for refueling. Also, safety concerns might be lesser with this method. Implementing such a system comes with some additional considerations, however. Firstly, similar to the issue with the bowser trucks, logistic limitations could be expected due to the high number of pods that may need to be transported airside once large-scale adoption of LH2 aircraft has happened. Second, these pods only work for an aircraft that is specifically designed for them. If this system competes with other systems, effectiveness is greatly decreased. Thus, an airport will likely need to choose between fully operating using this method or traditional refueling methods. This also means that aircraft refueled with this method can only fly to and from airports that have the pods and equipment to refuel said aircraft. Clearly, the use case of this new and developing technology will need to be understood more clearly. The TRL level is estimated to currently be between a 2 to 4, but this is based solely on the limited promotional material that is publicly available.

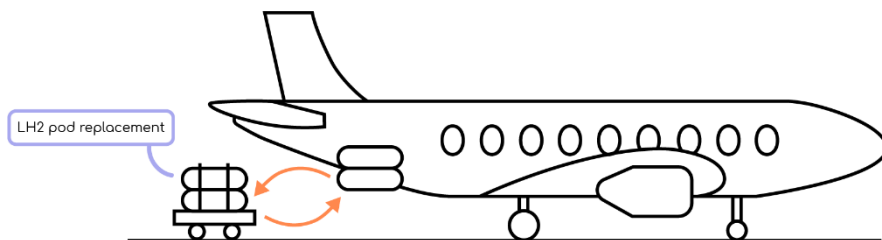


Figure 8: Refueling via LH2 pod replacement

The choice of which refueling infrastructure to apply at an airport depends mainly on two major factors: economics and meeting demand practically. Meeting demand in a practical way is quite simple. Basically, an airport will at a certain point in time have a certain LH2 demand based on the number of planes flying from that airport within a specific time frame and the size and range of these aircraft. The airport will either need to be able to meet that demand, or it cannot service this number of LH2 aircraft and will need to lower the LH2 flights that it allows. Generally, a relatively low LH2 demand can be met using any of the three methods explained above. As demand rises (due to growth of the airport and/or increased adoption of LH2 aircraft and flight routes) refueling via bowser trucks may become less feasible because the logistics of handling hundreds of trucks can become unsafe and practically unfeasible. Similar issues could arise with the tank replacement refueling system because these tanks need to be transported around. However, due to the radical nature of this solution, there are both potential workarounds and significant unknowns. A hydrant system would likely be one of the better options because it is far more scalable and requires less logistic hassle.

The second factor for the choice of refueling infrastructure is the economics of it. This can be broken down into both the investment costs (CapEx) + operations costs (OpEx) and the efficiency of the turnaround times (Hoelzen et al., 2021). Using a bowser truck refueling system means less physical infrastructure needs to be built at the airport. Only the purchase of the bowser trucks (not considering the other logistic infrastructure earlier in the chain) is required. The same could potentially be said for the tank replacement system dependent on the implementation. On the other hand, a hydrant system will require significant investment in permanent infrastructure which may not always be economically feasible for an airport (McKinsey & Company & Clean Sky 2, 2020). For all three methods the operational costs also need to be considered, but without deeper analysis, this is very hard to estimate at this point in time. Thus, when the demand allows for it and an airport wishes to keep their investment low, then a bowser system or tank replacement system may be the best way to go from a financial point of view. However, the turnaround times also need to be considered. Airlines lose money if an aircraft is grounded for too long (Hoelzen et al., 2021)(FlyZero, Postma-Kurlanc, et al., 2022). They wish for their aircraft to do all of the needed ground operations as quickly as possible to ensure their

asset is making money as much as possible. So each refueling infrastructure's impact on the refueling speed (and thus the turnaround times) also needs to be carefully considered by an airport. This directly impacts the net operating expenditures for such a new refueling system.

3.3.2. Storage

One step back in the chain of LH2 infrastructure at the airport is storage. As soon as an airport faces a regular LH2 demand from the aircraft that it services, it is crucial for that airport to have a system with which to store LH2 on site. The main reason for this is ensuring a logistic buffer for resilience against supply chain shortages (FlyZero, Postma-Kurlanc, et al., 2022) (McKinsey & Company & Clean Sky 2, 2020) (Hoelzen et al., 2021). No matter how an airport gets its LH2, there is always the possibility of shortcomings. If there is no buffer in this system, then any delay in LH2 supply will cause significant delays in all LH2 flights and ruin the main business model of the airport. For LH2 to be competitive with traditional fossil fuels, adequate storage systems that reduce that risk as much as possible and increase reliability of the fuel source are a must. However, due to the characteristics of LH2, storage comes with a new set of challenges. Hydrogen must be stored in liquid form to ensure the aforementioned logistic supply chain risks are reduced optimally. To keep hydrogen liquid it needs to remain at or below -253°C which requires specialized equipment. Normal storage tanks allow too much energy to enter the system causing the temperature of the hydrogen to rise and boil-off to occur, turning the LH2 into GH2 over time. If this happens fuel (and thus money and energy) is lost, and safety concerns can arise. Storage tanks must be designed with a high level of insulation to maintain a conditioned atmosphere inside which allows for the LH2 to be stored for extended periods of time with low losses to boil-off.

The types of storage tanks used for LH2 are insulated in very much the same way as the tanks that hold the LH2 inside of an aircraft. As explained in the previous section, these tanks are insulated using a vacuum insulation system in combination with thermal radiation shielding and the use of low thermally conductive support elements (Demaco Holland B.V., 2022b) (Swanger, 2022). Ultimately, these measures ensure a tank is able to reduce boil-off significantly. Another factor that influences the boil-off of LH2 is the size of the tank. A larger storage tank has a lower outside area to inside volume ratio (because area requires the radius to be squared and the volume requires the radius to be cubed). Since energy enters the system through the outside area of the storage tank, theoretically a larger tank could reduce the boil-off to storage volume ratio. However, as storage tanks need to be built larger, more structural support is needed for the inner tank which would increase the number of thermal bridges and increase energy inflow. The value from increasing size needs to be looked into. Currently the largest LH2 tank is located at the NASA Kennedy Space Center and has a capacity of $4,732\text{ m}^3$ (21.4-meter inner tank diameter) (Swanger, 2022). The estimated boil-off rate of the tank is around 0.03% per day, meaning that LH2 could be stored for a very long time.

When it comes to hydrogen storage at the airport, there are a couple of considerations to be made. Logically the first consideration is the amount of storage that is required. At least a 2-to-3-day buffer stock is suggested to be desirable (FlyZero, Postma-Kurlanc, et al., 2022) (McKinsey & Company & Clean Sky 2, 2020). Based on the airports expected demands, total buffer stock, and thus total storage capacity should be calculated. It is recommended that storage is calculated from peak demand (FlyZero, Postma-Kurlanc, et al., 2022). In addition, it can be valuable to oversize the storage tanks even more for two reasons. Firstly, this ensures a higher level of future-proofing so that the system will not need to be adjusted if LH2 aviation gains extra market share or adoption increases. Secondly, hydrogen storage for other applications outside of refueling could be an additional source of revenue (FlyZero, Postma-Kurlanc, et al., 2022). For one, other airport operations (including lighting, heating, cooling, etc.) could be powered from this supply. Also, hydrogen needs for the surrounding area could be supplied. This could potentially be done at a profit which reduces the total operating expenses of LH2 aviation. Once the desired LH2 storage is known, decisions can be made on the number of tanks that this requires. Depending on the size of the airport and thus the LH2 demand, this can vary greatly. As stated earlier, tank sizing can be based on the requirements of the airport, but also the amount of boil-off that is acceptable.

Next, a decision needs to be made on whether the hydrogen is stored at one central location or spread around the airport. A comparison of these two options at Schiphol can be seen in Figure 9. This decision is expected

to be based on considerations regarding, resilience/robustness against failures in the system, safety, rules and regulations, costs, and efficiency. Having multiple separate LH2 storage locations around the airport can, for example, be more efficient if planned well. Then hydrogen will need to travel the least amount of distance to the aircraft stand, resulting in less losses. The degree to which this is significant needs to be understood better. However, potentially LH2 will only be allowed to be stored in certain areas and special safety precautions need to be considered. This may make spread storage infeasible. The considerations here need to be thought through thoroughly. Finally, another aspect that needs to be considered is liquefaction or boil-off. It is clear that a perfect system in which boil off is 0 is impossible. During transport, storage, and refueling always some amount of energy enters the system. All LH2 infrastructural elements must have ways to deal with the GH2 buildup to ensure that there is no excessive pressure buildup that can rupture the system (FlyZero, Postma-Kurlanc, et al., 2022). This can be done either by releasing the GH2 into the air, but optimally, it is captured and re-liquified to ensure less energy loss. If this is desired, then a liquefaction system needs to be installed that gets supplied by the refueling and storage boil-off GH2 and feeds back into the main storage.

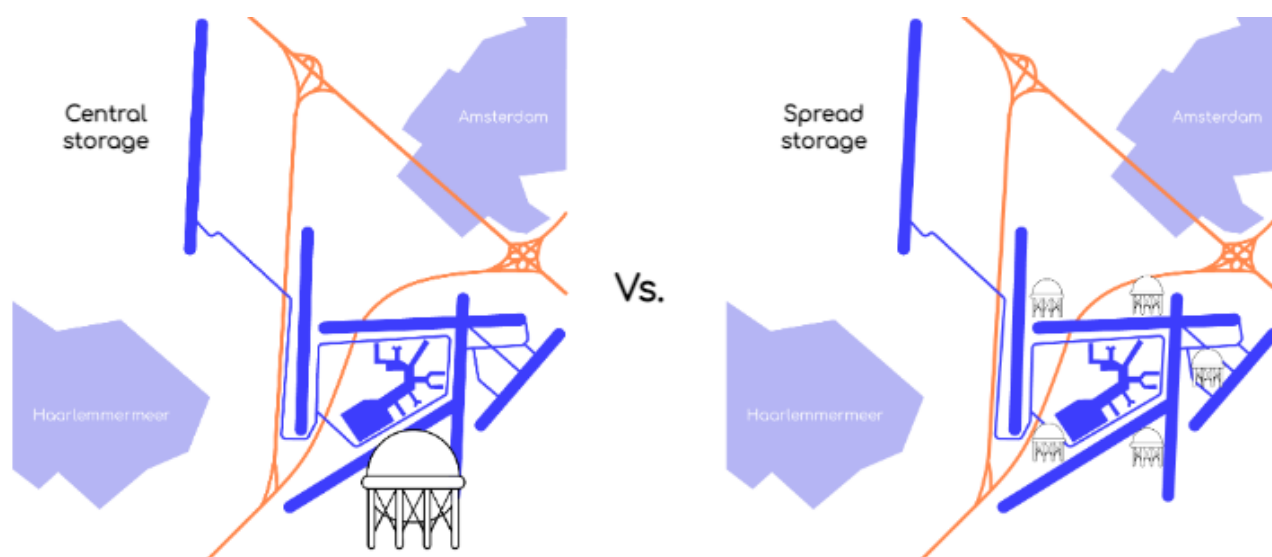


Figure 9: Centralized vs. spread LH2 storage

3.4. Liquid Hydrogen Infrastructure – Outside of the Airport

The final piece of the logistic chain to ultimately get LH2 into an aircraft, as discussed in the previous section, is the LH2 supply. Without an LH2 supply, the storage and refueling infrastructure does not have a function. The reason that this piece of the puzzle is taken apart from the others is because there are multiple, very different ways in which this can be achieved which do not only involve the airport, but also the greater logistic value chain outside of the airport. Each method of supplying LH2 is highly dependent on a variety of factors which can make this element quite difficult to understand correctly. As stated, understanding the technology niche and the many nuances it carries with it, is an important part of managing the transition correctly. In the literature, three methods of supplying LH2 to an airport are most commonly considered. They are the following (McKinsey & Company & Clean Sky 2, 2020) (Hoelzen et al., 2021) (FlyZero, Postma-Kurlanc, et al., 2022) (SYSTEMIQ, 2022):

1. Offsite LH2 production + LH2 delivery trucks
2. Offsite GH2 production + GH2 pipeline + Onsite LH2 production
3. Onsite GH2 production + Onsite LH2 production

Each of these three options delivers the same result – LH2 supply to the airport – but elements of the LH2 production process are done at different steps in the logistic chain leading up to the airport. Which is most

optimal for an airport largely depends on the circumstances of each airport. “The method to generate and deliver hydrogen to the airport will depend on the airport’s size, location, geography and the scale of hydrogen demand (FlyZero, Postma-Kurlanc, et al., 2022).” Each method will first be explained, and the considerations mentioned. Then, the factors which make a scenario realistic or not will be analyzed.

3.4.1. Offsite LH2 Production + LH2 Delivery Trucks

As the name suggests, this LH2 supply method has the entire LH2 production process take place outside of the airport. First GH2 is created via electrolysis of water using renewable energy sources such as wind, solar, or marine/hydro energy (van der Brug, n.d.). As mentioned earlier this process commercially takes around 50 kWh (with a theoretical low of 40 kWh) to produce one kg of GH2. Around 9 liters of water feedstock is required as input for every 1 kg of hydrogen generated through electrolysis (Bergman & Johnstone, 2021). In addition, more water is needed for cooling this process (Webber, 2007). After this, the GH2 needs to be liquified at a liquefaction plant. This process also requires energy which needs to, once again, come from a renewable energy source. Liquefaction of hydrogen can be expected to take between 5 and 20 kWh per kg of LH2 produced (Yin & Ju, 2019) (Connelly et al., 2019). After the LH2 is produced it needs to be brought to the airport’s LH2 storage location. For this method, the last step in this process is a delivery via truck. Depending on the production location, before the LH2 is loaded onto a truck for the last mile delivery, it may have been transported over long distances via ship or train. At the airport the truck unloads its LH2 cargo into the airport’s LH2 storage tank. The trucks used for this need to be trucks that are designed with a high level of insulation to ensure minimal LH2 loss to boil off. Also, for this process to be truly green, the transportation methods need to run of renewable energy as well. This whole process (minus importation) is shown in a simplistic way in Figure 10.

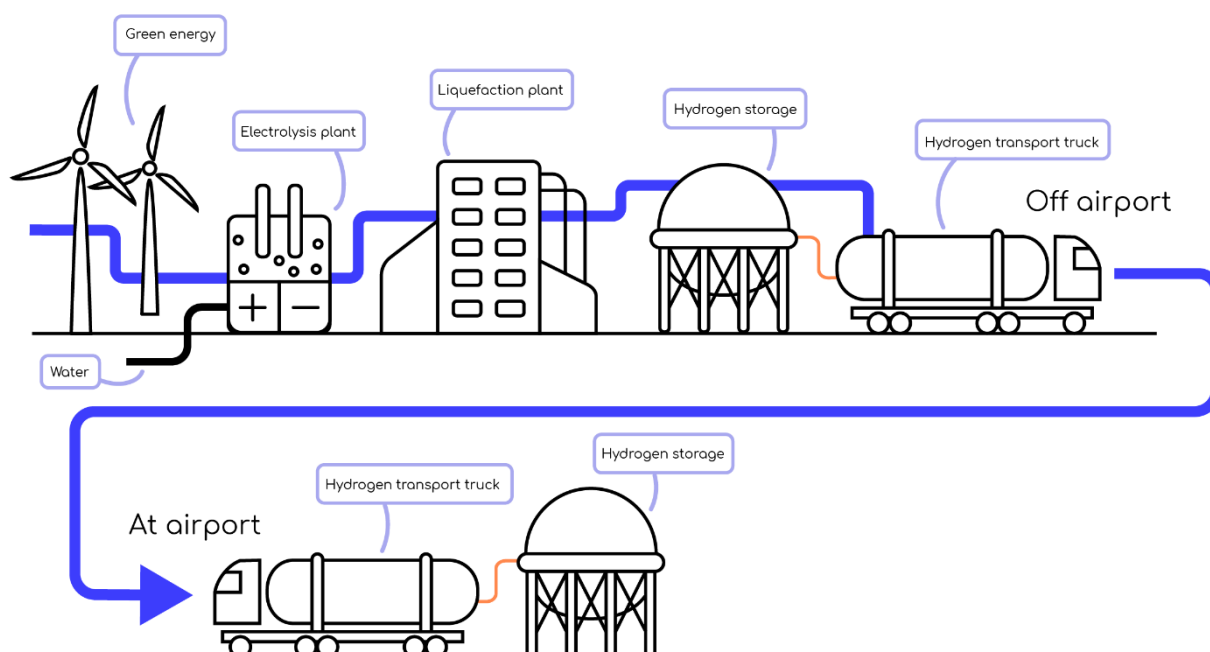


Figure 10: LH2 supply via offsite LH2 production + LH2 delivery trucks

There are a number of factors that influence the effectiveness of this method of LH2 supply for an airport. Firstly, the LH2 demand at an airport plays a big part in deciding whether this supply method is feasible. Logically, the number of daily LH2 truck deliveries scales with the LH2 demand of the airport. Large airports that adopt LH2 as a central propulsion method leading up to 2050, can expect to reach a point at which they will need hundreds of truck deliveries per day to supply their aircraft (FlyZero, Postma-Kurlanc, et al., 2022). As an example, according to early estimates, a larger hub airport that has only switched 25 percent of its fuel infrastructure to LH2 could expect 500 tons a day equating to 125 daily LH2 truckloads (McKinsey & Company & Clean Sky 2, 2020). At that point, questions need to be asked about safety and efficiency. Based on current

understandings, once demand reaches a certain point, other methods of LH2 supply will be both safer and more efficient/cost effective (Hoelzen et al., 2021). One thing to consider in solving this issue is the possibility of replacing trucks with another last mile delivery method. Using barges if the airport's geographic location allows for it could potentially mean logistic issues can be solved. Compared to LNG barges, an LH2 barge with a capacity of 1500 m³ may be realistic (Kaup et al., 2017). This would mean nearly 100 tons of LH2 can be transported by one barge. With the earlier mentioned 500 tons of LH2 needed per day, this may be much more achievable using barges. This is something to consider

For a smaller airport, or an airport that has not adopted LH2 aviation at a large scale yet, using this method of LH2 supply may be a good choice, though. In such a situation, the scale issues are outweighed by the relatively low capital investment and ease of adoption. This method of LH2 supply requires minimal investment in infrastructure for an airport. Outside of the storage and refueling infrastructure that will be needed anyways, the airport will likely not need to invest in any other major physical infrastructure in order to be able to service the low amount of LH2 aircraft. The generation of renewable energy, electrolysis of GH2, liquefaction of LH2, and transport are all outsourced to one or more third parties. This significantly lowers initial investment but may increase the operating costs in some cases. However, in other cases, an airport will not be situated optimally to harvest the large amounts of renewable energy needed to produce GH2, thus, doing this away from the airport gives more freedom to do this optimally. Thus operating costs can potentially be the same or lower depending on the situation.

Another thing to consider is the growth potential of the airport or the adoption of LH2 aircraft. As stated, once the demand for LH2 reaches a certain point, truck deliveries become unmanageable and other methods of last mile delivery may be unfeasible. If the LH2 demand is expected to rise quickly, investing in more future-proof infrastructure earlier on may be more efficient than doing that only once it's required. The location of an airport also highly influences the effectiveness of this supply method. If the airport is located in a location where renewable energy resources are abundant, then other methods may ultimately be more cost-effective. On the other hand, if there are shipping locations nearby, then transportation may be relatively cheap and a good option. In the end, all of these considerations come down to two things: practical achievability and costs. Firstly the method needs to be practically achievable. For this supply method, it likely will for most cases unless there is high LH2 demand. Secondly, the costs need to be as low as possible to make it financially sustainable. If the transport costs are so immense that they offset the savings from not having to build infrastructure, then another method may be more reasonable.

3.4.2. Offsite GH2 Production + GH2 Pipeline + Onsite LH2 Production

For this LH2 supply method, the liquefaction of GH2 to LH2 is moved further down the logistic supply chain and taken over by the airport itself. This gives the airport more control over the liquefaction process, but also more responsibilities. Similar to the first method, GH2 is produced outside of the airport through electrolysis using renewable energy. The GH2 is transported to the airport via pipeline. Depending on the production location and amount of hydrogen needed, before the last-mile-delivery of the GH2 to the airport takes place via pipeline, it may have to be imported to the country of the airport via international pipeline, ship or train. There are a number of forms in which the GH2 can be transported over long distances. The three most common are it's liquefied form (LH2), bonded to ammonia, and liquid organic hydrogen carriers (LOHC) (Weichenhain, 2021). Other options are liquid inorganic hydrogen carriers (LIHC), solid inorganic hydrogen carriers (SIHC), and even blending green hydrogen with natural gas (Green Hydrogen Transportation – Role of Natural Gas Pipelines, 2020) (Port of Amsterdam et al., 2021). In one of these forms the hydrogen will arrive at a distribution center where it is converted back to GH2 before it is pumped into a pipeline destined for the airport (unless hydrogen is transported as LH2, then it would be more efficient to not convert it back). The pipeline can potentially be adapted from a natural gas pipeline if the area already has that infrastructure (FlyZero, Postma-Kurlanc, et al., 2022). At the airport, the GH2 will then be liquified before entering the LH2 storage and ultimately being used in an aircraft. This means that at the airport there will need to be a liquefaction plant and a sufficient power supply able to handle the LH2 demand (FlyZero, Postma-Kurlanc, et al., 2022). Once again, all steps of this process need to utilize renewable energy for the hydrogen to be truly green. This entire process (minus importation) is shown in a simplistic way in Figure 11.

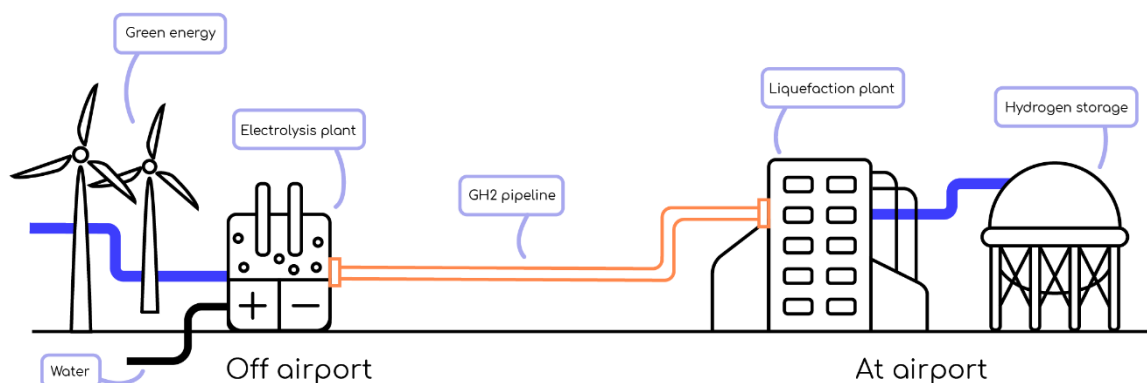


Figure 11: LH2 supply via offsite GH2 production + GH2 pipeline + onsite LH2 production

Whether this method is effective or not is dependent on multiple factors. Firstly, due to the use of a pipeline instead of trucks, this logistic system lends itself better to situations in which there is a larger demand for LH2 at the airport (FlyZero, Postma-Kurlanc, et al., 2022) (McKinsey & Company & Clean Sky 2, 2020). If delivery from trucks is not practically feasible, effective, and/or safe, then this is worth considering. The amount of LH2 that can be supplied using this method is dependent on the GH2 supply and the energy supply. If not enough GH2 can be shipped to the country of use and/or produced there, then the high demand of that airport also can't be supplied. If this is the case, then the first method would also not have been feasible. On the other hand, to liquefy the GH2 at the airport a significant amount of renewable energy will need to be brought to the airport. Questions need to be asked about the renewable energy supply and whether the demand for renewable energy can be achieved locally. Importation of Energy from other locations seems unlikely, however excess GH2 could potentially be used to generate energy for liquefaction. This does increase the energy inefficiency of the system and should be avoided if possible but could be looked into more if needed. Also, a liquefaction plant will be required at the airport for the liquefaction process. This can take up a significant amount of space. Some initial rough estimates show that a large hub airport could require up to 180,000 square meters for a liquefaction plant with projected 2050 LH2 requirements (FlyZero, Postma-Kurlanc, et al., 2022). If an airport is in an area with very limited space and strict zoning laws (such as a city) this could pose an issue

3.4.3. Onsite GH2 Production + Onsite LH2 Production

If circumstances allow or even require it, an airport could choose to incorporate the majority of the LH2 supply chain into its own operations. This would mean that the airport only takes the raw resources such as water and energy as inputs and uses them to first make GH2 through electrolysis and then liquefy it. The End result is the same; an LH2 supply to meet the demand of the airport. This would require two very large facilities; one for electrolysis and another for the liquefaction process. Regarding the inputs, this can be done in a few ways. Water will need to be supplied to the onsite electrolysis plant. If the airport is near a large body of water this could be rather simple, however, if the airport does not have that luxury, then water will need to be pumped to the airport via pipeline. Using water trucks is not realistic and/or logical since then similar truck congestion issues can arise as for with the first LH2 supply option. Estimates show that for a medium or large airport between 2035 and 2050 the water requirements for this could easily surpass the multiple hundreds of thousands of liters per hour (FlyZero, Postma-Kurlanc, et al., 2022). Also, a significant renewable energy supply will be needed. As explained earlier, for just the production of LH2 a total of 53 to 73 kWh per kg of LH2 (with a theoretical low of about 45 kWh) is needed. This can either be supplied from a third-party renewable energy generator or can be produced at the airport itself using renewables. The power requirement is so high, that a medium or large airport can already expect into the multiple GWs of daily power demand before 2050 (FlyZero, Postma-Kurlanc, et al., 2022). Thus, unless there is very little demand, it is very unreasonable to expect the airport to produce the required amount of energy itself, meaning that an outside party will need to supply the energy. If this party is very far away, transporting energy over long distances requires investment in such infrastructure. However, when producing the GH2 and LH2 onsite there will be

very little to no additional losses from the production location to the onsite storage location leading to significantly fewer efficiency losses from transportation. This process is shown in Figure 12.

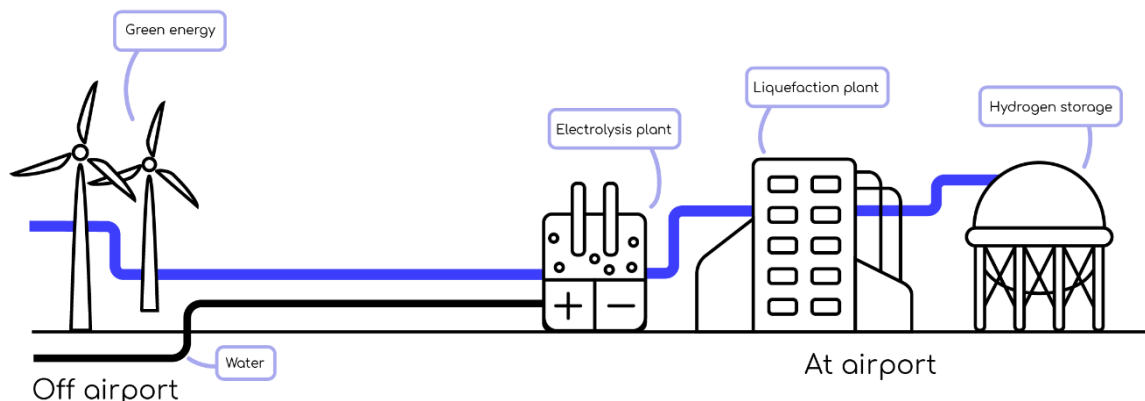


Figure 12: LH2 supply via onsite GH2 production + onsite LH2 production

The logistic scenario sketched here will likely only be the most logical choice in very select situations. First of all, traditionally airports play a much more passive role in the production of their fuel supply since they purchase it from third-party manufacturers (Airlines for America, 2018). Incorporating nearly the entire fuel generation process at the airport means the airport itself will take on increased responsibility. Very roughly stated, the first scenario in which LH2 is brought to the airport via trucks lends itself very well to low demand situations and the second scenario is likely better when there is higher demand. Due to the space, renewable energy, and water demands that this scenario has, unless very specific features are present, it will likely not be reasonably achievable for very high LH2 demand. An airport would need to have a significant amount of free space for both the electrolysis and liquefaction plants. In addition, the airport would need a large water source nearby as its feedstock. Finally, large amounts of cheap renewable energy needs to be produced at or close to the airport and transported there. If any of these elements are not present, then likely one of the other options is better. If an airport does not have enough space for the required production facilities due to its geographic location, then it will be more logical to outsource all (method 1) or some (method 2) of the LH2 production process. If an airport does not have a reasonable water supply that can be pumped to the production facilities, then bringing water to the airport would be very inefficient and likely infeasible to do practically and safely. Finally, very few locations will have enough renewable energy and very little competition for that electricity to be able to supply the energy the airport will need for LH2 production. Based on these scenarios this option will only be realistic for very specific airports.

3.5. LH2 Aviation, logistics, and Infrastructural Evolution over Time

Section 3.2 on Liquid Hydrogen Aviation ends with a short discussion of the timeline related to the introduction of LH2 aircraft into service. The conclusion there was that large-scale LH2 adoption (meaning for more than just a few LH2 aircraft) will likely begin between 2030 and 2035. Given this, airports will need to have their first LH2 infrastructure ready to operate at that time. Clearly this estimate is exactly that, an estimate, and will become more accurate and precise as time passes, but in the early stages of this transition it gives an initial starting date to work from. Between 2030 and 2035 the adoption of this new form of sustainable aviation will begin, but full adoption will not happen from one day to the next. Naturally, over time the number of LH2 aircraft into service, and thus the demand for LH2 at airports, will increase. With the increasing LH2 demand comes a required increase in the sizing of the LH2 infrastructure at airports, capabilities of the LH2 logistic infrastructure, and amount of renewable energy that is required. Increasing these elements is in many cases not an easy task that will require meticulous planning and increased investments. Thus, if an airport knows what magnitudes of increases they can expect and when, future proofing and better planning can take place which makes the management of this transition and all of the complexities that come with it more effective. Predicting how the adoption of LH2 aircraft by the market will go is clearly a difficult task, especially considering the early stages that the market is in. However, even rough estimates can already create

significant value in giving airports and their stakeholders and partners some early expectations to work with. Similar to the estimate for the moment of initial adoption, the predictions regarding growth of LH2 aviation will improve over time as the niche matures.

3.5.1. Modeling LH2 Aircraft Adoption

As established predicting the exact way in which LH2 aviation will be adopted and proliferate through the industry is very difficult and not possible to do accurately at this point in time without a lot of luck. However, getting an initial estimate helps the airport and its stakeholders and partners to make better decisions early on and not make mistakes that due to path dependence could hinder them in the future. In the literature there are a number of different simple predictive models that have been developed in this early phase exactly for that purpose. For the purpose of this research six adoption scenarios from two different large-scale aviation industry reports are taken to represent the different possible ways in which LH2 aircraft proliferate through the market. They can be seen in the following table (Table 2):

Table 2: Literature-based LH2 aircraft adoption scenarios

LH2 Aircraft Adoption Scenarios						
Scenario	Name	Descriptors				Source
Scenario 1:	Efficient Decarbonization	Start adoption in 2030	16% of all aircraft replaced by 2040	40% of all aircraft switched by 2050	50% of all medium-range and all new regional and short-range switched by 2050	(McKinsey & Company & Clean Sky 2, 2020)
Scenario 2:	Maximum Decarbonization	Start adoption in 2028	8% of all aircraft switched by 2035	60% of all aircraft switched by 2050		(McKinsey & Company & Clean Sky 2, 2020)
Scenario 3:	Midsize Accelerated	Regional adoption start 2042, 34% by 2050	Short-range adoption start 2037, 53% by 2050	Medium-range adoption start 2033, 77% by 2050	Long-range adoption start 2038, 46% by 2050	(FlyZero, Cole, et al., 2022)
Scenario 4:	Regional Accelerated	Regional adoption start 2033, 65% by 2050	Short-range adoption start 2037, 49% by 2050	Medium-range adoption start 2044, 17% by 2050	Long-range adoption start 2049, 12% by 2050	(FlyZero, Cole, et al., 2022)
Scenario 5:	Midsize Unaccelerated	Regional adoption start 2042, 34% by 2050	Short-range adoption start 2042, 27% by 2050	Medium-range adoption start 2035, 49% by 2050	Long-range adoption start 2050, 5% by 2050	(FlyZero, Cole, et al., 2022)
Scenario 6:	Regional Unaccelerated	Regional adoption start 2035, 13% by 2050	Short-range adoption start 2047, 9% by 2050	Medium-range adoption start 2055, 0% by 2050	Long-range adoption start 2060, 0% by 2050	(FlyZero, Cole, et al., 2022)

The first two scenarios were taken from a 2020 fact-based study on hydrogen technology and economics in aviation by McKinsey & Company for the Clean Sky 2 and Fuel Cells and Hydrogen 2 joint undertakings. In this report they look at two possible adoption scenarios. The efficient decarbonization scenario is based on how hydrogen can be used most efficiently and sees adoption begin by 2030. By 2040 16% of all aircraft are switched to LH2. In the decade to 2050 adoption ramps up resulting in 40% of all aircraft being LH2 by then. This is achieved by having about 50% of medium-range and all new regional and short-range aircraft being LH2 propelled. On the other hand, the maximum decarbonization scenario puts the focus on cutting CO2 as much as possible. Here adoption already begins quickly in 2028 all newly purchased aircraft up to 10k range being LH2. By 2035 already 8% of the global fleet is LH2 propelled and by 2050 that number rises significantly to 60%. Clearly these are very positive and hopeful scenarios.

A 2022 research report on the LH2 aviation market forecasts and strategy performed by FlyZero (funded by the UK government) is the source for the final four adoption scenarios. These four scenarios are based on either the proliferation of midsized first or regional aircraft first and whether there was high ambition

(accelerated) or less ambition (unaccelerated). They approached the modeling slightly different than the previous piece of referenced literature because they first looked at the market entry of aircraft at different range/size categories. They also gave an estimate on how much of the global fleet of these categories may be LH2 versions by 2050. In the Midsize focused scenarios the midsize concepts of LH2 aircraft enter the market earlier than the regional (and short-range) aircraft. The same, but then for regional aircraft, is the case for the regional focused scenarios. Then, the scenarios which are accelerated are slightly more ambitious regarding both the entry into service and adoption percentage by 2050. The unaccelerated scenarios posit that there is not as much push for these aircraft to enter the market and thus they come later and proliferate the market slower. The intense difference that this leads to is sometimes quite apparent such as a 46% adoption of long range LH2 aircraft in 2050 for the midsize-accelerated scenario whereas in the regional-unaccelerated scenario adoption of these types of aircraft doesn't start until 2060. This goes to show how much there is still unsure because the technology itself is still in development.

There are a number of considerations to be made when it comes to these estimates. Firstly, they are estimates for overall adoption of LH2 aviation, so although it is an indication, at every specific airport it could be very different dependent on a variety of factors. For one their ability to supply the LH2 demand is a key factor. Other factors are the airlines which fly from the airport, and which routes they fly. In addition, the growth rates of the airport will increase (or decrease) the overall number of flights from the airport over time which will also have an effect on the number of LH2 aircraft they service. The fact that initially LH2 aviation will not be adopted by all airports simultaneously means that as adoption grows, this will also mean that more and more airports will begin to be able to facilitate LH2 aircraft. This will have a compounding effect with the general increase in adoption because then additional routes that were previously not achievable using LH2 will become possible. Ultimately it is important that it is understood that these factors combining with the fact that these estimates are very early, and the development and market entry could go wildly different mean that the predictions are not, and cannot be expected to be very accurate as of now. In addition to this, the models addressed in this report come from literature that, although attempting to be realistic on the topic, are quite positive about the potential of LH2. This should also be considered, and the models should be taken with a grain of salt.

3.5.1. LH2 Aircraft Adoption Effect on Airport Infrastructure and Logistics

Although the exact magnitude and timing of the increase in LH2 aircraft adoption, and thus the LH2 demand at an airport, is as of yet not very clear, if LH2 aviation is initially adopted, it will likely grow over time. For an airport and its stakeholders and partners, it is important to understand what effect this growth has on the infrastructure they must manage in order to keep up with the demand. A few things are immediately apparent with growth in LH2 demand:

1. The refueling infrastructure will need to be able to deal with increasingly more aircraft
2. The storage infrastructure will need to be able to store higher amounts of LH2
3. The production and logistics infrastructure (whether at the airport or elsewhere) will need to be able to produce and deliver higher amounts of LH2
4. There will be a higher demand of water and renewable energy to generate the LH2

Logically, with more aircraft to refuel with LH2, the infrastructure will need to increase in its ability to meet that demand. This could mean either sizing up the initial method of refueling or could mean that an airport switches to another form of LH2 refueling infrastructure which is better suited for high demand. An example of this could be an airport first switching from a bowser truck system towards a hydrant system. It is also possible that as this switch is taking place both operate simultaneously. A similar story could be expected from the storage infrastructure. As LH2 demand increase the storage systems will need to be updated. This could mean simply adding a number of new tanks, but his could also mean a switch in philosophy such as going from a centralized storage location to a more spread-out system. This switch would likely and logically go hand-in-hand in some form with the changes made to refueling infrastructure.

Additionally, if the supply of LH2 does not increase, then the demand at an airport will be left unfulfilled and the airport will not be able to adopt the technology further. Then sizing up the storage and refueling

infrastructure is not needed. To increase the possible production infrastructure the airport or another third party that produces the LH2 would need to both increase their electrolysis and liquefaction capabilities while also getting more water and renewable energy to fuel this. One interesting opportunity here is to capitalize on economies of scale when significant amounts of hydrogen are needed making the economics of this technology potentially more sustainable later on in adoption (Hoelzen et al., 2021). Likely the most difficult component of that is the sourcing of large amounts of additional renewable energy. If there are issues with this, the best way this could be done is by building additional wind, water or solar energy generation infrastructure. Also, if LH2 production can be ramped up, the logistic infrastructure also needs to increase accordingly. If this infrastructure is located at the airport this will be less of an issue, but if it is not there are two options. Either the airport and/or the supplier/producer ramps up the current logistic infrastructure, or they switch to another type which is better able to handle the increased load. An example of a switch in infrastructure could be that originally LH2 trucks were used, but that due to the high demand too much road congestion and safety hazards were created so the switch a GH2 pipeline and liquefaction plant at the airport is made.

4. Results

As explained in the chapter on research methodology (Chapter 2), to begin gaining understanding on how the transition towards LH2 infrastructure will go, the first part of the transition management cycle will be performed. The Transition management cycle, as created by Loorbach (2007), consists of four main steps:

1. Problem structuring, establishment of the transition arena and envisioning,
2. Developing coalitions and transition agendas
3. Mobilizing Actors and executing projects and experiments
4. Evaluating, monitoring, and learning

This cycle was created with the intent to be continually performed to manage a transition as it progresses and matures. Thus, with each iteration of the transition management cycle it can be expected that more is learned about the transition at hand, and it can be managed more effectively. In this research, the first iteration of this cycle for this transition will be looked into. Steps 1 and 2 will be in large part thought through and prepared. In addition, initial thoughts on how to perform step 3 of the cycle will also result.

Steps one, two and three of the transition management cycle will be approached in the following way: First, a vision of the infrastructure will be created which will give a more accurate idea of what the end point of the transition could look like. With an infrastructure vision and the intermediate steps that need to come with it, clearer structuring of the problem and creation of transition arenas can be done. This transition vision will be created in an iterative way using knowledge from literature and expert interviews (section 4.1). Then, the specific nuances that come with this transition vision will be translated to opportunities and challenges which will structure the problem more clearly (section 4.2). These governance activities are part of step one of the transition management cycle and thus are also focused more on the strategic scale level. With step one of the transition management cycle completed, a transition agenda can be built and valuable coalitions can be explored as the second step of the cycle. The governance activities performed here are on the tactical scale level. A transition agenda will be created through building a roadmap for the transition that will need to take place at Schiphol (section 4.4). The resulting roadmap will clarify which actors need to be mobilized and which projects and experiments need to be executed. To more effectively create this roadmap, transition, complexity, and stakeholder management theory will be taken into account (section 4.3). Then, these results will further be strengthened through the process of validation (section 4.5).

