H_2 SOLUTIONS IN AIRPORT GROUND POWER EQUIPMENT

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Abbreviations

GPUs Ground power units
h-GPUs Hydrogen-based groud power units
d-GPUs Diesel Ground power units
GSE Ground support equipment
h-GSE Hydrogen-powered ground support equipment
LCA Life cycle assessment
GWP Global Warming Potential
FCEVs Fuel Cell Electric Vehicles
BEVs Battery electic vehicles

Managerial Summary

Sustainable and zero-emission practices are increasingly prevalent across all sectors, including the aviation industry (Ellaban et al., 2014; ACI, 2019). Given the anticipated significant growth of the air transportation industry in the forthcoming years, it is important to prioritize the development of low-carbon emission equipment for this sector (Testa et al., 2014). The ground power unit (GPU) is one of the ground support equipment that can be considered as a significant source of carbon emissions in airports since they are responsible for about 10% of the total emissions (Dube & Nhamo, 2019; Balli & Calliskan, 2022). In this context, there is increasing emphasis on developing zero-emission solutions for GPUs to meet decarbonization and emissions reduction targets (Testa et al., 2014). Hydrogen has emerged as a promising solution to achieve the net-zero carbon emission targets due to its carbon-free features and high energy efficiency (Qyyum et al., 2021). The adoption of hydrogen as a replacement for the conventional diesel GPUs could substantially reduce emissions of carbon dioxide (CO_2), carbon monoxide (CO), and other harmful gases, making the transition to hydrogen-based ground power units (h-GPUs) an effective strategy for minimizing environmental harm (Testa et al., 2014). However, to entirely investigate the carbon emissions reduction potential of h-GPUs, it is important to consider their environmental impact throughout their entire life cycle, from production to disposal (Cetinkaya et al., 2012).

Alongside analyzing the environmental impacts of this transition, it is important to evaluate its economic impact since hydrogen technology deployment in GPUs necessitates establishing a robust infrastructure, substantial investments, and operating costs. A dedicated cost and benefit analysis is therefore necessary to understand the means for this transition. By conducting such an analysis, valuable insights into the economic sustainability of hydrogen technology can be obtained, enabling policymakers and stakeholders to make informed decisions regarding its adoption.

Despite the wide benefits of h-GPUs, such as the reduction of greenhouse gas emissions, reduced noise pollution, and positive environmental impact, the deployment of the technology is hindered by several barriers, including limitations in technology, high hydrogen prices, and the lack of regulatory standards. Moreover, building a robust hydrogen infrastructure and training a capable workforce have also presented significant challenges for the widespread adoption of h-GPUs (Baroutaji et al., 2019; Papadis & Tsatsaronis, 2020). Therefore, it is also essential to investigate and analyze these barriers considering the different perspectives and views of the stakeholders relevant to the transformation. Such an analysis would enable policymakers and stakeholders to identify the potential challenges and develop strategies to overcome these barriers. Furthermore, it would facilitate the development of a conducive environment for the adoption of h-GPUs and accelerate the transition to sustainable aviation.

This project aims to explore the feasibility and the grounds for the implementation of hydrogen solutions for GPUs and develop a comprehensive framework that provides recommendations and suggestions for the transformation. The aim is to support the goal of attaining emissions-free ground operations by 2030 and address various technical, environmental, and economic challenges associated with the development of hydrogen ecosystems in airports. To this end, the project covers a Life Cycle Assessment (LCA) analysis to investigate the environmental impact of deploying hydrogen, a cost-benefit analysis to evaluate the economic feasibility and an analysis of barriers considering the stakeholders relevant to the transformation. The specific tasks and objectives of the project are outlined below:

- Conducting a LCA to analyze relevant technical/operational aspects (e.g. minimal power output, maintenance) and CO_2 gains of h-GPUs.
- Development of a cost-benefits model to evaluate the economic impact of the transition to h-GPUs.
- Analysis of operational, economic, legal and regulatory, technical, safety barriers for the transformation.
- Determining the learning points in the transformation to h-GPUs for regional airports here and beyond to facilitate replicability in other regions.
- Proposing recommendations to support policy, stakeholders enhancing knowledge, and facilitating further research.

This report first provides an overview of the key findings in the transition of ground power units (GPUs) by referring to the specific tasks outlined above. The report then presents detailed analyses, models, and findings in the Appendices A, B, and C. Appendix A presents the results of the environmental impact assessment of deploying h-GPUs, including the assessment of potential emissions and mitigation strategies. Appendix B provides the results of the cost-benefit analysis of deploying h-GPUs. Finally, Appendix C discusses the barriers to the hydrogen transition for GPUs, including a comprehensive analysis of the economic, technological, political, regulatory, social, and environmental factors that must be addressed to ensure successful implementation.

1. Life Cycle Assessment

Increased awareness on environmental sustainability calls for emission-free solutions in GPUs (Barke et al., 2020). Accordingly, replacing the fossil fuels with renewable sources is an important step to decrease greenhouse gas emissions. Hydrogen can be used for this purpose. However, this transition will necessitate establishing a transportation infrastructure or local production facilities. It is worth noting that emissions from the production and transportation of hydrogen also contribute to the sector's carbon footprint (Wulf et al., 2018). Therefore, to entirely assess the environmental impact of h-GPUs, it is crucial to consider the whole lifecycle of the unit, from production to disposal, as well as all its related activities (Cetinkaya et al., 2012; Wulf & Kaltschmitt, 2018). In order to map the environmental impacts of the h-GPUs by an on-site solar power plant, a LCA analysis has been performed in this research.

This analysis has been utilized to determine the amount of carbon dioxide (CO_2) reduction that can be achieved by replacing diesel GPUs with h-GPUs. Further, a comparison between the diesel and hydrogen supply chain LCA is provided.

The first stage of the LCA is inventory analysis to determine the materials used in each supply chain component. Related data is gathered from a thourough review of previous literature, expert opinions, and semi-structured interviews. The semi-structured interviews focuses on obtaining information about the materials, production processes, and usage phases. Additional information is gathered from the Ecoinvent database within SimaPro 9.4. The second stage of this LCA investigates the environmental impact, which is categorized into various impact categories (Curran, 2015). The emissions within each category are analyzed individually (Goedkoop, 2008). The selection of impact categories is based on commonly used categories in related studies. The primary focus of this research is on the GWP (Global Warming Potential), with the ReCiPe method used to assess emissions in other impact categories. The final step of this method involves the interpretation of the results and determining their alignment with the defined goals.

The results are assessed based on different settings of airport operations. The base scenarios are established using the information provided by Groningen Airport Eelde (GAE). Five scenarios are developed based on potential flight frequencies (a single flight vs three, five, ten, and fifteen flights) departing per day. The environmental impacts of h-GPUs are evaluated by considering production, transportation, and storage necessities. Similarly, comparable scenarios are developed for the diesel supply chain by focusing on the diesel production, transport, storage, diesel GPUs, and diesel combustion. The comparison of the environmental impacts of d-GPUs vs. h-GPUs and the diesel vs. hydrogen supply chain are presented in the following subsections.

1.1 Environmental Impact of Diesel vs. Hydrogen-based Ground Power Units

In order to investigate environmental impact of diesel vs. hydrogen-based GPUs, the Global Warming Potential (GWP) of the two options is analyzed. Results are depicted in Figure 1 and Table 1. The life cycle GWP of the diesel GPUs is significantly higher than that of the hydrogen GPUs. The diesel GPUs has a GWP of 41,17 kg CO2-eq, which is 10.4 times larger than the 3,90 kg CO2-eq of the h-GPUs. Results indicate that the major contributor to the difference in GWP between the two GPUs is the generating set inside the diesel GPUs, accounting for 98.3% of the total GWP. Using renewable energy sources in the production process of the generating set could significantly reduce the GWP of diesel GPUs. Materials used for the converter and packaging of both GPUs are similar, resulting in similar GWP amounts for those components. The only component of the h-GPUs with a higher GWP than its counterpart in the diesel GPUs is the storage tank, which has a GWP more than three times higher than the diesel storage tank.

Table 1. GWP of the different components of the diesel GPU compared with the GWP of the components of the hydrogen GPU

d-GPU			**h-GPU**		
	Unit	**GWP (x1000)**		**Unit**	**GWP (x1000)**
Generating Set	kg CO_2-eq	40.47	Fuel Cell	kg CO_2-eq	2.89
Diesel Storage	kg CO_2-eq	0.06	Storage	kg CO_2-eq	0.19
Converter	kg CO_2-eq	0.40	Converter	kg CO_2-eq	0.40
Packaging	kg CO_2-eq	0.20	Packaging	kg CO_2-eq	0.20
Waste Management	kg CO_2-eq	0.04	Battery	kg CO_2-eq	0.12
Total	kg CO_2-eq	41,17	Waste Management	kg CO_2-eq	0.11
			Total	kg CO_2-eq	3.90

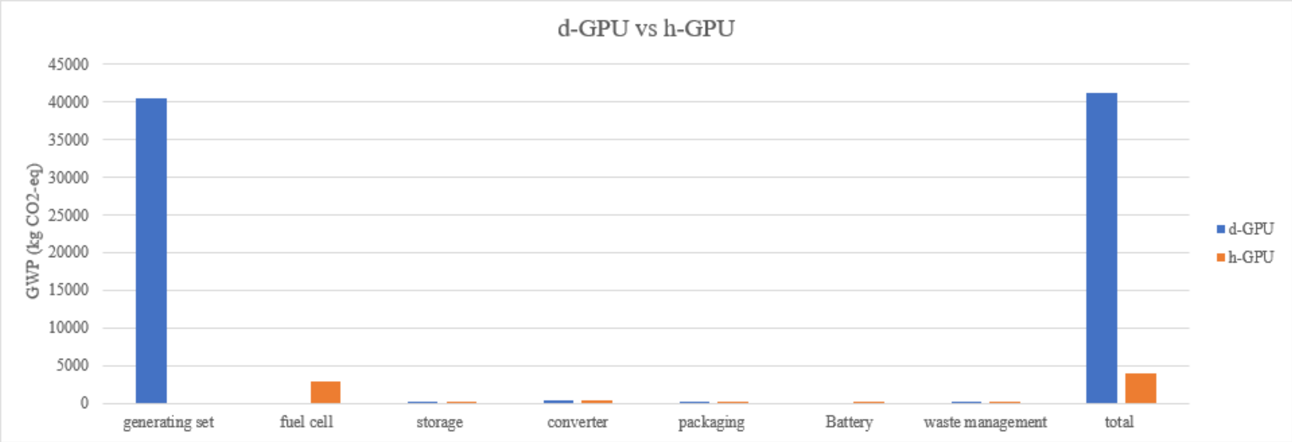

Figure 1. The GWP of the separate components of the d-GPUs and h-GPUs

1.2 Environmental Impact of Diesel vs. Hydrogen Supply Chain

In this section, we extend our GWP analysis to incorporate the overall supply chain components of both types of GPUs. Five different scenarios are established based on a single flight, three, five, ten, and fifteen flights departing per day. The GWP for the supply chain involves the production phase of all components, the usage phase and the disposal of all components. The burning of diesel in the diesel GPU and water usage in the hydrogen GPU are further considered in the calculations. Table 2 and Figure 2 provides a visual representation of the comparison between the GWP of the overall supply chain for the diesel and the hydrogen GPUs.