After the process described above, half of the first iteration of the process management cycle will have been completed. Step 4 where evaluating, monitoring, and learning is required (reflexive governance activities) is something that can only be done after step 3 has been implemented and actual projects and experiments have been executed. Thus more operational governance activities are required here. As the transition progresses, Schiphol will need to further perform this cycle in order to manage the transition effectively.

The final step of the results will consist of generalization of the aforementioned results (section 4.6). The previously stated application of the transition management cycle is specific to Schiphol and their eventual transition to LH2 infrastructure. The learning from this case study can be used to gain a better understanding of how this could go for all airports.

4.1. Step 1: Iterative Transition Vision Construction

Before a general idea for how to manage the transition to LH2 infrastructure for the airport can be derived, the management of this transition will be closely analyzed for a specific case, Schiphol. The first step in managing this transition, is to get an accurate idea of what the transition will be towards. Although it is a given for this research that some form of LH2 infrastructure will be needed at Schiphol, understanding in what form is key in understanding how to get there. To do this, the first step is to build a plausible and likely infrastructure vision for the LH2 logistics, storage and refueling infrastructure. In this chapter the process used to build this infrastructure vision is explained and the result of this process is discussed. The entire iterative process which was followed to reach this vision is more clearly explained in Appendix section A.1. There, an initial

infrastructure vision will be built based on literature and publicly available information on the technology, its feasibility in general, and the Schiphol case. After the first infrastructure vision is built, it will iteratively be tested through interviews with experts/stakeholders. This allows for specifics of the vision and the environment in which it exists to be better understood to ultimately improve the vision. After multiple iterations, the vision will have been tested and improved in many different dimensions, thus making it the most feasible, logical, and likely scenario based on current information. It needs to be stated though, that although an attempt is made to get an accurate picture of this transition, due to both the complexity of the industry and the early stage of this analysis, there are no guarantees and things may change. As time goes on an many assumptions and/or guesses become clearer, elements of the infrastructure vision may change.

The process for vision iteration (which can be seen in Appendix section A.1.) went as follows. First the initial vision was built from literature and publicly available information. As part of this initial vision a LH2 demand forecasting model was built which gave more clarity as to the expected numbers and required sizing of infrastructural elements. The findings from this are explained in detail in the first section of Appendix A.1. and the model itself is visible in Appendix A.2 and A.3.. Then, this first vision was used in the discussion with a member of the Schiphol Master Plan department to gain extra information on how Schiphol prepares for such future developments. After that, the updated vision was discussed with two parties well versed in cryogenic infrastructure technology, Demaco and Cryoworld, in order to understand infrastructure technology and its feasibility. After the feasibility of this technology was established, a look was taken at the feasibility from a safety and regulations standpoint. The fourth interview was conducted with the Dutch Ministry of Infrastructure and Water Management (Min I&W), the fifth was conducted with the Schiphol Fire Brigade, and the sixth was conducted with the Dutch Human Environment and Transport Inspectorate (IL&T). These parties helped in gaining an understanding of what needs to be thought through regarding safety, regulations, and policy when Schiphol wishes to supply LH2 to the airport and fuel aircraft in a new manner with LH2. Finally, to look into the logistic feasibility side of the puzzle, a seventh interview was performed with the Port of Amsterdam on their potential role in the supply of (liquid) hydrogen to the region. After each interview the vision was improved based on new information and expert opinion on the matter. Ultimately, after the final interview, the final infrastructure vision on which the subsequent steps of the methodology will be based could be determined.

The parties selected for interviewing were a deliberate choice. Based on the elements which influence which infrastructure and logistics vision works best for a given airport learned from the literature, key players in Schiphol's environment were selected. Schiphol Masterplan, Schiphol Fire Brigade, Ministry of I&W, IL&T, and the Port of Amsterdam are all parties that have a big role to play in such a transition for Schiphol and have a significant amount of information on how their respective elements of the industry function. Demaco and Cryoworld are not yet as active in the Schiphol network, but since at the moment Schiphol has limited knowledge on LH2 cryogenics it is valuable to have their expert knowledge and years of experience to add to the research. The order in which the interviews were conducted was also deliberate. First Schiphol Masterplan was approached to give an initial view on how Schiphol prepares for and works with changes that need to happen on a long time-span and further in the future than a couple of years. This gave a clearer starting point for what Schiphol would need to know and do. Then, technology development parties were interviewed next since they could confirm what is feasible and what isn't which would confirm whether the initial vision can be expected to be possible, or whether an overhaul in thinking is needed. With confidence in the achievability of the technological side of the transition, rules, regulations, and safety were considered because without a clear grasp of this it is not realistic to implement the new infrastructure and operations at an airport such as Schiphol. Then, to understand what's involved with the logistic supply of LH2, a party which from research could play a big role here –the Port of Amsterdam– was approached. Thus, the priority of importance in the overall feasibility of the infrastructure vision was the leading factor in the order of the interviews.

4.1.1. Building an LH2 Infrastructure Vision

Knowing what vision regarding the LH2 infrastructure for logistics, storage, and refueling is best over time for Schiphol specifically depends on a number of complex factors. The following are the main ones:

- The expected LH2 demand of the airport over time
- Technological development of possible infrastructural elements over time
- Financial viability of each infrastructural element (CapEx and OpEx)
- Geographical location of the airport and surrounding features
- Stakeholder capabilities and wishes
- Rules, regulations, and safety

Each iteration of the infrastructure vision (viewable in Appendix section A.1.) was based on the best knowledge of these factors at that point in time. As interviews were performed, more light was shed on the specifics of these factors meaning that the infrastructure vision changed during this process. Each change to the infrastructure vision was newly discussed in the subsequent interview meaning that that interview was in part influenced by it. Over time the vision became more and more accurate as more interviews were performed.

Each vision focuses on the three main infrastructural elements which have been discussed at length earlier in the literature review (Chapter 3.). They are the logistic infrastructure to supply LH2 to the airport, the storage infrastructure to store LH2 at the airport, and the LH2 refueling infrastructure. How each of these elements are done is very important. Another key factor is time. Over time technology, demand, and other key factors can be expected to change meaning that the best solution may change as well. Thus, two different moments in time are selected. The first is 2035 when this infrastructure is first expected to be needed, and thus it is still very new, and demand is lower. The second is 2050 when LH2 aviation is expected to be more accepted, adopted significantly more on a global scale, and thus demand is on the higher side.

4.1.2. Finalized LH2 infrastructure vision

The final LH2 infrastructure vision which has been derived iteratively based on literature and expert opinion is shown here. Table 3 shows phase 1 infrastructure, Table 4 shows phase 2 infrastructure, and Table 5 shows the specific considerations related to these two infrastructure visions.

Table 3: Infrastructure vision phase 1 (2035)

2035 (Phase 1)		
Logistics	Storage	Refueling
Offsite LH2 production + Truck delivery of LH2 to Schiphol	Centralized LH2 storage location	LH2 bowser trucks used for aircraft refueling away from the gate at centralized location
<p>The diagram shows a production facility with wind turbines, solar panels, and industrial buildings. A truck is shown transporting LH2 from the facility to the airport. Labels include 'Off airport', 'At airport', and 'Transporter'.</p>	<p>The map shows a central storage location between Amsterdam and Haarlemmermeer, with a truck icon and a storage tank icon.</p>	<p>The diagram shows an LH2 bowser truck connected to the fueling system of an aircraft on the tarmac.</p>

Table 4: Infrastructure vision phase 2 (2050)

2050 (Phase 2)

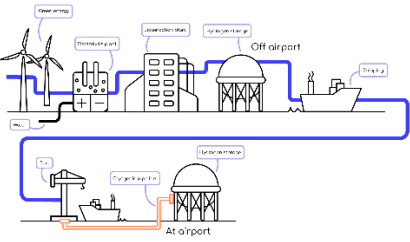
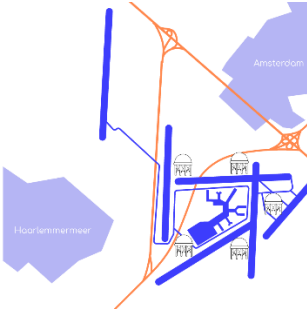
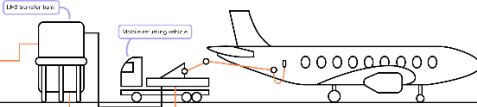
Logistics	Storage	Refueling
Offsite LH2 production + Cryogenic LH2 pipeline delivery to Schiphol	Spread LH2 storage	LH2 Hydrant refueling at the gate
		

Table 5: Specific considerations for phase 1 and phase 2 infrastructure visions

Specific Considerations
<ul style="list-style-type: none"> • LH2 logistics, storage, and refueling infrastructure is achievable and largely will use existing technology. A number of things need to be specifically developed: 1. Breakaway couplings, 2. Purge-less couplings, 3. Larger storage tanks, 4. Long-distance cryogenic pipelines, 5. Aviation specific operation equipment such as refueling vehicles and hydrant system • In all stages it is likely best to import LH2 for Schiphol via the Port of Amsterdam (possibly through Zenith). Early on this can be transported to Schiphol from the port via trucks (or barges) and later (likely between 2040 and 2050) via cryogenic pipeline. • An LH2 supply strategy where GH2 is produced elsewhere and liquefied at Schiphol may still be possible in certain low demand scenarios. There are already plans for large electrolysis projects. In this case Schiphol could be connected to the HyWay 27 GH2 lines. • Importing enough LH2 for Schiphol can be an issue since the EU may limit LH2 supply if it cannot supply enough for all member states. • Early on about a 10-meter radius LH2 storage tank will likely be enough. Later additional more (and possibly bigger if developed) tanks will need to be added. • LH2 bowser trucks will be a realistic option for refueling for the first few years but will likely become overwhelming sometime between 2040 and 2050. Then investments should be made to build a hydrant refueling system. • If turnaround times allow for it, when refueling is done with LH2 bowser trucks, it would be wise to do this away from the gate to ensure safety early in the transition. When the transition to a hydrant system is made the technology will have progressed, If risks of refueling are low enough refueling could take place at the gate. • Installing a hydrant refueling system around the same time as bigger LH2 aircraft enter the market will allow for two birds to be killed with one stone because this will allow for aircraft stand redesign. This is needed because there is a real chance that efficient aircraft servicing will require more space than there currently is. • Infrastructural plans need to be discussed at length and early on with airlines to ensure infrastructure will match the demand from the planned aircraft acquisition. • The development and building of integrated infrastructure technology will require early dialogue to take place between developers and authorities. First The technology development is needed for safety and risk analyses to be performed. Only then can regulations be made for it. • Since Schiphol operates on the longer-range and larger side of aviation, it can be expected that adoption will benign slower, but go faster later on.

4.2. Step 2: Definition of Opportunities and Challenges

The final infrastructure transition scenario which was derived iteratively in the previous step gives a great overview of what infrastructure likely will work best over time for Schiphol based on literature and expert information. However, translating this to actionable steps that can form a roadmap requires additional analysis. In addition to the methods of logistics, storage, and refueling given in 2035 and 2050 shown for the infrastructure scenario, a third table shows the specific considerations. This has been added, because there is a lot of nuance that comes with the implementation of this type of infrastructure at Schiphol. This nuance has also been learned partly through both the literature and the expert interviews. It attempts to summarize and encapsulate the deeper learning that has come throughout the process of determining which infrastructural elements would be best for Schiphol's situation and when. In this section these specific considerations will be further analyzed by categorizing them into either challenges (negative aspects) and opportunities (positive aspects). Identifying which aspects of the transition towards this type of infrastructure will be challenging for Schiphol, its network, and the industry as a whole is the first step in dealing with them. Working on dealing with these threats will be done in subsequent chapters. Also, identifying the opportunities allows for Schiphol, its network, and the industry to capitalize on them and make use of the potential value that can be gained from them. Once again, the specifics for how these opportunities can be capitalized on will be discussed in subsequent sections.

4.2.1. Challenges

As with any transition, there are challenges to overcome. If a transition like this was easy and had no obstacles, then it would already have taken place. There are challenges that any airport which adopts LH2 aviation will face and there are challenges that are more specific to Schiphol and its situation. Here is a list of the identified challenges:

1. **Low amount of LH2 knowledge within Schiphol:** As of the execution of this research, internally at Schiphol there is not a significant amount of knowledge on LH2 aviation, and specifically, the LH2 infrastructure needed for this. Understanding what can be expected and what is possible is key in making good transition management decisions. More information needs to be gained quickly if the correct steps are to be taken already early on in the transition process. Although this is a challenge for Schiphol, this is likely the case for many airports around the world.
2. **Need to maintain low turnaround times:** For aviation to be profitable, aircraft need to be constantly in the air flying. Any time they are on the ground not being used is wasted profits. Thus, lowering the time needed for refueling, boarding, and other services (the turnaround time) is at a high priority for airlines and airports alike. If an LH2 aircraft cannot be refueled at the gate, at the same time as other servicing procedures take place, or when passengers board, this will increase the turnaround time and thus lose airlines and the airport money. This is a general challenge with LH2 aviation.
3. **Aviation market weakened by Covid-19 pandemic:** Due to the recent Covid-19 pandemic global travel dropped significantly. This was a big hit for the aviation industry as a whole. All parties including airlines, manufacturers, and airports had much less business which required them to shrink. As mentioned by Rob ten Hove in his interview, Schiphol has been predominantly focused on building back up now that the pandemic has mostly subsided and allowed for global air travel to return to normal again. This means that fewer resources such as manpower and money can be invested in preparation for sustainable aviation. Although issues from the pandemic are currently very visible at Schiphol, this is a problem for the whole industry.
4. **Higher direct operating costs (DOC) from LH2 aviation:** It is expected that LH2 aviation will have higher costs attributed to the initial investments for infrastructure and aircraft and the costs for operation such as the LH2 fuel, crew, and maintenance. This will add expenses throughout the entire value chain, including the airport. The feasibility of LH2 aviation in general will depend on if these extra costs can be handled by the market. This is an issue that the whole industry will face. Also for specifically the chosen method of LH2 supply chosen for Schiphol, the fuel cost may be even higher

because of the need for long-range transportation. It needs to be mentioned however that this does mean that no liquefaction (and electrolysis) plant(s) need to be built for Schiphol which reduces investment cost. What this means for the overall costs is yet to be determined.

5. **Limited LH2 supply from importing because of EU policy:** Vera van Lint mentioned in her interview that in the Netherlands there are currently limitations as to how much SAF can be mixed with regular fuel on flights because the EU wants to ensure that all member states get and use an equal amount (to ensure that there are no imbalances in the market causing price differences). The same issue could arise with LH2. Since the EU is a stronger party for negotiations regarding the buying and importation of fuels, they are the party which handles that. However this means that internally member states will need to negotiate for the amount of fuel that they can get and use. If LH2 supply is limited, the adoption of LH2 aircraft at Schiphol (and all other European airports) would be limited as well. This could have a greater effect on the global effectiveness of LH2 aviation.
6. **Importing LH2 makes Schiphol dependent on multiple 3rd parties and other countries:** There are talks of producing hydrogen (and potentially in liquid form) in different countries such as Chile and transporting this to Europe. In such a situation the logistic supply chain for Schiphol would be dependent on another country and the parties that are generating electricity and hydrogen and transporting it. This is more similar to how it is currently done with kerosene. However, questions need to be asked about the consequences of this.
7. **Causality dilemma regarding the development of LH2 infrastructure regulations:** As became clear from the various interviews, the technology developers are waiting on regulations for the infrastructure whereas the regulatory parties are looking to make laws based on the technology capabilities. This shows that there is the real potential for a chicken and egg situation where both parties are waiting on each other and no progress is made.

4.2.2. Opportunities

Due to the fact that the infrastructure scenario from the previous step has been crafted specifically for Schiphol and its specific environment, there are a number of opportunities that clearly arise. If identified these can be capitalized on to strengthen the transition to LH2 infrastructure. Most opportunities specifically arise from the chosen infrastructure scenario for Schiphol but could be the same for other airports that choose to make similar choices. They are the following:

1. **Importing LH2 via the port of Amsterdam:** Because on-site liquefaction (and electrolysis) would be very difficult for Schiphol, the concept of importing hydrogen in its cryogenic form is one that deserves attention. Since the PoA is so closely located to Schiphol and already has a background being a fuel shipping port, there is a perfect opportunity to import LH2 for Schiphol here. The port is already looking into ways to supply hydrogen to the area and even has a party (Zenith) which is looking for potential LH2 users. Importing LH2 to be converted to gas is not economically advantageous in traditional cases, but if it is directly used in its liquid state by the end user (like for aviation) then this is a very interesting option for them as well.
2. **Expanding Aircraft stands and installing a hydrant system when larger LH2 aircraft enter the market:** The potential to kill two birds with one stone appears during the eventual transition from LH2 bowser truck refueling to a hydrant system. To install the hydrant system big changes need to happen to the aircraft stand. It was also pointed out that if many or all aircraft servicing operations need to be performed simultaneously at the aircraft stand (to reduce turnaround time) that the current average aircraft stand at Schiphol would be too small, especially for larger LH2 aircraft. It is expected that later in the adoption process the larger-scale and longer-range LH2 aircraft will enter the market. With the adoption of these aircraft and the desire to switch to a hydrant system, Schiphol should also expand their aircraft stands because there will already be large-scale construction happening.

3. **Economies of scale when producing LH2 outside of Schiphol at a central location improving efficiency:** If LH2 is not produced at or near the airport, but instead produced at a central location (for example Chile) to export to a variety of locations and industries, then in all likelihood a much larger amount of LH2 will be produced in this one location. This allows for economies of scale to be at work and reduce the average production cost of each unit of hydrogen or LH2. The potential production locations mentioned also are selected because of their significant natural, renewable resources. This would further lower costs of energy and thus hydrogen. It needs to be mentioned that the hydrogen will need to be transported to the final use location, thus adding costs. The net gain/loss from this trade-off is yet to be determined
4. **Large scale LH2 storage can improve robustness of LH2 supply and can function as an additional form of renewable energy for Schiphol energy demands or income by supplying other users:** Since Schiphol will need to store LH2 to be able to refuel their aircraft reliably, there is an opportunity here. Firstly, large-scale storage of multiple days worth of hydrogen will increase the robustness of the logistic system. If for one or two whole days no LH2 can be supplied to the airport, then this buffer can ensure that operations can continue as normally. In addition to this, with such a large storage capacity which will for the majority of the time go unused, there is the possibility for Schiphol to use this to supply/supplement its own power requirements for lights, electric or hydrogen vehicles, and any other needs. In addition, Schiphol could become a de facto hydrogen hub in the area which sells either LH2 or GH2 to other smaller consumers in the area. If this scenario is pursued, this may even lower the airports operating costs of utilizing LH2 aviation.
5. **Rapid experimentation and information gathering through research initiatives such as TULIPS and using resources such as the smaller Rotterdam the Hague Airport:** Schiphol has a unique chance to gain a lot of information on LH2 aviation, and thus LH2 infrastructure as well, through research initiatives such as TULIPS. In the future, research with more focus on LH2 could be very valuable. Luckily there are a lot of innovative parties in the Netherlands looking at this possible future. This type of research can also be more easily performed at an airport such as Rotterdam the Hague Airport. Since it is a much smaller scale, but still part of the Schiphol group, this could potentially be a testing ground for elements of the LH2 infrastructure.
6. **Storing LH2 spread around the airport improves safety, supply robustness, and efficiency:** The Schiphol fire brigade made it clear that regarding safely storing hazardous substances such as LH2, there are a number of considerations to be made. Storing LH2 in a spread-out manner means that each storage is smaller and thus will have a less extreme effect in case of an emergency. Both in terms of the danger from fires and/or explosion and in terms of less LH2 supply being lost so that a portion of operations could still continue. Also, this means that there is a much lower chance of multiple tanks failing due to the domino effect. This pairs well with the fact that storing LH2 in multiple locations around the airport would mean that when a hydrant system is used, shorter LH2 pipelines (lowering losses) and potentially fewer buffer tanks are needed. Thus both safety and efficiency could increase with the choice to store LH2 in multiple locations.
7. **Refueling away from the gate when using LH2 bowser trucks for refueling allows for increased safety and a period of use to improve safety of systems before a hydrant system is implemented at the gate:** In accordance with the chosen LH2 infrastructure scenario, during the phase of adoption when there are still relatively few LH2 aircraft being serviced and refueled at Schiphol, LH2 aircraft will be refueled by LH2 bowser trucks and away from the gate. A potential opportunity can arise here. It is generally expected that it should be possible to refuel with LH2 in a safe manner, but as it is with many technologies, the initial version of it could have issues and requires a phase of learning before it can be used more optimally (and safely). If Schiphol is indeed a rather early adopter as it is expected to be, then it may be possible that safety is lower in its earlier years than eventually will be possible. During these early years, instead of using a LH2 hydrant system, LH2 bowser trucks will be used which

gives the freedom to refuel wherever desired. Schiphol could choose to be safe during this phase and refuel away from other operations and the gate. Although this will impact turnaround time drastically, since LH2 aviation is still rather novel and not as common, it may be less of a critical issue.

8. **Ending the use of APUs so planes use electricity from the airport makes refueling safer:** Aircraft use auxiliary power units (APUs) to generate electricity while at the gate of an airport (Mark, 2021). It was explained in the IL&T interview that the use of APUs could potentially be hazardous during LH2 refueling since it is a potential ignition source. A switch to ground-based power which is delivered directly to the aircraft instead of the use of an APU would potentially make LH2 refueling safer. Transitioning away from APUs is already a goal of many airports and this would also benefit LH2 aviation.

4.3. Step 3: Application of Management Theory

Sections 4.1 and 4.2 have resulted in a transition vision, a more structured problem, and clarity on the transition arenas needed. Thus, the first step of the first iteration of transition management cycle has been thought through. Before the second and third step can be worked out through the creation of a roadmap, more management theory will be applied to the case to ensure that the elements of a transition, complexity, and stakeholders are more effectively managed. The theoretical basis that will be applied in this chapter was explained earlier in section 3.1. The conclusions drawn from the application of this theory will further help to build an effective roadmap for Schiphol.

4.3.1. Progressing the Transition Effectively

Originally developed by Geels et al. (2017), the **three mutually reinforcing processes** is a framework for how a transition can be stimulated. It consists of three overarching strategic activities which influence the effectiveness of the transition (Loorbach & Wijsman, 2013). Each process, if aimed at the same goal, support each other further progress the transition at hand. The first process is *increasing momentum of niche innovations*. In the context of the transition tackled in this research, the niche is LH2 aviation and more specifically, the infrastructural system needed to service LH2 aircraft. Thus, ensuring that the LH2 aviation and its infrastructure is supported and strengthened is a key activity in progressing the transition. The three niche processes can aid in this.

Three Niche Processes

The **three niche processes** from Kamp and Vanheule (2015), is a framework of dynamically interrelated processes which give guidance on how niche innovation can be strengthened. The first niche process is to *shape and voice expectations*. Thus, in the process of developing LH2 infrastructure at the airport, it is important to set goals which are clear and shared by multiple actors. Within the roadmap, specific expectations for the progression of development need to be set in order to make it easier for participants to join the niche and invest effort, money, and time. For example, instead of stating that infrastructural subsystems and elements need to be developed over a period of time, clarity needs to be given as to what elements need to be developed and when they need to be developed. In addition giving clear directions for the results of development, such as reaching a certain technology readiness level, would be beneficial. Such specific and robust goals which make niche development, and thus the transition, more effective, could be set for the development of technology, operations, policy, networks, etc..

In addition, the second process is *network formation*. Schiphol needs to understand which parties it needs to work together with and how it needs to work with them in order to form effective networks for niche development. Thus, in the roadmap, it needs to be clear which parties Schiphol needs to open a discourse with or work together with to achieve a certain goal. This goes hand-in-hand with the first process of voicing expectations since setting clear goals allows for partners to be found more easily and for networks to be shaped around what needs to happen. Regarding, for example, the end goal of securing of a robust LH2 supply, it needs to be clear in the roadmap what parties Schiphol needs to open a discourse and start a

network with to work towards this goal. Then, with a specific goal it is easier for participants to join the development process. Aligning parties with similar end goals in networks helps sustain niche innovation. To further aid in this, the last niche process is to *learn*. This goes together well with the previous two since the voiced expectations and formed networks play a role in the learning process. As goals are set and networks form to work towards these goals, learning is required to ensure that the niche develops in relevant ways. It is key to incorporate learning processes into the roadmap for all different elements of the transition. Regarding, technology development, policy implementation, financial viability, etc., there are a number of things which will need to be learned along the way as the niche matured and the transition progresses.

The above discussed niche processes aid the increasing of the momentum of niche innovations, however, to further stimulate the transition to LH2 infrastructure at the airport, the *existing system also needs to be weakened*. The existing system, in this case traditional infrastructure for kerosene-based flight, needs to be weakened in order to be removed from its incumbent position as the current socio-technical regime and be replaced by the developing LH2 niche. There are a couple of ways in which this could realistically come about. Firstly, there are uncontrollable landscape factors at play currently which already pose a threat to the existing system. Two clear ones are the eventual depletion of natural resources requiring an eventual switch to renewables and climate change. Climate change influences whole countries and industries to move towards more sustainable processes which causes kerosene-based aviation to be weakened. This weakening comes about from the changing of agendas towards sustainability which results in new policy which favors sustainability and weakens fossil-fuel based operations. Over time these can only be expected to further increase as the public and private sectors both feel the pain of climate change. Although this is in a sense something that cannot be controlled directly by the aviation industry, and more specifically Schiphol, it is important that the right steps are taken. One clear example is that Schiphol can focus on lobbying to change agendas to be more in accordance with sustainable aviation (and thus LH2).

Weakening the existing system is closely related to the third mutually reinforcing process, *strengthening exogenous pressures*. Exogenous pressures, otherwise known as coming from the landscape, are pressure that come from the environment which influence the way that the niche and regime interact. An example of such a pressure is climate change. This is an exogenous pressure, which also weakens the existing system. Thus, if Schiphol does, as an example, lobby the government for favorable policy for sustainable aviation, both the exogenous pressures are strengthened, and the existing system (regime) is weakened. In addition, the momentum of niche innovations is also increased. In this example, it can be clearly seen how certain actions interact with all three of the mutually reinforcing processes developed by Geels et al. in 2017. This also works the other way around. Investing to increase the momentum of the niche may take away from the regime which further weakens it. The dynamic interrelatedness of these processes shows how individual actions can have ripple effects throughout the entire transition. The takeaway from this is that all actions and governance activities suggested in the roadmap for Schiphol need to be thoroughly considered. The effects on both the regime and the niche need to be understood and aligned for these activities to be valuable in the greater transition. This inherent interconnectivity of all elements of the transition and the actions that are performed means that there is a high degree of complexity to be dealt with.

4.3.2. Transitioning in a complex environment

In the previous section, while developing an understanding of how the transition can be stimulated, it was also concluded that this is an inherently complex endeavor. Maintaining clarity through this complexity is key in effectively managing the transition to LH2 infrastructure at the airport. In a 2009 paper, Rotmans and Loorbach explain a set of **5 basic principles for how to deal with complexity during socio-technical transitions**. The first is that *management at the system level is important*. Implemented changes can be clearly observed and reflected on at a system level. This means that while management of the specifics of a transition is clearly important, it is also important to look at it from a higher level to fully understand the consequences of actions. This brings with it that management at different levels of detail is key in effectively working with complexity. “Emergent properties might be hidden at higher (or lower) scale level[s]... (Rotmans & Loorbach, 2009).” Relating this to LH2 aviation, it is important to approach the transition by working on the minute details of, for example, specific elements of the infrastructural technology in addition to the big picture. Developments of a

specific element may influence niche development as a whole by making certain things possible or not possible. A single piece of technology which is not technically feasible could hold back LH2 infrastructure from being effective, weakening the entire niche. The opposite effect could also happen. Therefore, it is important to take into account with the building of the roadmap that as niche development takes place at high and low detail levels, the effect of this development needs to be tracked across all levels of detail.

Next, *the status (performance) of the system determines the way it is managed*. This principle of complexity management means that “the dynamics of the system create feasible and nonfeasible means for management (Rotmans & Loorbach, 2009).” Thus, it is important to understand aviation, how all elements of the industry function, and the current regime in order to effectively manage a transition. Although a transition changes the system in place, elements of the landscape in which this industry is situated, such as regulations and policy, need to be respected to a certain extent for the transition to take place. Understanding how policy influences aviation and what actions can influence policy leads to better increases of the momentum of the niche and weaken the existing system more effectively. Development of the roadmap needs to take into account these existing structures which cannot (or should not) be completely changed by the transition at hand and use them effectively to make the changes that are desired.

The third principle of complexity management is that *objectives should be flexible and adjustable at the system level*. Complexity “is at odds with the formulation of fixed objectives (Rotmans & Loorbach, 2009).” This refers to the fact that if a fixed objective is set, due to complexity unforeseen things may happen which can change the feasibility of said objectives. If a system is set up to not be impacted as much by such events, it is more effective in a complex environment than one that is rigid. As learning and development takes place, it needs to be possible to use these lessons to further development instead of halt it. This goes hand in hand with the niche process of *shaping and voicing expectations* which states that there is a need for setting clear goals. A balance needs to be found with setting specific and robust goals that can be worked towards and setting goals which are rigid and cannot flexibly deal with changes that come from complexity. Often, clarity results from rigidity, meaning that these two concepts can be at odds. A way to deal with this is that at a high level of detail, small goals are clearly set in a more rigid and fixed manner. However, system level goals must be flexible and able to change based on the outcome of development. Thus, the system overall is flexible while specific goals are maintained to fuel development and actor investment.

Fourth on the list of principles to manage complexity is *using disequilibria rather than equilibriums*. Meaning, that change comes from a period of disorder instead of order. The stagnation that comes from balance hinders innovation and progression. There needs to be an imbalance in terms of desires to influence change towards a better system. If there is no such disequilibrium, then there is no reason for a transition to take place. Currently, due to climate change, all industries using fossil fuels are currently producing undesired results; polluting the earth and wasting resources to generate value. The desire is to move towards an economy where value can be created in a sustainable manner using renewable energy sources. Thus industries, such as aviation, are currently at a disequilibrium which drives change. Then to strengthen the transition towards LH2 aviation and infrastructure, this imbalance needs to be progressed to the point at which regime change is required. This comes back to the 3 mutually reinforcing processes for transition (Geels et al., 2017). Thus, the instability and chaos that comes with such disequilibria, although they bring complexity, need to be accepted for they are the catalyst for change.

The final principle is that *creating space for agents to build up alternative regimes is crucial for innovation*. This relates back to the first of the reinforcing processes for transitions (*increasing momentum of niche innovations*), the three niche processes for innovation, and the creation of transition arenas from the transition management cycle. Clearly, development of the niche for it to replace the incumbent regime is a central part of a transition. Managing a transition effectively means creating space for agents to do this. This is also interpreted as that complexity needs to be removed from development as much as possible. Agents need to be able to focus on development of individual elements without worrying about the interconnectedness with the rest of the transition. Thus, effective management of a transition required the management team to focus on the complexity while individual agents can focus on specifics without the other noise. This division between

the rules of high-level decision making and the specific development at a high detail level needs to be clearly portrayed in the roadmap.

4.3.3. Path Dependence and Working with Stakeholders

Path dependence is the tendency of institutions or technologies to become committed to develop in certain ways as a result of the structural properties of their beliefs and values (Greener, 2019). Because of path dependence, current and future states of a firm or system depend on its past (Rotmans & Loorbach, 2009). Understanding what causes path dependence and how it can be dealt with therefore allows for it to be avoided when needed to ensure more flexibility in an organization. As previously established, flexibility in the face of complexity is much more valuable than the rigidity that would come with a process (like a transition) which is heavily path dependent. Lamberg et al. (2008) have identified four elements that typify a process as path dependent. Firstly, a firm's *dependence on initial conditions* is important. This comes down to an organization's current and past relations with stakeholders. It is therefore suggested that Schiphol takes time to gain full understanding of their stakeholder relations in the early phases of the transition. A history of conflicts, for example, gives key insights into how to deal with stakeholders. And previous conflicts with important stakeholder groups which may cause the initial conditions to be negatively favored for a transition to LH2 infrastructure should be dealt with accordingly. Else this could create a "vicious cycle of conflict escalation that [is] difficult to reverse (Lamberg et al., 2008)."

This concept also is closely related to the second element of path dependence, *the web of commitments*. It is important that Schiphol has a full and clear grasp of the commitments that they are entangled in before drastic changes from the transition take effect. For this, once again, an understanding of the stakeholders and the commitments to them is needed. If for example, Schiphol had a deal with certain parties related to the current socio-technical aviation regime, this could influence how effective Schiphol will be at moving away from it and towards the LH2 niche. If in the unfortunate case that commitments need to be broken, then having a firm grasp of what they are will also give additional future insight into how certain firms will react and the consequences. This allows for more informed decision making to take place. Also, knowing the complexity of the web of commitments leads to Schiphol better being able to adopt strategies equal to the complexity of this environment (Lamberg et al., 2008). Lamberg et al. (2008) explain that one strategy to deal with the contractual commitments that a firm may have is to involve these actors in initial negotiations. Thus, identifying the commitments to stakeholders and talking to these stakeholders early on should be of high priority to Schiphol.

The next element which typifies a process as path dependent is the *network effect*. The basic concept here is that the larger the network, the more complex. More contractual linkages thus leads to an actor network which is less predictable and harder to work with. A balance needs to be found between building a direct network with all of the information and capabilities needed for the transition at hand, without increasing clutter to an unmanageable level. To do this, Schiphol will need to first have a very clear overview of the capabilities and knowledge needed for the transition to new LH2 infrastructure. Based on that, only the stakeholders needed for this should be selected to be directly worked with. In this way the initial conditions and the web of commitments can also be limited as much as is possible.

Then, the final element of path dependence, is the *sequence of events*. In a tactical sense it is clear that a process such as the transition of an organization and industry plays a key role in how to approach it. Both in the past the sequence of events and how the sequence of events will need to play out in future developments plays a role in the path dependence of a process now. At this point, it is key for Schiphol to gain an understanding of the expected required sequence of events for the transition to ensure this is considered for current decisions. This will lead to more informed current decisions leading to less path dependence of the transition. One such event in the sequence which should be taken into account are the complex, multi-party negotiations which are associated with the initiation of change. Often this is seen as something to be avoided and not planned around, but instead this should be seen as an inevitability which should be considered as part of the process sequence. Such processes will doubtlessly arise for Schiphol and thus the created roadmap will need to take this into account.

4.4. Step 4: Building of LH2 Aviation Infrastructure Roadmap for Schiphol

Here, the roadmap which has been developed specifically for Schiphol will be presented. The intended function of this roadmap is to help guide Schiphol in the transition to the LH2 infrastructure vision derived in section 4.1. Figure 13 shows a basic overview of the roadmap.

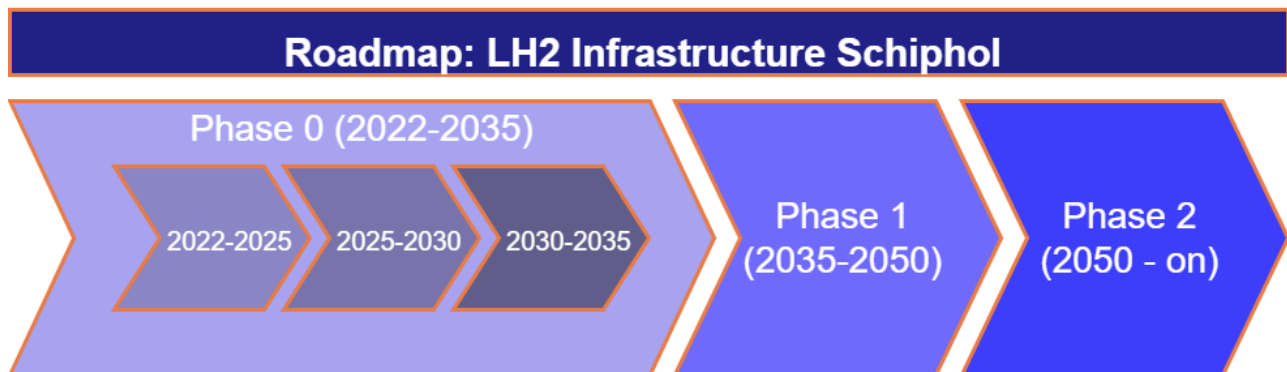


Figure 13: Basic overview LH2 infrastructure roadmap for Schiphol

The basic structure is that of three phases. This structure has been chosen because it pairs well with Schiphol's infrastructure vision. The first phase (phase 0) is completed with the finalized building of the first infrastructure vision for 2035. Then, the second phase (phase 1) ends with the building of the infrastructure vision for 2050. From there the third phase (phase 2) highlights the maturing of the technology into the future. The numbering of the phases begins at 0 because phase 0 is characterized by the lack of LH2 aviation as of yet. During this period this entire technology niche is still in development and not yet functioning outside of potentially some experimental and learning cases. It isn't until phase 1 that LH2 aviation really begins to take off.

Phase 0 is expected to run from now (2022) to 2035 and details the journey needed to go from the current situation as of the writing of this paper to the point at which Schiphol will be able to service LH2 aircraft at the airport. A large portion of the transition outlined in this research will take place during this phase since by the end of it LH2 aviation should be possible to a certain extent. It will end with the building of the phase 1 (2035) infrastructure as shown in the second infrastructure vision derived in section 4.1. Phase 0 is split into three different subphases; from 2022-2025, 2025-2023, and 2030-2035. This is done to allow for more detail to be given to the initial niche development phase. There is more clarity as to what needs to be done in the nearer future than further along the line in phase 1 and 2. The first subphase which runs from 2022 to 2025 will highlight the first steps that are suggested to be started as soon as possible. The second subphase from 2025 to 2030 is intended for progress to be made based on the earlier activities, and the first conclusions to be reached. Then, in the third sub-phase from 2030 to 2035 the final development goals are to be reached and the infrastructure required for phase 1 needs to be built.

With the completion of phase 0, phase 1 will initiate. The focus of this phase is to learn and improve from early implementation of LH2 infrastructure and to use these improvements to scale up leading towards 2050. As LH2 aviation numbers increase over time, a point will be reached when elements of the infrastructure must fundamentally change to allow for effective scaling. Based on forecasting this is expected sometime between 2035 and 2050, but at this point in time, the exact moment when this will happen is not yet sure. Phase 1 ends when the infrastructure has reached the final scaled version as shown in the second infrastructure vision derived in section 4.1. When this happens (likely before 2050 already, phase 2 is initiated. The focus of this phase is on the technology maturation and further learning, improving, and scaling up as LH2 aviation moves towards it's full market potential.

4.4.1. Phase 0: 2022 – 2035

Phase 0 is the phase in which the transition to LH2 aviation will largely take place. During this time period LH2 aviation is expected to develop to the level of maturity where it is market ready and can begin to establish itself as a part of the aviation regime. Transitioning to sustainable aviation options such as LH2 will not go overnight, thus the establishment of LH2 aviation will be a process that goes slowly over a number of years. That is expected to begin around the end of phase 0. However, to understand phase 0 and the actions that Schiphol must take to ensure LH2 infrastructure can be ready for the establishment of LH2 aviation in the regime, first the starting point needs to be known.

Starting Point Phase 0

As explained in section 4.3, it is crucial for a firm, such as Schiphol, to understand its initial conditions before a transition takes place. Both the position of Schiphol relative to the market and its stakeholders is important, but also the initial conditions of the market and industry itself. The initial conditions of the contractual web of commitments of Schiphol is something which needs a significant amount of analysis and is out of the scope of this research. This will be part of the roadmap. On the other hand, the market and industry can be seen as the landscape in which LH2 aviation will need to develop and establish itself and more specifically the landscape in which Schiphol will need to develop and establish LH2 infrastructure. Two main elements of this landscape will be discussed here: a number of relevant actors in it and the state of development.

Firstly, the actors and their current relation to LH2 aviation is a valuable thing to understand. For this research a number of parties which are relevant for this transition were contacted and a select number were interviewed. From the contact with these parties it became clear how they currently view LH2 aviation and the infrastructure that will need to come along with it. Here is a list explaining the current level of focus and knowledge on LH2 aviation of different actors/actor groups which are relevant for the development and implementation of LH2 infrastructure at the airport. Some actors are bundled together, whereas others are kept as an individual. Keep in mind that this is a list of many relevant parties which gives a rough overview, but it is not a comprehensive list.

1. **Schiphol** → LH2 aviation (and infrastructure) is low priority and seen as something in the further future. Focus is currently still on more short-term sustainability solutions which are relevant in the coming years. Hydrogen is considered, but still mostly for ground operations and in the gaseous form. LH2 aviation is on the radar, and they are open to new knowledge, but as of yet knowledge within the organization is very basic.
2. **Policy makers (Ministry of I&W and the Ministry of EZK)** → Hydrogen is a hot topic which has a lot of interest around it. A hydrogen backbone is therefore something that is in development and supported. However, most of this focus is on hydrogen in its gaseous form and more general to the energy economy. There is not yet a lot of knowledge on LH2 for aviation. Regarding sustainable aviation the focus is on more established forms like SAF since they are relevant now. They need more information on how LH2 will work in aviation and its potential and are therefore waiting on the market to develop more before more direct action like developing policy is taken. If LH2 aviation effectively helps reach climate goals for the Dutch govt. then support for this will be high.
3. **IL&T (policy enforcement)** → Since they enforce policy made by the policy makers, their focus is more on the everyday operation than future potential. When it comes to the implementation of new policy, they traditionally have more of a reactionary role than developmental. LH2 is still relatively low on the radar and more knowledge within the organization would be needed.
4. **Safety authorities (Schiphol fire brigade, HSE)** → Their focus is on the safety of day-to-day operations. Currently there is only basic knowledge on LH2 at the fire brigade. However, there are protocols for dangerous substances which they can utilize. Also, there is extensive knowledge on general safety.
5. **KLM (airline)** → LH2 aviation is still a low priority. There is no strategy for it at the moment. They are looking at the market and waiting for more development to take place. They are however committed to being an industry leader and are already in early talks with aircraft developers about future possibilities.

6. **Cryogenic infrastructure technology developers (Demaco and Cryoworld)** → LH2 infrastructure is a well-known technology that they work with on a daily basis. LH2 is already used in select other industries and these parties have experience with that. The use of LH2 for aviation is still rather new and thus development is needed on that front. They are taking early steps, but more development time and money needs to be invested before LH2 infrastructure technology is ready to implement at an airport.
7. **Researchers (FlyZero, Clean Sky 2, TU Delft)** → These parties are where the information on LH2 in aviation's impact for the industry is currently at. They have researched the literature and begun theorizing about the future possibilities based on current technological progress. Within the field of research for aviation, LH2 is a topic with a lot of hype around it.
8. **LH2 aircraft developers (Airbus, ZeroAvia, HAPSS)** → Technological progress within the aviation industry when it comes to LH2 results from the work of these parties. Knowledge on feasibility and the potential is centered here.

As is clear from the above list, most of these parties have very little knowledge on LH2 aviation. LH2 aviation is still in a very early stage where only the parties who are at the forefront of development have a high level of knowledge on the topic. As is expected, the forefront of innovation is research and development. Large-scale industry reports and research project are taking place to begin looking into the possibilities of LH2 aviation. This knowledge will then trickle down to the active members of the market such as the airlines and airports. As of now this information transfer downstream is just starting off. Schiphol, airlines like KLM, policy makers, policy enforcers, and the safety authorities which will all play a key role in making LH2 aviation a reality are still at a very basic level.

Another thing to consider in the starting point of this transition is the level of technological development. Regarding aviation, this is centered currently around one of the groups listed above, LH2 aircraft developers. These firms are the parties that are actively developing and strengthening the niche. There are large parties such as Airbus and Fokker (through HAPSS) which are incumbents to the industry that understand the future potential of LH2 and are looking into LH2 aviation and planning to build some of the first LH2 aircraft that will enter the market; HAPSS with 6 converted aircraft and Airbus Zero-e with three entirely new models. Developing and building such aircraft will require individual technical components to be developed, built, tested, and iterated upon. In addition to these large established firms, there are newer entrants into the market working on carving out a place for themselves in the future regime by working on developing this niche. Two examples of this are Universal Hydrogen and ZeroAvia. They are tackling the development of LH2 aircraft and in some cases even the logistics infrastructure. There is a lot of knowledge in these technology development firms, but much of the technology is still concentrated there since few tangible results have come from development thus far. In addition there is a significant amount of mature knowledge on cryogenic infrastructure with the cryogenic infrastructure developers since these technologies have been used for many years in other industries. As of yet there is little to no application of this infrastructure technology for aviation, but when this is being developed, knowledge from these parties will be crucial.

With an understanding of the starting point, the next steps can be determined. The first steps that need to be taken are given in the first subphase of phase 0.

2022-2025: Subphase 1

In this section the steps that need to be taken now by Schiphol given the current landscape and developmental progress around LH2 aviation and the infrastructure that will be needed at the airport are given. There are 6 categories of activities relating to different aspects of the transition and it's process. They are the following (given in no particular order): **LH2 supply chain**, **LH2 aviation adoption**, **technical development**, **operational development**, **regulatory policy**, and **financial**. There are a number of actions that need to be taken in this early stage which will be categorized under these six different categories. Each action will include the key parties and how Schiphol should work with them. Also, the connection of each action to the challenges and opportunities defined in section 4.2 are stated

LH2 supply chain

- **Search for LH2 supply lines** → It is important to establish which options there are to get an LH2 supply to Schiphol. Since LH2 demand at Schiphol may exceed local capacity for generation quite quickly, a robust and sizable supply is needed. However, the option to perform liquefaction locally needs to also be considered. Keep the options open but look into all of them. Shipping via the Port of Amsterdam is one such option.
 - Schiphol works with *suppliers/importers* (Like Port of Amsterdam, Port of Rotterdam, Zenith Energies, etc.) and *Local energy authorities* to determine best option
 - Challenge: 1, 4, 5, 6 and Opportunity: 1, 3
- **Build improved LH2 demand forecasting model** → It is key to gain a better understanding of the expected demand to base LH2 supply line development on. Also improve this model as more knowledge is gained over time. For this it is important to also look into routes which can be flown by LH2 aircraft. This is an input for the decisions made regarding LH2 supply.
 - Schiphol works with *airlines* (like KLM and others) and *other airports*
 - Challenge: 1, 5, and Opportunity: 4
- **Open discourse with Dutch govt. and EU about LH2 supply scarcity** → LH2 scarcity on a global or European scale may become an issue holding back efficient LH2 aviation adoption (similar to what can be seen now with SAF as explained by Vera van Lint). To ensure this is foreseen if it becomes an issue, begin discussions now. LH2 producers should also be involved with this as well.
 - Schiphol works with the *Dutch govt., EU, and LH2 producers*
 - Challenge: 1, 5, 6 and Opportunity: 1, 3

LH2 aviation adoption

- **Open discourse about LH2 adoption plans with airlines (like KLM)** → It is important that discussions on when and how quickly LH2 aircraft will be and can be adopted begins. In this early phase not too much can be sure yet, but it is good to open the discussion. Any findings here can be used as inputs for the improved LH2 demand forecasting model.
 - Schiphol talks with *airlines and LH2 aircraft developers*
 - Challenge: 1, 3, 5 and Opportunity: -

Technical development

- **Work with technology developers to develop specific infrastructural pieces for phase 1** → LH2 infrastructure exists and it is feasible for aviation but needs to be designed specifically for it. The following items need to still be developed for it to be feasible: breakaway couplings, purge-less couplings, bowser refueling trucks. These items are technically feasible but require a time and money investment. Apart from that, the rest of the infrastructure needs to be specified for aviation as well. It is recommended that a proof of concept is already reached (TRL of 3 or 4).
 - Schiphol working with *LH2 infrastructure technology developers* and facilitating collaboration between the *technology developers* and safety and regulatory parties (to design for aviation)
 - Challenge: 1, 2, 8 and Opportunity: 5
- **Open and facilitate discourse between LH2 infrastructure technology developers and relevant aviation parties** → To ensure that technology development and infrastructural design is in line with aviation safety standards it is suggested that Schiphol play a role in ensuring that the infrastructure is designed with these in mind. Also, to ensure that the infrastructure is consistent with LH2 aircraft design (such as coupling sizes, pressure, etc.) close contact between the LH2 infrastructure developers and LH2 aircraft developers is needed.
 - Schiphol facilitates *LH2 infrastructure technical developers* to work with *aviation safety authorities* and *LH2 aircraft developers*
 - Challenge: 1, 8 and Opportunity: 5

Operational development

- **Begin looking into safe and efficient operating procedures for LH2** → Along with the new infrastructure, new operational standards and procedures are needed. As development progresses with infrastructure and more clarity as to the final version is gained, together with aviation safety authorities, progress the design of operational techniques to go along with that. Use this as another input for infrastructure design. It is expected that for phase 1 infrastructure refueling will need to happen away from the gate. This needs to be considered when designing the new operating procedures.
 - Schiphol works with and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
 - Challenge: 1, 7, 8 and Opportunity: 5, 7, 8

Regulatory policy

- **Facilitate collaboration between developers and policy makers for LH2 infrastructure** → To ensure that technology does not exceed regulatory policy and that infrastructural design can be done within the bounds of the law, collaboration between LH2 infrastructure developers, policy makers, and safety, regulatory authorities needs to take place early on in the development and design phase.
 - Schiphol facilitates collaboration between *LH2 infrastructure developers, policy makers* (Min I&W, Min EZK, Province), and *safety/regulatory authorities* (Fire Brigade, HSE)
 - Challenge: 1, 7, 8 and Opportunity: 6, 7
- **Ensure that steps are taken to make LH2 aviation and the operations that are required for that feasible within the law** → A discourse needs to be opened with relevant regulatory and governmental bodies to discuss the use, storage, and movement of LH2 at and outside of the airport. For example, the RED (which says what can be used as a fuel based on a life cycle analysis) needs to have LH2 in it.
 - Schiphol discusses with *relevant regulatory and governmental bodies* (for example the province)
 - Challenge: 1, 8 and Opportunity: -

Financial

- **Aim for lowering DOC of LH2 aviation** → Because of the potential for a nearly doubling of the DOC of LH2 aircraft, it is important to focus on reducing that wherever possible. Much of this comes from the costs of LH2 fuel, which means that the largest gains can be made by improving efficiency in supply lines.
 - Schiphol collaborates with *LH2 producers and importers*
 - Challenge: 1, 2, 3, 4, 5 and Opportunity: 1, 3, 4
- **Do market research together with airlines to understand the impact of increased DOC** → Because Schiphol and airlines are businesses at the end of the day, the increased DOC will result in higher costs for customers. Gaining an understanding of what this means for the bottom line will help in decision making.
 - Schiphol work with the *airlines*
 - Challenge: 1, 2, 3, 4 and Opportunity:
- **Allocate costs for CapEx and OpEx** → Both capital expenditures for R&D and building phase 1 infrastructure and higher operational expenditures are expected. How these costs are allocated between Schiphol itself, the Dutch govt., airlines, and the market needs to be discussed.
 - Schiphol discourse with the *Dutch govt. and airlines*
 - Challenge: 3, 4 and Opportunity:

Clearly, the above actions that are recommended to Schiphol are largely built around starting conversations where needed and learning. It is not wise to invest large amounts of time, money, and attention into developing

directions which will end up being fruitless. As was clear from complexity management literature, flexibility is important in dealing with complexity in a transition. Because the niche is not yet fully developed, there are a lot of potential options. Complexity is high, thus in this early stage it is best to not commit to any single strategy yet, but instead gather information which can be used towards more effective decision making in later stages. With that said, it is of course important to start pursuing some specific goals in order to increase the momentum of niche innovation. These goals are still often aimed towards niche innovation or learning about the status of the system. This allows for Schiphol to both aid in creating space for agents to build up the potential alternative regime and to develop strategies for how to manage the transition given the systems status respectively.

All three niche processes are in some form put to action already in this first subphase. A big focus in this first period is on building informal networks which will be required for further development and scaling of LH2 aviation. Formal agreements with select parties can be initiated in a later stage, but for now opening discourse allows for learning and network formation while minimizing the web of commitments. This early discourse is also a way for Schiphol to involve parties with which it has contractual agreements in an early stage. This also takes into account the desire to not become too path dependent early on in the transition process. In addition, the other two niche processes of shaping and voicing expectations and learning are central in this subphase. The point is really to set expectations for the rest of the transition through the learning processes that must take place. Once again, these niche processes can be seen to be very interrelated and all work to increase the momentum of niche innovation. A lesser focus is put on weakening the existing systems and strengthening exogenous pressures since strengthening the niche already has that effect to a certain extent.

2025-2030: Subphase 2

Next, after the initial actions of the first subphase of phase 0, the second subphase can begin. This is expected to be around 2025. Now the processes initiated can be built upon, the connections formed can be strengthened and expanded into more formal networks, and the niche development can progress.

LH2 supply chain

- **Continually improve and update LH2 demand forecasting model** → As more clarity is gained on the development of LH2 aircraft and when airlines plan to adopt them, the assumptions on which such a model is based can be reduced and thus the outcome can be more valuable to base decision on. Continual improvement of this forecasting model is recommended.
 - *Schiphol works with airlines* (like KLM and others) and *other airports*
 - Challenge: 1, 5, 6 and Opportunity: 1, 3
- **Make decisions for LH2 supply line choices** → Based on improved LH2 demand forecasting, more accurate sizing of supply lines should be possible. Based on this and prior research into the possible methods, decisions need to be made as to how Schiphol will meet the LH2 demand (local liquefaction or fully imported). More formal collaboration on establishing the infrastructure should begin.
 - *Schiphol works with suppliers/importers* (Like Port of Amsterdam, Port of Rotterdam, Zenith Energies, etc.) and *Local energy authorities*
 - Challenge: 5, 6 and Opportunity: 1, 3
- **Continue discourse with Dutch govt. and EU on LH2 scarcity** → With improved LH2 demand forecasts and more clarity on the supply lines, it is important to keep the Dutch and EU governing bodies in the loop of plans and to discuss with them whether that is possible.
 - *Schiphol works with the Dutch govt., EU, and LH2 producers*
 - Challenge: 1, 5, 6 and Opportunity: 1

LH2 aviation adoption

- **Continue discourse with airlines on LH2 aircraft adoption** → With the increased knowledge gained over the previous sub-phase, more clarity should be able to be gained in these discussions. Also at this point in time it is possible that select LH2 aircraft enter the market (such as from HAPSS) so

discussions need to be had about how these aircraft will be utilized (early operational tests are an interesting option).

- *Schiphol* talks with *airlines* and *LH2 aircraft developers*
- Challenge: 1, 3, 5 and Opportunity: 5

Technical development

- **Further develop infrastructure for phase 1** → The specific infrastructural components mentioned in the first subphase should be progressed to the point of testing in an operational environment (TRL 7) which means they are ready to begin being utilized in actual operation. This testing could be done at other airports in the Netherlands such as the RTHA. Depending on if there are LH2 aircraft on the market (like HAPSS), it may potentially be possible to test early versions of infrastructure at smaller airports or at Schiphol in operational environments.
 - *Schiphol* working with *LH2 infrastructure technology developers* and facilitating collaboration between the *technology developers, safety authorities, regulatory parties (to design for aviation), and the RTHA*
 - Challenge: 1, 2, 8 and Opportunity: 5
- **Continue working closely with LH2 infrastructure technology developers and relevant aviation parties on development** → As LH2 infrastructure technology is furthering and nearing finalization of development, collaboration with LH2 aircraft developers and safety authorities is more important than ever. This is also the case for the design of the general infrastructure.
 - *Schiphol* facilitates *LH2 infrastructure technical developers* to work with *aviation safety authorities* and *LH2 aircraft developers*
 - Challenge: 1, 7, 8 and Opportunity: 5
- **Decision making on development on infrastructure for phase 2** → Based on improving LH2 demand calculations, the point of transition to phase 2 infrastructure should be clearer. There are a number of specific technologies that need to be developed for this to be possible. Decisions need to be made as to what infrastructure is needed and when development should begin.
 - *Schiphol* working with *LH2 infrastructure technology developers, airlines, and LH2 aircraft developers*
 - Challenge: 1, 2, 7, 8 and Opportunity: 2, 6

Operational development

- **Perform risk and safety analyses for operation with new infrastructure** → With development of the infrastructure technology and design it is key for the operations and development of policy to understand the risks associated with it. Perform extensive analyses on this together with the parties who made the technology (technology developers) and safety authorities. The risks are not fully understood yet, so analyses are needed.
 - *Schiphol* works with and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
 - Challenge: 1, 2, 7, 8 and Opportunity: 5, 6, 7, 8
- **Further develop new operating procedures** → Base this development on learnings from the earlier subphase and the risk and safety analyses which have been performed. Collaboration with infrastructure developers and safety authorities is very important here.
 - *Schiphol* works with and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
 - Challenge: 1, 2, 7, 8 and Opportunity: 5, 6, 7, 8

Regulatory policy

- **Facilitate collaboration between developers and policy makers for the finalization of LH2 infrastructure development and design** → As the technology development and design reaches a

finalization point it is even more crucial for collaboration to take place between the developers and policy makers. It is important that the infrastructure is coherent with regulatory law. The risk and safety analyses done for operation should also be taken into account in the creation of these laws.

- *Schiphol facilitates collaboration between LH2 infrastructure developers, policy makers, and safety/regulatory authorities*
- Challenge: 1, 2, 7, 8 and Opportunity: 5, 6, 7, 8
- **Ensure that all other legal aspects of LH2 aviation are finalized** → In addition to laws for the building and operating of infrastructure, legalities regarding any part of the LH2 logistics chain from production to aircraft needs to be fully dealt with.
 - *Schiphol discusses with relevant regulatory and governmental bodies*
 - Challenge: 1, 8 and Opportunity:

Financial

- **Compare achievable DOC with market research** → In order to know whether LH2 aviation will be financially viable for Schiphol, compare the minimally achievable DOC with market research. The Dutch gov. should be involved with this as well since they may be able to help with subsidies, tax breaks, etc.
 - *Schiphol discourse with the Dutch gov. and airlines*
 - Challenge: 1, 2, 3, 4 and Opportunity: 3, 4, 7
- **Obtain funding for investment costs for LH2 infrastructure** → Funding will be needed to build the LH2 infrastructure for phase 1. It is expected to be low, relative to phase 2, but buying operational equipment and building a storage tank will have significant costs. Contacts from both the Dutch gov. and KLM have acknowledged that responsibility for this infrastructure is shared, so this must be allocated with them.
 - *Schiphol discourse with the Dutch gov. and airlines*
 - Challenge: - and Opportunity: -

The main goal of this subphase is to take the knowledge gained from the earlier activities from subphase one and build on them to prepare Schiphol and the other important parties for the building of the LH2 infrastructure. Technical development is progressed, decisions are made, and networks are tightened. The technology required for the LH2 infrastructure to be functional for aviation should be completed or nearly completed. Along with that, the operations that go with that should have been developed. This has been done in collaboration with governmental authorities to ensure that regulatory policy is written in parallel. The focus on policy development shows that some larger structures which are inherent to the landscape in which this transition takes place are preserved and need to be respected in this transition. The same is the case for the market forces that have an impact on this transition. The new niche must be economically sustainable. Research into that began in the earlier subphase, but in this subphase it is recommended that economic sustainability is established and ensured. Planning and preparing for LH2 aircraft adoption is a common theme in this subphase which means that less flexibility can be maintained. Decisions need to be made in order to invest time and effort into a specific direction. Due to the learnings of the earlier phase, it should be possible to gain more clarity in the face of complexity.

With the progression of the niche, the niche processes which take place must also progress. Expectations must be updated based on the learnings in an iterative fashion. Also, as stated, networks are formed more formally in order to progress the niche. This will end up increasing the network effect and the web of commitments, thus increasing path dependence, but this is required for effective niche development. The momentum of niche innovation should ramp up towards the eventual first implementation in the final subphase of phase 0. The principles for complexity management also play a role in this subphase of the roadmap. With the status of the system more accurately defined from many of the activities of the previous subphase, management of the transition can be more effective. Thus, better support and space can be given to agents who are developing the niche into becoming an alternative regime. Also, the disequilibria which are arising in the market can be used more effectively to benefit the niche and weaken the existing system.

2030-2035: Subphase 3

The third and final subphase of phase 0 is focused on finalizing preparations for Schiphol to be able to service LH2 aircraft at the airport. It is expected that during this period of time the first LH2 aircraft will enter the market and airlines will begin to purchase them. Thus at this point the niche will be expected to first enter the regime level. At this point adoption will still be relatively small when compared to future potential. However much more LH2 aircraft are expected at this point than the few outliers that may have been seen in the subphase 3 (for example from HAPSS).

LH2 supply chain

- **Continually improve and update LH2 demand forecasting model** → As in the earlier phases, this model needs to continually be updated as more information is gained. This model will not only be valuable for sizing phase 1 infrastructure, but also for predicting the rate of LH2 adoption and thus infrastructure scaling up which will be required. The point at which phase 2 infrastructure will be required is dependent on the increase in LH2 demand.
 - *Schiphol works with airlines (like KLM and others) and other airports*
 - Challenge: 1, 5, 6 and Opportunity: 1, 3
- **LH2 supply chain up and running** → The supply chains for LH2 that have been set up over the previous years need to be finalized and ready for operation by the time that aircraft get adopted.
 - *Schiphol works with suppliers/importers (Like Port of Amsterdam, Port of Rotterdam, Zenith Energies, etc. but these are subject to change)*
 - Challenge: 5, 6 and Opportunity: 1, 3
- **Continue discourse with Dutch govt. and EU on LH2 scarcity** → As first adoption begins and scaling up is expected, it is still crucial to keep an eye on LH2 scarcity.
 - *Schiphol works with the Dutch govt., EU, and LH2 producers*
 - Challenge: 1, 5, 6 and Opportunity: 1

LH2 aviation adoption

- **Continue discourse with airlines on LH2 aircraft adoption** → Leading up to first adoption it is even more crucial to have frequent discussions with airlines and close connections in order to know exactly what is expected. This way Schiphol's expected capabilities can also be relayed back to airlines in order to ensure that demand matches supply when adoption first takes place. Also it is important to discuss future plans for adoption with Airlines as well. This can be used to further improve the accuracy of the LH2 demand forecasting model.
 - *Schiphol talks with airlines and LH2 aircraft developers*
 - Challenge: 1, 3, 5 and Opportunity: 5

Technical development

- **Building of phase 1 infrastructure** → With LH2 aircraft adoption looming, it is important to begin building LH2 infrastructure. With development of the technology and design of a holistic LH2 system in the previous years, at this point it should be possible to begin the building process. This includes building physical infrastructure at Schiphol and building the operational equipment like bowser trucks off site and bringing them to Schiphol. At this point the technology should have been qualified (TRL 8) and be ready to prove itself in regular operation.
 - *Schiphol working with LH2 infrastructure technology developers and facilitating collaboration between the technology developers, safety authorities, and regulatory parties (to design for aviation)*
 - Challenge: - and Opportunity: -
- **Further development of phase 2 infrastructure** → After the first adoption, scaling up could happen rapidly. Infrastructure technology for phase 2 needs to be developed by the time that it needs to be built. Specific elements that need development time are long-distance LH2 pipelines, large-scale LH2

storage tanks, and an LH2 hydrant system (intermediate tanks and mobile refueling vehicles). While a focus is on first adoption, development of these items should not be forgotten. It is recommended that because scaling up could be required within only a couple years of first adoption, during this subphase proofs of concept are already reached for these elements (TRL of 3 or 4).

- Schiphol working with LH2 infrastructure technology developers and facilitating collaboration between the technology developers and safety and regulatory parties (to design for aviation)
- Challenge: 1, 2, 7, 8 and Opportunity: 2, 6

Operational development

- **Finalize operating procedures for phase 1 infrastructure** → Based on the finalized LH2 infrastructure technology and design, safety and risk analyses, and regulatory policy, safe and effective operating procedures need to be finalized so that they can be used once LH2 infrastructure is up and running at Schiphol.
 - Schiphol works with and facilitates collaboration between LH2 infrastructure developers and aviation safety authorities
 - Challenge: 2, 8 and Opportunity: 7
- **Train people for the new operating procedures** → Because LH2 is quite different from traditional jet fuel and because new operating procedures have been developed for the new infrastructure, it is important that refueling operators, truck drivers, etc. all understand the risks and can safely and effectively work with the new infrastructure. There may be limited people available, so recruitment of these people also needs to begin early on.
 - Schiphol works with new and old employees and facilitates collaboration between LH2 infrastructure developers and aviation safety authorities
 - Challenge: - and Opportunity: -

Regulatory policy

- **Ensure that all policy and legalities that are required for LH2 aircraft to be serviced at and take-off from Schiphol are finalized** → With the adoption coming soon, these elements need to be done.
 - Schiphol discusses with relevant regulatory and governmental bodies
 - Challenge: - and Opportunity: -
- **Look into new policy and legalities that will come with scaling up** → The increase of LH2 aircraft at Schiphol over time will mean more LH2 and phase 2 infrastructure will be required. Exploratory research into what this means from a legal perspective should begin during this phase since scaling up could happen quite quickly.
 - Schiphol discusses with relevant regulatory and governmental bodies
 - Challenge: 1, 2, 7, 8 and Opportunity: 5, 6, 8

Financial

- **Fund building LH2 infrastructure for phase 1** → Utilize the secured funds to build the phase 1 infrastructure needed before 2035.
 - Challenge: - and Opportunity: -

Through niche development, the niche has now entered the regime level. Competition of LH2 aviation (next to potential other forms of sustainable aviation) weakens the existing system and strengthens exogenous pressures which are processes which further stimulate the sociotechnical transition, as explained by Geels et al. (2017). As has been the trend from the previous two subphases of phase 0, complexity is reduced and path dependence is created as the transition progresses. Although this is not suggested for early in such a complex transition, this is required for development. Flexibility, which was one of the main solutions to complexity earlier on in the transition, is reduced by increasing path dependence as networks are tightened, commitments grow, resources are invested in specific routes of development. Due to learnings from the

previous subphases it is expected to be possible to reduce complexity enough to allow for the reduction in flexibility and additional development.

This final subphase of the roadmap phase 0 consists of the final steps before LH2 aviation is feasible from Schiphol. Based on learning and development from the first subphase and the continued progress from the second, now all of the prior work comes to fruition in building LH2 infrastructure for servicing LH2 aircraft at Schiphol which is both safe and effective and completely within the law. Apart from a few early outliers, large-scale adoption of LH2 aircraft can take place after this subphase has taken place. The niche has been strengthened significantly through the progress that has taken place for multiple different aspects of the transition. With LH2 aviation taking place at Schiphol, the focus must turn to how scaling this up can be done smoothly.

4.4.2. Phase 1: 2035 – 2050

After the phase 1 infrastructure has been built and the first LH2 aircraft have been adopted by airlines and have flown from Schiphol, phase 1 begins. This is expected to happen around 2035. The main goal of phase 1 is to go smoothly from relatively small-scale adoption to much larger adoption over the years. This large adoption will result in a significantly higher LH2 demand at the airport which means that Schiphol and its infrastructure will need to evolve. Along with that, the supply chain needs to grow, operational procedures need to improve, and policy will need to adapt. All of this needs to be done in a financially sustainable, and even more importantly, safe way. This will be possible because of the knowledge that can be gained from learning and improving when adoption has taken place. Actually servicing LH2 aircraft at the airport will help to improve safety, efficiency, robustness and financial sustainability of LH2 aviation and its infrastructure immensely and allow for the rapid scaling up which is expected.

Phase one is set to last from 2035 to 2050, but in reality the transition from phase 1 to phase 2 will likely take place before 2050. Once the transition to phase 2 infrastructure is done because of higher LH2 demand at the airport, the phase will change. The point in time at which this will take place is dependent on the rate of LH2 adoption by the market. Since Phase 1 is further in the future than phase 0, forecasts of expectation are much less accurate. This also means that the recommended actions for Schiphol will be less extensive in this phase. However, it is already clear what concepts will need focus and development, specifically related to the infrastructure itself. Here, the steps that need to be taken in this phase will once again be divided into the same 6 categories as in the previous section.

LH2 supply chain

- **Continually improve and update LH2 adoption models** → Even after first adoption it is important that models are still upkept and used to forecast future LH2 requirements to predict when the scaling up of infrastructure will be required.
 - Schiphol works with *airlines* (like KLM and others) and *other airports*
 - Challenge: 1, 5, 6 and Opportunity: 1, 3
- **Scaling up of LH2 supply lines** → With increased adoption and thus increased LH2 demand, supply will need to go up as well. Supply lines need to increase in size and also will likely need to become more robust to lower risk. Learning from phase 1 supply lines will help with scaling up. Also, it may be possible to capitalize on economies of scale here.
 - Schiphol collaborates with *LH2 producers and importers*
 - Challenge: 5, 6 and Opportunity: 1, 3
- **Continually reassess whether higher LH2 demand can be met** → Because of the potential of LH2 scarcity because of lack of renewable energy, especially with high demand, it is important to continually assess together with the Dutch Govt. and the EU whether it is feasible to purchase the amount of LH2 that is expected to be required.
 - Schiphol works with the *Dutch govt., EU, and LH2 producers*
 - Challenge: 5, 6 and Opportunity: 1

LH2 aviation adoption

- **Continually discuss LH2 aircraft purchases with airlines** → As airlines continue to invest in expanding the number of their LH2 aircraft, Schiphol needs to keep continual contact and an open discourse with them. Before purchases are made it should be assessed whether the infrastructure and available LH2 supply can handle additional LH2 aircraft at Schiphol.
 - *Schiphol* talks with *airlines* and *LH2 aircraft developers*
 - Challenge: 1, 3, 5 and Opportunity: 5

Technical development

- **Finalization of technical development of phase 2 infrastructure** → Long-distance LH2 piping, large-scale LH2 storage tanks, and a LH2 hydrant system (including transfer tanks and a mobile refueling vehicle) need to be further developed and tested to ensure that they are ready to be used by the time that the switch to phase 2 infrastructure is needed. They need to be qualified (TRL level 8) by testing them in an operational environment which can be done at Schiphol or other smaller airports.
 - *Schiphol* working with *LH2 infrastructure technology developers* and facilitating collaboration between the *technology developers*, *safety authorities*, *regulatory parties (to design for aviation)*, and the *RTHA*
 - Challenge: 2, 8 and Opportunity: 2, 4, 5, 6, 8
- **Building phase 2 infrastructure** → Before phase 2 infrastructure is needed according to forecasting models, projects to build phase 2 infrastructure should begin.
 - *Schiphol* working with *LH2 infrastructure technology developers* and facilitating collaboration between the *technology developers*, *safety authorities*, and *regulatory parties (to design for aviation)*
 - Challenge: - and Opportunity: -

Operational development

- **Continually perform safety and risk analyses** → As LH2 infrastructure is first used in a truly operational environment, perform safety and risk analyses. Based on these analyses, changes to make it more efficient and/or safe may be possible
 - *Schiphol* works with and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
 - Challenge: 1, 2, 7, 8 and Opportunity: 5, 6, 7, 8
- **Improve safety and efficiency of LH2 operational procedures** → As LH2 infrastructure is first used in a truly operational environment, a lot is learned. These learnings need to be used to improve how efficient and safe LH2 operations are. This may allow for refueling to no longer take place at a central location, but instead at the gate which reduces turnaround times.
 - *Schiphol* works with and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
 - Challenge: 2, 8 and Opportunity: 5, 7
- **Adjust operational procedures to work with phase 2 infrastructure** → With the development of LH2 infrastructure for phase 2 progressing and the learnings from phase 1 infrastructure operational procedures, new and improved procedures for phase 2 infrastructure will need to be developed. It is expected that these can be more efficient and safer.
 - *Schiphol* works with and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
 - Challenge: 2, 8 and Opportunity: 5, 6, 7, 8
- **Train employees to work with phase 2 infrastructure** → Before phase 2 infrastructure is ready to operate, refueling operators and other employees working with the infrastructure need to be trained accordingly

- Schiphol works with *new and old employees* and facilitates collaboration between *LH2 infrastructure developers* and *aviation safety authorities*
- Challenge: - and Opportunity: -

Regulatory policy

- **Continually work with policy makers and regulatory authorities to ensure policy is updated for phase 2 infrastructure** → With the eventual scaling up of infrastructure to phase 2 infrastructure, new policy or adjustments to existing policy may be needed. As development of the infrastructure itself and operations progresses, continually work with policy makers and regulatory authorities to ensure that policy does not lag behind
 - Schiphol facilitates collaboration between *LH2 infrastructure developers, policy makers, and safety/regulatory authorities*
 - Challenge: 2, 7, 8 and Opportunity: -

Financial

- **Profiting from economies of scale** → Larger LH2 demand leads to larger production facilities being needed. When producing at such a scale, economies of scale may allow for DOC to be lowered.
 - Schiphol collaborates with *LH2 producers and importers*
 - Challenge: 4, 6 and Opportunity: 1, 3, 4
- **More efficiency from lower turnaround times** → Hydrant refueling and new refueling operating procedures to go with it will likely lead to a significant decrease in turnaround times for LH2 aircraft. This will decrease the DOC and improve financial sustainability of LH2 aviation. Capitalize on this.
 - Schiphol collaborates with *Airlines*
 - Challenge: 2, 4, 8 and Opportunity: 2, 7, 8

The main focus of this phase is improvement through learning and using this to prepare for phase 2 infrastructure. As is logical, early LH2 demand estimates, which are explained in Appendix section 4.1. show that the rise in LH2 demand at Schiphol varies greatly depending on the expected LH2 aircraft adoption rate. This adoption rate then varies based on the expected entry into market of LH2 aircraft of different sizes and ranges and the speed at which airlines transition to this new way of flying. Since these variables are still very much unknown, it is impossible to accurately predict when the transition from phase 1 to phase 2 infrastructure will be needed. If one specific scenario is chosen, then an idea as to when phase 2 infrastructure will be needed can be gained. Take for example a scenario where there is no growth at Schiphol and growth scenario 4 expected. Then, as shown in graphs in Appendix section A.1., the amount of LH2 delivery trucks and LH2 bowser truck movements per day increase rather quickly, especially after 2045. When phase 2 infrastructural solutions will be needed exactly is then dependent on what Schiphol considers to be too many delivery trucks for example. When it is no longer safe and/or efficient then new infrastructure will be needed. However, for most scenarios, it is expected that this transition will be before 2050. With the advent of phase 2 infrastructure, phase 2 of the roadmap begins.

4.4.3. Phase 2: 2050 - Onwards

Phase 2 is the final phase of the roadmap and is also therefore the furthest in the future. At this point LH2 aviation is expected to have been around for a number of years and has had a chance to mature more within the market. It is expected that at this point it has become a central part of sustainable aviation and therefore has a sizable market share. At Schiphol a large amount of LH2 aircraft will need to be serviced every day and thus the infrastructure has developed over time and been scaled up to meet this demand. From this point onwards, the infrastructure that is being employed can easily be scaled up even further if needed. Based on current understanding of the technology, it is not expected that there will be much more efficient means of LH2 supply, storage, and refueling. Thus, in order to further scale up infrastructure more elements or elements that have been sized to be larger are simply needed. However, it is expected that at a certain point LH2 demand at Schiphol will stagnate. Currently there is a limit of 440,000 annual flight movements set on

Schiphol. With the advent of sustainable aviation this cap may be removed (even before phase 2 begins) because these aircraft pollute less and a portion of them may make significantly less noise because of their use of electric motors instead of combustion engines. This could allow for growth at Schiphol. However, this growth will be capped because of consumer demand and simply the limited space at the Schiphol location. Interesting questions that will need to be answered in the future are what this maximum demand will be and if it will be feasible to supply such a demand. This is a question which will need to be answered in phase 2.

Phase 2 will see further maturation of LH2 aviation and infrastructure technology from the continual use in an operational environment. During phase 2 it is therefore key to continually learn from this and further improve. Key activities include:

- **Analysis of performance, robustness, safety, economic viability, and efficiency of the infrastructure and supply chains** → To learn and improve performance
- **Forecasting of trends, capabilities, and technologies** → to keep up with future demand and developments
- **Reflection on the transition and networks** → To improve future processes and stakeholder relations

Specific actions that need to be taken cannot at this point in time be forecasted with any realistic accuracy. As technology within and outside of the industry progresses entirely new possibilities which may not be thought possible at this point in time may arise. Therefore, continually iterating on plans and developments as the transition to LH2 aviation takes place is an activity central to success. As can be seen in the transition management cycle, transition management is not a linear process, but instead, as is in the name, a continual cycle. Iteration is needed to allow for future decisions and progress to be influenced by current progress and learnings. Thus this is also the suggestion for the actions being taken in the final phase of the roadmap.

4.4.4. Concluding the Roadmap: Key Takeaways and What to Keep in Mind

The roadmap described above can be described best as an iterative process with continual learning. This is very similar to the transition management cycle which has been used as inspiration for the main methodological framework used to derive this roadmap. The early phases of the transition are characterized by a low amount of knowledge and accuracy of predictions. As Schiphol takes the first steps by starting discourse and collaboration with multiple parties, learning results from discussion. This learning should then be used to improve models and development. Over time as these models and development progress, discourse can also progress which leads to new learnings. This is the basic process described in the roadmap. The key facets of development for LH2 infrastructure at the airport progress from the first sub-phase of phase 0 (2022-2025) to the point that the first LH2 infrastructure is feasible at Schiphol at the end of phase 0 (2035).

With the first LH2 aviation infrastructure and the systems which are required for it in place (moving from phase 0 to phase 1), learning still must persist. Now, even more can be understood about LH2 infrastructure through operational experience. Improved knowledge needs to still be used to further progress in terms of safety and efficiency; especially as scaling-up is required. Phase 1 highlights this process of scaling up. What is clear is that the same facets which needed to be developed in phase 0, need to progress during phase 1 to be able to move into phase 2. And since phase 2 is still very far in the future, not much can be accurately expected yet other than that learning will still be central to success there too.

4.5. Step 5: Roadmap Validation

The results derived through following the research methodology can be open to some degree of scrutiny. Questions can be raised as to the validity of these results due to the methods employed. Literature review is susceptible to confirmation bias since the researcher reading and selecting literature is human and therefore not impervious to such biases. Also, as was suggested in the section 2.3 on data analysis, the data gained from interviews can be criticized because of the respondent's unwillingness to discuss certain things they know or inability to convey their point clearly. On the other hand, there could be issues on the side of the interviewer's ability to interpret the respondent's answers. To reduce this issue, each interview was recorded

and transcribed. This transcript was sent back to the respondent to check for any interpretation issues. However, the other issues still stand and could be considered rightful criticisms. To remedy this as much as is reasonably possible, a round of validation meetings were held with the results which had been developed up to this point.