Table 2. The global warming potential of one year for the d-GPU and the h-GPU

		GWP (kg CO_2-eq)	
Scenario	**Unit**	**d-GPU (x10,000)**	**h-GPU (x10,000)**
Scenario 1	1 flight a day	36.40	1.17
Scenario 2	3 flights a day	109.06	3.01
Scenario 3	5 flights a day	182.43	4.90
Scenario 4	10 flights a day	362.49	9.51
Scenario 5	15 flights a day	543.65	14.20

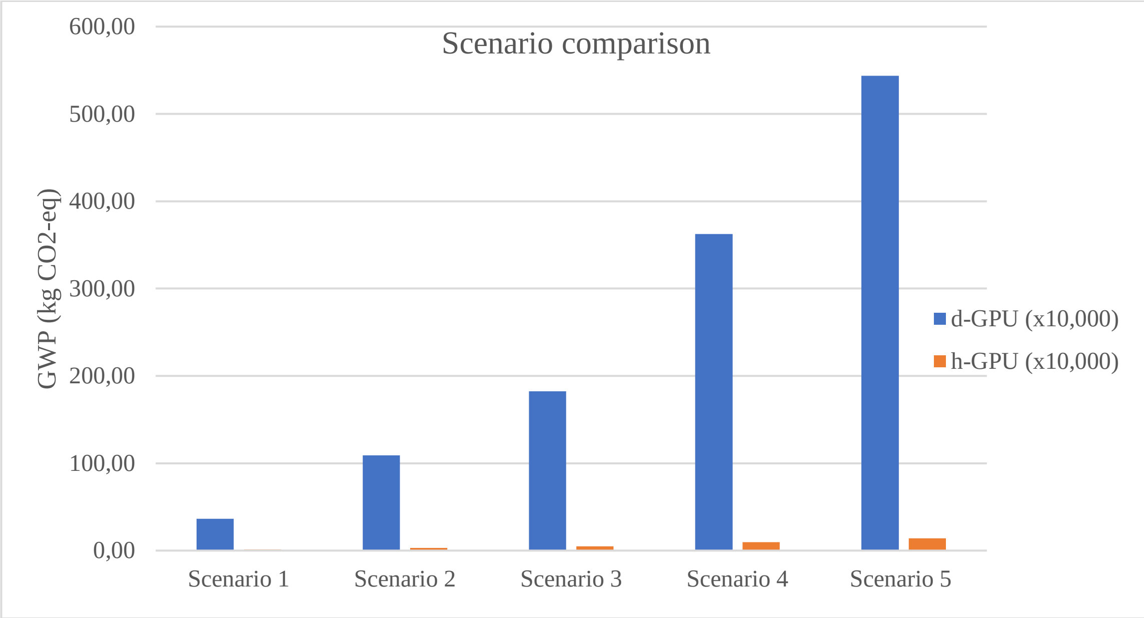

Figure 2. A comparison in global warming potential between the supply chains of the d-GPU and the h-GPU

The LCA results indicate that a hydrogen supply chain is much more environmentally friendly than a diesel supply chain. The GWP of the hydrogen supply chain is lower in every scenario and the GWP of the diesel supply chain increases with the number of flights. The hydrogen supply chain is more favorable, with a difference of 31.1 times in scenario 1 which is based on a single flight departing per day and 38.3 times in scenario 5 which is based on fifteen flights departing per day. As the number of flights increase, the hydrogen supply chain becomes even more favorable due to the scalability of production and storage.

To provide a different perspective on this GWP amounts we can compare them to the GWP of human beings, and passenger cars. For scenario 3, which assumes five flights leaving GAE per day, the hydrogen supply chain has a GWP of 49,000 kg CO_2-eq per year, while the diesel supply chain has a GWP of 18,243,000 kg CO_2-eq per year. In comparison, a human has a GWP of 4,470 kg CO_2-eq per year (Statista, 2022). This means that the hydrogen supply chain has an environmental impact equivalent to almost 11 humans, while the diesel supply chain equals 4,081 humans. Likewise, driving a diesel passenger car has a GWP of 0.178 kg CO_2-eq per km. The GWP of the hydrogen supply chain is equivalent to 275 thousand kilometers, whereas the diesel supply chain is equivalent to 102 million kilometers (Helmers et al., 2019). Based on these comparisons, it is evident that using hydrogen to power the GPUs is much more environmentally friendly than using diesel. However, the solar park and the hydrogen storage are points of improvement for the hydrogen supply chain. Further research into hydrogen storage and PV panels can benefit further reduction of those emissions.

Appendix A contains a comprehensive discussion of the LCA analysis regarding the deployment of hydrogen in GPUs.

2. Cost and Benefits Analysis

The second objective of this research is to provide a cost and benefits analysis for the transition to h-GPUs by assessing economic feasibility based on the entire lifecycle of the h-GPUs. To assess the financial feasibility of investing in h-GPU for regional airports, the model is developed by considering the net present value (NPV) of the investments. This analysis includes several cost components such as the CapEx (capital expenses) for the energy devices (d-GPU, h-GPU, HST, and electrolyzer), and the annual OpEx (operational expenses) which is made up maintanence cost and the cost of energy (COE). The COE is determined by the demand for hydrogen, electricity, and diesel, which varies depending on the type of GPU utilized.

For the hydrogen setting, the general framework of the airport energy supply and demand can be represented as in Figure 3. The energy is sourced from the grid and/or PV and utilized by the terminal, h-GSEs and h-GPUs for daily operations. The utilization of the h-GPUs depends on flight frequencies, whereas the energy production of the solar park is subject to variations in solar irradiance and temperature. Obtaining energy from the grid acquires financial costs. The PV is assumed to be directly connected to the electrolyzer to prevent energy losses. The microgrid transforms the electricity obtained from the national grid or PV to the terminal for daily operations or transfers the national grid electricity to the electrolyzer for producing hydrogen. In the diesel setting, emissions produced by d-GPUs require the imposition of a carbon tax.

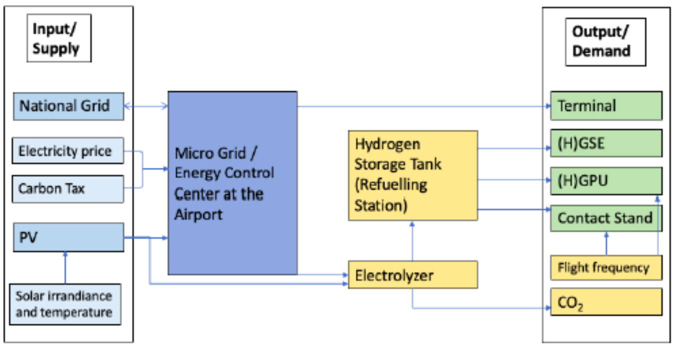

Figure 3. Airport Energy Supply and Demand Layout (adopted from Xiang et al., 2021)

The model data is primarily sourced from the airport and its stakeholders. Additionally, quantitative data from various sources such as literature, public sources, and reports is utilized. The study incorporates various experimental factors, such as green hydrogen production by solar energy and hydrogen demand at the airport, to determine the relevant variables. These factors are analyzed based on prior research, and a cost model is developed to comprehensively assess the associated costs. The base scenario is developed by considering the current low flight frequency at GAE. We note the effect of Covid-19 on flight frequencies at all airports. Three scenarios are then developed as an extension from the base model where for example flight frequencies are increased and carbon tax policies are introduced. These scenarios are listed in Table 3.