In the validation meetings the Schiphol-specific infrastructure vision and transition roadmap were discussed with a number of experts. These experts then had a chance to ask critical questions and give direct feedback on these results in order to identify any issues with these results. These meetings were held in a less structured way than the interviews which were used for the iterative development of the infrastructure vision for Schiphol. The validation meetings consisted of a presentation given to the expert(s) and an open discussion based on a select number of broad questions on their opinion of the results and if they noticed issues or anything missing. During the presentation questions were also often asked which in some cases were simply to clarify things, but in other cases raised interesting points of concern. Three validation meetings were held. These meetings were held with members of relevant parties in the Dutch aviation sector. Also, specifically experts which were not interviewed during the earlier phase of this research were met with to avoid any bias from previous contact. The first meeting was held with three members of the management team of Aircraft Fuel Supply (AFS) which delivers fuel to Schiphol. The second meeting was held with a group of participants from the TU Delft, RTHA, and Airbus with a more specific focus on future research options. The third meeting was held with Linda van Wamelen, a policy maker at the Ministry of I&W. The main takeaways from these meetings and what impact they have on the validity of the results will be discussed here.

One of the main findings from the validation meeting is that the results presented to these parties generally are largely new to them. As stated in section 4.4.1, many relevant parties in the aviation industry still are not very well versed in LH2 aviation. The knowledge is still very much concentrated around research organizations. AFS and the Ministry of I&W both currently have a much greater focus on SAF since this is a technology which is being used right now whereas LH2 is still something which has yet to prove itself. This means that when the results of this study were presented the general consensus was that it was not possible for these parties to give very clear answers as to if this seems realistic or not. This confirmed the new and explorative nature of the research performed here but did not really validate the results much more.

However, some of the questions that were posed when presenting the results at the meetings did raise interesting points. Here is a list of key takeaways which came from discussion and questions on the results:

- Linda van Wamelen from the Ministry of I&W made it clear that the certification of LH2 aircraft will likely take a very long time and isn't very well represented by the entry into market estimates found in the literature. Therefore a 2035 start date of LH2 aviation is questionable. This is an interesting contrast to some more technical sources which believe that an even earlier date is feasible. For example, HAPSS which aims to have the first 6 converted LH2 aircraft available in 2028, is the other side of the estimate. Because preparing for an earlier scenario is better than assuming a scenario where LH2 aviation comes later and then not being prepared on time for a sooner market entry, a 2035 ready to operate date for LH2 infrastructure will still be maintained. But these comments are important to keep in mind.
- Johan van Tiggelen, managing director of AFS made the comment multiple times that it is best to learn by beginning small. He stated that small-scale implementation of LH2 technologies early on would be one of the best ways to further the development of this niche. In the Schiphol-specific roadmap there are mentions of developing LH2 operations and infrastructure through early implementation for, for example, the 6 planned HAPSS aircraft. This could allow for effective learning before full-scale market adoption takes place. Such methods of learning need to be considered more actively.
- Ahmad Bakkar from the RTHA asked a series of questions regarding LH2 importing vs local production. Within the infrastructure vision it has been deemed most feasible to import LH2 due to the high demand at Schiphol, however on-site liquefaction is still considered to be a possibility in certain cases. Ahmad was unsure about importation being considered the better option. He cited a plan to build multiple hundreds of MW electrolyzing capacity on the Maasvlakte (Hartog, 2021). This

is an interesting point, but due to the massive power demand to produce LH2 for Schiphol along with the fact that Schiphol will not be the only party with demand in the area, it is still questionable if local production (or just liquefaction) is feasible. However, Ahmad's comments do point out that taking a more serious look at supply lines will be required in the future. This is in line with suggestions in the roadmap.

- From multiple parties, questions on the LH2 demand calculations were raised during the interview. The concerns came largely from the fact that there is a large degree of uncertainty connected to these forecasts. Assumptions and very rough estimations needed to be made on a number of key inputs for the model. The accuracy, simply because it is such an early stage, is therefore not very high. This is known and accepted and to remedy this in the future the development of a better and more accurate forecasting model is suggested for Schiphol.

In addition to these comments one very interesting comment was made by Linda van Wamelen which brought forth a new way to look at LH2 demand. The LH2 demand forecasting calculations which were done for Schiphol were based on what may be possible from a technical standpoint. Which aircraft, and thus which flights, could be replaced by LH2 aircraft at Schiphol were taken. Then, based on estimates regarding speed of adoption the LH2 demand over time was calculated. Linda made the astute point that it may be more valuable to forecast LH2 demand based on what would be required to meet climate goals. An example of such climate goals is reducing CO₂ to half of 2005 numbers before 2050 as set by the Paris Agreement. How many flights from Schiphol would need to be converted to LH2 by 2050 to reach this goal? Such questions need to be asked for all climate goals set on a national and international level. This may give insight into the lower bound of adoption that will be required and therefore which can be expected. Forecasting LH2 demand in this way is a good addition which will add additional clarity to what can be expected and should therefore be recommended to Schiphol and all other airports. This will be added to the generalized results and recommendations which will be discussed subsequently.

4.6. Step 6: Generalization of Transition to Wider Aviation Industry

The sixth and final step of this research's methodology consists of taking the resulting LH2 infrastructural vision, transition roadmap, and all other learnings which are specific to the Schiphol case and generalizing it for all airports. Although the Schiphol results have aspects which are specified to Schiphol, a significant number of points can be taken from here which are applicable to all airports. What types of information needs to be gathered, what actions must be undertaken, what is generally feasible, and what factors influence what the infrastructure may look like are all elements which can be generalized. The results of this will be a general infrastructure vision with provisions for how to determine specifics along with a general roadmap of steps which any airport will need to take. This result is also the objective of this research and will therefore also answer the main research question. In this section first the main general takeaways which can be extracted from the Schiphol case study will be summarized. Then, the general infrastructure vision will be explained, followed by the general transition roadmap.

4.6.1. Main Takeaways from the Case Study

Before generalized versions of the infrastructure vision and transition roadmap can be created, it's important to understand what the main takeaways are from the case study which was analyzed. As explained earlier, the use of a case study can give in-context know-how which can be very valuable in a complex situation such as this one. Schiphol was also a good candidate for a case study on the transition to LH2 infrastructure because of its size and role as a hub airport within the market (thus an extreme, critical and paradigmatic case as explained in section 2.1). The transition here will be quite large and can be expected to be one of the most difficult and significant. Learning from this case therefore can give a lot of insight into the important factors influencing feasibility of this transition in a general sense. The specific things that need to be considered in Schiphol's case give insight into specifics which other airports will need to take time to look into for their transition.

Main Takeaways: Infrastructural Vision

The infrastructural vision generated for Schiphol along with the specific considerations and the opportunities and challenges that go along with it gives insight into what might be possible or not possible for other airports. Here is a list of points which need to be considered. It is split into takeaways related to supply, storage, and refueling.

Supply

- Renewable energy requirements to produce LH2 completely at an airport is very high (~50-70 kWh per kg of LH2). Just performing liquefaction at the airport is much more realistic in terms of energy requirement (~5-8 kWh per kg of LH2).
- There is also a high water requirement for electrolysis meaning that a water supply must be close if an airport wishes to perform electrolysis on-site.
- Performing electrolysis + liquefaction or just liquefaction at the airport requires the investment into large facilities. This also requires a significant amount of space to be available at the airport.
- Transporting GH2 via pipeline is feasible and could make use of converted existing natural gas networks.
- Transporting LH2 via truck is likely most realistic at low demand (smaller airports), early in adoption, and over distances larger than a couple of kilometers.
- Transporting LH2 via truck to the airport may create dangerous scenarios on the roads. Special thought needs to be put into this by authorities.
- If possible, the option of last mile delivery of LH2 via inland barge is an interesting one which may clear up congestion.
- Transporting LH2 via cryogenic pipeline is possible over limited distances. To allow for multiple kilometers of cryogenic piping to be feasible, additional development is required. This would realistically allow for a greater volume to be transported.

Storage

- Centralized storage facilities of LH2 allows for better oversight and is similar to established fuel storage.
- Spread LH2 storage facilities around the airport may reduce risk of domino-effect (more robust) in the case of a drastic failure and may be more efficient in terms of reducing losses from transport to refueling. However, this does mean it is more difficult to keep oversight on.

Refueling

- Refueling with LH2 in general is technically feasible but there are certain elements which are recommended to be developed which would improve safety and efficiency. They are break-away couplings and purge-less couplings.
- LH2 bowser trucks used for refueling are technically feasible but will need to be developed for specifically for aviation.
- It may not be possible to refuel some larger LH2 aircraft with just the volume of one LH2 bowser truck. This means that two or more may be needed in some cases just from a volume perspective. It may also be more effective to use multiple bowser trucks for shortening turnaround times.
- Refueling via LH2 hydrant system is technically feasible but requires the development of certain subsystems like intermediate tanks and a mobile refueling vehicle.
- Combining a hydrant system with spread LH2 storage may be more efficient because then the LH2 needs to be piped less far reducing losses.
- LH2 infrastructure experts believe that refueling with LH2 can be designed to be done safely although some other parties believe there could be safety concerns.

- If refueling can be done with passengers in the aircraft and/or can be done at the gate, turnaround times will be much lower than if that isn't possible which improves the viability of LH2 aviation on an economic front.

General:

- Transitioning from one piece of infrastructure to another which is capable of handling higher volumes will be dependent on when these volumes are required. Base plans for scaling up on LH2 demand forecasting models

Main Takeaways: Transition Roadmap

The transition roadmap developed for Schiphol gives insight into the practical steps which need to be taken to reach the infrastructure vision. A lot can be learned from this roadmap because similar steps will need to be taken by all airports who wish to transition. The takeaways are as follows:

Dealing with LH2 demand

- Developing models to forecast LH2 demand at the airport will be very important for determining which infrastructure is required and feasible at the airport. It is also important to approach LH2 demand calculations from both the point of view of the minimal switch to LH2 required to meet climate goals and the point of view of the maximum possible adoption.
- Continual discourse with airlines and LH2 developers will be needed to gain clarity on the LH2 aircraft adoption timeline. Information gained here helps improve demand forecasting, infrastructural design, and supply line development.
- Global LH2 scarcity resulting from a lack of renewable energy harvesting and LH2 production infrastructure is a real possibility. The threat from this needs to be well understood by airports. Discourse with government bodies must also take place here because they often play a role in securing supply on a global market.
- Developing LH2 supply lines is of utmost importance for an airport. Constant comparison with the forecasted LH2 demand needs to take place to ensure that these match up. If not, either supply lines must be upgraded or LH2 aircraft adoption must decrease.

Technical and operational development

- Focusing on developing the required technical subsystems and components which make LH2 infrastructure much more effective like break-away couplings, purge-less couplings and safety systems should be a priority.
- Designing an LH2 infrastructural system fit for an airport will require specific development since such systems do not exist yet. Also communication with LH2 aircraft developers is needed to
- To develop infrastructure and operating procedures which are safe and within the confines of the law, it is important to facilitate collaboration between infrastructure developers, aviation safety authorities, and policy makers.
- Extensive safety analyses will be needed for the development of safe and legal infrastructure and operations. Perform these as development takes place.
- To more effectively develop infrastructure and operations, it is generally wise to begin small early on to learn.

Economic sustainability

- The direct operating costs (DOC) of LH2 aviation are expected to be higher than traditional aviation. This is largely because of the renewable energy required for producing LH2 and shipping the LH2. Working on ways to reduce these costs (by producing LH2 locally or working with suppliers) is important for airports and airlines.

- The (likely still after the first point) higher costs for consumers of LH2 flight may make it unattractive. Market research should be done to understand the consequences. This should be done together with airlines.
- The high investment costs and operational costs must be allocated fairly among the airport, airlines, and governments. Discuss with these parties how this will be handled.

4.6.2. Generalized Infrastructure Vision

In section 4.1 an infrastructure vision was iteratively built specifically for Schiphol. This infrastructure vision took into account Schiphol's geographic location, size, capabilities, and parties existing within Schiphol's ecosystem. This means that this infrastructure vision makes sense based on Schiphol's specific case, but it may not be the most optimal or even realistic for other airports. It is important to understand what is generally realistic and can be expected and what is very dependent on the specifics of each case. It is also important to understand which factors influence the feasibility of different infrastructural options. This can be learned from the process that was used to create Schiphol's infrastructure vision. In this section provisions for how to determine the most effective infrastructure vision for an airport will be given.

LH2 Supply

Based on geographic location and the airport's size and capabilities, the way in which the LH2 demand will be met can vary greatly. The logistic chain goes from the inputs of renewable energy and water to electrolysis to liquefaction to the storage tank at the airport. This is fixed and cannot change. Where these elements of the logistic chain take place can vary greatly. For Schiphol specifically it was determined to be unrealistic to perform both electrolysis and liquefaction at the airport due to space and renewable energy scarcity locally. An airport which has a large amount of space and renewable energy could facilitate either just liquefaction or both electrolysis and liquefaction (if also a water supply is present) at the airport. It may even be possible to produce the renewable energy at the airport. Figure 14 shows the different options when it comes to supply infrastructure that an airport could have.

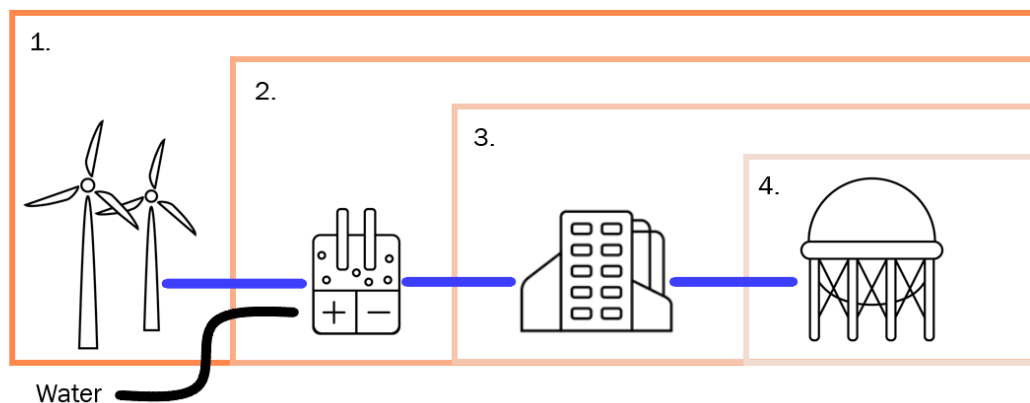


Figure 14: Different options for LH2 supply infrastructure at the airport

Whether an airport will have enough space and resources available to incorporate more of the supply infrastructure at the airport is dependent on the expected LH2 demand at that airport. An airport with a large amount of space and natural resources but a relatively small number of daily flights will likely find building more supply infrastructure at the airport much more feasible. An example of this could be an airport in a remote section of the world. Delivering LH2 from an outside source to these airports would also be more difficult and expensive in this scenario meaning that becoming less reliant on outside help may be even more beneficial. Then box number 1 or potentially number 2 in Figure 14 could be how their infrastructure looks at the airport. However, when it comes to building more of the supply infrastructure at the airport another thing needs to be considered, investment costs. Building renewable energy generation infrastructure, an electrolysis plant, and a liquefaction plant requires a lot of capital. This may not be feasible for many airports. On the other hand, if such infrastructure is built, the airport will not need to transport LH2 to the airport from another

location which may overall lower DOC. A balance between finding realistic initial capital investment and sustainable operating costs will need to be determined for each airport individually based on their specific situation.

If it is determined that an airport cannot host all or most of the LH2 generation infrastructure at the airport, then the way in which the LH2 gets to the airport needs to be looked at. Firstly, if it is most realistic for an airport to perform liquefaction at the airport, but not the earlier sections of the generation (This corresponds with box number 3 in Figure 14), then GH2 needs to be brought to the airport. This could be done via vehicle or pipeline. Moving GH2 via vehicle is very inefficient and would likely not be realistic at all outside of some very fringe cases. A GH2 pipeline system would likely be the best for an airport in this scenario since it allows large volumes to be moved with very little losses and little energy cost. For this investment is needed to build such a pipeline, but often existing gas pipeline could be converted to hydrogen (PricewaterhouseCoopers Advisory N.V., 2021) (NZKG, 2021). On the other hand, if an airport determines that none of the supply infrastructure is feasible to be built at the airport (as was the case for Schiphol), then LH2 will need to be brought to the airport via some method. This scenario corresponds with box number 4 in Figure 14. Last mile delivery of LH2 to the airport will need to be via mobile transport or a pipeline. Mobile transport, most likely a truck, is feasible, but only for low demand airports. Large airports will likely see multiple hundreds of deliveries per day at some point in time. It may be feasible early on but is not sustainable with growth. However the use of an inland barge may also be interesting if an airport's geographic location allows for it and may be more feasible with higher demands. A cryogenic LH2 pipeline is a good option which would allow for much higher volumes to be transported, but this is not entirely realistic over very long distances. Thus, if a port or station where LH2 can be delivered to from another location is near to the airport, it may be realistic to move LH2 the last couple of kilometers with this method. If this is not available, other methods will need to be employed.

To summarize the factors which determine LH2 supply infrastructure for an airport Figure 15 was made.

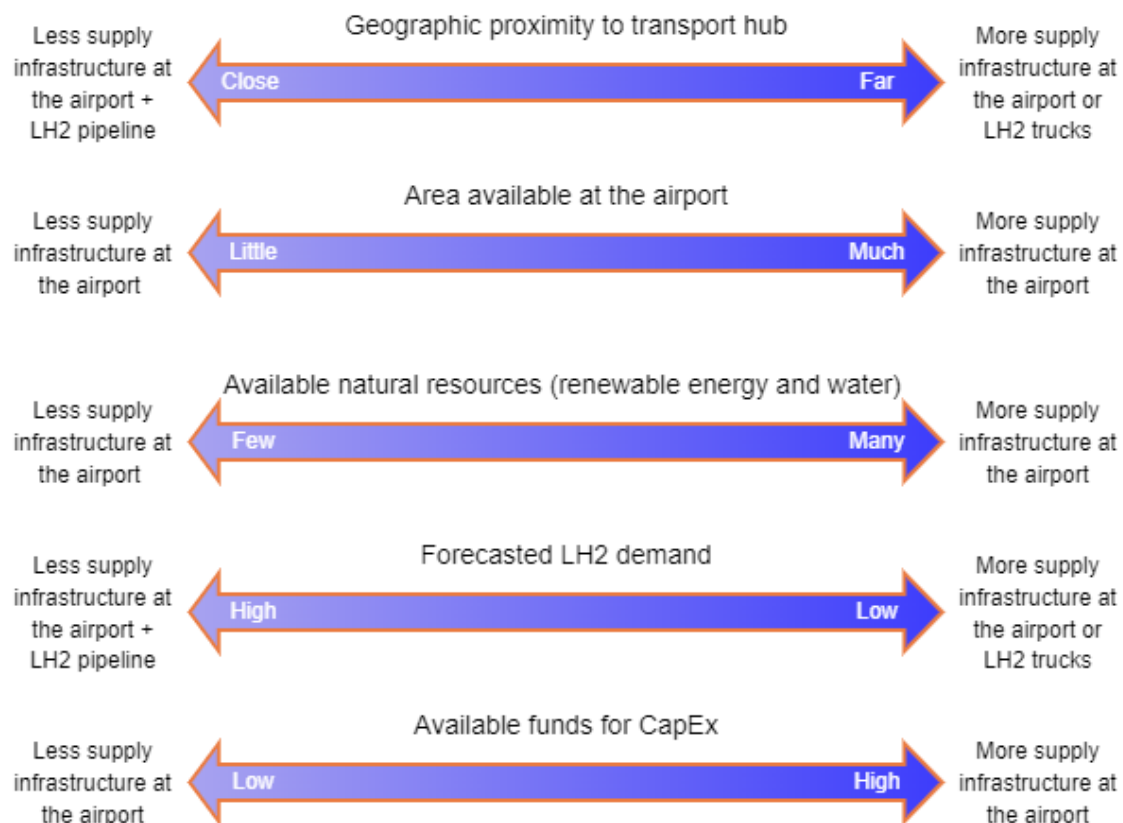


Figure 15: Factors determining LH2 supply infrastructural decision making

LH2 storage

There are two main decisions to be made when it comes to LH2 storage; centralized vs. spread, and tank size vs. tank number. Firstly, the tank size vs. tank number decision is based on the simple fact that if an airport wishes to use smaller LH2 tanks, then they need more of them. On the one hand a larger number of smaller tanks may be safer because, as mentioned by the fire brigade interviewed during this research, the extreme risks of smaller tanks are less than that of big tanks. Also, multiple tanks means that the system is more robust against the failure of one tank or supply line. And if LH2 is delivered to the airport via trucks, multiple tanks would theoretically allow for multiple trucks to resupply the LH2 supply at the same time making it more efficient. Multiple tanks could also be spread around the airport which work well with a hydrant refueling system whereas one single tank would mean a central storage strategy is forced. On the other hand, moving towards fewer larger tanks or even one big tank means that less losses are observed during long-term storage, and less different locations need to be maintained. This could also be potentially less expensive to build up to a certain limit. In the end this decision is one that depends on the airport's LH2 storage demand, supply method, refueling method, and safety considerations. Airports with a higher LH2 demand will likely prefer multiple tanks because of their supply infrastructure (potentially an LH2 pipeline or large number of trucks) and refueling infrastructure (potentially a hydrant system or large number of bowzers). Smaller airports will likely prefer central LH2 storage for the safety, cost and ease benefits.

As was already referred to, spread or central storage is very closely linked to the other infrastructure which is very closely linked to the LH2 demand at the airport. Central storage lends itself well to one or a few large LH2 tanks which have efficiency benefits and cost benefits. However, if there are a lot of trucks moving to supply LH2 and refueling aircraft with LH2, then this wouldn't be realistic. Therefore, small airports which do not face logistic issues like that may prefer centralized storage. Spread storage works well at a high LH2 demand airports since there multiple tanks will be needed anyways and they will likely need to use a hydrant system. This works well in conjunction with a hydrant refueling system since these storage tanks could be located closer to the individual gates lessening losses van LH2 transport via pipeline. Also, this means that if there is an issue with one tank, the others could still operate and less of the airport is at a halt.

LH2 Refueling

From working with the Schiphol case it became clear that there are two main ways in which refueling an aircraft with LH2 could likely be done: via LH2 bowser trucks or an LH2 hydrant system. How an airport chooses which to utilize will be based on the size of the airport, the level of LH2 adoption at the airport, and the capability to invest in expensive infrastructure. Regarding expenses, an LH2 bowser system is significantly less expensive to invest in than a hydrant system. The airport does not need any physical permanent infrastructure for an LH2 bowser system to work; only the LH2 bowser itself. Theoretically an airport could easily purchase the amount of LH2 bowzers that it needs and, assuming it has safe operating procedures and an LH2 supply, utilize them to refuel aircraft. Scaling up the use of LH2 bowser systems is undemanding since the airport only needs to purchase additional bowser trucks. However, scaling at even greater LH2 demand numbers is relatively difficult since at a certain level the number of LH2 bowser trucks which would be needed becomes so large that it is logistically not feasible anymore. An additional factor at play here is that there may need to be multiple bowser trucks present to refuel one aircraft to reduce turnaround times and because of the sheer volume of LH2 needed by an aircraft.

At higher LH2 demand levels at an airport, an LH2 hydrant system is much more effective. This refueling system does employ mobile refueling vehicles so there is some logistics involved, however, these vehicles do not need to continually go back and forth from the LH2 storage to the aircraft. Also, although two bowser trucks may be needed for some aircraft, theoretically only one mobile refueling vehicle may be needed at a time because they can have multiple lines. However, a LH2 hydrant system has the negative that it will require a large amount of funds to build. Securing funding to initially invest in building such a system will not be easy for most airports and likely not feasible for some others. Building such a system includes running cryogenic pipelines to each aircraft stand, placing transfer tanks at each stand, and purchasing the mobile refueling vehicles. In addition to this, a hydrant system is well paired with a spread hydrogen storage system which

could also require more investment. Smaller airports which do not need the efficiency of a LH2 hydrant system will therefore likely not deem the hydrant system worth the cost, especially in the early years.

To summarize, a small airport which will likely not have a large LH2 demand would likely prefer to utilize an LH2 bowser refueling system. This could work for a long period of time. A large airport with the potential to have very high LH2 demand, especially later towards 2050, may choose to start with a LH2 bowser system, but will likely need to and wish to switch to a hydrant system when demand becomes too high. If paired with a spread hydrogen storage system this makes a lot of sense.

4.6.3. Generalized Transition Roadmap

With more clarity on what influences the way that airports will need to choose which LH2 infrastructure to utilize, a roadmap for how to get there can be developed. As was explained, airports will need to make the choice of infrastructure based on a number of factors. Then, they will need to work towards this chosen vision. The generalized transition roadmap will highlight the steps which every airport will need to take on the transition to LH2 infrastructure to create their infrastructure vision and then what they must do to get there. Because this roadmap does not incorporate any of the specifics which Schiphol's roadmap does, less detail will be used. Still a 3-phase structure will be used, but phase 0 will not have the three sub phases as it did for Schiphol. Thus the structure of the roadmap is as can be seen in Figure 16.

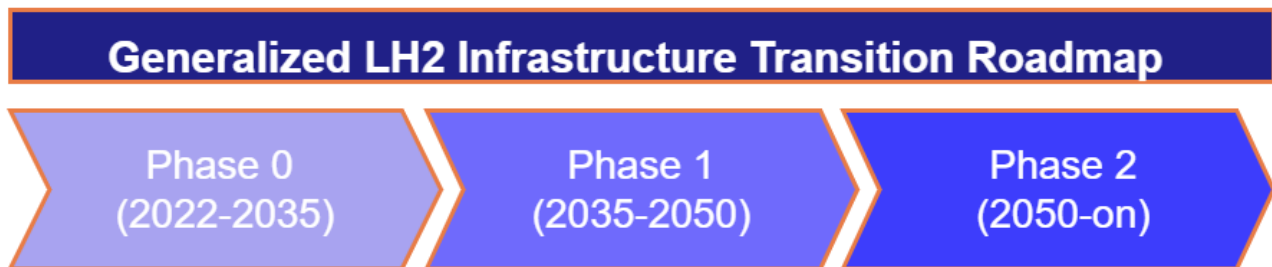


Figure 16: Roadmap for developing and adopting LH2 infrastructure for all airports

The generalized roadmap has the same years as the Schiphol roadmap. Phase 0 still is from the finalization of this research to the point at which LH2 adoption is first expected. Realistically not all airports globally will complete the first phase of the transition at the same time, but because 2035 is the estimate for when it will be first expected, it is logical to still consider this as the point in time when phase 1 infrastructure will be needed. Then, phase 1 goes from 2035 to the point at which infrastructure needs to be scaled up to keep up with rising LH2 demand as adoption increases over the years. As for with Schiphol, the moment when phase 2 infrastructure is needed is estimated to be before 2050 but could vary greatly dependent on the airport. Phase 2 thus begins when this switch is made. Some airports may not need to make a switch to different infrastructure and thus will remain in phase 1. For such airports the roadmap will be more simplistic.

Phase 0: 2022 – 2035

In phase 0 the majority of niche development will take place. This is the phase in which the niche will need to develop to the point that it is capable of entering the regime level and functioning in an operational environment. To understand what needs to take place in phase 0 for this to happen, it is important to understand the starting point.

Before a transition takes place, a firm, such as an airport, needs to understand their level of path dependence by looking into their initial conditions and web of commitments. This means both understanding the starting point of the airport itself and its network. Currently LH2 has a lot of buzz around it within the aviation industry. There is a significant amount of interest, however the level to which certain parties are currently working on real development of the LH2 aviation infrastructure niche varies. Both the airport itself and key stakeholders need to commit to learning and development for the transition to take place. The following is a list of key stakeholder groups (in no particular order) which an airport looking to transition to LH2 needs to open a

discourse with. Understanding their capabilities, level of experience, and view on LH2 aviation at the beginning of the transition helps to build the transition agenda for the airport.

1. Cryogenic infrastructure developers
2. Policy makers
3. Policy enforcement
4. Safety authorities
5. Airlines
6. Research organizations
7. LH2 aircraft developers

What has been observed is that at this point in time select stakeholder groups have significantly more interest and knowledge in LH2 aviation and infrastructure than others. Research organizations and LH2 aircraft developers logically are at the forefront of niche innovation and therefore are important parties for information. Cryogenic infrastructure developers are incumbents to the cryogenic infrastructure market and have a significant amount of knowledge there but are not specialized in the aviation industry since there previously was little overlap between these technologies. Then policy makers and enforcers, safety authorities, airlines, and the airport itself have been observed to have relatively little knowledge on LH2 aviation and infrastructure. It is on the radar and there is a general level of knowledge, but a deeper understanding must be developed in the initial phases of the transition. However, it is important to keep in mind that what has been observed may end up being different for each individual airport. It is important that an airport spends time to gain knowledge on their network and the initial conditions and web of commitments for their specific conditions.

Then, with the starting point of the transition more clearly defined, developing a transition agenda allows for actionable steps which the airport needs to take to be defined. In this roadmap a focus will be put on the actions which each airport will need to do. Logically, since every airport is different, there will end up being a difference in the actions required during this transition. However, many of these specifics will become clear as learning takes place, and the transition develops. Here the actions will be given based on 6 categories (given in no particular order): LH2 supply chain, LH2 aviation adoption, technical development, operational development, regulatory policy, and financial. In Figure 17 a scheme of the actions that need to be taken and the connections between these actions can be seen. Many actions feed into each other as an input because this transition requires a significant amount of iteration as learning and development takes place. As can be seen the scheme of actions and their connections is quite complicated because of the inherently interconnected nature of many of the elements of development. Some actions have a close feedback loop. These are marked with the word iteration. Steps are given in a general order of when they should occur, but these may differ from airport to airport. The actions taken culminate in three actions shown in a darker color of blue which then lead to the adoption of the first LH2 aircraft becoming possible.

General Airport LH2 Infrastructure Transition Roadmap: Phase 0

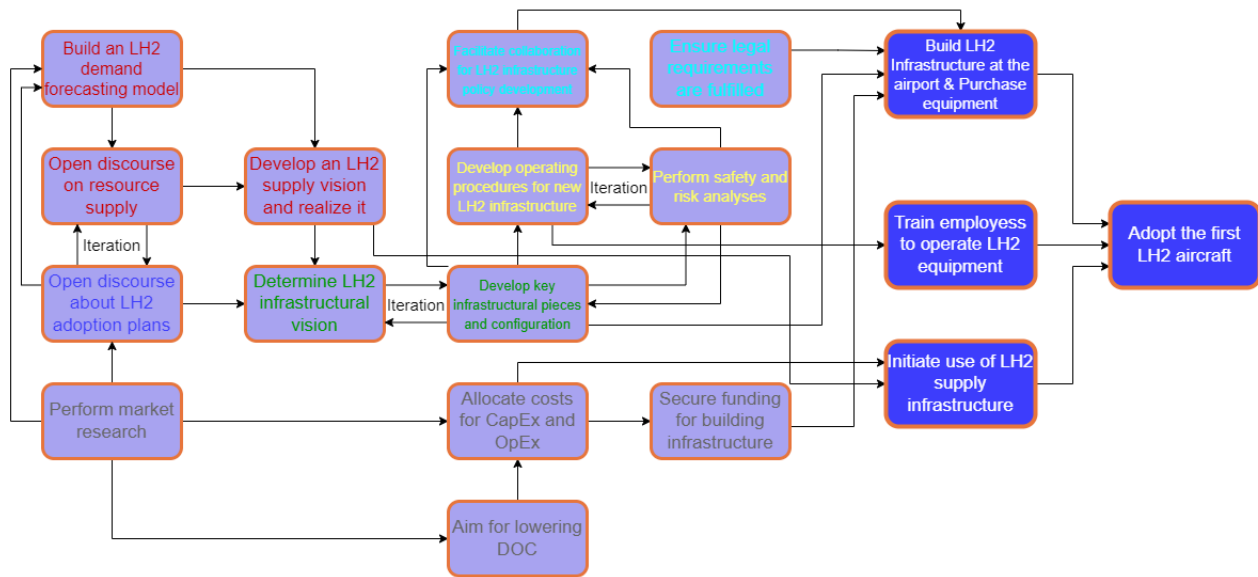


Figure 17: Phase 0 transition roadmap scheme

Because of the complex nature of the scheme, more clarification on the actions which need to be taken, their connection to each other, and the parties which will likely need to be involved is given below.

LH2 supply chain

- (early) **Build an LH2 demand forecasting model** → One of the first actions that must be undertaken is to estimate how much LH2 demand is expected at the airport over the years. Many decisions regarding supply and airport infrastructure will be dependent on this. Gather data from important parties such as LH2 aircraft developers, airlines, etc. to build a model as accurate as possible. Early on accuracy will be lacking, but as development progresses and more information is gained this model will need to be updated to give more accurate results. It is important to approach LH2 demand forecasting considering both what is feasible and what is minimally required to meet sustainability goals.
- (early) **Open discourse on resource supply** → Understanding what and in what quantities resources are available locally is an important factor in deciding which LH2 supply strategy will function best for the airport and whether it is even realistic to meet demand. A discourse needs to be opened with the local government and other relevant parties to discuss either the generation of renewable energy locally or the importing of hydrogen. LH2 demand forecasts will be an important input for this.
- (early) **Develop an LH2 supply vision and realize it** → Based on forecasted LH2 demand at the airport, it is important that a vision for how this demand will be met is created. This comes back to the decision explained in 4.6.2 on LH2 supply infrastructure. This will be very dependent on the available resources and should therefore be developed in conjunction. Based on the iteratively improved vision, the supply chain then needs to be established together with the relevant parties based on the developed vision.

LH2 aviation adoption

- (early) **Open discourse about LH2 adoption plans** → The rate at which airlines choose to purchase LH2 aircraft and use them in flights to and from the airport will determine the LH2 demand. Open a discourse with airlines as an input for the LH2 demand forecasting model. Also,

discuss airport supply capabilities with airlines to ensure that their demand will not be higher than what is possible to supply. Continue discussions as development progresses and the eventual first adoption comes closer. It may be wise to include LH2 aircraft developers in these talks as well to get their input.

Technical development

- (early) **Determine LH2 infrastructural vision** → Apart from the LH2 supply vision, it is also important for the airport to develop a vision for the infrastructure which is within the airports sphere of control. This includes refueling infrastructure, storage infrastructure, and maybe certain elements of supply infrastructure depending on the strategy chosen there. The airport infrastructure vision should be based on being able to handle the forecasted LH2 demand and LH2 aircraft adoption. How infrastructure may need to be scaled up over time should also be considered here. A discourse is needed with cryogenic infrastructure developers and potentially some safety and aviation authorities to determine feasibility.
- (later) **Develop key infrastructural pieces and configuration** → With feasibility of supply and infrastructure considered, it is important to ensure that development of infrastructural pieces takes place. The airport will likely not play a central role in the development process but should facilitate this process and help where needed. Dependent on the level to which an airport is an early adopter of LH2 aviation, more or less development of individual components and technologies will be required. Apart from that, a specific design of the infrastructure configuration for the airport will be needed before it can be built. This process may also create new knowledge which may feed into determining the infrastructural vision for the airport. Also, this process needs to be used as an input for operational development and safety/risk analyses and these analyses then need to feed back into this development process.

Operational development

- (later) **Develop operating procedures for new LH2 infrastructure** → As development of the airport's LH2 infrastructure takes place it is important to simultaneously work on operational development to create procedures for how to use the infrastructure in the most safe and efficient manner. This development should take place in collaboration with LH2 infrastructure developers, safety authorities, and aviation authorities. This should iteratively be developed based on safety and risk analyses inputs.
- (later) **Perform safety and risk analyses** → In order to develop operating procedures which are safe and function within the law, it is important to continually perform safety and risk analyses based on the most recent developments of the infrastructure and operations. This should be done with the combined knowledge of the LH2 infrastructure developers, safety authorities, and aviation authorities. Outcomes of these analyses should be used as inputs for the further development of infrastructure and operating procedures. These analyses should also influence the development of policy around LH2 infrastructure and operating procedures.

Regulatory policy

- (later) **Facilitate collaboration for LH2 infrastructure policy development** → Along with the development of infrastructure and operating procedures, policy needs to be developed as well. As development takes place and safety and risk analyses are performed, these should be used as inputs for the writing of new policy or changing of existing policy. This policy needs to be completed before the LH2 infrastructure is built to ensure that the airport is able to stay within the confines of the law. Collaboration between policy makers, LH2 infrastructure developers, safety authorities, and aviation authorities must be facilitated by the airport.

- (later) **Ensure legal requirements are fulfilled** → Outside of specific policy for infrastructure and operations there are a number of other legal aspects which will likely need to be dealt with by an airport. The use of LH2 as a fuel is an example of something which may be regulated and needs to be discussed. The logistics of transporting LH2 to the airport may be another if this is within the supply vision. The extent to which the airport and its network must deal with such legalities must be understood and to ensure everything is being followed the airport must follow the proper channels.

Financial

- (early) **Perform market research** → LH2 aviation can be seen as a new product for consumers. LH2 aviation is expected to be more expensive than traditional aviation (at least initially). What higher prices for consumers may mean for the market needs to be understood. This will allow airports, airlines, and all other partners to prepare for future circumstances from a financial point of view. This needs to be researched in collaboration with airlines and any other parties which have a stake.
- (early) **Aim for lowering DOC** → The direct operating costs of LH2 aircraft are expected to be as much as two times as much as traditional aircraft. Based on what market research shows this may impact the market in certain ways. It will be better to lower DOC as much as possible. A major factor for a higher DOC will be fuel supply. Therefore take the financial aspect into account when making decisions regarding supply. Also, work with suppliers (if within the vision) to reduce the DOC as much as is reasonable.
- (later) **Allocate costs for CapEx and OpEx** → LH2 aviation will cost money. Investment costs and operational expenditures will need to be allocated to different parties. Airlines and the local government are two parties who will likely need to play a role in the financial side of LH2 aviation. Open a discourse with these parties to discuss costs allocation. Use this as an input for infrastructural decisions as well.
- (later) **Secure funding for building infrastructure** → Before infrastructure can be built, funds will be required for the construction projects and purchase of operational equipment. Work with investors, the government, airlines, etc. to secure these funds for construction. Also use the capability to secure funds as an input for infrastructural decisions

One of the main takeaways which becomes clear from looking at phase 0 of the roadmap is that the initial focus on feasibility is centered around the LH2 supply. Only later it becomes important to develop the other facets which are needed for final implementation like policy. However all aspects of this transition will need to be done before 2035 when it is expected that the first LH2 aircraft will enter the market and begin flying routes. Phase 0 culminates with the building of infrastructure for LH2 supply, storage, and refueling; the training of workers to operate LH2 infrastructure; first use of the LH2 supply chain; and first adoption of LH2 aircraft at the airport. At this point the roadmap progresses from phase 0 to phase 1

Phase 1: 2035 – 2050

Once LH2 aircraft are first serviced at an airport phase 1 begins. At this point there is infrastructure present, and it can be operated safely, within the confines of the law, and in an economically sustainable way. However, it is expected that over time, in order to reach climate goals, airlines will continue to adopt more LH2 aircraft into their fleet. Thus, the ratio of LH2 flights to flights using another form of energy carrier will increase and the LH2 demand at an airport will increase. As LH2 demand increases the LH2 supply and the capacity of the storage and refueling infrastructure must increase accordingly. For some airports this may only mean increasing capacity of existing infrastructure whereas for other airports this might require a switch to different infrastructure. Whatever the case, the goal of phase 1 of the roadmap is to ensure that the process of scaling up goes as smoothly as possible for an airport, causing minimal disruption and costs. A scheme of the steps which have been outlined for an airport to follow to achieve this goal can be seen in Figure 18. Once again, the steps are given shown relative to when they are suggested, however because of the iterative nature and the differences between different airport things will likely look different for each specific case.

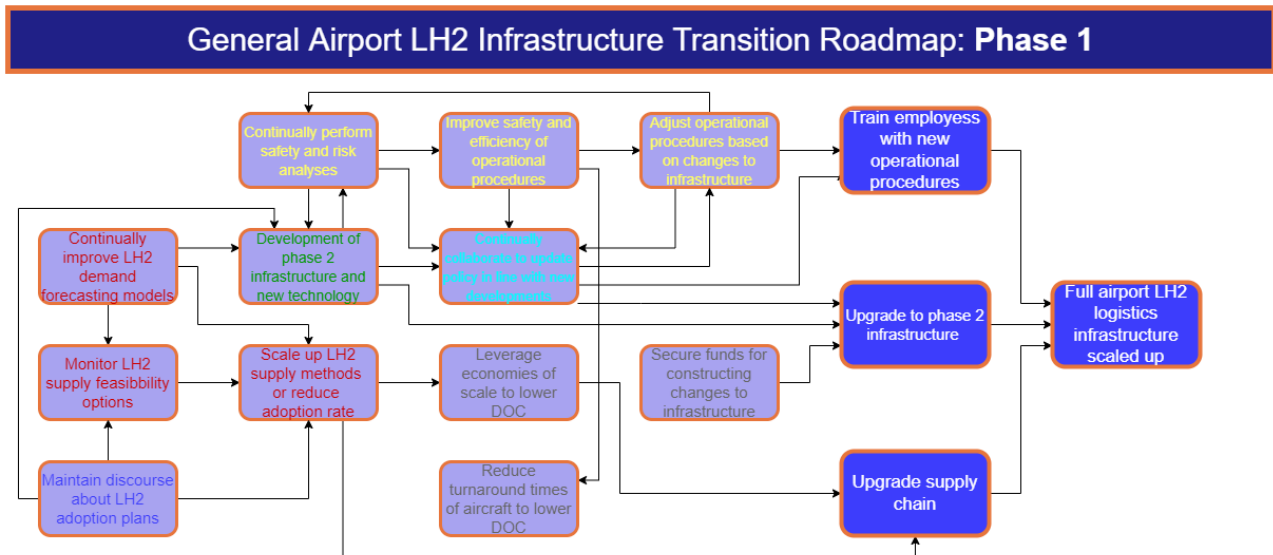


Figure 18: Phase 1 transition roadmap scheme

As with the scheme for phase 0, there are number of connections between suggested actions making the figure quite complex. Explanations of the tasks, their connections, and the parties which are involved are given below.

LH2 supply chain

- **Continually update and improve LH2 demand forecasting models** → Even after initial adoption it is still very important to continually use new information from airlines, LH2 aircraft developers and any other parties to improve forecasting models for future LH2 demand at the airport. Continually upgrade and update this model when possible. Decisions on supply and infrastructure will need to be made based partially on the outcomes of this model.
- **Continually monitor LH2 supply feasibility and other options** → As models for future LH2 demand are updated, it is important to compare this with what LH2 supply numbers are feasible. If the airport is importing LH2 or GH2 look at global demand and your ability to secure the amount needed. If production takes place at the airport, forecast the resource requirements and check for feasibility.
- **Scale up LH2 supply methods or reduce adoption rate** → Based on the comparison of supply capability and LH2 demand forecasts, work on either increasing the supply or reducing adoption rate accordingly. It is important to keep continual discourse open with supply partners and partners which add to the demand to discuss possibilities

LH2 aviation adoption

- **Maintain discourse about LH2 adoption plans** → As an input to LH2 supply chain and infrastructure upscaling decisions, a continual open discourse with airlines and LH2 aircraft developers is needed. It is also important to be able to discuss options if supplying more LH2 is not feasible.

Technical development

- **Development of phase 2 infrastructure changes and new technology** → As LH2 demand increases at the airport the infrastructure will need to be upgraded accordingly. For some airports this will mean simply increasing the sizing or number of components whereas for other airports this will mean changing the entire system or certain subsystems. Decisions as to the most effective infrastructural vision need to be made and development needs to be focused on that. Development will need to take place well before it is expected that the new changes are required to be implemented at the airport.

For large airports which are at the forefront of innovation this may require technology development whereas for others existing technology need only be utilized and prepared for their airport. This will require collaboration with LH2 infrastructure developers and many authorities in addition to demand forecasts.

Operational development

- **Continually perform safety and risk analyses** → In order to improve operations, as LH2 infrastructure is used in an operational environment the safety and risks must be monitored and analyzed. This will be one of the central ways in which learning can take place. Also as infrastructure and operations are upgraded such analyses must continue to take place. Collaboration with technology developers, safety authorities, and aviation authorities will be required here. These analyses will then be used as inputs for further development.
- **Improve safety and efficiency of operational procedures** → To improve the viability and economic sustainability of LH2 aviation, increasing efficiency is key. Also, maintaining safety, even in potentially more hazardous situations is of utmost importance. Using safety and risk analysis and learnings from use in an operational environment, efficiency of procedures must increase as safety levels are maintained or also increased. This can be done through collaboration with technology developers, safety authorities, and aviation authorities.
- **Adjust operational procedures based on changes to infrastructure** → In line with changes to infrastructure as LH2 adoption increases, operational procedures must change as well. Learnings and analyses from initial implementation can be used to make these changes as smoothly as possible. Also, combining these changes with the effort to improve in efficiency and safety is recommended. This can be done through collaboration with technology developers, safety authorities, and aviation authorities.

Regulatory policy

- **Continually collaborate to update policy in line with new developments** → As supply, infrastructure and operations evolve over time, the policy must evolve as well. Work with policy makers and technology developers, safety authorities, and aviation authorities to ensure that policy is updated accordingly to ensure that development is not hindered by policy.

Financial

- **Leverage economies of scale wherever possible to lower DOC** → As scale of operations increases (more for some airports than others), attempt to utilize economies of scale to lower costs of LH2 and reduce DOC. This will improve market position of LH2 aviation and further the transition. Work with suppliers of either resources or LH2 itself to capitalize on this possibility.
- **Reduce turnaround times of aircraft to lower DOC** → Another way to improve economic sustainability and the market position of LH2 aviation is through lowering the DOC via lowering turnaround times. New operating procedures and infrastructure which is designed to be more efficient while maintaining safety standards can aid in this. When developing these new pieces, remember to focus on lowering the turnaround times of aircraft. This can be done through collaboration with technology developers, safety authorities, and aviation authorities.
- **Secure funds for constructing changes to infrastructure** → Upgrading or building new infrastructure will once again require a large amount of funds. This could even require significantly more funds for some airports than phase 1 infrastructure because of the more robust and larger scale nature of this infrastructure. Before construction can take place funds are required. Discuss with airlines, the local government, financiers, and any other partners which may be able to help.

Phase 2: 2050 – Onwards

Compared to the Schiphol-specific roadmap, the point at which phase 2 will be initiated for the general roadmap is much less clear. For Schiphol there was a clear distinction between phase 1 infrastructure and phase 2 infrastructure. For other airports this may not be the case. Depending on the specifics of each airport, the final form of infrastructure may be no different than the initial form. In any case, phase 2 is the same for all airports since it just gives a general overview of actions which need to be taken once the final form of infrastructure has been reached.

Nonetheless, similar to the previously developed roadmap, phase 2 is still very much in the future. Most literature and experts do not look this far. However, the same principles as in earlier phases still apply; learning is crucial. Taking knowledge gained from the operational use of LH2 and applying this to further improve and develop on all fronts is how aviation can continue to progress. The following are key activities to continue development and maturation of LH2 as a part of the aviation regime:

- **Analysis of performance, robustness, safety, economic viability, and efficiency of the infrastructure and supply chains** → To learn and improve performance
- **Forecasting of trends, capabilities, and technologies** → to keep up with future demand and developments
- **Reflection on the transition and networks** → To improve future processes and stakeholder relations

These basic activities coupled with the experience which has been gained at this point and the specifics of each airport's circumstances will lead to continual improvement of LH2 infrastructure at the airport.

5. Discussion

Throughout this report a significant amount of content has been covered to gain a better understanding of the transition to LH2 infrastructure for airports. In the transition to LH2 aviation this infrastructure is crucial because without it LH2 aircraft could not refuel and therefore be useless. A large global network of airports with LH2 infrastructure will be needed if LH2 aviation is to take-off. It has become clear that currently the transition towards this infrastructure at airports is in its early phases. Relevant knowledge on LH2 infrastructure for the airport is still limited and concentrated around research and development parties. Other key parties in the aviation industry have relevant knowledge about their section of the industry, but do not yet have LH2 aviation fully in their focus. This is in large part because the technology is not fully proven yet and because knowledge is still rather limited. The research conducted here aims to aid in the solution to this problem.

As has been made clear, the main goal of this research is to gain a better understanding of the transition to infrastructure for LH2 supply, storage, and refueling at the airport. This has been approached using a basis of transition management along with relevant literature and expert expertise. The context of the transition to this new form of infrastructure has been viewed using the multi-level perspective while the transition itself has been attempted to be better understood using the transition management cycle. The concept here is that the management team of an airport would use this cycle as a basis for managing his transition. To learn from this framework, a first iteration of this cycle has been run through for a specific case airport (in this case Schiphol). The transition was first envisioned more clearly through the development of an infrastructural vision for Schiphol based on literature and a set of expert interviews. To accompany that, the opportunities and challenges connected to this vision were defined. Then, the second step of the transition management cycle was completed through the building of a transition roadmap highlighting actionable steps which Schiphol should take. This was further supported by different management theory on transitions, complexity, and stakeholder management. To strengthen these results, they were validated through further discussion with experts.

The resulting infrastructure vision and transition roadmap for Schiphol were valuable tools with which to understand how such a transition could take place and what considerations need to be made. The goal of the research was to use these results to learn what is relevant for all airports. To generate a method for all airports to determine their own infrastructure vision which is tailor made for their specific situation and a roadmap which all airports can generally follow to develop and implement an LH2 infrastructural system which works for them. This has been achieved with the final step of the research methodology.

The aim of this discussion chapter is to take a step back and take a look these results, and the method employed to get them. First, section 5.1 will analyze the results and the method by looking at the real value created and thinking critically about how this value was achieved. Then, section 5.2 will tie back to the beginning and answer the research question posed in the first chapter of this report.

5.1. Analysis of the Results

The results obtained from this research are intended to do two main things:

1. Give airports clarity about what they can expect future LH2 infrastructure to look like.
2. Develop an agenda of activities which an airport can follow to begin developing the LH2 infrastructure niche further.

These will be discussed and also the general methodology.

5.1.1. Analysis Infrastructure Envisioning

As is logical, the infrastructure vision created specifically for Schiphol and then the general infrastructure vision section both aim to shed light on what can be expected from future LH2 infrastructure at the airport. A significant amount of research went into developing these results. First an extensive literature review was

performed. This literature review was intended to build both a foundation of basic knowledge on LH2 aviation and gather the current knowledge on LH2 infrastructure for airports. With this knowledge the first iteration of the infrastructure vision was created for Schiphol. This infrastructure vision took into account the knowledge gained from the literature review and basic knowledge on Schiphol which was publicly available and relatively easy to track down. This included things which were logically expected to be important such as the size, location, etc. and also specific calculations regarding future LH2 demand. The LH2 demand calculations were generated using data from literature and publicly available flight data. There is accuracy left to be desired for these calculations. The Schiphol flight data was very basic and in the future more advanced flight data could be utilized to improve accuracy. Since this research was done while development of LH2 aircraft is still in the early phases, data on these aircraft was also very limited and basic. As development progresses this data could improve. In addition, rough assumptions were made when it came to other variables such as the average LH2 consumption of each aircraft in flight. Better LH2 aircraft data and LH2 flight data along with an analyses of new potential routes and more specified LH2 adoption forecasts could lead to an LH2 demand calculation model which is much more advanced and accurate. However, having said that, the basic model used in this research does give an initial indication of the order of magnitude of LH2 that can be expected at Schiphol over time. At this phase of development this is enough to develop an infrastructure vision for Schiphol.

The resulting first iteration of the infrastructure vision was a good starting point to begin interviewing experts on. An iterative process was chosen to develop the first version into the final version. The interviewing process focused on both discussing the infrastructure vision with the respondent (which progressed the iterations) and gaining knowledge on their field of expertise. This knowledge was used for the building of the roadmap and will be discussed shortly. Each interview was able to shed new light on the infrastructure vision for Schiphol which allowed this to be improved. Key learning which changed the infrastructure vision, drastically in some cases, was gained. Because of this, this process is considered quite successful. Knowledge which is specific to the parties interviewed and was therefore previously not combined with knowledge on LH2 infrastructure seemed to have been combined for the first time during this process which means new knowledge was developed. This knowledge is very valuable for Schiphol to develop a specific infrastructure vision. Gaining an initial view of what is expected can help Schiphol orient and determine which development avenues to pursue. This knowledge and the infrastructure vision developed with it could also be used to derive the section on the general infrastructure vision

The general infrastructure vision section was not able to conclude anything specific because of the lack of case-dependent airport data. Logically, it was therefore not possible to give one infrastructure vision which is applicable to all airports. However, the section on the generalized infrastructure vision gives airports the tools to generate their own infrastructure vision. The idea is that information from the literature review could be combined with knowledge on other specific airports in the way explained in the section on the generalized infrastructure vision to generate the first infrastructure vision for that specific airport. This is considered a valuable result since it is applicable to any airport and gives them a starting point. This is a way for an airport to create a vision as explained in the first step of the transition management cycle. Thus following this process is a way for an airport to begin the transition.

5.1.2. Analysis Roadmapping

Since the main focus of this research is the transition to LH2 infrastructure at airports, the roadmaps developed are central to reaching the goals set. As with the infrastructure visions, first a roadmap was created specifically for Schiphol. Then, based on the process used to generate that roadmap and the learnings from the roadmap itself, a general roadmap was derived. The aim of this general roadmap is to give all airports regardless of their specifics a starting point from which to begin the transition. It highlights which steps will likely need to be taken by all airports and a rough order in which they need to take place. Since many of the steps require iteration (a clear synergy with the transition management cycle) the connections between different steps are clearly defined here.

The process with which the Schiphol-specific roadmap was generated built forth on the infrastructure vision created for Schiphol earlier in the methodological process. The methodology of this research followed a significant portion of the transition management cycle which gave it structure and clear goals to achieve. The second step of the transition management cycle aims to set a transition agenda along with developing coalitions and images. The roadmap created for Schiphol does exactly that. An agenda of important points which need to be addressed as the transition progresses has been created. The infrastructure vision attempts to answer some of these questions, but a significant portion of them are still left unanswered. This is simply because they are out of the scope of this research. However, now Schiphol should have clarity about what actions to take and what the value is of each action. In addition the roadmap also begins the process of forming coalitions because it suggests clear partnerships and networks which will likely be needed for a successful transition. Also, the roadmap forms a more complete picture of the transition which is much more overseeable than it was before. Thus, this is considered to have created a clearer “image” as is expected in step two of the transition management cycle.

The generalized transition roadmap does the same as the one which was specified to the case except for that select steps could not be as specific and actionable. Since for each airport the LH2 infrastructure vision (including the LH2 supply vision) will differ, it's not yet possible to know exactly what should be done. The general roadmap focusses on giving airports a clear guide for the things that they need to figure out. This roadmap gives actionable steps which an airport can take as an initial input for what they must do to achieve LH2 infrastructure at their airport. As development progresses and learning takes place it is possible that deviation from the roadmap may occur, but since this is one of the first clear roadmaps that has been created for this transition and is thus very early, this can be expected. The generalized roadmap, along with the Schiphol-specific roadmap, are therefore considered to have successfully given an agenda of actions which an airport can follow to begin developing LH2 infrastructure for their airport.

5.1.3. Analysis Methodology

The methodology utilized to achieve the desired result has already been discussed to a certain extent in the previous sections. However, a key component which needs to be considered is how this methodology and the results it generated fits into the bigger picture of the transition. As has been made clear, managing a transition is not a linear path. This can be seen in the transition management cycle which, as the name suggests, is designed for the steps to be iteratively reperformed in a cyclical pattern as development progresses. The roadmaps which have been developed also show the iterative and interconnected nature of a transition. Thus, as the transition to LH2 infrastructure will progress over the years, the findings of this research can be taken and built upon. The research has been designed with this exact plan in mind.

The research methodology was designed to follow a significant portion of the first cycle of the transition management cycle. The idea here is that by following this cycle relevant results will be generated for both Schiphol and airports in general. Then, the airport must continue on this progress to further the transition at hand. The first and second step of the first iteration of the transition management cycle have been completed and the beginning of the third step has been reached. The focus of this step is to mobilize actors, begin projects, and experiment. The tools have been given to the airports to do this. Specifically for Schiphol, clarity has been reached on that types of experiments and projects need to take place and the which coalitions need to be mobilized. As will be explained in the later chapter on the recommendations, it is recommended that Schiphol do these things to learn more and develop the niche further. The same can be said for other airports and the general results. However, in these cases other airports will need to first use the tools given to them to generate their specific infrastructural vision and transition roadmap. From there, they can also begin projects and experiments together with their network.

In performing step 3 of the transition management cycle after this research a significant amount of learning is performed. Knowledge is gathered which will be crucial for niche innovation. As stated, the transition management cycle will need to be iteratively run through to progress the transition. This is expected. After step 3 is performed, step 4 is centered around evaluating, monitoring, and learning. These important actions are also highlighted in the roadmaps. A successful first run through of the transition management cycle will

result in more information centered around key parties in this transition and from there the transition will be able to continue successfully. The research methodology developed and utilized here gives a good start to airports and gives them the tools to continue the rest of the first cycle. Then, subsequent cycles can take place and the transition can move forwards. The research methodology has enabled this making it successful.

5.2. Answering the Research Question

The main research question which was posed in section 1.3.1 based on the set objectives for this research is as follows:

What factors will determine airport LH2 logistics infrastructure design, and what steps does an airport need to take in the socio-technical transition towards this infrastructure?

Then, in order to split up the research into more manageable parts and determine the answer to the main research question in a more calculated way, the following 4 sub research questions were developed:

1. *What is the current state-of-the-art of LH2 infrastructure technology and how can it be used at an airport?*
2. *Based on literature and expert opinion, what factors dictate airport LH2 infrastructure design?*
3. *How can the complex process of a socio-technical transition be guided most effectively?*
4. *What steps must an airport take to develop the multiple facets of a successful LH2 infrastructural system?*

Throughout the research process each of these sub questions were answered. Firstly, sub research question 1 is focused on the state-of-the-art LH2 infrastructure technology. This question was answered in two ways. Firstly, the literature review looked into the current knowledge on airport LH2 infrastructure which gave an overview of the possibilities put forth by current research organizations. Many of the sources utilized were from the past two years meaning that the technology discussed there was very current. The focus of select reports was to research feasibility of this infrastructure and the various options that exist. Other reports looked at LH2 aviation more generally, but also investigated the infrastructure as well. In addition to these reports peer reviewed papers and other reputable sources were used where possible to gather additional information on elements of LH2 infrastructure. Then, next to the literature two different cryogenic infrastructure development parties were interviewed during the iterative infrastructure vision creation process. These cryogenic infrastructure companies both have extensive experience with LH2 and have built infrastructure systems for other industries. They understand what is feasible and what is not with current technical standings. Also these companies have key insight into what would need to happen to achieve what needs to be achieved at the airport. These interviews were key in broadening the knowledge on LH2 infrastructure at the airport. The combination of the interviews and literature have led to the successful answering of sub research question 1. This information can be found in sections 3.3, 3.4, and Appendix A.1.3..

The second sub research question which aims to understand which factors dictate airport LH2 design was also answered through the combined use of literature and expert interviews. Similar literature sources as were used for the first sub research question were also used here. Instead of focusing on a general understanding of what is possible with LH2 infrastructure, here the focus was on implementation of this infrastructure combined with the characteristics of an airport. Now the relevant factors influencing LH2 infrastructure decisions at an airport were looked into. Literature gave this information, but a significant amount of additional information was gained through the expert interviews performed. Now, instead of just a focus on technology, other factors influencing design like supply feasibility, policy, and safety were also considered. The expert interviews added a significant amount of knowledge based on their specific field of expertise. The literature and interview knowledge was combined to first form a specific infrastructure vision for Schiphol along with a set of opportunities and challenges and then later this was generalized to all airports. The discussion and guide on general infrastructure visions given in section 4.6.2 thus answered the second sub research question.

The third sub research question took a step back and looked at the way in which this transition could be guided. With the first two questions leading to a vision, a transition would be needed to work towards that. Managing and guiding such a transition can be an overwhelming process, especially in such a complex and innovative environment. To aid in this and ultimately developing the results to answer the main research question, looking into management techniques, frameworks, and principles was determined to be valuable. This knowledge was gained exclusively from literature review. Peer reviewed literature from some of the most prominent researchers in the transition management, complexity management, and stakeholder management fields was read and analyzed and the most relevant concepts were taken. The review of this literature can be found in section 3.1. Then, this literature was applied to the Schiphol case in order to utilize it effectively in the building of the transition roadmap. The application of this theory, and thus the answer to sub research question 3, was given in section 4.3. Here the takeaways regarding transition management theory for the transition to LH2 infrastructure are highlighted.

Then, the fourth and final sub research question was focused on the steps which an airport would need to take to develop an LH2 infrastructural system. Simply put, this was answered through the creation of the two roadmaps. First, the Schiphol-specific roadmap answered this question for Schiphol (see section 4.4). What Schiphol must do develop and build a successful LH2 infrastructure system as envisioned in the Schiphol-specific infrastructure vision based on the research was given there. This was then used to develop the general roadmap which answered this very same question for all airports. Through the building of the general roadmap (given in section 4.6.3) the second step of the transition management cycle was completed, and the fourth sub research question was answered.

The main research question was answered through the answering of the previous four sub research questions. The first part of the main research question states “what factors will determine airport LH2 infrastructure design”. The first two sub questions have led to an answer to this being created. This is in the form of the general infrastructure vision given in section 4.6.2. Then, the second part of the main research question states “and what steps does an airport need to take in the socio-technical transition towards this infrastructure?” This was answered by the third and fourth sub research questions through the creation of the general transition roadmap given in section 4.6.3.

6. Conclusion

The aim of this thesis report was to explain in a logical manner the exploratory research that has been performed to gain a better and more practical understanding of the transition to LH2 infrastructure at the airport. The first chapter introduced the problem, its context, and clearly defined the research question. In order to answer the research question and reach the goal of this research, a methodological framework was designed based on an existing transition framework. This, along with the specifics of the methodology were explained in detail in the second chapter. From there, the exploratory research, and thus the relevant content for LH2 aviation, was first addressed in chapter three. There the findings from the extensive literature review were summarized. Information on transition management, LH2 aviation, and LH2 infrastructure from relevant studies, articles, and peer-reviewed literature was explained in a structured manner in order to develop a base of knowledge which could be applied to answer the research question. The fourth chapter's focus was the execution of the methodological framework and the eventual reaching of research results. The results and their implications were then addressed in the discussion chapter (the fifth chapter).

The main results of this research are an infrastructure vision and a transition roadmap. Both of these elements were first created for the case studied in this research, Schiphol. Throughout the research methodology information from literature and expert interviews were combined to create the Schiphol-specific infrastructure vision using an iterative process. Opportunities and challenges related to this infrastructure vision were defined. After that, using transition management literature as a guide, a transition roadmap was made for Schiphol which highlighted the actions which Schiphol would need to take in the coming years to successfully progress the transition to LH2 infrastructure. Then, after some validation of the Schiphol-specific results, generalized versions of the infrastructure vision and transition roadmap were derived from the specific versions so that the findings of this research would be applicable to the transition through which most airports will need to go. The factors which determine an airports infrastructure vision and the transition roadmap derived throughout the research directly answer the main research question.

The main takeaways from this research can be derived from the finalized results. The LH2 infrastructure vision is a vision which every airport will need to create based on their specific characteristics. Regarding the supply of LH2, an airport needs to consider its geographic proximity to a transport hub; forecasted LH2 demand; and the area, natural resources, and funds available to the airport. Generally, if an airport has high LH2 demand and does not have the area, resources, and funds required to meet this demand, it will need to source LH2 elsewhere and import it. Whereas if it does have the capability to meet its demand locally, this is something which needs to be seriously considered. Storage methods will largely be based on an optimization of efficiency, required sizing, and safety. If large amounts of LH2 are to be stored and used at the airport, then a more spread-out storage strategy may allow for safety and efficiency to be optimized. At lower LH2 amounts this effect may be less and central storage can be considered. Finally, the refueling infrastructure will likely be dependent on LH2 demand, safety considerations, and the funding available. The choice of infrastructure is bound closely to the amount of LH2 which needs to be processed by the airport but is also highly dependent on whether can be done safely and cost effectively. With high LH2 demand refueling with a hydrant system may work best whereas with lower demand a bowser system may be effective. Then it is also important to consider whether refueling at the gate or at a centralized location can be done safely and efficiently. The factors stated here are important for an airport to consider in making the decision as to what infrastructure is right for them.

Envisioning the infrastructure which is most effective for a given airport to work towards is just a part of the work that is required to further this technology and progress the transition. The transition roadmap which has been developed also shows that, in addition to setting up the supply chain and developing the infrastructure, a simultaneous focus is needed regarding economic sustainability, operational development, and policy development. Working on all different facets of the transition will be required to successfully transition to LH2 infrastructure for aviation, as is expected to be required by 2035. Currently, as was visible in the Schiphol case, most of the progress which has been made regarding LH2 aviation, and thus the knowledge, is centered around research and development parties and not the airports which will eventually need to play a central

role. Leading up to 2035 it is important that airports begin to take a more active role in developing the infrastructure they will soon need to host and the many facets which accompany this. The following needs to take place:

- **Development of an LH2 supply chain** – through demand forecasting, supply vision creation, and discourse with airlines and suppliers
- **Research into LH2 aviation adoption** – by opening discourse with LH2 aircraft developers, airlines, and the market
- **Technical development** – through developing an LH2 infrastructural vision and working with technology developers to develop key systems, subsystems, and components
- **Operational development** – through the development of operational procedures for the new infrastructure and the facilitation of collaboration between technology developers and safety authorities to perform safety and risk analyses
- **Development of regulatory policy** – by communicating with relevant legal authorities and facilitating collaboration between technology and operational development parties with safety authorities and policy makers
- **Ensuring financial sustainability** – by performing market research, lowering DOC, allocating capital and operational expenditure costs with airlines and governing parties, and securing funding required for capital investment

These important points of focus require continual iteration as the transition develops to continually progress effectively. A focus on all of the above areas of development will allow for the eventual construction of LH2 infrastructure at the airport and the transition of LH2 aviation from a niche level to part of the aviation regime. Then, priority will become learning, improving and scaling up this first implementation of LH2 infrastructure. The same six points of focus explained above are still relevant, but instead of the emphasis being the infrastructure required for 2035, the focus must be on the further adoption of LH2 aviation, the rising LH2 demand which will come with this, and the changes to infrastructure which will be needed to make this feasible. Thus, it is important that adoption and growth is closely monitored while scaling up of the LH2 supply chain is looked into. Also the infrastructure technology and the operations and regulatory policy that go along with it need to be continually developed. And it must be ensured that this can be done in a financially sustainable way.

With the insights on infrastructure visioning and the roadmap which has been developed, a clearer image of the transition to LH2 infrastructure has been achieved. Clearly, this transition is still in early stages and much development and iteration is still required, but with this first view, more targeted activities can begin to take place. Thus, to compliment the conclusions derived throughout this report, a set of recommendations have been crafted. They can be found in the next and final chapter (chapter 7). These recommendations focus on the next steps which are a logical continuation of the research performed here.

7. Recommendations

A set of recommendations have been developed from the findings of this exploratory research on the transition to LH2 infrastructure at the airport. The focus of these recommendations is what an airport should do to progress their own transition to LH2 infrastructure at the airport. As explained, the first two steps of the transition management cycle was performed for the Schiphol case. It is recommended that an airport looking to facilitate LH2 aviation through the development of LH2 infrastructure spends time to develop a specified infrastructure vision and transition roadmap based on what has been explained in this thesis. After that, it is recommended, that as discussed in the discussion, the airport in question carries on the work that has been performed in this research by continuing this iteration of the transition management cycle. Within this thesis the first two steps of this cycle on problem envisioning and creating an innovation agenda have been explained. The third step of the cycle in which projects and experiments are executed and coalitions are mobilized has been prepared. The recommendations given here are specifics which are suggested that an airport performs as part of this third step of the transition management cycle. They are as follows:

- **Improve LH2 demand forecasting model:** In this study a simplistic LH2 demand forecasting model has been created for Schiphol. Schiphol and all other airports will need to build an improved model as an important puzzle piece in developing the rest of the transition. Use better flight data, discuss potential future routes with airlines, discuss adoption with airlines and LH2 aircraft developers, etc.
- **Develop LH2 adoption targets in line with climate goals:** LH2 demand forecasting can be approached from the point of view of looking at what is technically feasible. On the other hand, it would be valuable to approach it from the point of view of looking at what amount of LH2 aircraft adoption would allow the country in question to reach national and international climate goals. This could be another way to determine how much LH2 supply is needed and what the infrastructure will need to look like to meet these goals.
- **LH2 supply feasibility study:** Based on LH2 demand forecasts, it is important to look into the feasibility of supplying this amount of LH2. Take a deeper look into where LH2 could be produced and how it would be potentially imported. Determine feasibility of meeting LH2 demand forecasts by discussing these things with relevant parties like LH2 importers and government parties.
- **Development of specific technical components and subsystems for LH2 infrastructure:** Developing the technical components for airport LH2 infrastructure is central to its feasibility. Technical development of these components together with relevant development parties will allow an airport to take the role as an industry leader giving them a strong position in the market.
- **Assess safety and risks related to LH2 refueling and logistics infrastructure and the specific operations with them:** One of the central questions when it comes to feasibility of LH2 at the airport is whether the needed infrastructure and operations can be safe. Understanding what the safety concerns are is crucial for developing safer systems and developing laws and regulations which are appropriate.
- **Look into economic sustainability of LH2 aviation:** Another important aspect of LH2 infrastructure, is ensuring that the use of this infrastructure as part of the LH2 aviation system is economically sustainable for the airport. This includes both the investment costs to build infrastructure and purchase equipment and the operational costs which will come largely from fuel costs. How this can be done in an economically sustainable way and where costs are allocated is important to figure out early in development.

The recommended actions to be taken above are key in ensuring the achievability of the transition to LH2 aviation and the infrastructure that comes with it. This niche technology needs to move from fragility to robustness through effective development. The recommendations highlighted here focus on learning and beginning that development process. It is important that clear development goals are established in this process to allow for more direct progress to be made. In this research a general sense of what will be required for a robust and effective LH2 logistics infrastructural system has been gained, but this will need to be further clarified and specified for each case at an airport. The recommended actions here are mutually influential to each other and will therefore need to develop in an iterative and combined manner. Each element either

directly or indirectly influences others. As an example, forecasting adoption and LH2 demand at an airport has implications for the feasibility of supply and technology while also affecting the safety and economics of the infrastructure. These connections and the many other ones have been clearly explained in this thesis and it is important to keep these in mind when setting goals.

As stated, these recommendations are part of the projects, experiments, and further research that need to be performed in step 3 of the transition management cycle. In addition to those recommendations, it is also recommended that the transition management cycle is further progressed. Learning from these projects and experiments as suggested in step 4 is recommended. Then using these learnings to restart the transition management cycle for a second iteration and even more iterations afterwards to continuously progress the transition towards LH2 infrastructure at the airport is also recommended.

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For any student taking on a master thesis is a large undertaking. It is likely the largest project that one has undertaken up to this point in their academic and professional career. For me this has definitely been the largest individual undertaking I have done solely by myself. Although this was challenging at times, I learned a lot about my topic, performing research, and myself. I also think I have grown as a professional and am much more ready to contribute to society.

Prior to this thesis on LH2 infrastructure at the airport I had the one-of-a-kind opportunity to spend a year full-time working on the development of an LH2 aircraft as part of Delft-based student team AeroDelft. Before this LH2 and its potential role in aviation was entirely unbeknownst to me. This year of work allowed me to learn a significant amount about LH2 and its application in aviation. This, coupled with my background in civil engineering and transition management from my studies meant that I had a unique knowledge base for this research. I hope that I was able to put this to good use for this thesis.

One of the more special aspects of the research performed here is that it was possible to do it for the largest airport in the Netherlands, Schiphol. At Schiphol I was very fortunate to receive a significant amount of practical guidance from Fokko Kroesen. He was very helpful with many aspects of my research and therefore deserves a special thanks. In addition to the guidance I had at Schiphol, doing this research as an intern for them meant that I had more opportunities to meet with important parties in this research which made gathering relevant and valuable data much more achievable. I was luckily able to interview and meet with a significant number of very interesting parties which will all have a role to play in this transition. A big thanks needs to be given to all those who took time out of their busy schedules to meet with me for an interview and discuss LH2 aviation infrastructure.

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References

- AeroDelft. (2022, March 27). Home. Retrieved July 18, 2022, from <https://aerodelft.nl/>
- Aerospace Engineering in top five global QS Subject Ranking. (2020, March 4). TU Delft. Retrieved July 17, 2022, from <https://www.tudelft.nl/en/2020/1r/aerospace-engineering-in-top-five-global-qs-subject-ranking>
- Air BP. (2000). Handbook of Products. Air BP Ltd. https://web.archive.org/web/20110608075828/http://www.bp.com/liveassets/bp_internet/aviation/air_bp/STAGING/local_assets/downloads_pdfs/a/air_bp_products_handbook_04004_1.pdf
- Air Liquide Energies. (2017, October 6). How is hydrogen stored ? Retrieved July 6, 2022, from <https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored>
- Air Transport Action Group. (2020, September). Waypoint 2050: Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency. https://aviationbenefits.org/media/167187/w2050_full.pdf
- Airbus. (2021, June 24). ZEROe. Zero Emission - Airbus. Retrieved July 8, 2022, from <https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe>
- Airbus. (2022, February 22). The ZEROe demonstrator has arrived. Retrieved July 18, 2022, from <https://www.airbus.com/en/newsroom/stories/2022-02-the-zeroe-demonstrator-has-arrived>
- Airlines for America. (2018, January). Jet Fuel: From Well to Wing. <https://www.airlines.org/wp-content/uploads/2018/01/jet-fuel-1.pdf>
- Alshenqeeti, H. (2014). Interviewing as a Data Collection Method: A Critical Review. English Linguistics Research, 3(1), 39–45. <https://doi.org/10.5430/elr.v3n1p39>
- Antweiler, W. (2020, September 28). What role does hydrogen have in the future of electric mobility? Prof. Werner Antweiler, Ph.D. Retrieved July 6, 2022, from <https://wernerantweiler.ca/blog.php?item=2020-09-28#:~:text=How%20much%20electricity%20is%20needed,kWh%20per%20kg%20of%20hydrogen.>
- ATAG Air Transport Action Group. (2020, September). Waypoint 2050. https://aviationbenefits.org/media/167187/w2050_full.pdf
- Aziz, M., Oda, T., & Kashiwagi, T. (2019). Comparison of liquid hydrogen, methylcyclohexane and ammonia on energy efficiency and economy. Energy Procedia, 158, 4086–4091. <https://doi.org/10.1016/j.egypro.2019.01.827>
- Ball, M., Basile, A., & Veziroglu, N. T. (2015). Compendium of Hydrogen Energy: Hydrogen Use, Safety and the Hydrogen Economy (Woodhead Publishing Series in Energy Book 4) (1st ed., Vol. 4). Woodhead Publishing. <https://doi.org/10.1016/B978-1-78242-364-5.00013-0>
- Bergman, N., & Johnstone, E. (2021, October 25). Water access for hydrogen projects: don't let your options dry up. Allens. Retrieved July 20, 2022, from <https://www.allens.com.au/insights-news/insights/2021/10/Water-access-for-hydrogen-projects/>
- Blain, L. (2021, November 1). Universal Hydrogen to convert 15-plus airliners to run on H2 pods. New Atlas. Retrieved July 7, 2022, from <https://newatlas.com/aircraft/universal-hydrogen-airliners-pods/>
- Cloud, M. (2020, August 21). What is the Energy Density of a Lithium-Ion Battery? Flux Power. Retrieved July 6, 2022, from <https://www.fluxpower.com/blog/what-is-the-energy-density-of-a-lithium-ion-battery>

Connelly, E., Penev, M., Elgowainy, A., & Hunter, C. (2019, August). DOE Hydrogen and Fuel Cells Program Record: Current Status of Hydrogen Liquefaction Costs (No. 19001). Department of Energy. https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf

Cryoworld, van der Togt, L., Keezer, M., & Derking, H. (2019, November 4). Liquid Hydrogen Storage: Status and Future Perspectives [Slides]. Utwente. <https://www.utwente.nl/en/tnw/ems/research/ats/Events/chmt/m13-hendrie-derking-cryoworld-chmt-2019.pdf>

De voorzitter van de Tweede Kamer. (2021, December). Kamerbrief marktordening en marktontwikkeling waterstof (No. 0000001003214369000). <https://open.overheid.nl/repository/ronl-40699ddf-c679-435e-8b30-e7adb299d913/1/pdf/21294248.pdf>

Demaco Holland B.V. (2022, May 27). The energy density of hydrogen: a unique property - Demaco Holland B.V. Demaco Cryogenics. Retrieved June 27, 2022, from <https://demaco-cryogenics.com/blog/energy-density-of-hydrogen/>

Demaco Holland B.V. (2022b, June 22). Liquid hydrogen storage: increasingly larger storage tanks. Demaco Cryogenics. Retrieved July 7, 2022, from <https://demaco-cryogenics.com/blog/liquid-hydrogen-storage/>

Deutscher Luft- und Raumfahrtkongress, Seeckt, K., & Scholz, D. (2009). JET VERSUS PROP, HYDROGEN VERSUS KEROSENE FOR A REGIONAL FREIGHTER AIRCRAFT (No. 121195). Hamburg University of Applied Sciences. https://www.fzt.haw-hamburg.de/pers/Scholz/GF/GF_Paper_DLRK_09-09-08.pdf

Dorian, J. P., Franssen, H. T., & Simbeck, D. R. (2006). Global challenges in energy. *Energy Policy*, 34(15), 1984–1991. <https://doi.org/10.1016/j.enpol.2005.03.010>

Elzen, B., Geels, F.W., Green, K. (Eds.), 2004. *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*. Edward Elgar, Cheltenham.

Flinders, D. J. (1997). InterViews: An introduction to qualitative research interviewing. *Evaluation and Program Planning*, 20(3), 287–288. [https://doi.org/10.1016/s0149-7189\(97\)89858-8](https://doi.org/10.1016/s0149-7189(97)89858-8)

Flybjerg, B. (2006). Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, 12(2), 219–245. <https://doi.org/10.1177/1077800405284363>

FlyZero, Cole, J., McClintock, W., & Powis, L. (2022, March). Market Forecasts & Strategy (FZO-CST-REP-0043). Aerospace Technology Institute. <https://www.ati.org.uk/FlyZero-reports/>

FlyZero, Postma-Kurlanc, A., Leadbetter, H., & Pickard, C. (2022, March). Hydrogen Infrastructure and Operations: Airports, Airlines and Airspace (FZO-CST-POS-0035). AeroSpace Technology Institute. <https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf>

FlyZero, & Debney, D. (2022, March). Zero-Carbon Emission Aircraft Concepts (FZO-AIN-REP-0007). Aerospace Technology Institute. <https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf>

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, 1(1), 24–40. <https://doi.org/10.1016/j.eist.2011.02.002>

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017). Sociotechnical transitions for deep decarbonization. *Science*, 357(6357), 1242–1244. <https://doi.org/10.1126/science.aao3760>

Green Hydrogen Transportation–Role of Natural Gas Pipelines. (2020, April 27). FutureBridge. Retrieved July 20, 2022, from <https://www.futurebridge.com/industry/perspectives-energy/green-hydrogen-transportation-role-of-natural-gas-pipelines/#:%7E:text=One%20of%20the%20key%20challenges,methods%20of%20transporting%20green%20hydrogen.>

Greener, I. (2019, January 9). path dependence. Encyclopedia Britannica. <https://www.britannica.com/topic/path-dependence>

Griffee, D. T. (2005). Research Tips: Interview Data Collection. *Journal of Developmental Education*, 28(3), 36–37.