Table 3. Overview of Scenarios

	Demand	CO_2 Tax
Baseline	*Based On The Current Flight Frequency*	*No*
Scenarios		
A (Doubled Demand)	Based On The Doubled Flight Frequency	No
B (CO_2 Tax)	Based On The Current Flight Frequency	Yes
C (Doubled Demand And CO_2 Tax)	Based On The Doubled Flight Frequency	Yes

We first summarize our analysis for the cost components of the d-GPUs and h-GPUs for the base case where we consider low flight frequencies and where CO_2 emissions are not financially penalized. It should be noted that, since for the use of a h-GPU, the infrastructure for hydrogen production should also be built, we consider its overall supply chain. On the other hand since diesel is more accessible we assume that the fossil fuel is externally sourced. The results of the cost analysis is represented in Figure 4. The analysis shows that the total capital investment required for the h-GPU is €200.000, whereas this stands at €85,000 for the d-GPU. If we consider the entire hydrogen infrastructure equipment, the total capital investment amounts to €1.2 million. The maintenance cost for h-GPU, and d-GPU are, €32,000, and €50,000, respectively. Notably, the maintenance of the h-GPU is lower than that of the d-GPU, which is consistent with the previous research conducted by Eefting (2022). The operating expenses of the entire hydrogen supply chain, amounts to €5.25 million. The COE for the h-GPU is €143000, whereas this is €79,000 for the d-GPU since the per unit cost of hydrogen is higher than the per unit cost of diesel at the infancy stages of hydrogen economy. The calculation of the annual COE is done by multiplying the annual hydrogen consumption by the current hydrogen unit cost. Likewise, the COE for the d-GPU is calculated by multiplying the annual diesel consumption by the diesel price. The energy consumption of hydrogen and diesel is obtained from the cost model.