Hartog, J. (2021, October 21). Interesse Vattenfall in conversiepark Maasvlakte. Europort Kringen. Retrieved September 1, 2022, from <https://www.europortkring.nl/interesse-vattenfall-in-conversiepark-maasvlakte/>

Heid, B., Martens, C., & Orthofer, A. (2021, July 15). How hydrogen combustion engines can contribute to zero emissions. McKinsey & Company. Retrieved July 5, 2022, from <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions>

Hodges, A., Hoang, A. L., Tsekouras, G., Wagner, K., Lee, C. Y., Swiegers, G. F., & Wallace, G. G. (2022). A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen. *Nature Communications*, 13(1). <https://doi.org/10.1038/s41467-022-28953-x>

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., & Hanke-Rauschenbach, R. (2021). Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps. *International Journal of Hydrogen Energy*, 47(5), 3108–3130. <https://doi.org/10.1016/j.ijhydene.2021.10.239>

Hydrogen Association. (n.d.). Hydrogen Safety - Fact Sheet. U.S. Department of Energy. https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_safety_fsheets.pdf

Hyfindr. (2022, May 2). FAQ Guide - Hydrogen Tank (types, characteristics, design) | HYFINDR.COM. Hyfindr.Com. Retrieved July 18, 2022, from <https://hyfindr.com/hydrogen-tank/>

IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Jaffe, A. M., Medlock III, K. B., & Soligo, R. (2011). The status of world oil reserves: conventional and unconventional resources in the future supply mix

Jolly, W. L. (2020, June 1). hydrogen - Reactivity of hydrogen. Encyclopedia Britannica. Retrieved July 6, 2022, from <https://www.britannica.com/science/hydrogen/Reactivity-of-hydrogen>

Kamp, L. M., & Vanheule, L. F. (2015). Review of the small wind turbine sector in Kenya: Status and bottlenecks for growth. *Renewable and Sustainable Energy Reviews*, 49, 470–480. <https://doi.org/10.1016/j.rser.2015.04.082>

Kaup, Magdalena & Łozowicka, Dorota & Slaczka, Wojciech. (2017). A concept of an inland LNG barge designed for operation on the Odra waterway. *Scientific Journal of Silesian University of Technology. Series Transport*. 95. 75-87. [10.20858/sjsutst.2017.95.8](https://doi.org/10.20858/sjsutst.2017.95.8).

Lamberg, J., Pajunen, K., Parvinen, P., & Savage, G. T. (2008). Stakeholder management and path dependence in organizational transitions. *Management Decision*, 46(6), 846–863. <https://doi.org/10.1108/00251740810882635>

Loorbach, D. (2007). *Transition management: New mode of governance for sustainable development*. Utrecht, the Netherlands: International Books.

LOORBACH, D. (2010). Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework. *Governance*, 23(1), 161–183. <https://doi.org/10.1111/j.1468-0491.2009.01471.x>

Loorbach, D., & Wijsman, K. (2013). Business transition management: exploring a new role for business in sustainability transitions. *Journal of Cleaner Production*, 45, 20–28. <https://doi.org/10.1016/j.jclepro.2012.11.002>

Ltd, V. (2022, July 20). *EN – Global EV market 2022 pillar page*. Virta.Global. Retrieved August 26, 2022, from <https://www.virta.global/en/global-electric-vehicle-market>

Marcaillou, L. (2022, April 12). Universal Hydrogen et H3 Dynamics conçoivent leur avion à hydrogène à Toulouse. *Les Echos*. Retrieved July 7, 2022, from <https://www.lesechos.fr/pme-regions/innovateurs/universal-hydrogen-et-h3-dynamics-concoivent-leur-avion-a-hydrogene-a-toulouse-1400101>

Marconi, E. M. (2004, June 24). *NASA - Cleaner Skies*. NASA. Retrieved July 18, 2022, from https://www.nasa.gov/missions/research/f_cleaner.html

Mark, R. (2021, November 9). *How an Auxiliary Power Unit Works*. FLYING Magazine. Retrieved August 27, 2022, from <https://www.flyingmag.com/how-an-auxiliary-power-unit-works/>

McKinsey & Company & Clean Sky 2. (2020, April). *Hydrogen-powered aviation: A fact-based study of hydrogen technology economics and climate impact by 2050*. European Commission. <https://doi.org/10.2843/471510>

McKinsey & Company. (2020, November). *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*. https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf

Ministerie van Algemene Zaken. (2022, June 24). *Government limits flight movements at Amsterdam Schiphol Airport*. News Item | Government.Nl. Retrieved August 27, 2022, from <https://www.government.nl/latest/news/2022/06/24/government-limits-flight-movements-at-amsterdam-schiphol-airport>

Mukhopadhaya, J., & Rutherford, D. (2022, January). *Performance Analysis of Evolutionary Hydrogen-Powered Aircraft*. The International Council on Clean Transportation. <https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf>

NASA Spinoff. (2019). *Battery Innovations Power All-Electric Aircraft | NASA Spinoff*. Retrieved July 6, 2022, from https://spinoff.nasa.gov/Spinoff2019/t_1.html#:~:text=Lithium%20Dion%20batteries%20are%20the.run away%2C%E2%80%9D%20ending%20in%20combustion.

Netherlands Enterprise Agency. (2021, April 8). *Operational wind farms in the North Sea* | RVO.nl. Rvo.Nl. Retrieved August 28, 2022, from <https://english.rvo.nl/subsidies-programmes/sde/offshore-wind-energy-sde/existing-wind-farms-north-sea>

NZKG. (2021). Hydrogen Hub Amsterdam North Sea Canal Area. <https://www.noordzeekanaalgebied.nl/wp-content/uploads/2021/10/Hydrogen-Hub-NZKG-v9-04-10-NEDERLANDS-1.pdf>

Piesing, M. (2022, March 21). The epic attempts to power planes with hydrogen. BBC Future. Retrieved July 18, 2022, from <https://www.bbc.com/future/article/20220316-the-epic-attempts-to-power-planes-with-hydrogen>

Port of Amsterdam. (2020, November 5). Kerosene. Retrieved September 1, 2022, from <https://www.portofamsterdam.com/en/business/cargo-flows/liquid-bulk/kerosene>

Port of Amsterdam, EVOS, Electriq Global, Hydrogenious, & HYSILABS. (2021, November). Importing one million tons of green hydrogen via the port of Amsterdam. H2A. https://www.portofamsterdam.com/sites/default/files/2022-02/H2A_external_report_06%20%281%29.pdf

PricewaterhouseCoopers Advisory N.V. (2021, June). HyWay 27: hydrogen transmission using the existing natural gas grid. <https://www.hyway27.nl/en/latest-news/hyway-27-realisation-of-a-national-hydrogen-network>

Riccaboni, M., & Moliterni, R. (2009). Managing technological transitions through R&D alliances. *R&D Management*, 39(2), 124–135. <https://doi.org/10.1111/j.1467-9310.2009.00545.x>

Ritchie, H. (2020, October 22). Climate change and flying: what share of global CO2 emissions come from aviation? Our World in Data. Retrieved January 19, 2022, from <https://ourworldindata.org/co2-emissions-from-aviation>

Rivard, E., Trudeau, M., & Zaghbi, K. (2019). Hydrogen Storage for Mobility: A Review. *Materials*, 12(12), 1973. <https://doi.org/10.3390/ma12121973>

Rotmans, J., D. Loorbach, and R. Van Der Brugge. 2005. *Transitiemanagement en duurzame ontwikkeling: Co-evolutionaire sturing in het licht van complexiteit*. [Transition management and sustainable development: Co-evolutionary steering in light of complexity]. Beleidswetenschap Juni. The Hague: Lemma

Rotmans, J., & Loorbach, D. (2009). Complexity and Transition Management. *Journal of Industrial Ecology*, 13(2), 184–196. <https://doi.org/10.1111/j.1530-9290.2009.00116.x>

Royal NLR - Netherlands Aerospace Centre. (2021, September 14). EU consortium Tulips to accelerate innovations for a more sustainable aviation. NLR.Org. Retrieved July 17, 2022, from <https://www.nlr.org/news/european-consortium-tulips-to-accelerate-innovations-for-a-more-sustainable-aviation/>

Schiphol. (2020). *Traffic Review 2019*. <https://www.schiphol.nl/en/schiphol-group/page/traffic-review/>

Slanger, D. (2022, March 2). Run on Less with Hydrogen Fuel Cells. RMI. Retrieved June 27, 2022, from <https://rmi.org/run-on-less-with-hydrogen-fuel-cells/#:%7E:text=By%20contrast%2C%20hydrogen%20has%20an,12%E2%80%9314%20kWh%20per%20kg.>

- Sripad, S., & Viswanathan, V. (2021). The promise of energy-efficient battery-powered urban aircraft. *Proceedings of the National Academy of Sciences*, 118(45), e2111164118. <https://doi.org/10.1073/pnas.2111164118>
- Statista. (2021, July 23). Global carbon dioxide emissions 1965–2020, by region. <https://www.statista.com/statistics/205966/world-carbon-dioxide-emissions-by-region/>
- Stolten, D., Samsun, R. C., & Garland, N. (2016). *Fuel Cells: Data, Facts, and Figures* (1st ed.). Wiley-VCH.
- Swanger, A. N. (2022, May 6). World's Largest Liquid Hydrogen Tank Nears Completion. Cryogenic Society of America Inc. Retrieved July 7, 2022, from https://www.cryogenicsociety.org/index.php?option=com_dailyplanetblog&view=entry&year=2022&month=05&day=05&id=48:world-s-largest-liquid-hydrogen-tank-nears-completion#:~:text=Construction%20of%20the%20world%27s%20largest,550%20ft
- SYSTEMIQ. (2022, May). A Vision for Hydrogen Flying at Rotterdam The Hague Airport. SYSTEMIQ Ltd.
- TU Delft in International Rankings. (n.d.). TU Delft. Retrieved July 17, 2022, from <https://www.tudelft.nl/en/about-tu-delft/facts-and-figures/tu-delft-in-international-rankings>
- Veenstra, A. (2022, June 13). World's first hydrogen-powered aircraft is "Made-in-Holland" and zero emission. InnovationQuarter. Retrieved July 5, 2022, from <https://www.innovationquarter.nl/worlds-first-commercial-hydrogen-powered-aircraft-is-made-in-holland-and-zero-emission/>
- Universal Hydrogen. (2022, February 10). About the Company. Retrieved July 7, 2022, from <https://hydrogen.aero/company/>
- Universal Hydrogen. (2022b, June 16). JetBlue Technology Ventures. Retrieved July 7, 2022, from <https://www.jetblueventures.com/portfolio/universal-hydrogen/>
- van der Brug, L. (n.d.). 15 things you need to know about hydrogen. TNO. Retrieved July 20, 2022, from <https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/hydrogen-for-a-sustainable-energy-supply/15-things-you-need-to-know-about-hydrogen/>
- VSL. (2020, April 11). Hydrogen purity analysis for fuel cell vehicles | Vsl.nl. Vsl.Nl. Retrieved July 20, 2022, from <https://www.vsl.nl/en/about-vsl/news/hydrogen-purity-analysis-fuel-cell-vehicles#:~:text=Hydrogen%2Dpowered%20vehicles%20however%20require,only%20a%20few%20nmol%2Fmol.>
- Webber, M. E. (2007). The water intensity of the transitional hydrogen economy. *Environmental Research Letters*, 2. <https://doi.org/10.1088/1748-9326/2/3/034007>
- Weichenhain, U. (2021, November). FOCUS: Hydrogen transportation | The key to unlocking the clean hydrogen economy. ROLAND BERGER GMBH. <https://www.rolandberger.com/en/Insights/Publications/Transporting-the-fuel-of-the-future.html>
- Yin, L., & Ju, Y. (2019). Review on the design and optimization of hydrogen liquefaction processes. *Frontiers in Energy*, 14(3), 530–544. <https://doi.org/10.1007/s11708-019-0657-4>
- ZeroAvia. (2022). First Practical Zero Emission Aviation Powertrain | USA & UK. Retrieved July 17, 2022, from <https://www.zeroavia.com/about-us>

Appendix

In the appendix additional information which is valuable for the research, but not crucial for the main storytelling is displayed.

A.1. Iterative LH2 infrastructure Vision Development Process

In the main text (section 4.1) a general overview of the process used to develop the infrastructure vision for Schiphol is given. Here the specific, iterative steps in this process are explained in more detail. The first iteration (section A.1.1.) is built based on information from the literature review and LH2 demand modelling. Then, the second, third, fourth, and fifth iterations (sections A.1.2., A.1.3., A.1.4., and A.1.5. respectively) come forth from the interviews conducted. In each of these sections an overview of the data used to build or change the infrastructure is explained and analyzed and afterwards the newest infrastructure vision is given. The final Infrastructure vision resulting from this process is given in section 4.1.2 in the main text.

A.1.1. Iteration 1 – Literature Based Schiphol Transition Scenario

The first iteration was formulated based entirely on literature and publicly available data on Schiphol, its stakeholders, and the surrounding environment. This was then used as a starting off point for the first interview performed. The factors which influence how the scenario will look explained above all needed to be understood before this scenario could be built..

First, to begin understanding what type of infrastructural needs Schiphol could expect, the LH2 demand of the airport over time would need to be estimated. Because LH2 adoption in aviation, and thus the demand for it at an airport, is still quite far away, it is not feasible to accurately predict this at this point in time. However inaccurate, it is still quite valuable to give thought to the future LH2 demand, since the steps taken now already depend on what it may be. Over time accuracy of these estimates will likely increase. For now, making predictions gives an idea as to the possible range of LH2 demand at certain points in time as well as shining a light on what variables this depends on. In addition, because the sizing of and type of LH2 logistics, storage and refueling infrastructure is very dependent on the LH2 demand at an airport, to make the initial scenario it is crucial that estimates are made.

LH2 Demand Calculations

The LH2 demand was modelled using basic data and a set of assumptions (largely made from literature) in a multi-step process to calculate LH2 demand at Schiphol Airport. The process followed is very similar to the process that FlyZero used to calculate LH2 demand for airports in a more general sense, as was made clear in an email from senior technologist at FlyZero, Alejandro Block Novelo. Here this process is specified to Schiphol. The model was built in a series of google sheets documents and images of these sheets can be found in Appendix A.2. and A.3. The process started with the analysis of existing flight data from Schiphol. This is flight data from the 2019 Schiphol Traffic Review, because this was the last year of normal, pre covid pandemic operation. Data on the amount of passenger and freighter flights and which aircraft flew these flights was collected from this document. A set of conceptual future LH2 aircraft (which were discussed in section 3.2. Of the literature review) were used to see which flights could potentially be flown by LH2 aircraft instead of traditional ones. Then based on the LH2 consumption of the conceptual LH2 aircraft, the total yearly, monthly, and daily LH2 demand at Schiphol could be predicted based on 2019 numbers and assuming full adoption. The amount of LH2 consumed by these aircraft on average was very crudely estimated based on a flight distribution of 50% typical missions (design mission), 25% long-range missions (max range), and 25% short-range missions (50% of typical mission). To take into account the fact that the switch to LH2 will take time and to extrapolate these numbers to 2035 and up to 2050, estimates regarding adoption and growth are used. Six adoption scenarios from different industry reports discussed earlier in section 3.5. of the literature review were used for this. These calculations allowed for the creation of a tool that could estimate Schiphol's LH2 demand over time based on both the six adoption and three growth scenarios. Figure 19 shows all 18 possible LH2 demand curves displayed in a graph:

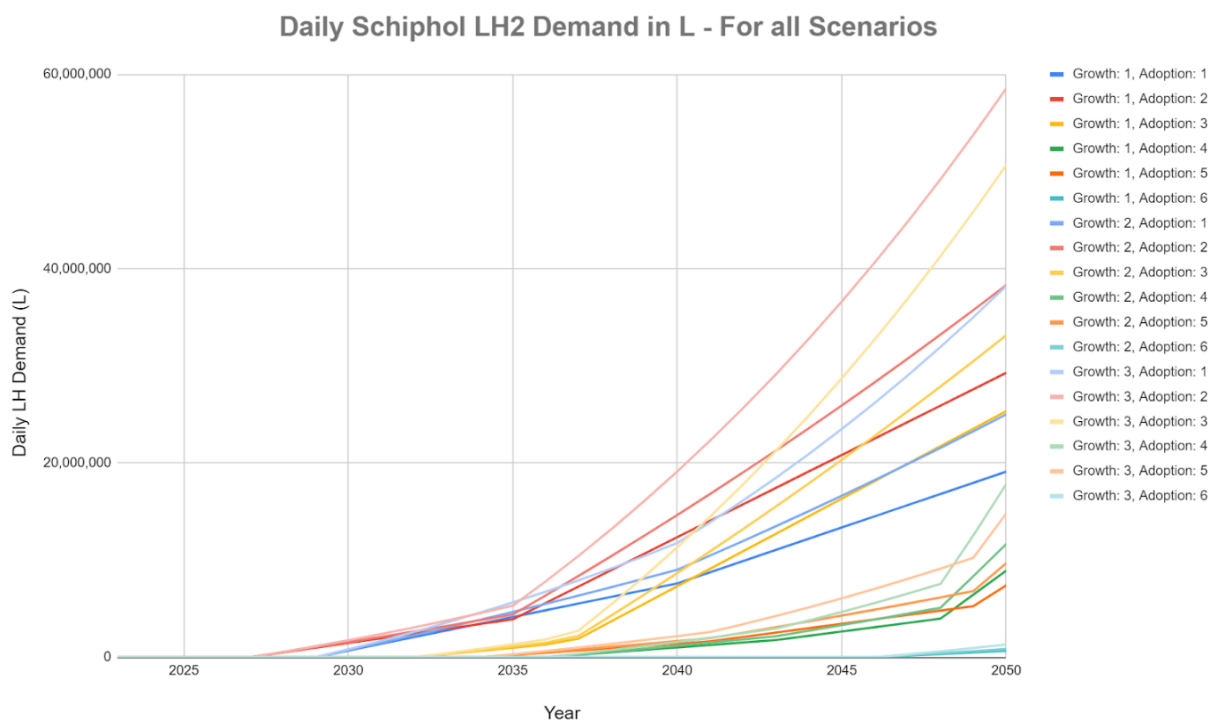


Figure 19: Range of all LH2 demand scenario combinations

As can be seen in the graph, the range of LH2 demand at the airport is extremely large and gets even larger as time goes on. Logically, the further in the future, the more difficult it is to predict, and thus less accurate that any predictive models will be. However, this does give an indication as to the maximum and minimum expectations for LH2 demand. Also it gives an indication as to the range of possibilities at each point in time. As can be expected, the LH2 requirements are quite dependent on the growth of an airport. If the number of total flights at an airport grows, then, assuming a constant level of LH2 adoption, the number of LH2 aircraft will grow as well. If, for example, the assumption was made that Schiphol would not grow in size, then the spread of the LH2 demand over time is less drastic. This can be seen in Figure 20. There the difference in the LH2 demand is solely based on the adoption scenarios. This shows that even without any growth, there is still a large of variance between the different scenarios. However, the maximum LH2 requirement is significantly lower than that of the previous graph in which growth was counted. Meaning, that if Schiphol is indeed limited to the 440,000 flight movements like recently announced, the LH2 demand may be more manageable (Ministerie van Algemene Zaken, 2022). Another thing that becomes clear when the growth is removed, is that the LH2 demand increases at a much higher rate later in the adoption process. This is because, generally, it is expected that the adoption of large aircraft will tend to be later than that of small aircraft, and these aircraft consume significantly more LH2. Thus, the LH2 demand increase accelerates.

Daily Schiphol LH2 Demand in L - No Growth, All Adoption Scenarios

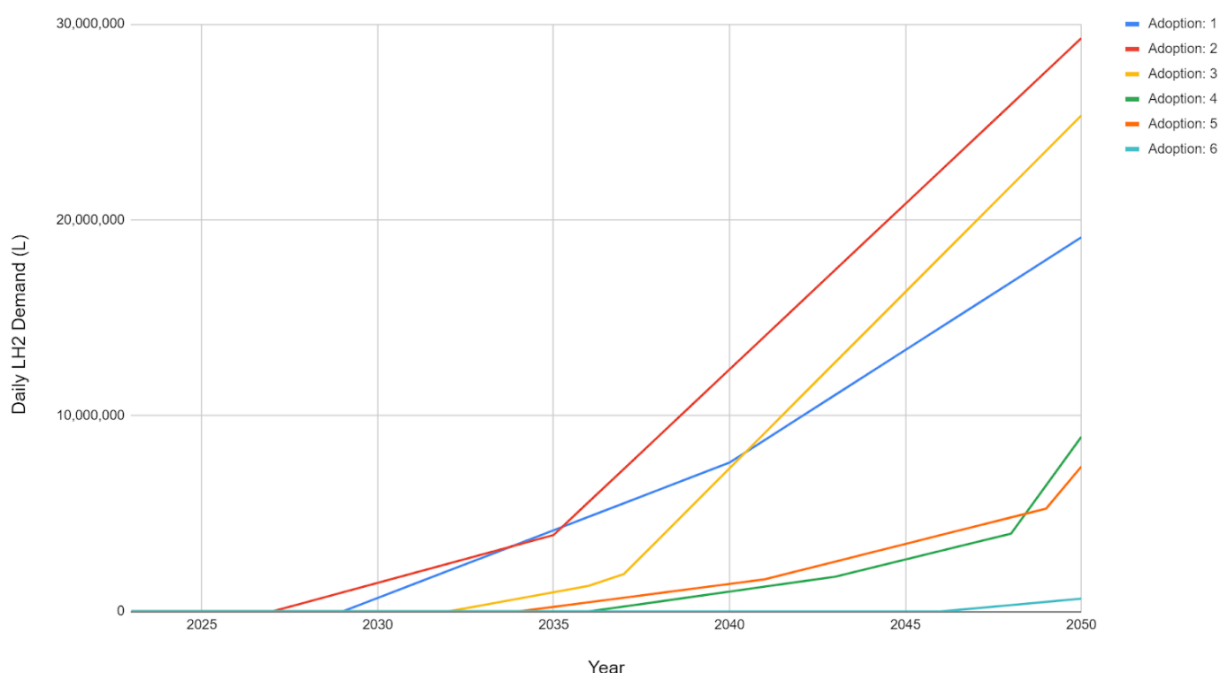


Figure 20: Range of all LH2 adoption scenarios and no growth

Based on the predictive model for LH2 demand at Schiphol, a first indication of the amounts of LH2 that the airport infrastructure will need to be able to handle over time is gained. It is clear that this is very dependent on a number of assumptions. One of the major assumptions is the LH2 aircraft adoption rate. Other examples of assumptions are the LH2 aircraft design, Schiphol growth rates, constant flight range distribution in subsequent years, etc. Because of these assumptions and uncertainties, the range of LH2 requirements is large. This range widens the further away the model gets in terms of time. Two things are certain: Schiphol is a large hub airport which will have a relatively high LH2 demand if it adopts at similar or higher rates than the rest of the industry and this demand will increase significantly over time.

LH2 Infrastructure Requirements Calculations

The LH2 demand calculations are interesting but need to be translated into units which give information relevant for the development of an infrastructure scenario for Schiphol. Three dependent variables are important to understand the requirements of this infrastructure: 1. LH2 trucks needed for transport, 2. Energy requirements for production, and 3. Sizing of storage capabilities. There are two different ways in which this information can be understood and visualized. Firstly, each variable could be computed for each of the 18 adoption and growth scenarios to show the full range of possibilities. In addition, it can be valuable to look into one specific likely scenario to clear out the clutter that comes when adding the 17 other scenarios. Both methods will be employed. The single scenario chosen is that of zero growth (growth scenario 1) and regional-accelerated adoption (adoption scenario 4). It can be seen clearly as the green line in Figure 20. This choice has been made because, firstly, this scenario has been deemed to be one of the most logical based on the information from the literature review. This is because the scenario expects adoption to begin first with smaller aircraft and later be expanded to larger aircraft and begins between 2030 and 2035. Also, since recently Schiphol has been limited to 440,000 air traffic movements annually, it can be expected that this will stay this way for the coming future and no growth is allowed. In addition to these reasons, the fact that this scenario is on the lower end of expectations means that anything infeasible for the infrastructure means that it may be even more unreasonable for the other scenarios. However, the calculation tool that has been created does have the ability to calculate the infrastructure requirements for any scenario.

Using the LH2 demand at the airport, the amount of truck deliveries that would be needed to transport this amount of LH2 to Schiphol, if such a delivery method was chosen, can be calculated. This gives an idea as to how feasible this strategy would be. Figure 21 shows the number of LH2 delivery trucks over time for the chosen scenario:

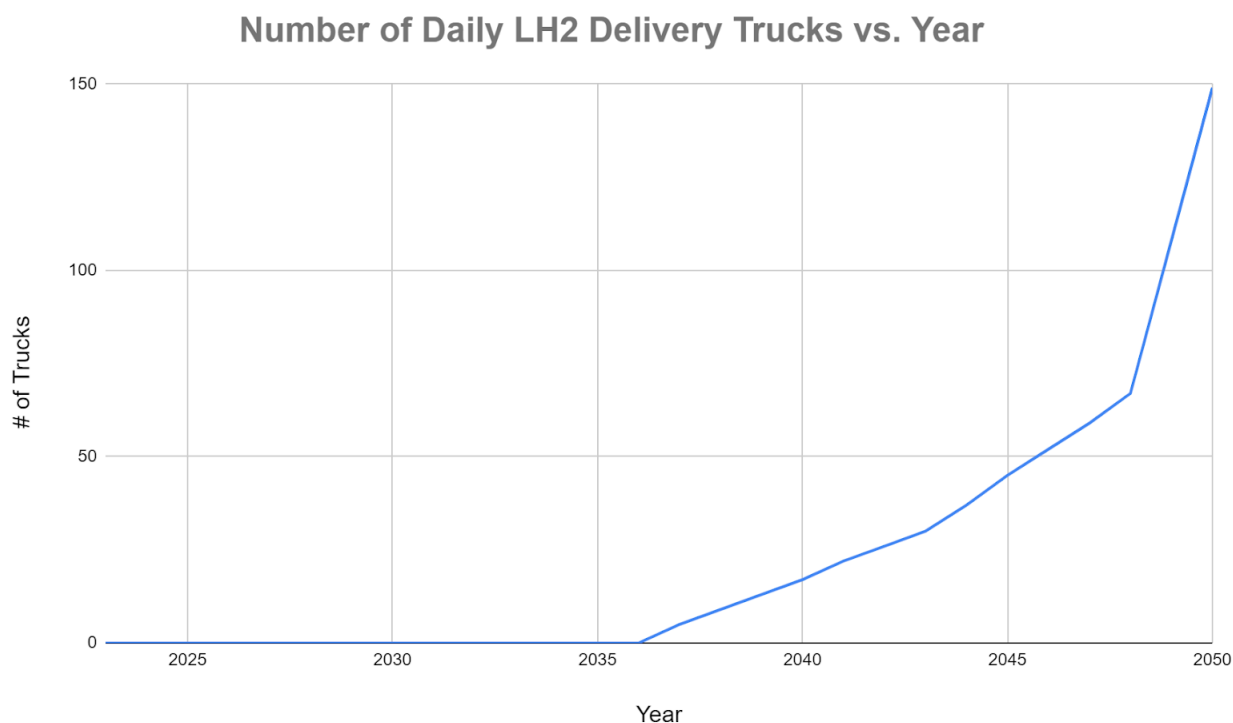


Figure 21: Number of LH2 truck deliveries that are needed to supply Schiphol with LH2 over time (for growth scenario 1 and adoption scenario 4)

As can be seen, over time the need of LH2 trucks rises significantly as adoption increases. For this calculation a 60,000 L capacity LH2 tank truck is used (Ball et al., 2015). If this method of transportation is implemented, by 2046 over 50 trucks would be needed per day, and by 2049 over 100. 50 trucks a day, considering even distribution throughout the day (which is not very likely meaning that even more congestion could be expected at certain times of the day) would mean a new truck approximately every 29 minutes. And 100 would equate to a new truck every 14 minutes. Also, since larger aircraft get adopted later and the increase in LH2 demand over time speeds up, the increase of truck requirements can be expected to speed up even further post 2050. Since this scenario is on the lower end, it is still rather manageable for a period of time, but if a higher demand scenario was taken, truck numbers would shoot through the roof. This can be clearly seen in Figure 22 where the truck predictions for all 18 scenarios are compared. The most progressive scenarios would require multiple hundreds of daily truck deliveries before 2040 already and nearing 1000 by 250. Even a less intense scenario such as growth 1, adoption 2 already results in more than 50 truck deliveries being needed in 2034 already and 489 by 2050. Hence, it can be concluded that it may be possible to use LH2 trucks to supply Schiphol for a period of time after first adoption, but that a switch will need to be made far before 2050 considering many scenarios.

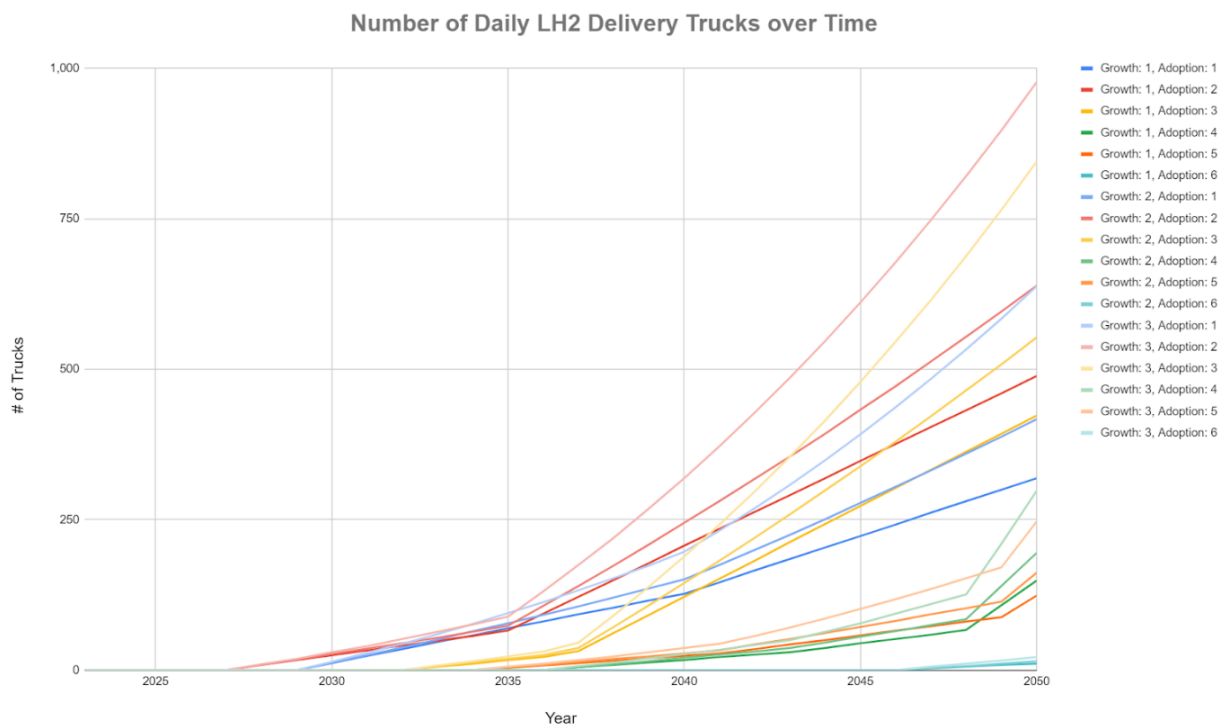


Figure 22: Number of LH2 truck deliveries that are needed to supply Schiphol with LH2 over time (for all scenario combinations)

There is a second type of LH2 trucks that could be required within the logistic chain; LH2 bowser trucks for refueling. It is difficult to estimate how many of these would be needed exactly, but the number of refuels that would be needed per day will correlate with the number of movements these trucks need to make. This will be dependent on the number of LH2 aircraft take-offs that take place within a given time period. The basic calculation for daily LH2 bowser truck movements over time for all scenario combinations can be seen in Figure 23. This is simply based on the assumption that for each take-off (and thus each time an aircraft needs refueling) a single LH2 bowser truck movements is needed. Assuming a single truck can make multiple movements each day, the number of actual bowser trucks needed will be significantly lower. However, the number of movements is an indicator of the congestion at the airport that will result from LH2 refueling requirements. An additional factor here is that to lower turnaround times, it may be wise to utilize two bowser trucks at once for the refueling on one aircraft. In some cases this may even be required. Referring back to the proposed LH2 aircraft in Table 1 in section 3.2.1, it can be seen that the largest LH2 aircraft will need 9,677 kg of LH2 for a typical mission. This equates to more than 136,000 liters of LH2 which will likely be much larger than one bowser truck. Two or even more will be needed to refuel this aircraft one time. This is the worst case however and smaller aircraft will require less LH2. If this is done, the number of movements shown in the graph (and thus bowser truck requirements) may increase drastically (depending on how many aircraft would need multiple vs one truck). An additional thing to consider is that each bowser truck will need to first drive to the storage location to collect LH2, then drive to the aircraft to refuel it, and then drive back (or to another aircraft). This means that each movement shown in the graph below can be considered as multiple individual movements of each truck. Taking that and the use of multiple trucks into account, the numbers displayed in the graph could be up to a factor 10 higher. This shows that bowser truck movements could be very high, especially later down the line when adoption has increased, and more larger aircraft are used.

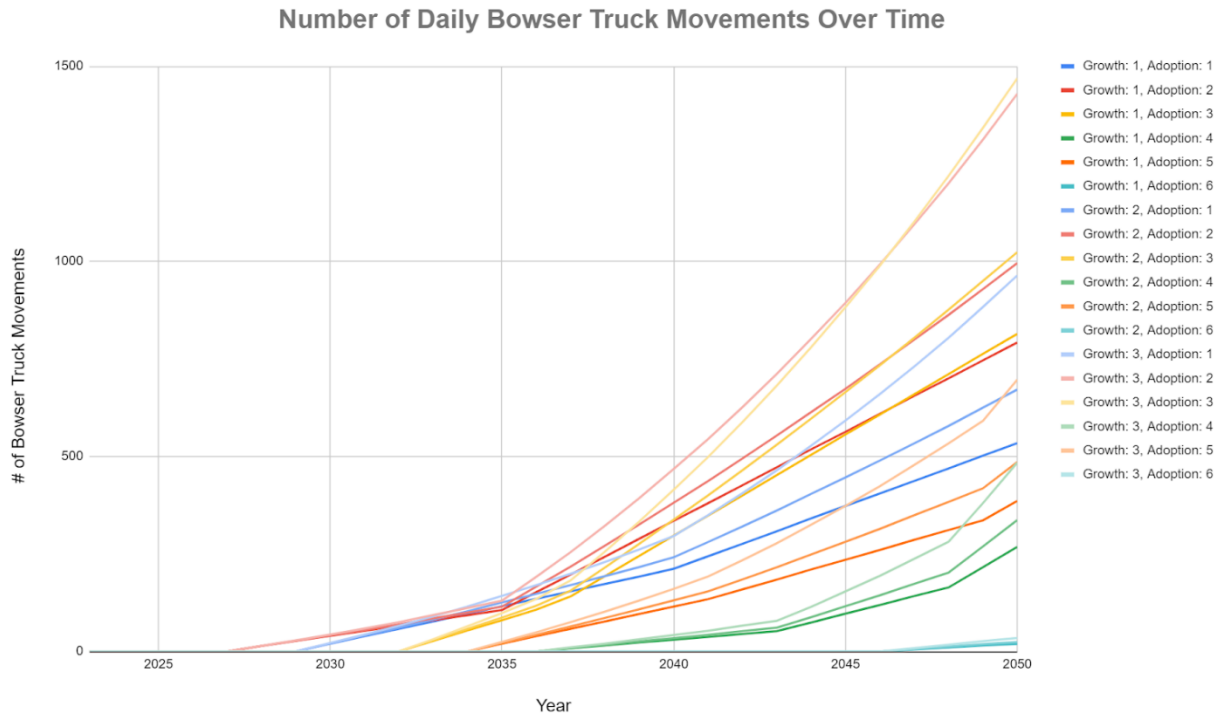


Figure 23: Number of daily LH2 bowser truck movements that are needed for refueling at Schiphol over time (for all scenario combinations)

As can be seen in the figure above (Figure 23), a large number of LH2 bowser truck movements can be expected. Considering that what is shown here is the low end (because multiple trucks can be used and multiple movements would be needed for one refuel), the total number of actual movements that need to take place at the airport on a daily basis could reach into the multiple thousands. At a certain point this could become very cumbersome and logistically infeasible for an airport with as much demand at Schiphol. To give more context, specifically the LH2 bowser truck movements for growth 1, adoption 4 can be seen in Figure 24. Even with this mild scenario, multiple hundreds of movements are expected in the latter half of 2040 even at the low end. Both this and the earlier graph make it clear that using LH2 bowser trucks could be a good option early on in LH2 aircraft adoption, but that before or in the 2040's a switch will likely be needed for Schiphol.

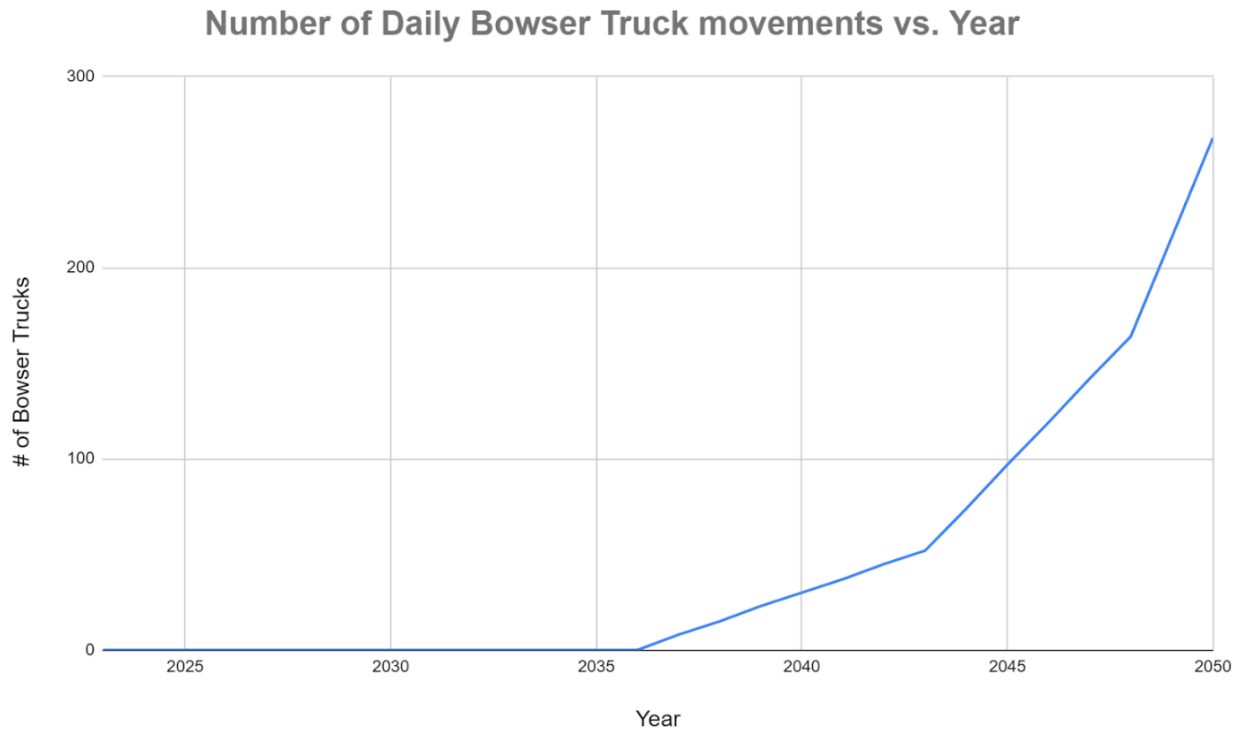


Figure 24: Number of daily truck movements that are needed for refueling at Schiphol over time (for adoption scenario 4)

Next it's important to understand the power requirements that are connected to the LH2 demands of Schiphol. Regarding supplying that demand, there have been options discussed in the literature where either liquefaction or both electrolysis and liquefaction take place at the airport. To assess whether this is realistic, it's important to begin with the power requirements that this would entail. Once again, this can be analyzed specifically for adoption scenario 4 and no growth. Figure 25 shows the daily energy requirements for performing liquefaction at the Schiphol and Figure 26 shows the daily energy requirements for performing both electrolysis and liquefaction.