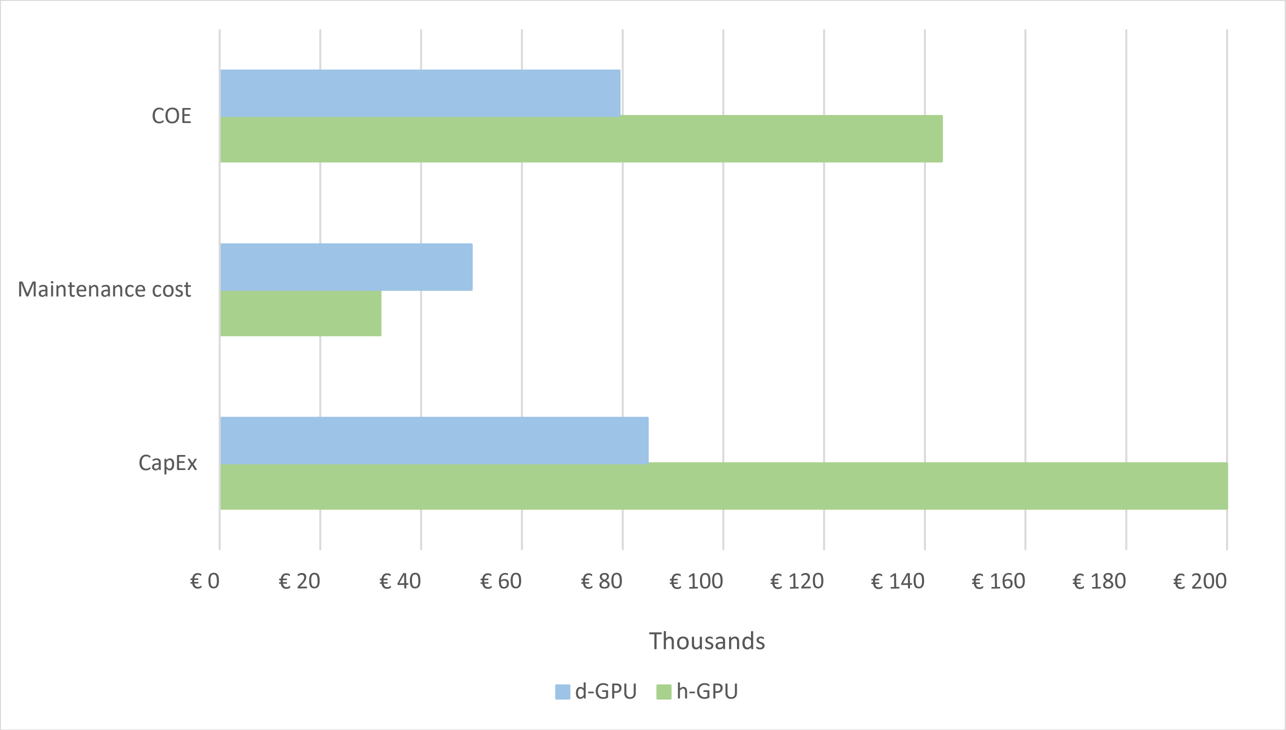

Figure 4. Cost Assesment of h-GPUs and d-GPUs

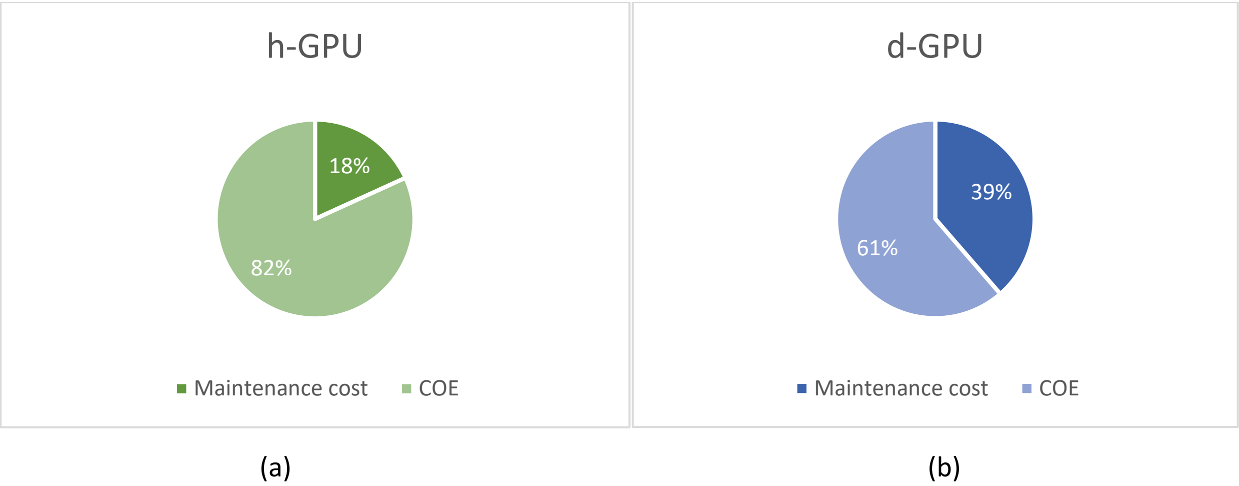

Figure 5. Portion of Maintenance Cost and COE within the OpEx (a: h-GPU, b: d-GPU)

Figure 5 shows the portion of maintenance cost and COE of GPUs within the OpEx. The COE accounts for the majority of the OpEx of the h-GPU, representing 82%. The remaining 18% corresponds to the maintenance cost of h-GPU. The maintenance cost and COE of d-GPU accounts for 39 % and 61%, respectively. These findings suggest that, while the h-GPU incurs higher energy costs, it has lower maintenance cost over its lifetime than the d-GPU. The difference in these cost proportions is primarily attributable to the higher hydrogen unit cost than diesel unit cost. However, it is expected that if the hydrogen demand increases and hydrogen consumption levels rise, the cost of hydrogen per unit will decrease, leading to a reduction in the overall COE. The h-GPU project provides an opportunity to diversify its revenue sources beyond electricity sales, that is by hydrogen sales. Hydrogen sales make up 46% of the overall revenue, while electricity sales constitute the remaining 54% for the h-GPU. The hydrogen production cost is predicted to be €5.97 per kg., which is expected to decrease over time. The current market price for selling hydrogen can be approximated as €17 per kg. In the long term, this is expected to decrease aligning closer with the production cost. Therefore, although the introduction of hydrogen sales provides the airport with an opportunity to diversify its revenue opportunities, it is crucial to consider that the revenue generated by hydrogen sales may stabilize over time. As can be seen in Figure 6, for the base case where we consider a low flight schedule and no CO_2 taxes, the h-GPU's revenues will be insufficient to cover its costs from 2035 onwards. The cumulative revenue for the h-GPU and d-GPU is €8.3 million and €5.5 million, respectively. Although the h-GPU generates more revenue than the d-GPU, its net present value (NPV) is lower than that of the d-GPU. This is because the total cost of transition to hydrogen is higher than that of the d-GPU and revenue for HGPU is used to cover the costs. The analysis highlights the significant contribution of hydrogen sales to the overall revenue of the airport.

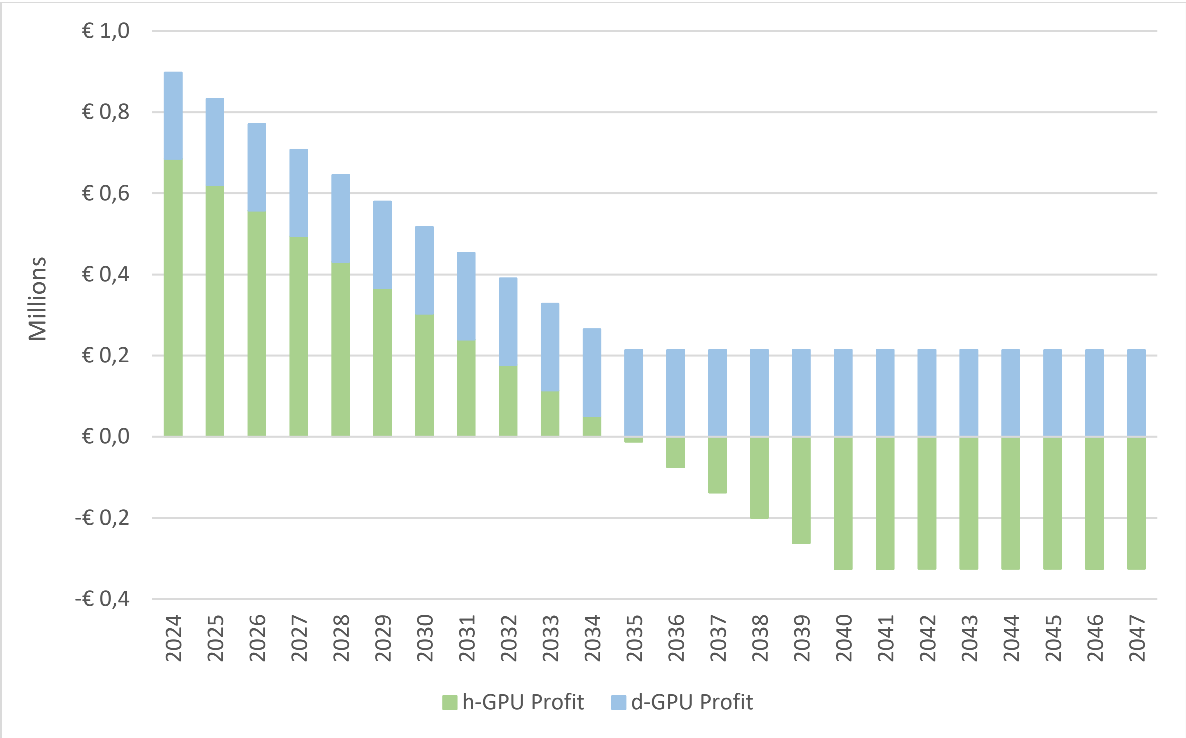

Figure 6. Annual Profit of h-GPU and d-GPU

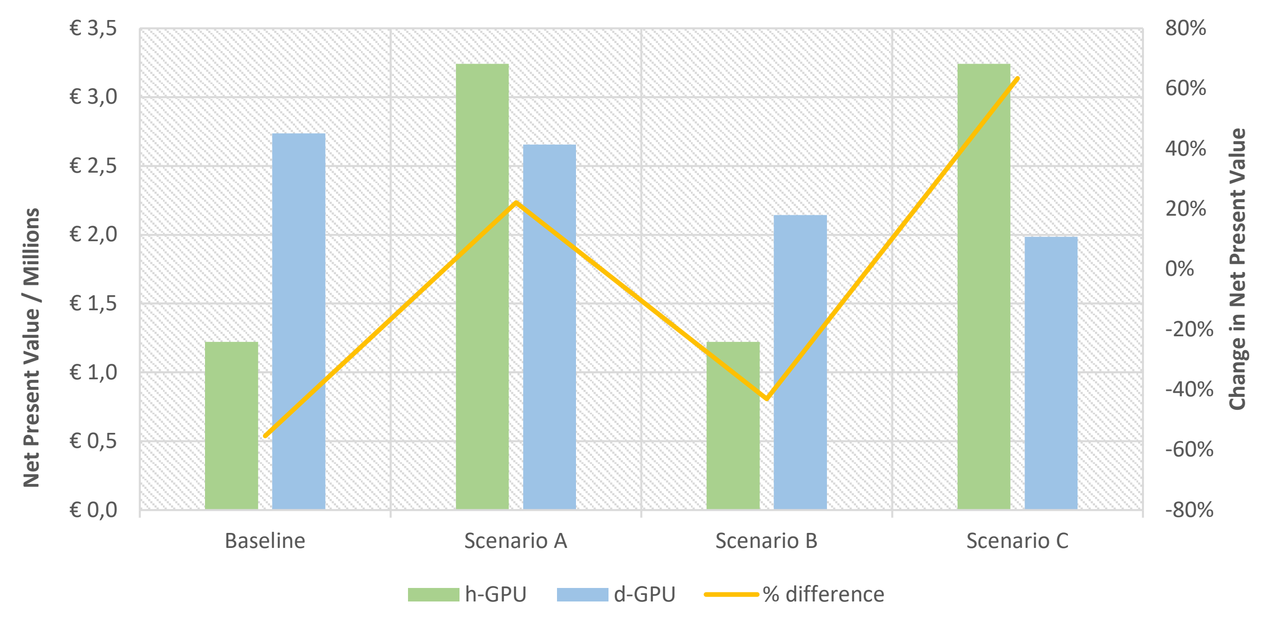

Figure 7. The NPV for h-GPU and d-GPU for all scenarios

We continue our analysis with summarizing the results for the scenarios presented in Table 1. We underline that this study incorporates the overall hydrogen supply chain in the calculations. As depicted in Figure 7, the results indicate that the h-GPU has a higher net present value (NPV) than the d-GPU in Scenario A and C. Especially, in the combined scenario where the demand is doubled, and the carbon emission tax is implemented (Scenario C), the transition to h-GPUs create an important market opportunity for the airport. The unit cost of hydrogen drops from €5.97/kg to €3.80/kg, which leads to an increase in the NPV for the h-GPU. The cost for the d-GPU increases with the carbon emission tax, leading to a lower NPV.

Sensitivity analyses is carried out in order to observe the effects of critical variables such as the electricity price, carbon tax and the diesel price. The sensitivity analysis conducted within the simulations shows that the carbon emission tax has a significant impact on the total cost of the d-GPU. Additionally, the analysis demonstrates a close link between the unit cost of electricity and the hydrogen production cost.

In conclusion, the results show that deploying a h-GPU system at an airport can lead the path to important market opportunities, particularly when considering increased flight frequencies and the adaptation of the carbon emission tax regulations. Transitioning to h-GPUs can be considered under adequate hydrogen demand that can stem from both airside and landside operations. We refer the reader to Appendix B for the details to the cost study and the results..

3. Barriers towards the transition to Hydrogen-Based Ground Power Units

Hydrogen is widely recognized as a crucial energy carrier for achieving net-zero emissions, as it offers an effective means of storing renewable energy. However, replacing conventional energy sources with hydrogen poses significant challenges. Exploring the potential barriers to establishing a hydrogen ecosystem at the local level is necessary. Table 4 summarizes the barriers towards the transition to h-GPU.

Table 4. Barriers to transition to h-GPUs

Business model hydrogen	Economic barriers
Diesel cheaper	
High hydrogen price	
High investment costs	
No viable business model	
Subsidies	
Availability	Technological barriers
Hydrogen infrastructure	
Technology excists	
Research and knowledge	
Technical staff and skills	
Technology development	
Missing stimulating policy	Political and regulatory barriers
Policy not consistant and slow	
Regulation	
Permits	
Hinder environment	Social and environmental barriers
Inform public	
Positive for environment	
Safe and responsible	
Resistance airport	
Safe distance people	
Safety concerns	
Social acceptance	
Social support hydrogen	
Support airport	

Economic barriers impede the widespread adoption of hydrogen as an energy source, primarily encompassing high investment costs, operational expenses, the feasibility of business models, and subsidy acquisition. Hydrogen faces an unfavorable comparison to fossil fuels due to its high operating and capital expenditure. The primary drivers of these costs are high hydrogen pricing and investment costs. As such, an economically feasible business model is challenging, especially for small-scale airports and businesses with limited budgets. Nevertheless, experts are optimistic that this scenario will change by 2040, given the expected rise in hydrogen supply and demand, leading to price reductions. Additionally, augmenting renewable electricity supply will lower the cost of producing green hydrogen, further propelling hydrogen's competitiveness relative to fossil fuels.