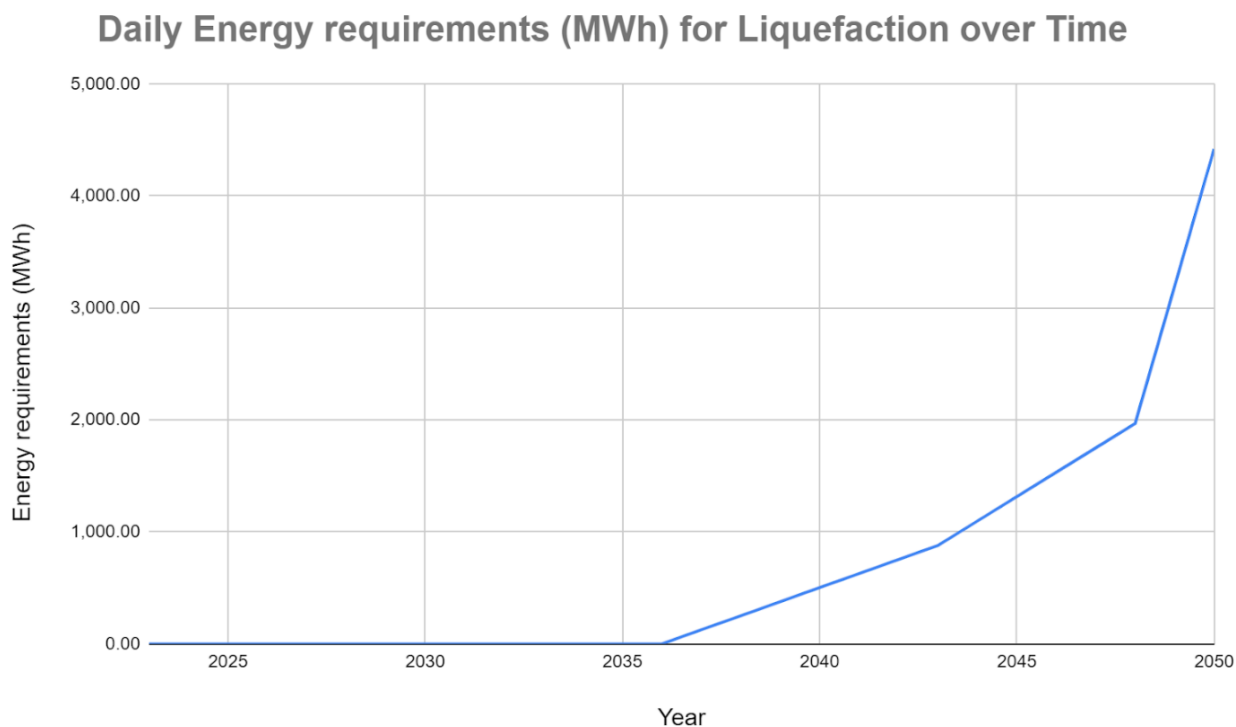


Figure 25: Energy needed for liquefaction to meet LH2 demand (for adoption scenario 4)

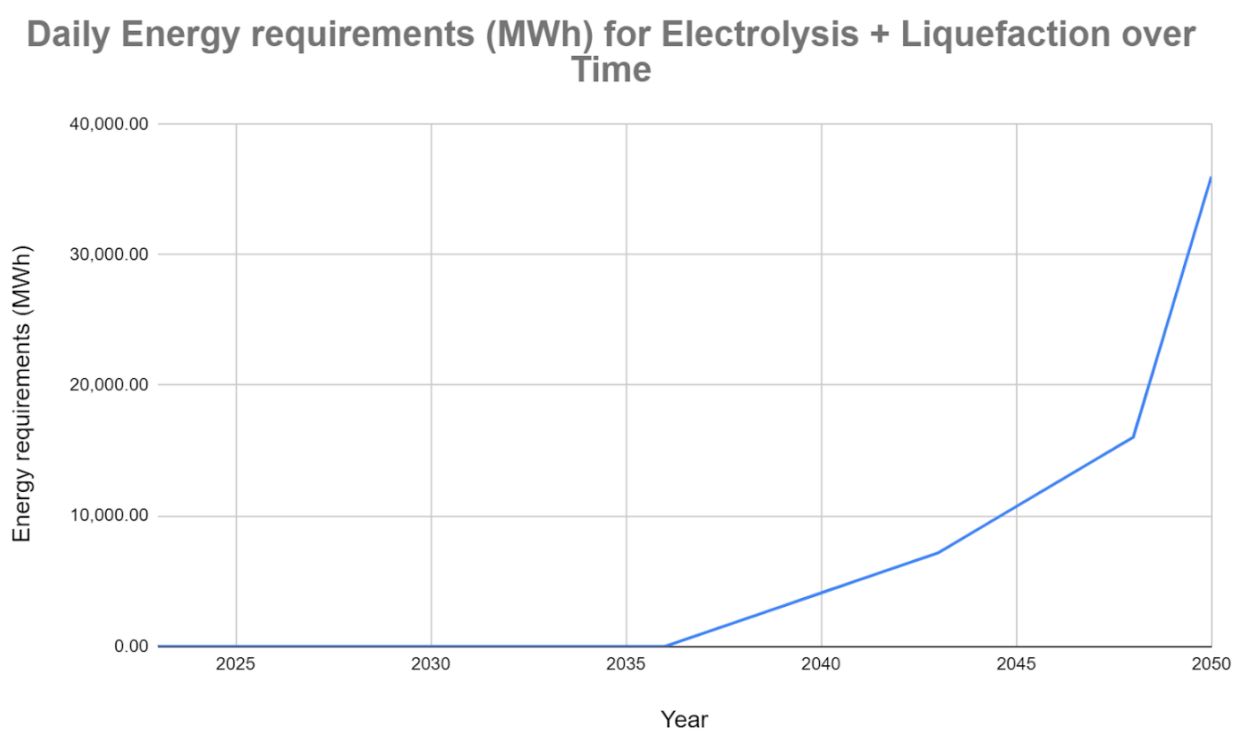


Figure 26: Energy needed for both electrolysis and liquefaction to meet LH2 demand (for adoption scenario 4)

Logically, performing just liquefaction instead of both electrolysis liquefaction at Schiphol requires much less energy. However, to meet the increasing demand, before 2045 the daily requirement for just liquefaction is already above 1,000 MWh (or 1 GWh) and by 2050 this number would already be up to nearly 5,000MWh. Thus, this would require 42 MWs worth of renewable energy to be continually brought to the airport before

2045 and 209 MWs by 2050. To both perform electrolysis and liquefaction the daily power demand is about tenfold of that. Over 10,000 MWh by 2045 and nearly 40,000 MWh by 2050 (420 and 1660 MW continuously respectively). To put this into perspective, the current entire North Sea wind energy production of the Netherlands is only 2450 MW at the moment (Netherlands Enterprise Agency, 2021). Considering this is for one of the least intensive scenarios, the energy that needs to be brought to Schiphol directly, especially if also electrolysis is performed, will be very large. The extreme possibilities regarding energy requirements are even further shown when all scenarios are visualized as in Figure 27 and Figure 28. In the most demanding cases power demand can go over well 100,000 MWh daily (~4160 MW continually) for both electrolysis and liquefaction and 20,000 MWh daily (~830 MW continually) for just liquefaction. What this shows is that it's in some cases not very realistic to expect this amount of renewable energy to be produced locally in the Netherlands. Especially considering that aviation (and within that only Schiphol) will by far not be the only industry/party requiring for renewable energy locally. It is there for potentially more realistic to have the LH2 be produced elsewhere. This is an option that needs to be considered.

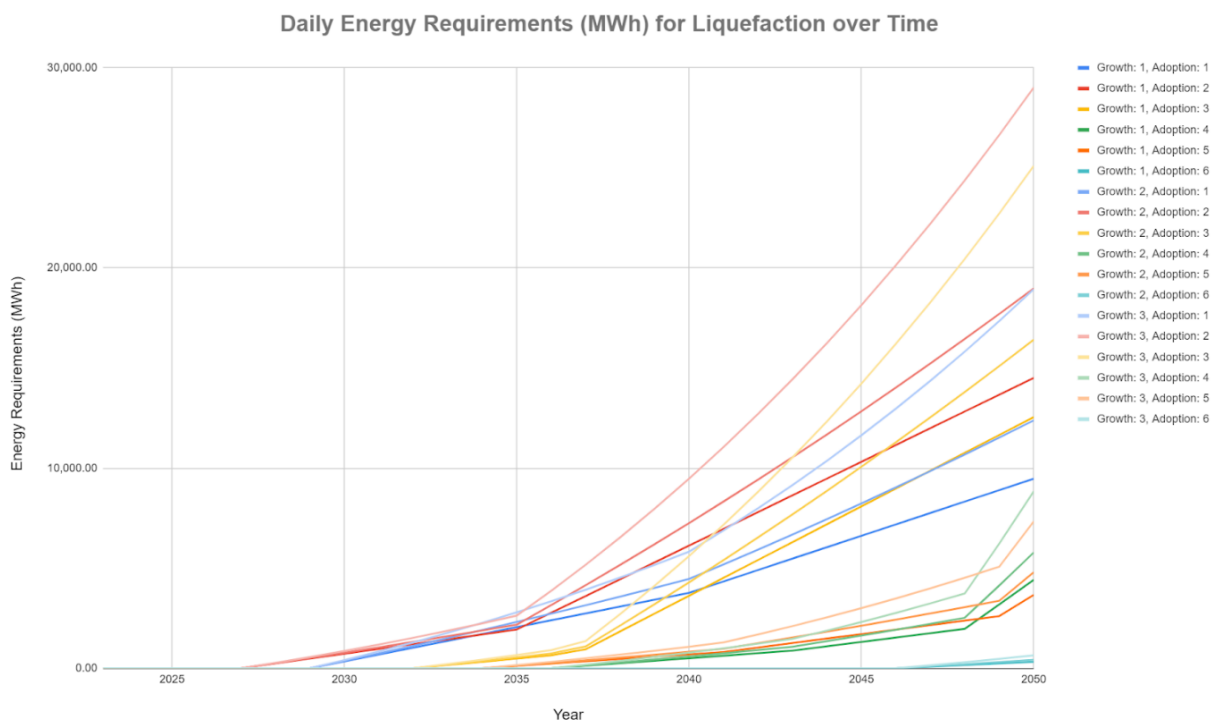


Figure 27: Energy needed for liquefaction to meet LH2 demand (for all scenario combinations)

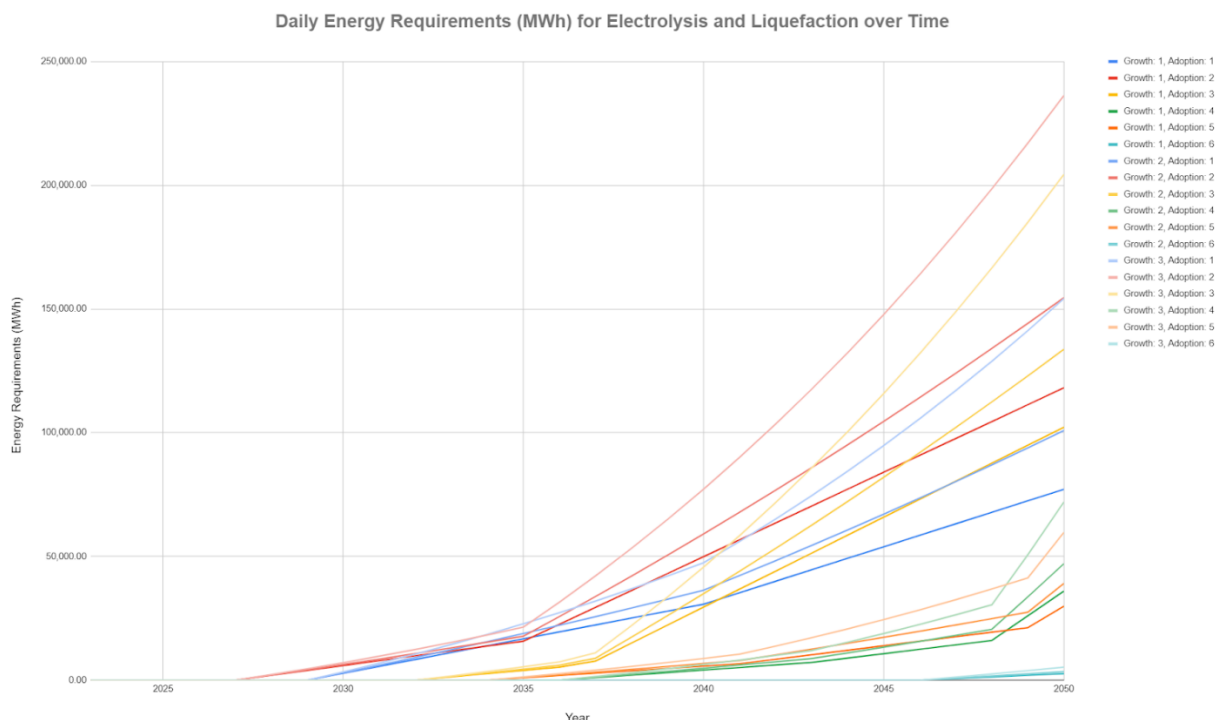


Figure 28: Energy needed for both electrolysis and liquefaction to meet LH2 demand (for all scenario combinations)

Another important piece of the logistic and infrastructural chain for which additional insight can be gained by doing a number of calculations is the on-airport storage of LH2. This is directly related to the actual LH2 demand of the airport at any given moment in time. Literature has highlighted that it is wise for an airport to keep at a supply equal to the demand for three days of operation to ensure additional robustness of the system (FlyZero, Postma-Kurlanc, et al., 2022) (McKinsey & Company & Clean Sky 2, 2020). With a known volume of storage that Schiphol should have, the storage facilities can be sized. Sizing these facilities is a function of the tank design, tank size, and number of tanks. Storing LH2 in large quantities will likely take place in circular tanks because of the mechanical properties and the minimization of outside surface area to volume ratio which has the potential to reduce boil-off. This has been seen in other cases where LH2 is stored in large quantities (Swanger, 2022). The size of tanks may depend on current technical ability and/or the desire of the airport to have a low or high number of LH2 tanks. Since these things cannot be accurately predicted at this point in time, some simple calculations as to the number of tanks that would be needed given a specific tank size that is employed gives an idea as to the feasibility. Below, Table 6 shows a brief overview of this for adoption scenario 4 given no growth. What is displayed here is the expected storage volume for a given year and compares how many tanks would be needed for different tank sizing options (5m, 10m, 15m and 20m radius). Currently the largest LH2 storage tank in existence has a radius of roughly 10m (Swanger, 2022). However, as the technology develops larger storage could become possible. As can be seen here, larger tanks of 15-to-20-meter radius would mean Schiphol would need significantly less tanks. Considering the scenario used for these calculations is on the lower demand size, these may potentially be needed one day.

Table 6: Overview of LH2 storage tank options (for adoption scenario 4)

LH2 Storage Tank Options (growth 1, adoption 4)	
	Number of Tanks

Year	Total Storage Volume Req. (m ³)	Option 1: 5m radius	Option 2: 10m radius	Option 3: 15m radius	Option 4: 20m radius
2037	760.82	2	1	1	1
2040	3,043.28	6	1	1	1
2045	7,963.19	16	2	1	1
2050	26,762.30	52	7	2	1

Other

Other factors also need to be considered to build the infrastructure scenario. Regarding technological development, since the infrastructural elements discussed in this research all originate from peer reviewed literature and industry reports, they are all supported to be theoretically technically feasible by 2035. There has been nothing found in the literature which suggests that the infrastructural elements discussed thus far are not technically feasible. One large element then are the investment (CapEx) and operational (OpEx) costs of this infrastructure. From the literature, one thing that was established is that an LH2 hydrant system would likely be very expensive to install at an airport and would thus not be cost-technically feasible for some time. On the other hand, it is also clear from the LH2 demand calculations, that it is infeasible to use bowser refueling trucks when significant LH2 aircraft adoption has taken place due to the logistic and practical limits in terms of trucks that can realistically move on an airport. Thus, the decision has been made that it is worth the high investment cost to install an LH2 hydrant system by 2050, but that it is not yet recommended around 2035. As explained in section 3.2.5 on the economics of LH2 aviation, the costs for infrastructure are an element of the higher expected DOC. Reducing the costs of infrastructure where possible, especially in early phases, will help the economic sustainability of LH2 aviation.

In addition, thought has been put into the logistic side of the LH2 chain. One option for both logistics and refueling which has been discussed in section 3.3.1 is to use a pod replacement system. Regarding LH2 implementation at Schiphol it is expected that this will not be the chosen method for a number of reasons. The most major reason is that for an LH2 pod replacement system to be effective, all or most LH2 aircraft will need to be designed in this way. If only a portion of LH2 aircraft use such a system, then each airport will need both a more traditional infrastructure system and one for these pods. Because there are many other parties which are working on LH2 aviation without such a pod system, it is expected that not most aircraft will be like this. In this case, it is much more efficient for airports to only cater to the traditional LH2 refueling system. A second reason for why an LH2 pod system is not realistic, is that Schiphol is expected to see such large numbers of LH2 aircraft that the logistics needed to transport LH2 pods for all these aircraft is expected to be unrealistic. The same issue arises as with bowser refueling trucks since the pods will also need to be delivered via truck. At a certain point too many trucks would be needed, and another system will be more efficient. Because of this logic, the use of an LH2 pod system at Schiphol is not considered.

Another factor influencing LH2 infrastructure at the airport which needs to be considered are the rules and regulations. With the new aircraft and infrastructure, new operational procedures for refueling, taxiing, etc. will be needed. Safety is of major concern here. Regulations will need to be created which also keep this operation safe. LH2 infrastructure design will need to take this into account. Early in the transition to LH2 infrastructure there may be more risks because of the newness of this technology. Designing infrastructure and the operational procedures to take this into account is a wise decision.

Infrastructure vision 1

Based on knowledge gained from literature review and publicly available information pertinent to Schiphol's case, Table 7 shows the first iteration of the infrastructural vision:

Table 7: Infrastructure vision - first iteration

2035 (Phase 1)		
Logistics	Storage	Refueling
Offsite LH2 production + Truck delivery of LH2 to Schiphol	Centralized LH2 storage location	LH2 bowser trucks used for aircraft refueling at the gate

2050 (Phase 2)		
Logistics	Storage	Refueling
Offsite GH2 production + Pipeline to Schiphol + Onsite LH2 production	Centralized LH2 storage location	LH2 Hydrant refueling at the gate

Specific Considerations
<ul style="list-style-type: none"> • In the early stages of LH2 adoption LH2 can be brought to Schiphol via trucks (or barges). Likely between 2040 and 2050, for logistic purposes, Schiphol will need to invest in a liquefaction plant and secure the needed renewable energy resources. • Early on about a 10-meter radius LH2 storage tank will likely be enough. Later additional more (and possibly bigger) tanks will need to be added. • LH2 bowser trucks will be a realistic option for refueling for the first few years but will likely become overwhelming sometime between 2040 and 2050. Then investments should be made to build a hydrant refueling system.

A.1.2. Iteration 2 – Schiphol Masterplan Interview

The infrastructure vision iteration was tested in an interview with Schiphol Masterplan. Schiphol Masterplan's focus is how the airport will look in the future (currently up to 2050). They create a vision for how future developments can be accommodated at the airport to ensure that likely scenarios are not made infeasible or much more difficult/expensive based on current decisions. The aim is to create and maintain a masterplan which details the range of possible ways that the future of Schiphol could look based on new developments and growth. This plan gives Schiphol a guideline in terms of their current developments to ensure that they do not conflict with possible future developments. This is a sub-department of the Schiphol department on strategy and airport planning. The respondent was Rob ten Hove. His focus is specifically on airport operations and infrastructure. The main takeaways from the interview are listed here:

- As of late the masterplan department was focused predominantly on surviving the covid pandemic. But in general they look into new technological developments in aircraft and how these new aircraft can be accommodated at Schiphol. In the coming years the main focus will be on sustainability and meeting the goals set for that.
- The writing of the Schiphol masterplan is an ongoing process. The expected market developments and new technologies are used to develop a vision which helps guide Schiphol in decision making. The masterplan takes into account special provisions for airport developments but is not accurate to the exact meter. The scope of the masterplan is currently until 2050.
- Knowledge about LH2 aviation (and specifically the infrastructure for it) is still in very early stages. Within the masterplan department LH2 knowledge is not very high so they are working on acquiring

information on it since this technology may help solve sustainability issues. Currently the focus is on research and not a lot of money is invested yet.

- How LH2 technology will practically be applied at the airport is the main focus. For example, how refueling can be done safely is a central topic. Questions about refueling at the terminal vs. elsewhere and using bowser trucks vs. a hydrant system are asked. There is already consensus that refueling will likely need to take place away from the terminal at first to maintain safety. Then the questions becomes how this can be done.
- Schiphol is interested in learning more about the business model for LH2 aviation, refueling LH2, LH2 supply, and how LH2 infrastructure will impact spatial planning. They look to discussions and work with partners (such as Airbus) to learn about these topics
- The consensus within Schiphol masterplan is that aviation cannot continue as it has been. There is still a large amount of uncertainty, but they expect batteries, LH2 and SAF to all end up becoming part of the market. Battery-electric aviation will be for small-scale and short-range aircraft, SAF for large and long-range aircraft, and LH2 will fit in between the two (roughly 20-100 PAX, 750-2000 km range). Schiphol operates on the higher end of ranges and aircraft sizes, so SAF is very interesting and LH2 also will likely have a place at the airport. Figure 29 shows this in a graph.

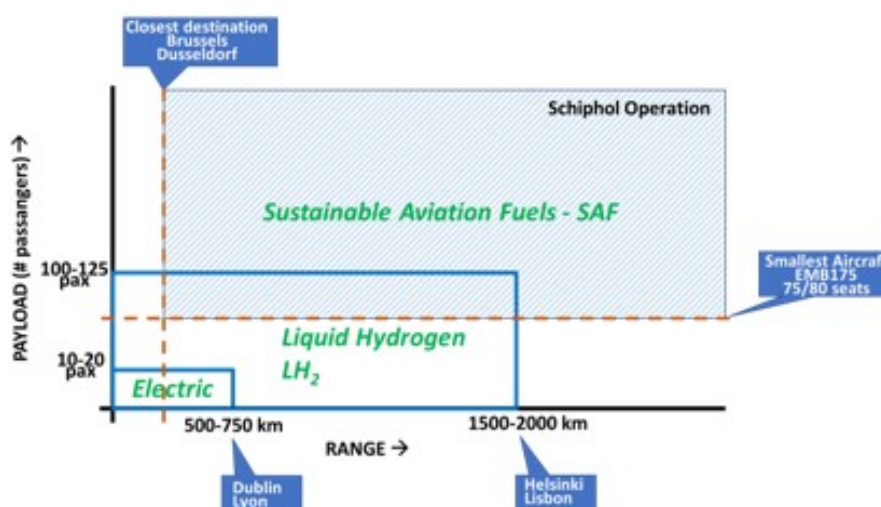


Figure 29: Graphical display of LH2 market (with overlay of the Schiphol market)

- Over time LH2 aircraft range may improve meaning that LH2 may take over more flights initially powered by SAF. But LH2 aviation will first need to be proven which will likely take a while. 2035/2040 is when Schiphol masterplan first expects these aircraft to enter the market and 2050 is when large scale adoption is foreseen. This will also depend on the business case of the airlines though. If kerosene becomes significantly more expensive quickly, the switch may happen faster. However, these airlines generally do not look very far in the future (typically only 3-5 years) meaning that they will not yet be focused on LH2 aviation.

This interview served to further confirm and validate a number of pieces of information also found in the literature. The estimates on when LH2 aviation would enter the market are further confirmed by Rob. In addition, the expected ranges and sizes also correspond with much that is found in the literature. However, the expectations given by Rob are slightly on the more pessimistic side for both the timeline and aircraft specifications. This is something to keep in mind. Also, this gave some insight into how Schiphol operates when it comes to planning for the future. This needs to be taken into account not as much in the scenario building process, but more for when management techniques need to be developed. Understanding how Schiphol traditionally works with change can be used to build new management techniques around. Regarding specific changes to the infrastructure scenario, one comment was made by Rob about the fact that refueling with LH2 would preferably be done away from the gate. This does shed some light on the fact that, especially in the early days of this transition, it could be advantageous to be safe and refuel away from the rest of airport operations. This is also more feasible in this phase since the refueling method is done via mobile LH2 bowser trucks.

Another thing learned which was interesting is that airlines typically do not focus on future developments further than 3-5 years away. Since the airlines are the parties which will need to purchase LH2 aircraft for them to enter into service, this is quite shocking. This means that if things remain the same, Schiphol will likely not know if they can expect LH2 aircraft until less than 5 years before they will need to be serviced. To confirm this statement by Rob, contact was made with the airline that operates the most flights from Schiphol, KLM (Schiphol, 2020). No formal interview was planned, but email contact was made, and a set of questions were asked. First, a question was asked to sustainability manager at KLM Bart van Lidth de Jeude about KLM's current thoughts on LH2 aviation. He made it clear that they currently have no strategy regarding LH2 aviation, but that they do keep a keen eye on the market. This made their position clear and seemed to confirm what Rob said about airlines not looking very far ahead in the future.

Further, some more questions were asked to KLM's director of sustainable strategy Remona van der Zon. From this email contact three things which will help understanding how the adoption of LH2 aircraft can be expected to go were discussed. Firstly, as was also mentioned by Rob in the interview, traditionally, when an airline purchases new aircraft there is only a limited amount of information that gets exchanged. A public press release is published which makes the purchase of aircraft known. Of course, and this was also discussed by Remona, there will need to be much more dialogue when the adoption of LH2 aircraft is on the table. She acknowledged that KLM has a responsibility to work together with Schiphol when new infrastructure for LH2 is required. Each would have their own responsibilities within that process. This includes the building up of knowledge, training of workers, and managing the needed infrastructural changes. And finally, Remona assured that KLM has the intentions to be an industry leader with regards to sustainability, meaning that if LH2 aviation becomes a reality, they will adopt it. She also says that hence KLM is already discussing the possibilities for hydrogen and electric flight with aircraft suppliers. This information on the stance of KLM gives insight into their role in this transition and what Schiphol can expect from them.

To conclude, the Schiphol Masterplan interview and subsequent email contact with KLM confirmed a lot of information and also added further information on specifics of this transition. Regarding the infrastructure scenarios, only one small change will be made. In 2035 the refueling will be done away from the gate for safety. Some of the learnings from this iteration have also been added to the specific considerations table.

Infrastructure vision 2

Based on the information gained from the interview with Rob ten Hove from the Schiphol Masterplan department, an iteration on the first scenario has been made. Changes can be seen in yellow. The second iteration of the infrastructure vision can be seen in Table 8:

Table 8: Infrastructure vision - second iteration

2035 (Phase 1)		
Logistics	Storage	Refueling
Offsite LH2 production + Truck delivery of LH2 to Schiphol	Centralized LH2 storage location	LH2 bowser trucks used for aircraft refueling away from the gate at centralized location

2050 (Phase 2)		
Logistics	Storage	Refueling
Offsite GH2 production + Pipeline to Schiphol + Onsite LH2 production	Centralized LH2 storage location	LH2 Hydrant refueling at the gate

Specific Considerations

- In the early stages of LH2 adoption LH2 can be brought to Schiphol via trucks (or barges). Likely between 2040 and 2050, for logistic purposes, Schiphol will need to invest in a liquefaction plant and secure the needed renewable energy resources.
- Early on about a 10-meter radius LH2 storage tank will likely be enough. Later additional more (and possibly bigger) tanks will need to be added.
- LH2 bowser trucks will be a realistic option for refueling for the first few years but will likely become overwhelming sometime between 2040 and 2050. Then investments should be made to build a hydrant refueling system.
- When refueling is done with LH2 bowser trucks, it would be wise to do this away from the gate to ensure safety early in the transition. When the transition to a hydrant system is made the technology will have progressed, so this will hopefully no longer be needed.
- Infrastructural plans need to be discussed at length and early on with airlines to ensure infrastructure will match the demand from the planned aircraft acquisition.
- Since Schiphol operates on the longer-range and larger side of aviation, it can be expected that adoption will begin slower, but go faster later on.

A.1.3. Iteration 3 – Technical Developer Interviews

The second iteration infrastructure vision was used as a jumping off point to discuss the technical feasibility of the proposed LH2 infrastructure with two parties: Demaco and Cryoworld. Since these parties are both experts on cryogenic technologies, and thus have a lot of similar information, their interviews together go towards building the third iteration of the infrastructure scenario.

Firstly, an overview of the main takeaways from the Demaco interview will be given. Demaco specializes in the design and building of cryogenic infrastructure for the transport, storage, and liquefaction of liquid gasses. For over 35 years they do work for multiple different industries including some experimental work in the aviation industry. The respondent was Ronal Dekker, owner of Demaco Holland b.v.. The main takeaways are as follows:

- Currently the largest LH2 tank has a volume of 3800 m³, but research is being done to develop spherical tanks of 20,000 to 100,000 m³. Storage is very possible and will for sure not hold back LH2 infrastructure. With large storage tanks boil off is very small, and since Schiphol will use great quantities on a daily basis, boil off is one of the least problematic things.
- Moving LH2 with trucks (either to the airport or for refueling) is an established technology already in use today. The most difficult part here is the connection of the LH2 truck to the tank/airplane it wishes to refuel into. Making a breakaway connection that will ensure that safety can be maintained even if an emergency, unplanned disconnection takes place. Although such a system is not developed yet, Ronald is confident that if a company is willing to invest money and only about two to three years, that this could be there. There only needs to be a demand for this and it will come.
- A LH2 hydrant system is technically achievable. None of the required elements for this (transfer tanks, refueler vehicle, etc.) are not feasible with our current technology. Some elements have not yet been developed for this specific case, but as soon as there is demand, the market will deliver. The breakaway coupling discussed earlier is another element that is needed here as well. But as stated and similar to the other elements, this can be there in a few years. Large scale piping systems for the hydrant could be possible since cryogenic piping already exists in other industries. Scaling it up for aviation is no issue because the technology stays the same.
- One of the most difficult parts of the LH2 logistics is getting the molecule to the airport. Getting GH₂ and then LH₂ will be difficult because of the amount of energy needed. Importing hydrogen is an option. If it is imported in a liquid form, it could be piped directly as LH₂ to the airport. Cryogenic pipelines are feasible over limited distances.
- According to Ronald, technology will not be a limiting factor. Another limiting factor (besides H₂ supply) for the quick adoption of this are the rules and regulations. There will need to be rules and norms for this one day. These need to come quick because if Schiphol were to build the infrastructure now when

there are no regulations yet, then when these regulations are in place they might need to change the system. So regulations need to come first before building, but currently the technology is ahead.

- Development of more fool-proof LH2 systems should be possible. Since cryogenic systems always use vacuum insulation, double containment is automatically included which reduced the chance for leaks. This together with automated systems, vacuum and hydrogen sensors, and new technologies like break-away couplings, this should allow for safe integrated systems to be built at an airport. Coupled with specially designed operating procedures, the implementation of this technology can be done safely at the airport
- Kerosene is theoretically and practically more dangerous because hydrogen escapes into the air, and the flame is less hot from a distance.
- To conclude: This technology is feasible. Much of it already exists and what doesn't, can be developed in a couple of years. Even moving LH2 through cryogenic pipelines is possible over limited distances. Designing full infrastructural systems that are safe is possible but needs to be done in a smart way. As of now, regulations are needed quickly to ensure that systems can be built according to them once these systems are needed.

Secondly, Cryoworld was interviewed. Cryoworld specializes in building cryogenic infrastructure (connections, pipelines, etc.) and is currently working on cryogenics for a variety of projects in different industries like trucking, shipping, and aviation. Regarding aviation, Cryoworld is working together with the NLR on developing elements for a small-scale LH2 aircraft. They are good at vacuum insulation and are predominantly experts on liquid helium and nitrogen. Cryoworld also works with LH2 because there are many similarities as with these other cryogenic liquids. The respondent was Marcel Keezer. Technical director at Cryoworld B.V.. He was joined by two engineers, Matthew Dekkers and Niels Goos. The main takeaways are as follows:

- Storing large quantities of LH2 in tanks is an existing technology, but larger storage tanks are still in development. If you want to store LH2 in very large quantities in one tank (for example a tank with a radius of 10-20 meters), then the mechanical forces will become so large that vacuum insulation is no longer possible. Then, aerogel isolation is a possible solution. Although aerogel delivers a lower quality of insulation, at such high quantities, boil-off is not a big issue. About 1% can be expected per day. Also, such tanks can have issues with metal shrinkage as the cryogenic liquid enters it, so special techniques are needed.
- Any LH2 boil-off from anywhere in transit or storage could be reliquefied or used in fuel cells to generate electricity for the airport.
- LH2 trucks for logistic delivery (and refueling and the line purging technology they need) are feasible and in many cases already exist. An important part of these trucks is the coupling. A coupling that doesn't require purging should be developed. It is realistic but doesn't exist yet.
- An LH2 hydrant refueling system (and the pumps and cryogenic pipes needed for this) is technically feasible. Most elements exist, but specific application may not yet. Time and money will need to be invested to develop versions specific for aviation. Pumping LH2 shouldn't be an issue. There are ways to pump it (submerged pumps and long spindle pumps for example) even over quite long distances. Specific pumps for this application may need to be developed though, but it is possible.
- Most of the central infrastructural pieces are technically feasible or already exist so one of the main issues will be getting LH2 at the airport. There are not a lot of parties currently that can delivery LH2 (only Linde and Airliguide are established).
- Marcel, Niels and Matthew estimate that liquefaction at the airport is not very feasible. A large amount of energy and space would be needed. It is however reasonable to reliquefy the relatively smaller amount of boil-off from storage and transportation.
- Cryogenic pipelines are currently feasible up to about a kilometer. So at the airport it should mostly not be an issue. To pump LH2 from, for example, a port to Schiphol (which is more than a kilometer away) you would need to put in extra research and development. However, if you supercool it or use intermediate buffers, then it may be possible. More research needs to be done here.
- Cryogenic pipelines which are currently used can expect about 1 watt of heat to enter the system per meter. So 1 kW per km. If enough LH2 is pumped through the pipeline, then the amount of boil off is not so much relatively speaking.

- There is no reason why LH2 refueling should be more dangerous than kerosene if the system is designed well and to be leak-proof. Automated systems would make this safer and fool-proof, but this costs extra money.
- Some issues that could arise with the implementation of this type of infrastructure is conformity with the aircraft and the rules and regulations. The risks and what they mean for the application of LH2 in aviation need to be analyzed. These risks need to be clear before regulations can be made and the systems that will be used at an airport can be designed.
- To conclude: All of the infrastructure is technically feasible and could largely already be built within a few years. Some details need to be elaborated on, but this can be done if a party is willing to invest money into the research. Safety, certification, and efficiency will be the biggest challenges. Current TRL of the general infrastructure technology is 7-9. However some elements are significantly lower because they still need to be fully developed.

These two interviews with experts on the technological feasibility of LH2 infrastructure shed a lot of light on what is possible and what the real challenges are. The main conclusion from these two interviews is that the infrastructure for logistics, storage and refueling of LH2 is largely technically feasible with current technology. Only the following elements were specifically mentioned to need some research and development: breakaway couplings, couplings that require no purging, and long-distance (more than 1 km) cryogenic pipelines, large-scale LH2 storage tanks. Development of the breakaway couplings, although not strictly necessary, would improve safety standards. Also, the development of purge-less couplings would mean that infrastructural equipment like bowser trucks and mobile refueling vehicles would no longer require purging systems as discussed in section 3.3.1. Furthermore other elements of the technology that are feasible just need to be developed for the specific application at an airport. All in all, it is realistic to expect this infrastructure to be possible from a technical viewpoint before 2035.

Two main issues face LH2 aviation infrastructure which were both touched on in both interviews. The first being having a sufficient LH2 supply and the second being the regulations that can hold back the development of integrated LH2 infrastructure systems. Regarding the LH2 supply, there are limited producers and also limited natural resources (especially in the NL) to produce LH2. Importing LH2 is a viable solution, which can already fit into the 2035 infrastructure scenario as it is. It was stressed in the interviews that it's not really realistic for large scale liquefaction (or also electrolysis) to take place at Schiphol due to the high energy demands. Thus, later on in the transition, towards 2050, it also would be the most logical to import LH2. Since logistically moving this LH2 via truck was not realistic this was also deemed very difficult. Before these interviews it was decided that on-site liquefaction was the least of these evils. Looking back at the calculations for the power requirements to liquefy LH2 at the airport in Figure 27 in Appendix section A.1.1., it can be seen that in some (low demand) scenarios the power demand may be low enough for it to be realistic, if the Netherlands invests heavily in renewable energy generation, to perform liquefaction at the airport. However, since both of the interviewed parties claimed that a cryogenic pipeline could be possible over limited distances, this could serve as a solution if/when LH2 demand is on the higher side. There is a special opportunity here since the Port of Amsterdam is so close to Schiphol meaning that a future cryogenic pipeline doesn't have to be very long and could theoretically be possible with further development. Based on a very simplistic sketch on google maps, the delivery location in the port and the storage location at Schiphol would be anywhere between 5 and 15 km away from each other as the crow flies (dependent on exact offloading location and storage location). Thus, it has been concluded that this is an interesting possibility that should be seriously considered.

The other main issue put forth in these interviews is that of regulations. The fact that the technology is largely there and what isn't there yet is achievable within a couple years of development is a positive one for the transition at hand. However, although possible, it also needs to actually be implemented at the airport. For such infrastructure to be realized at Schiphol there is usually a set of rules and regulations that need to be followed to ensure safety. The same is for all aspects of LH2 aviation. Although the infrastructure could nearly all be built now, if it was, then it would need to be done before these rules and regulations are written, meaning that once they are written, it could mean that aspects need to change. This fact makes it unrealistic to already

begin developing specific integrated systems that could be employed at an airport such as Schiphol. Per example, if LH2 needs to be refueled using an LH2 bowser truck, this type of specific truck needs to be developed. Because there are as of yet no LH2 bowser trucks for aviation, there are also no regulations which dictate design. This could cause such elements to be delayed not from a technological point of view, but because there is no clarity on the regulations in time. Because development takes at least some years, regulations need to come soon. It is clear from the technology developers that they need more of an open dialogue with the parties that work on maintaining safety by making laws and enforcing them to ensure that the technology will not be ahead of the regulations.

With the results of these interviews, the LH2 infrastructure scenario can be iterated on. What is clear is that the scenario for 2035 is still feasible. The infrastructural elements all exist and would be the easiest for Schiphol to implement early on in LH2 adoption. Also, due to the lower LH2 demand at this time logistic issues are not yet expected. The 2050 scenario may better be changed because of the LH2 supply worries that the technology developers had. Instead of liquefying hydrogen at the airport, it can better be imported into the Port of Amsterdam and transported via cryogenic pipeline to the storage at Schiphol. However, the option to perform liquefaction at the airport is not entirely ruled out and needs to be kept as an option. Exact decisions on the best course of actions can only be taken once more clarity on LH2 demand and renewable energy supply is available. In addition to this change, there are a number of additions that need to be made to the specific considerations table on the regulations and technology development for tanks and cryogenic pipelines.