The second main barrier of this transition is technical barriers which are linked to inadequate infrastructure, insufficient knowledge and skills, and limited applications. Currently, the hydrogen supply chain requires substantial investments to develop infrastructure on a large scale. There are currently few fuel cell electric vehicles (FCEVs) and refueling stations available due to limited hydrogen production on a large scale. Parties interested in promoting hydrogen use should invest in infrastructure and manufacturing facilities for fuel cell buses, trucks, and cars, among others. Moreover, qualified personnel is scarce in this sector, and more technically skilled employees are necessary to develop hydrogen infrastructure and applications. From a technological standpoint, hydrogen technologies are available, but integrating and scaling them is a challenge, particularly due to the mentioned economic barriers. The industry encounters challenges, lacking policies, and platforms to meet market demands for qualified employees.

Lack of regulations and standards, government knowledge, and complicated regulatory procedures can hinder the widespread adoption of hydrogen as an energy source. To overcome these political and regulatory barriers, the government needs to play a pivotal role in developing the market and reducing uncertainties. Additionally, social and environmental barriers such as a public lack of knowledge, safety concerns particularly due to perceived nuisance, also impede the progress of hydrogen adoption. To address these barriers, there needs to be an intensive effort to educate the public about the benefits of hydrogen and its safety and to find ways to mitigate their perceived nuisances, such as by locating hydrogen projects taking into account safety factors. The results indicate that there is relatively high social support for hydrogen projects as they can positively impact the environment and can be carried out safely at a distance from people. However, there are still safety concerns, particularly from people living near a hydrogen project, indicating that society needs to gain more knowledge about hydrogen. For instance, Groningen Airport Eelde's social acceptance is controversial, with opponents highlighting pollution, nuisance, and financial losses while supporters emphasizing its significance to society and the economy.

According to the literature, gaining social acceptance for new technologies and infrastructure can be a contentious process, which may result in protests from the population. To achieve social acceptance, it is essential to understand societal situations and conflicts, which can range from controversial arguments related to security, competitiveness, and environmental protection to consensual views on the common goal of addressing climate change and zero-emission targets (Glanz & Schönauer, 2021; Wu et al., 2022). However, achieving social acceptance for hydrogen ecosystems in airports can be particularly challenging due to the presence of both supporters and opponents in society. Despite concerns about combustible and explosive safety risks associated with building hydrogen infrastructure around communities, sustainable aviation practices such as electric flying can significantly reduce noise and pollution, which can help to reach broader social acceptance. To achieve this goal, embracing technology openness, information transparency, and citizen participation in the implementation process is essential, which can lead to broader acceptance. It is important to note that social perception and acceptance can appear contradictory, and it is not helpful to reduce these arguments to residents' irrational, selfish, or uninformed motivations. Instead, these should be taken seriously and included in the implementation processes through transparency and participation. Thus, effective engagement and collaboration with stakeholders can facilitate dealing with mentioned barriers.

Appendix C of the research report provides a comprehensive discussion of the potential barriers that impede the implementation of h-GPUs at regional airports. The following section discusses the development of a feasible pathway for the transition, structuring of a roadmap to serve as a blueprint, and the identification of the learning points to address the mentioned barriers.

4. Learning Points

Groningen Airport Eelde (GAE) aims to become Europe's first Hydrogen Valley Airport as part of the larger Hydrogen Valley initiative (GAE, 2021). GAE collaborates with external stakeholders such as the Province of Drenthe and Holthausen Clean Technology to develop a project that involves converting d-GPUs into h-GPUs, powered by solar energy from the airport's solar park or electricity from the grid. GAE is part of the Interreg North Sea Programme. It aims to be a pilot study for other airports by using green hydrogen and locally producing, distributing, and storing it (GAE, 2022). Although the analyses linking environmental and economic impacts of the GPUs through LCA and cost-benefit analysis were based on operational parameters specific to a particular airport, this study framework can serve as a blueprint for assessing environmental and economic feasibility across airports of diverse sizes and scopes.

The findings of this research can be applied to regional airports with specific characteristics. One important limitation regards to the land availability. Having sufficient space to install a solar park, electrolyzer, and a storage unit is important. Additionally, it is crucial to have access to external hydrogen demand opportunities to be able to generate revenue from selling excess energy since especially in the early stages of the transition the expected demand may be low and therefore be more costly. Looking into opportunites for the airport to serve as a hydrogen hub is therefore important for the success of the transition. The idea is to develop airports as "hydrogen hubs" to create the necessary market. To scale up the use of hydrogen in airports, a significant investment in infrastructure will be required. This includes the production, storage, and distribution of hydrogen fuel. Private investments can be attracted to build this infrastructure. It is essential to consider the most efficient and cost-effective methods for each of these processes to ensure scalability.

Compared to regional airports, larger airports have different characteristics and limitations. They serve higher demand with higher frequencies. Operating on electricity based vehicles may be problematic due to congestion issues on the electiricty grid. They are more likely to realize the hydrogen demand with their own GSE fleet and are therefore less dependent on external hydrogen markets. This also underlines the importance of large airports to have reliable and continuous access to hydrogen. It is necessary to ensure the availability and stability of this supply. This may entail the necessity for connections to the national hydrogen pipeline network. Developing a hydrogen hub in the surrounding region of the airport may help to achieve this. For example, in the future, the Port of Rotterdam could become a hydrogen trade hub (IRENA, 2022) and potentially support energy demand at Schiphol airport.

Local supply of hydrogen at larger airports can also be realized in areas where solar energy can be effectively utilized. However, these large airports are more likely to have restrictions on land availability. Depending on the location, installing a solar park may not be feasible from a spatial and technical perspective. Connections to wind parks may also be considered as an alternative solution (IRENA, 2022).

Hydrogen is a highly flammable gas, and therefore, safety is a critical concern when using it in airports. It's crucial to have robust safety protocols and procedures in place to mitigate the risks associated with hydrogen fuel. These protocols should cover everything from fuel storage and handling to maintenance and operations. Regulations and standards for the use of hydrogen in airports are still evolving. To achieve scalability, it is crucial to work closely with regulatory bodies to ensure compliance with all relevant regulations and standards.