Infrastructure vision 3

Based on the information gained from the interviews with Ronald Dekker from Demaco and Marcel Keezer from Cryoworld, an iteration on the second scenario has been made. Changes can be seen in yellow. The third infrastructure vision can be seen in Table 9:

Table 9: Infrastructure vision - third iteration

2035 (Phase 1)		
Logistics	Storage	Refueling
Offsite LH2 production + Truck delivery of LH2 to Schiphol	Centralized LH2 storage location	LH2 bowser trucks used for aircraft refueling away from the gate at centralized location

2050 (Phase 2)		
Logistics	Storage	Refueling
Offsite LH2 production + Cryogenic LH2 pipeline delivery to Schiphol	Centralized LH2 storage location	LH2 Hydrant refueling at the gate

Specific Considerations
<ul style="list-style-type: none"> LH2 logistics, storage, and refueling infrastructure is achievable and largely will use existing technology. A number of things need to be specifically developed: 1. Breakaway couplings, 2. Purge-less couplings, 3. Larger storage tanks, 4. Long-distance cryogenic pipelines, 5. Aviation specific operation equipment such as refueling vehicles and hydrant system

- In all stages it is likely best to import LH2 for Schiphol. Early on this can be transported to Schiphol from the port via trucks (or barges) and later (likely between 2040 and 2050) via cryogenic pipeline.
- An LH2 supply strategy where GH2 is produced elsewhere and liquefied at Schiphol may still be possible in certain low demand scenarios.
- Early on about a 10-meter radius LH2 storage tank will likely be enough. Later additional more (and possibly bigger if developed) tanks will need to be added.
- LH2 bowser trucks will be a realistic option for refueling for the first few years but will likely become overwhelming sometime between 2040 and 2050. Then investments should be made to build a hydrant refueling system.
- If turnaround times allow for it, when refueling is done with LH2 bowser trucks, it would be wise to do this away from the gate to ensure safety early in the transition. When the transition to a hydrant system is made the technology will have progressed and can be built safely, so it is expected that refueling at the gate will be possible.
- Infrastructural plans need to be discussed at length and early on with airlines to ensure infrastructure will match the demand from the planned aircraft acquisition.
- The development and building of integrated infrastructure technology will require early dialogue to take place between developers and authorities.
- Since Schiphol operates on the longer-range and larger side of aviation, it can be expected that adoption will begin slower, but go faster later on.

A.1.4. Iteration 4 – Safety, Rules, and Regulation Interviews

With a deeper understanding of the technical feasibility of LH2 aviation infrastructure an infrastructure vision which takes that into account could be crafted. However, building such infrastructure needs to be both safe and within the confines of the law. The interviews with cryogenic infrastructure developers clarified some of the questions regarding safety, however, to gain a full picture this also needs to be discussed with safety authorities. And when the infrastructure needs to be built and the operations developed, it is important that policy develops alongside it. This also needs to be discussed with the relevant parties. Taking into account safety, rules, and regulations when forming an infrastructure vision is key.

The Dutch Ministry of Infrastructure and Water Management (Min I&W) was interviewed because they play a key role in the writing of policy. This policy is often written to reach goals set by the national or EU governments. They then look at what is needed in terms of infrastructure to reach these goals. The interview respondent was Vera van Lint, a member of the department sustainability and more specifically a small team of four people that focus on sustainable fuels for the government. Her expertise is based in synthetic kerosene and hydrogen. The main takeaways are as follows:

- The Min I&W works with the airport to ensure that safety is maintained. For this they work together with IL&T which have an enforcement role (but also give practical knowledge for the policy making process). Also they work to ensure that the airport is able to fulfill the requirements set by the European Union and Dutch policy.
- The national plan for the energy transition (NPE) from the Ministry of Economic Affairs and Climate (Min EZK) looks at the Dutch demand for hydrogen and how current infrastructure can be used to help supply this demand.
- Currently the use of LH2 for aviation is still quite far away. Because of this, it still needs to be proven before more specific legislation will be written.
- Policy around the LH2 infrastructure at the airport will be written by the Min I&W in collaboration with the Min EZK. Who takes on which aspects specifically is still unknown. The IL&T will also play a role to look at achievability. And The National Hydrogen Program will give information for this policy.
- There is legislation for transport (pipeline and trucks), storage, and refueling with Kerosene and SAF. Similar legislation will be needed for LH2. There is some limited legislation already for the transport and storage, but this will need to be expanded based on the risks specific to the use in aviation. This expansion will take place once the use of LH2 in aviation has been proven more.

- There will also need to be new legislation for how LH2 can be used. The RED is a manual that says what may be used as a fuel based on a life cycle analysis. Hydrogen will need to be added to the RED. The European Commission is working on that right now.
- How long it could take to pass legislation is dependent on the use of LH2. If there are certain goals that the Netherlands or Europe has, then legislation will not be the limiting factor
- The Min I&W is willing to help the aviation industry in the transition towards sustainable aviation (and thus potentially LH2). The building of infrastructure and the importing/making of hydrogen will need to be done by the airport and the H2 suppliers respectively. Helping them with these goals is something the government is willing to do if that supports the goals of the Netherlands and/or the EU. Often this comes down to needing money, which the Min I&W cannot give very easily or has a lot of. They can attempt to help through different ways like reducing taxes or other costs so that the market has more money to work with in an indirect way.
- It is foreseen that a significant amount of hydrogen will need to be imported to supply the forecasted national LH2 demand. This responsibility is for the hydrogen producers and importers, however the Dutch govt. is prepared to play a role here if necessary (potentially by reducing costs and price).
- For the use of SAF, the Netherlands needs to negotiate with the EU regarding the amount we are allowed to use. This is because the EU attempts to ensure that all member states get a fair share of the SAF. A similar story may happen for LH2. If LH2 (or renewable energy) needs to be imported, then the Netherlands will need to share with the other member states meaning that there is the potential that due to limited supply, the Netherlands may not be able to get the amount of LH2 we desire.

An effort was made to discuss this topic with the Dutch Ministry of Economic Affairs. No interview was possible, but short email contact was made. Also, in December of 2021 a letter on the development and regulation of the Dutch hydrogen market was published which clarifies some of their stances (De voorzitter van de Tweede Kamer, 2021). The main takeaways from this were:

- The ministry sees a big role for green hydrogen as energy carrier in a future climate neutral economy.
- To meet future hydrogen demand it is expected that a portion of this hydrogen can be produced locally, but a significant amount of hydrogen will need to be imported via ports like the Port of Amsterdam, Rotterdam, and Groningen.
- Development of a network of GH2 pipelines throughout the Netherlands is underway. This project, called HyWay 27 is planned to be largely completed by 2030, but over time this will grow more. Schiphol could be connected to this (PricewaterhouseCoopers Advisory N.V., 2021).
- Electrolysis is foreseen as an important part of the future energy economy. Plans are to realize 500 MW electrolysis capacity by 2025 and 3-4 GW in 2030.
- Hydrogen is foreseen as an energy carrier for many industries. By 2030 a demand of up to 110 PJ of energy from hydrogen is forecasted. Only a portion of this is expected from mobility (30 PJ)

After this, the Schiphol Fire Brigade was interviewed. They are the force tasked with fighting fires at Schiphol for the aircraft, fuel storage, and the buildings. Fire risks related to hydrogen will need to be met by this party. They will therefore have an important role in ensuring LH2 is used safely at the airport. The respondents were Rein Hulst, manager emergency response, and Dick van Watering, expert fire safety. The main takeaways were as follows:

- The Schiphol fire brigade is a team of 150 people total with daily 21 people spread over three bases around Schiphol (Post Sloten, Post Vijfhuizen, Post Rijk). At each post 7 crew and three crash tenders are located. EASA requires that without the fire brigade ready, the airport cannot operate, they are very important for operation. They also fight fires in the airport buildings, for the fuel storage, for KLM, and potentially on the A4.
- There is basic knowledge on H2 and LH2 within the fire brigade right now. For more difficult questions the advisor for hazardous substances will be contacted. Also, a procedure for incident control of hazardous substances will likely need to be started whenever needs to be dealt with H2. If LH2 becomes more common at the airport, more knowledge will need to be gained and new procedures developed. Also potentially the safety teams may need to be adjusted based on requirements. The Health and Safety Executive (HSE) governmental office will need to play a key role in these changes.

- For all elements of the LH2 infrastructure, extensive risk analyses will need to be performed to understand what the likelihood and effects of an incident could be.
- To transport LH2 via trucks, the province will need to appoint a road on which these trucks can drive. This is done based on risk assessment.
- Regarding the building of new infrastructure, the fire brigade will have a role because they need to ensure that they can maintain safety and fight fires when needed. Thus it needs to be possible to shut things off and reach them easily for example.
- Regarding storage of LH2, the important thing is lowering the risk. Thus, if the possible effect can be lowered by reducing the size of storage it is desirable. Also you want to reduce the chance of a domino effect of one tank exploding to multiple other tanks. It can thus be much safer to have multiple smaller tanks spread around the airport. This can also ensure that the fuel supply is more robust and the entire LH2 supply is not lost from one incident. However, if they are too spread, then this can make fighting the fires efficiently also more difficult. A balance needs to be reached.
- Refueling at the gate is a question of risk vs reward. It would be best for safety if refueling can be performed away from all other people and activities, but if this may be economically unviable the solutions need to be found. Extensive risk analyses will need to be done to see what the risks are of refueling (in and way) at the gate.
- For the making of new legislation or handling procedures the fire brigade will be asked to give advice early on. Also for the use of new fuels the fire brigade and HSE are asked for advice. However, this stays advice and is often not binding.

Also, the Dutch Human Environment and Transport Inspectorate (IL&T), which has been named in the Min I&W interview, was interviewed. They are the party that perform the inspections of the aircraft themselves and to ensure that the general laws around aircraft operations and safety are followed. As mentioned in the Ministry of I&W interview, they are thus the party which enforces the government's policy and thus also have knowledge of how legislation is practically applied. The respondent of this interview was Raymond Voogt, inspector for IL&T. The main takeaways from the interview are as follows:

- At a UN level the ICAO is the basic international regulations for aviation. For Europe EASA is the implementation of that. Then at the national level the Netherlands has their own rules and regulations. IL&T's main role is in enforcing those regulations, but they will also play a role in the creating of those regulations through the HUF test. Also they can sometimes be asked for their expertise and advice from Dutch government bodies if they need it. Finally, if needed they can look at how well the regulations work and make a signal-effect rapport.
- Whether refueling at the gate is possible with LH2 is based on fire safety. If techniques get reliably very safe, then it may be possible. Thus, as the fire brigade has said, an extensive risk analysis is needed before whether or not it's possible can be known. Refueling with people on board is another question. Then you need to think even more critically about the safety concerns. For example, no ignition sources should be close by. Auxiliary power units (APUs) can be an ignition source, but maybe those can be entirely unneeded on the ground in the future. If the risks that come with LH2 refueling is higher than that of kerosene, then it can be expected that no passengers will be allowed onboard during refueling. This will have effects on the turn-around time.
- Making refueling safer by building new and strict procedures is hard because there is a lack of capable personnel that knows how to deal with the risks of refueling. New people will need to be trained and this takes time and money and still means these people lack experience.
- It's also not realistic to build fully fool-proof systems because as long as people are involved mistakes can and will happen.
- Built-in safety systems will be important to lessen risks for refueling but can only go so far.
- The risks for all of the operations for the transport, storage, and refueling of LH2 will need to be clearly known before regulations can be made. Only then objective rules can be created to ensure safety is ensured at the airport. Thus, the technology that will be used needs to be developed and known before regulations can be made.
- To develop good rules, in-depth knowledge on the technologies used is required. An organization like IL&T does not have that type of knowledge currently. Collaboration with developers and builders will be required.
- When wanting to refuel with LH2, we need to take into account the physical limitations. For example, there may not be enough space at the gate to use LH2 bowser trucks together with the other

operations equipment needed to restock the aircraft and do other things. Also the fact that trucks need to be able to drive away from the aircraft directly in case of an emergency needs to be taken into account.

The interviews summarized above clarify a lot of things and add some information that was not previously thought about. Firstly, information on the roles that the Ministry of I&W, Schiphol fire brigade, and IL&T have in this transition has been clarified. Although this information doesn't change the infrastructure scenario, it is important to be considered and will play a role in the creation of the Schiphol-specific roadmap. Also each interview had a couple of key points which do have a direct impact on the infrastructure scenario. Firstly the ministry of I&W had the following points:

- If a sustainability goal is threatened to not be met because of policy issue, the government is often able to move quicker to ensure that policy implementation goes fast.
- The government is willing to support such a transition in an economic sense if needed. Often this cannot be directly through giving money, but it could be done using tools like reducing taxes or other costs.
- The EU attempts to equally spread SAF supply to its member states. A similar situation would be expected if the import of LH2 becomes a thing.
- The technology for infrastructure (and the aircraft as well) needs to be there before regulations can be made. An open discourse is needed.

Also the Schiphol fire brigade made the following interesting points influencing the infrastructure:

- Spread hydrogen storage around the airport may be safer because it reduces the size of each storage and limits the domino effect.
- It is potentially possible to refuel at the gate if the risk vs reward ratio is correct.

Finally, from the IL&T interview the following things that influence the infrastructure were mentioned:

- Based on a visual representation of an LH2 aircraft servicing and refueling from FlyZero it is expected that a traditional aircraft stand will not be big enough and may need to be redesigned.
- The technology for the infrastructure needs to be clearly known before regulations can be made for it.
- Refueling at the gate can be possible if fire safety is high and techniques can be reliably safe. The use of APUs on the ground should no longer be regular in the future when LH2 aviation is utilized because all power should come from the electricity connection at the stand. Having this implemented would make refueling more reliably safe.

These points from the interviews combine to confirm a few things and introduce new concepts. Refueling at the gate with a hydrant system may be possible if designed well. Rules and regulations for infrastructure will first require the development of infrastructure that is as safe as possible and only then regulations can be made. Spread LH2 storage is feasible and may be preferable once large quantities are stored. This actually is good since it allows storage to also be closer to the refueling location. Finally, LH2 supply could be an issue for Schiphol if the EU cannot get enough LH2 for all member states. These allow for a new iteration of the infrastructure scenario to be made.

Infrastructure vision 4

Based on the information gained from the interviews with Vera van Lint from the Ministry of I&W, Rein Hulst and Dick van de Watering from the Schiphol fire brigade, and Raymond Voogt from the IL&T, an iteration on the third scenario has been made. Changes can be seen in yellow. The fourth infrastructure vision can be seen in Table 10:

Table 10: Infrastructure vision - fourth iteration

2035 (Phase 1)		
Logistics	Storage	Refueling
Offsite LH2 production + Truck delivery of LH2 to Schiphol	Centralized LH2 storage location	LH2 bowser trucks used for aircraft refueling away from the gate at centralized location

2050 (Phase 2)		
Logistics	Storage	Refueling
Offsite LH2 production + Cryogenic LH2 pipeline delivery to Schiphol	Spread LH2 storage	LH2 Hydrant refueling at the gate

Specific Considerations
<ul style="list-style-type: none"> LH2 logistics, storage, and refueling infrastructure is achievable and largely will use existing technology. A number of things need to be specifically developed: 1. Breakaway couplings, 2. Purge-less couplings, 3. Larger storage tanks, 4. Long-distance cryogenic pipelines, 5. Aviation specific operation equipment such as refueling vehicles and hydrant system In all stages it is likely best to import LH2 for Schiphol. Early on this can be transported to Schiphol from the port via trucks (or barges) and later (likely between 2040 and 2050) via cryogenic pipeline. An LH2 supply strategy where GH2 is produced elsewhere and liquefied at Schiphol may still be possible in certain low demand scenarios. There are already plans for large electrolysis projects. In this case Schiphol could be connected to the HyWay 27 GH2 lines. Importing enough LH2 for Schiphol can be an issue since the EU may limit LH2 supply if it cannot supply enough for all member states. Early on about a 10-meter radius LH2 storage tank will likely be enough. Later additional more (and possibly bigger if developed) tanks will need to be added. LH2 bowser trucks will be a realistic option for refueling for the first few years but will likely become overwhelming sometime between 2040 and 2050. Then investments should be made to build a hydrant refueling system. If turnaround times allow for it, when refueling is done with LH2 bowser trucks, it would be wise to do this away from the gate to ensure safety early in the transition. When the transition to a hydrant system is made the technology will have progressed, If risks of refueling are low enough refueling could take place at the gate. Installing a hydrant refueling system around the same time as bigger LH2 aircraft enter the market will allow for two birds to be killed with one stone because this will allow for aircraft stand redesign. This is needed because there is a real chance that efficient aircraft servicing will require more space than there currently is. Infrastructural plans need to be discussed at length and early on with airlines to ensure infrastructure will match the demand from the planned aircraft acquisition. The development and building of integrated infrastructure technology will require early dialogue to take place between developers and authorities. First The technology development is needed for safety and risk analyses to be performed. Only then can regulations be made for it. Since Schiphol operates on the longer-range and larger side of aviation, it can be expected that adoption will be slower, but go faster later on.

A.1.5. Iteration 5 – Logistic Supply Chain Interview

An infrastructure vision has now been iteratively built taking into account Schiphol, technical feasibility, safety, and policy. Now, a deeper look will be taken into the supply side of things. Supplying LH2 via importing it has been put forth as a potentially viable option. Thus, understanding the feasibility of this is important.

The final interview was performed with the Port of Amsterdam (PoA) because this could be a key player in the future logistic supply chain to get LH2 to Schiphol. The Port of Amsterdam is already a major importer of kerosene for Schiphol (Port of Amsterdam, 2020). There are proposed plans to utilize the PoA as a major importer of hydrogen for the future demands of the region and even potentially more of Europe (NZKG, 2021) (Port of Amsterdam et al., 2021) (PricewaterhouseCoopers Advisory N.V., 2021). In addition to this, due to Schiphol's close proximity to the PoA, a unique potential opportunity to transport hydrogen in its liquid form directly after importation is present. The respondent was Ellen van der Veer, Strategic Advisor Energy Transition at the PoA. The main takeaways from the interview are as follows:

- The PoA thinks that hydrogen will play a role in the future economy. 2035 for aviation is something that makes them less worried than the timeframes put forth by some other industries. They are looking to create a robust system to get hydrogen to its clients. Producing green hydrogen in the port is a possibility (HyCC is looking to purchase a half gigawatt electrolyzer). Also, they are looking into building hydrogen backbone infrastructure with Gasunie and a low-pressure hydrogen network in the port area itself.
- The expected hydrogen demand and the amount of available renewable energy do not match. Because of this they are looking into the possibility of importing hydrogen and other sustainable fuels. They are exploring different routes involving all non-toxic hydrogen carriers and LH2.
- Regarding the import of LH2, they have performed a feasibility analysis with Zenith. This analysis showed that from an economic perspective LH2 importing is not great, because a lot of energy is consumed for liquefaction and then reheating the hydrogen to get the gaseous form that can be put into the hydrogen backbone. However, with economies of scale this could still be interesting. Also, since Schiphol will want LH2 to not be reheated and the H2 will need to be liquefied somewhere in the supply chain anyways, then this is potentially a much more interesting route to go down. The PoA and Zenith are looking for potential clients and Schiphol could be one of them.
- The prospects of a cryogenic LH2 pipeline from the PoA to Schiphol have not been seriously considered yet by the PoA. They are happy with the kerosene pipeline from the port to Schiphol and can therefore see this being a good option somewhere down the line. First an exploratory study will need to be performed, but there is no reason to say no to this idea at this point in time. Other than Schiphol the market is not yet large for specifically LH2, so the market will also need to be understood more before such projects can take place.
- Renewable energy demand at the airport would be very high if either liquefaction or both electrolysis and liquefaction were to take place there. Schiphol already has issues with electricity demand and will therefore most likely not be able to meet that demand. Thus LH2 import is one of the best options. This is also more similar to how things have always been done, so it is expected to be less radical of a change.
- For further development Schiphol will need to be connected with the parties looking to import and produce hydrogen. The PoA is looking to lay a facilitatory role here. Also, as much information as can be gathered now should be gathered.

This interview largely confirmed that the opportunity to have LH2 imported via the PoA is a realistic one. Based on what the PoA has also seen, producing LH2 locally in very large amounts is unrealistic, thus importing is something they are looking at specifically. Zenith is a party looking into doing this in the cryogenic form which is a potential good opportunity for Schiphol. They are also open to the prospects of installing a cryogenic pipeline.

Infrastructure vision 5

Based on the information gained from the interview with Ellen van der Veer from the Port of Amsterdam, an iteration on the fourth scenario has been made. Changes can be seen in yellow. The fifth and final infrastructure vision can be seen in Table 11:

Table 11: Infrastructure vision - fifth and final iteration

2035 (Phase 1)		
Logistics	Storage	Refueling
Offsite LH2 production + Truck delivery of LH2 to Schiphol	Centralized LH2 storage location	LH2 bowser trucks used for aircraft refueling away from the gate at centralized location

2050 (Phase 2)		
Logistics	Storage	Refueling
Offsite LH2 production + Cryogenic LH2 pipeline delivery to Schiphol	Spread LH2 storage	LH2 Hydrant refueling at the gate

Specific Considerations
<ul style="list-style-type: none"> LH2 logistics, storage, and refueling infrastructure is achievable and largely will use existing technology. A number of things need to be specifically developed: 1. Breakaway couplings, 2. Purge-less couplings, 3. Larger storage tanks, 4. Long-distance cryogenic pipelines, 5. Aviation specific operation equipment such as refueling vehicles and hydrant system In all stages it is likely best to import LH2 for Schiphol via the Port of Amsterdam (possibly through Zenith). Early on this can be transported to Schiphol from the port via trucks (or barges) and later (likely between 2040 and 2050) via cryogenic pipeline. An LH2 supply strategy where GH2 is produced elsewhere and liquefied at Schiphol may still be possible in certain low demand scenarios. There are already plans for large electrolysis projects. In this case Schiphol could be connected to the HyWay 27 GH2 lines. Importing enough LH2 for Schiphol can be an issue since the EU may limit LH2 supply if it cannot supply enough for all member states. Early on about a 10-meter radius LH2 storage tank will likely be enough. Later additional more (and possibly bigger if developed) tanks will need to be added. LH2 bowser trucks will be a realistic option for refueling for the first few years but will likely become overwhelming sometime between 2040 and 2050. Then investments should be made to build a hydrant refueling system. If turnaround times allow for it, when refueling is done with LH2 bowser trucks, it would be wise to do this away from the gate to ensure safety early in the transition. When the transition to a hydrant system is made the technology will have progressed, If risks of refueling are low enough refueling could take place at the gate. Installing a hydrant refueling system around the same time as bigger LH2 aircraft enter the market will allow for two birds to be killed with one stone because this will allow for aircraft stand redesign. This is needed because there is a real chance that efficient aircraft servicing will require more space than there currently is. Infrastructural plans need to be discussed at length and early on with airlines to ensure infrastructure will match the demand from the planned aircraft acquisition. The development and building of integrated infrastructure technology will require early dialogue to take place between developers and authorities. First The technology development is needed for safety and risk analyses to be performed. Only then can regulations be made for it. Since Schiphol operates on the longer-range and larger side of aviation, it can be expected that adoption will benign slower, but go faster later on.

A.2. LH2 Demand Forecasting Model for Schiphol - Calculations Sheet

Here the sheet showing the calculations for LH2 demand forecasts at Schiphol is shown. Only the background calculations and assumptions are shown here. Another sheet displays the results of these calculations along with supporting graphs. This is shown in Appendix A.2.

LH2 Demand Schiphol - Calculation Sheet																																																																																																																																																																																																																																																																																																																																																																																																																											
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The total aircraft movements from 2019 was divided into the different aircraft used for each. This is based on that is reported in the airport traffic review of 2019. The PAZ and range of each aircraft was found from various sources. Based on the Aircraft PAZ and range they are classified based on the earlier defined classes.																																																																																																																																																																																																																																																																																																																																																																																																																											
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8000</td> <td colspan="3"></td> </tr> <tr> <td>Boeing 737 MAX 9</td> <td>Long-range</td> <td>6,225</td> <td>205-204</td> <td>11500-14000</td> <td colspan="3">Total take-offs between</td> <td colspan="3">3,074</td> </tr> <tr> <td>Boeing 737 MAX 8</td> <td>Long-range</td> <td>6,227</td> <td>212</td> <td>6600-10000</td> <td colspan="3">% of total take-offs</td> <td colspan="3">59.84%</td> </tr> <tr> <td>Boeing 737 MAX 8</td> <td>Long-range</td> <td>6,066</td> <td>218-253</td> <td>7200-10000</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A320neo</td> <td>Medium-range</td> <td>6,099</td> <td>105-104</td> <td>6,300</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A320XLR</td> <td>Long-range</td> <td>2,941</td> <td>200-400</td> <td>8000-12400</td> <td colspan="6"></td> </tr> <tr> <td>Embraer E175</td> <td>Regional</td> <td>6,027</td> <td>76-80</td> <td>2,000</td> <td colspan="6"></td> </tr> <tr> <td>Boeing 747-400</td> <td>Long-range</td> <td>2,791</td> <td>410-603</td> <td>13,500</td> <td colspan="6"></td> </tr> <tr> <td>Boeing 747-8</td> <td>Short-range</td> <td>2,063</td> <td>68-104</td> <td>2000-3000</td> <td colspan="6"></td> </tr> <tr> <td>Boeing 707-400</td> <td>Long-range</td> <td>1,529</td> <td>248</td> <td>11,000</td> <td colspan="6"></td> </tr> <tr> <td>Boeing 737 MAX 8</td> <td>Short-range</td> <td>1,325</td> <td>120-140</td> <td>4,200</td> <td colspan="6">Additional sources: Wikipedia (1), Airbus, Boeing, IATA</td> </tr> <tr> <td>Airbus A320neo</td> <td>Medium-range</td> <td>989</td> <td>120-160</td> <td>8,300</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A350-900</td> <td>Long-range</td> <td>920</td> <td>440</td> <td>15,000</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A330-300</td> <td>Long-range</td> <td>808</td> <td>640</td> <td>15,000</td> <td colspan="6"></td> </tr> <tr> <td>Boeing 747-400</td> <td>Long-range</td> <td>323</td> <td>245-271</td> <td>15,400</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A321neo</td> <td>Medium-range</td> <td>491</td> <td>244</td> <td>7400</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A320</td> <td>Medium-range</td> <td>490</td> <td>107-130</td> <td>6,740</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A320neo</td> <td>Short-range</td> <td>364</td> <td>85</td> <td>6,700</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A320neo</td> <td>Long-range</td> <td>396</td> <td>400</td> <td>15,100</td> <td colspan="6"></td> </tr> <tr> <td>Boeing 737 MAX 8</td> <td>Long-range</td> <td>382</td> <td>244</td> <td>13,000</td> <td colspan="6"></td> </tr> <tr> <td>Airbus A380-800</td> <td>Long-range</td> <td>201</td> <td>205-400</td> <td>13,700</td> <td colspan="6"></td> </tr> <tr> <td colspan="2">Total take-offs between</td> <td colspan="2">248,055</td> <td colspan="8"></td> </tr> <tr> <td colspan="2">% of total take-offs</td> <td colspan="2">59.71%</td> <td colspan="8"></td> </tr> </tbody> </table>												Tables of aircraft used at Schiphol (3)												Passenger aircraft						Freight aircraft						Aircraft type	Aircraft Class	# of take-offs in 2019	Aircraft size (PAZ)	Aircraft Range	Aircraft type	Aircraft Class	# of take-offs in 2019	Aircraft range				Boeing 737-800	Medium-range	14,674	107-109	4200-6400	Boeing 777-300	Medium-range	2,002	8000				Airbus A320neo	Short-range	9,224	96-130	2300-4000	Boeing 747-400	Medium-range	1,093	8000				Airbus A320	Medium-range	23,054	140-160	6172	Boeing 747-8	Medium-range	1,070	8100				Boeing 737 MAX 8	Short-range	22,342	85-99	2700-4000	Boeing 757-300	Medium-range	445	5300-7200				Boeing 737 MAX 7	Short-range	18,054	120-142	3000-5000	Airbus A300	Medium-range	365	3500				Airbus A320	Medium-range	14,717	126-158	6645	Airbus A330-300	Medium-range	222	6600-7400				Airbus A321	Medium-range	6,020	165-208	6020-7000	Airbus A350-1000	Regional	147	11700				Airbus A320XLR	Long-range	2,745	132-160	8200-11700	Boeing 737 MAX 8	Medium-range	134	6200				Boeing 777-300	Long-range	6,362	208 (300-400)	13,820	Boeing 737 MAX 7	Short-range	36	2700-4000				Boeing 737 MAX 8	Medium-range	6,354	177-189	4300-6400	Airbus A321	Medium-range	20	5800 - 8000				Boeing 737 MAX 9	Long-range	6,225	205-204	11500-14000	Total take-offs between			3,074			Boeing 737 MAX 8	Long-range	6,227	212	6600-10000	% of total take-offs			59.84%			Boeing 737 MAX 8	Long-range	6,066	218-253	7200-10000							Airbus A320neo	Medium-range	6,099	105-104	6,300							Airbus A320XLR	Long-range	2,941	200-400	8000-12400							Embraer E175	Regional	6,027	76-80	2,000							Boeing 747-400	Long-range	2,791	410-603	13,500							Boeing 747-8	Short-range	2,063	68-104	2000-3000							Boeing 707-400	Long-range	1,529	248	11,000							Boeing 737 MAX 8	Short-range	1,325	120-140	4,200	Additional sources: Wikipedia (1), Airbus, Boeing, IATA						Airbus A320neo	Medium-range	989	120-160	8,300							Airbus A350-900	Long-range	920	440	15,000							Airbus A330-300	Long-range	808	640	15,000							Boeing 747-400	Long-range	323	245-271	15,400							Airbus A321neo	Medium-range	491	244	7400							Airbus A320	Medium-range	490	107-130	6,740							Airbus A320neo	Short-range	364	85	6,700							Airbus A320neo	Long-range	396	400	15,100							Boeing 737 MAX 8	Long-range	382	244	13,000							Airbus A380-800	Long-range	201	205-400	13,700							Total take-offs between		248,055										% of total take-offs		59.71%									
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As can be seen, the take-offs considered here are not 100% of the take-offs. This is because there were only the top 32 and 10 aircraft for passenger and full freighter flights respectively. Because they are both over 50% this is considered representative.																																																																																																																																																																																																																																																																																																																																																																																																																											
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To understand the hydrogen usage for different flights, data was gathered on the LH2 usage of various proposed/assigned LH2 aircraft. These aircraft were gathered from various sources and their different classes of aircraft. Here is the list of aircraft and their specifications:																																																																																																																																																																																																																																																																																																																																																																																																																											
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1	Regional	LH2 turboprop	70	1200-1600	400	5,100	280	200	2005 (E)																																																																																																																																																																																																																																																																																																																																																																																																																		
2	Short-range	LH2 narrowbody	95	2000-3400	1600	6000	2200	2005 (E)																																																																																																																																																																																																																																																																																																																																																																																																																			
3	Regional/short-range	Fuel cell/turboprop	100	1000	800	2020	1004	2005 (E)																																																																																																																																																																																																																																																																																																																																																																																																																			
4	Short-range/medium-range	widebody/turboprop	200	4000	2000	11200	5511	2005 (E)																																																																																																																																																																																																																																																																																																																																																																																																																			
5	Regional	Regional	70	1000	700	207	420	- (E)																																																																																																																																																																																																																																																																																																																																																																																																																			
6	Mid-range	Narrowbody	160	4000	1800	2263	1241	- (E)																																																																																																																																																																																																																																																																																																																																																																																																																			
7	Long-range	Midsize	279	16000	6800	16181	8577	- (E)																																																																																																																																																																																																																																																																																																																																																																																																																			
As can be seen, LH2 aircraft have been proposed for a range of sizes and PAZ meaning that many of the currently used traditional aircraft can be replaced by LH2 aircraft.																																																																																																																																																																																																																																																																																																																																																																																																																											
In the table above the block fuel usage for both the typical and design mission are given. To translate that to size number, an average fuel usage of these aircraft needs to be estimated. To do this, an estimate of the flight ranges flown by each LH2 aircraft needs to be made (note the aircraft above has a maximum range). Here it is considered that an aircraft flies 8% typical mission (design range) 20% of the time, and a lower range mission (50% of typical mission) 20% of the time (source).																																																																																																																																																																																																																																																																																																																																																																																																																											
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Scenario 2	Mildly Accelerated	Regional adoption start 2042, 34% by 2050	Global usage adoption start 2027, 50% by 2050	Medium-range adoption start 2033, 77% by 2050	Long-range adoption start 2039, 40% by 2050	(FlyDm, CoE, et al., 2022)
Scenario 3	Regional Accelerated	Regional adoption start 2033, 50% by 2050	Global usage adoption start 2027, 49% by 2050	Medium-range adoption start 2044, 17% by 2050	Long-range adoption start 2046, 12% by 2050	(FlyDm, CoE, et al., 2022)
Scenario 4	Mildly Unaccelerated	Regional adoption start 2042, 34% by 2050	Global usage adoption start 2042, 27% by 2050	Medium-range adoption start 2035, 49% by 2050	Long-range adoption start 2050, 0% by 2050	(FlyDm, CoE, et al., 2022)
Scenario 5	Regional Unaccelerated	Regional adoption start 2045, 13% by 2050	Global usage adoption start 2047, 0% by 2050	Medium-range adoption start 2035, 0% by 2050	Long-range adoption start 2046, 0% by 2050	(FlyDm, CoE, et al., 2022)

The percentage of adoption over the years of each of the different aircraft classes for the different scenarios is calculated in the four tables below.

3.4. Applying LHD adoption estimates to find yearly LHD requirements with no growth against growth scenario adopted yet

The total number of flights that can take place each year need to be calculated. This is done by taking the total number of possible flights with each LHD aircraft and categorizing them into the four main different flight categories (including estimates)

Total flights per aircraft class distribution			
Regional (aircraft 1, 2, 3)	Short Range (aircraft 2, 4)	Medium Range (aircraft 5)	Long Range (aircraft 7)
0	37,361	116,859	87,304

This table can be used to calculate how much of each aircraft will be flown for each year for each scenario (see the background calculations 2.3). After this the total amount of LHD consumed at airports for each scenario can be calculated.

Year	Total hours per usage of all flights at Schiphol per year for each adoption scenario with no flight movement growth (kg)					
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2021	0	0	0	0	0	0
2026	0	10274888.81	0	0	0	0
2029	0	22681787.82	0	0	0	0
2030	18970951.11	33624985.53	0	0	0	0
2031	31048102.21	43609594.44	0	0	0	0
2032	47018163.32	58274482.55	0	0	0	0
2033	6588204.43	67683381.85	793707.204	0	0	0
2034	78926256.53	78924280.86	1034194.71	0	0	0
2035	89626208.84	89789788.47	12741232.08	0	5417333.47	0
2036	111703057.7	126265952.9	16268098.42	0	18384813.64	0
2037	127786068.6	188871817.7	44172138.81	585887.53	18252916.41	0
2038	147138480	26148132.9	89789997.43	18717016.86	27889287.88	0
2039	168768855.1	34958449.4	121620465.1	11978222.86	3586887.26	0
2040	170870663.2	288930762.2	149246712.7	25436036.12	32944632.82	0
2041	20226989.6	324717977.1	270841670.3	28232187.86	37811676.39	0
2042	28184335.6	382883381.9	292238427.9	35191045.16	48380283.46	0
2043	39423207.3	426268768.7	324478826.9	4183882.71	58199270.89	0
2044	302016500	447861821.8	33548343.1	8794626.24	6828123.35	0
2045	30881745.7	48182238.4	37711030.8	67318486.76	78877645.7	0
2046	33874780.3	52014885.2	438728758.4	71472972.26	88718883.65	0
2047	387747470	587619489	48626878	8927548.81	10558689.4	2787182.87
2048	388384645.1	68831238.9	501884173.8	8718126.83	119882878.8	7523388.828
2049	41488882.4	62164785.7	54389821.2	14832885.1	121432718.1	11288580.34
2050	441522818	676838819.5	58518888.9	208318211.6	15182182.7	15084783.81

Instead of giving the demand on a yearly basis, it can also be given on daily basis.

First calculations for the distribution of flights over the months needs to be done

Calculations for flight distribution over the year (M1)		
Month	PKZ per month (21000)	% of yearly numbers
January	5,005	0.023789
February	4,384	0.020364
March	5,838	0.027321
April	8,106	0.038183
May	8,441	0.039225
June	8,548	0.039763
July	8,724	0.040772
August	8,811	0.040985
September	8,483	0.039350
October	8,437	0.039208
November	8,234	0.037948
December	5,388	0.025112
Yearly total	71,136	1.000000

It can be seen that August is the most busy month. So an average day in August is a good day to choose as a daily expectation

Year	Total hours per usage of all flights at Schiphol per day for each adoption scenario with no flight movement growth (kg)					
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2021	0	0	0	0	0	0
2026	0	34848.88169	0	0	0	0
2029	0	88038.88219	0	0	0	0
2030	48652.79181	123263.8423	0	0	0	0
2031	67688.88383	138188.7244	0	0	0	0
2032	148788.2187	172723.4055	0	0	0	0
2033	189731.9837	291260.8385	23185.78814	0	0	0
2034	264883.8986	241428.1619	448571.81819	0	0	0
2035	308588.7616	276873.4487	86587.33843	0	18588.81881	0
2036	342529.5434	388185.3785	82743.15287	0	33187.83302	0
2037	381842.2383	518881.1343	135346.8726	17838.87076	48188.74888	0
2038	440881.1272	628888.8821	262882.8887	28881.24186	88188.88888	0
2039	488821.8181	758428.7689	388378.847	88882.91281	82384.82388	0
2040	638280.711	878182.8877	817888.8843	71882.88316	98181.49887	0
2041	818721.8888	988284.8156	848416.2218	88788.38388	118982.4188	0
2042	1181881.8888	1181881.2423	712881.8889	187788.8281	148177.8213	0
2043	782884.1722	1234888.071	803488.8888	128884.8888	180482.8271	0
2044	884188.2288	138428.888	1027888.233	158788.2888	212748.8238	0
2045	848788.4788	1418881.127	1158483.871	187382.4188	248133.2388	0
2046	132187.8888	1581881.8888	128881.8888	218888.8188	278184.8488	0
2047	110488.197	171818.382	1418818.345	258188.2384	388188.8588	1088.71884
2048	118888.881	188227.21	1883888.888	281222.8884	348888.8888	20878.43887
2049	1271811.084	1988888.088	1888888.888	458328.8372	37284.8817	34878.88881
2050	1188882.288	2272888.888	1788888.888	631428.478	62484.8888	48788.88734

3.5. Calculations for Truck requirements

Assumption for the amount of Ware that a delivery truck can hold is 30,000 Ware

Truck truck capacity (3) = 80000

Year	Daily amount of LHD trucks - no growth					
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2021	0	0	0	0	0	0
2026	0	9	0	0	0	0
2029	0	17	0	0	0	0
2030	12	28	0	0	0	0
2031	24	33	0	0	0	0
2032	38	41	0	0	0	0
2033	47	49	0	0	0	0
2034	58	57	11	0	0	0
2035	68	65	17	0	4	0
2036	81	84	22	0	8	0
2037	88	122	32	0	12	0
2038	104	153	42	0	18	0
2039	118	178	52	0	23	0
2040	127	207	127	17	28	0
2041	140	233	192	22	35	0
2042	160	263	192	30	38	0

A.3. LH2 Demand Forecasting Model for Schiphol – Results Sheet

Here the sheet showing the results for LH2 demand forecasts at Schiphol is shown. These results were calculated using a set of background calculations and assumptions which can be seen Appendix A.2.