The LCA results indicate that the highest GWP among all hydrogen supply chain components is due to the solar park. Advancements in the solar technologies to reduce the emissions is therefore crucial especially when considering the emissions within the boundaries of the airport when local production is followed. If the hydrogen is supplied externally, then the supply chain must be robust enough to support scalability. This includes everything from sourcing the raw materials needed to produce hydrogen to the delivery of hydrogen fuel to the airport. It is then important to consider the potential bottlenecks in the supply chain and develop strategies to overcome them. It is worth noting that the supply chain and the cost of diesel, electricity, and hydrogen can vary significantly across nations due to different policies and regulations, which could impact the cost analysis for airports and yield results that differ from those presented in this study. Likewise, public perception of hydrogen as a fuel source is critical for scalability and this can again have different influence among different regions. It is essential to communicate the facts related to hydrogen clearly, including its environmental benefits and economic figures.Addressing any concerns the public may have about the safety of hydrogen fuel is important for achieving scalability. The detailed learning points of hydrogen transition in GPUs are further discussed in the Appendices A, B, and C.

5. Implications

The Paris Agreement targets a significant reduction of carbon emissions by 2030, which entails that airports should divert to sustainable settings such as by using hydrogen-based groud service equipment. To realize this transition, the airport needs a feasible business model supported by subsidies, and regulations. This research highlights various practical implications for decision-makers, managers, local and global authorities to facilitate this.

From the local and global authorities' perspective, governments need to establish clear policies and regulations that facilitate a practical business model in order to promote a successful transition to hydrogen. They should provide the necessary support to municipalities that require additional information and better frameworks to assess safety-related permits, thereby increasing accessibility to hydrogen for smaller businesses. In addition, governments should subsidize and encourage hydrogen deployment through tax incentives, subsidies, loans, and grant programs to balance the high investment costs associated with the new technology. These initiatives will not only foster renewable energy sources investments but also support the achievement of decarbonization targets.

Currently, hydrogen technology is not mature enough to compete economically with fossil fuels. Considering the early stages of the hydrogen economy, a probable setting to overcome infrastructural challenges and the economic struggles is to produce hydrogen at or near the airports. Demand from an airport should then be high enough to enable economic viability. Thus, it is essential to generate demand from nearby industries to strengthen this positioning. It is imperative for the stakeholders and the governance to provide supportive policies to facilate the formation of hydrogen hubs within the airport regions. This entails the involvement and the co-working of different stakeholders. This cooperation includes businesses, governing agencies and the society. In that respect, in order to ensure social acceptance, airports can implement practices that promote technology openness, information transparency, and citizen participation. Civil society and critics should be involved in the decision-making processes, and applications that would enhance social acceptance should be implemented.

Laws and regulations will dictate how we attain the net-zero emissions targets. Some policies may need to be redesigned and discussed. For example, currently, it is not possible to create an autonomous grid in the Netherlands due to the laws and regulations. Therefore, instead of direct connections, solar parks and electrolysers are first connected to the grid, which leads to considerable losses. Creating an autonomous grid reduces the needed number of solar panels, thereby lowering the GWP of the hydrogen supply chain.

Technological innovations in the hydrogen infrastructure is one other key point affecting the roadmap towards low-carbon emissions. Innovation in electrolyser technologies is critical to ensure that this technology plays its role in the transition to a net zero energy system. Investment in new technologies that will increase electrolyzer efficiency can result in more hydrogen production with the same amount of renewable electricity. Focusing on material selection and the number of materials used during production makes a significant difference in the amount of carbon emissions. For example, if the multi-connected silicon panels used in PV panels is replaced with organic PV panels reduction in emission counts can be attained since solar parks constitute the largest share of the total GWP of the hydrogen supply chain. Recycling and reuse of materials in the supply chain components should be also be considered for lowering the overall emissions. Rather than being discarded at the end of their lifetimes, PV panels, electrolyzers, and fuel cells should be designed to allow for the majority of their metals to be recyclable.

There is a crucial need for skilled and certified personnel in the hydrogen sector. This is due to the limited pool of qualified professionals and the relatively new and evolving nature of this sector. Airport managers may play an important role here by providing training programs that help employees gain essential skills and knowledge. To address this challenge that impacts various sectors, it is vital to form alliances among various fields and academic institutions.

As a conlusion, the main emphasis of transition to hydrogen is positioned on addressing legislations, ensuring sufficient markets, preparing the industry for the advancement of hydrogen-powered technologies, and encouraging collaboration among different stakeholders. Investing in trainings, education, research and innovation is becoming increasingly important for countries striving to stay ahead of the developments and be a front runner, The transition to a low-carbon society, requires the development and implementation of effective regional and national strategies.

References

1. ACI, S. (2019). What is net zero? Airports Council International Europe. Accessed by August 25, 2022, retrieved from https://www.aci-europe.org/netzero.
2. Balli, O., & Caliskan, H. (2022). Environmental impact assessments of different auxiliary power units used for commercial aircraft by using global warming potential approach. *Environmental Science and Pollution Research*, 29(58), 87334-87346.

3. Barke, A., Thies, C., Melo, S. P., Cerdas, F., Herrmann, C., & Spengler, T. S. (2020). Socio-economic life cycle assessment of future aircraft systems. *Procedia CIRP*, 90, 262-267.
4. Baroutaji, A., Wilberforce, T., Ramadan, M., & Olabi, A. G. (2019). Comprehensive investigation of hydrogen and fuel cell technology in the aviation and aerospace sectors. *Renewable and sustainable energy reviews*, 106, 31-40.
5. Cetinkaya, E., Dincer, I., & Naterer, G. F. (2012). Life cycle assessment of various hydrogen production methods. *International journal of hydrogen energy*, *37*(3), 2071-2080.
6. Curran, M., 2015. Life Cycle Assessment Student Handbook. United Stated of America: Scrievener Publishing LCC.
7. Dube, K., & Nhamo, G. (2019). Climate change and the aviation sector: A focus on the Victoria Falls tourism route. *Environmental Development*, 29, 5-15.
8. Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and sustainable energy reviews*, 39, 748-764.
9. GAE (2022) Development of hydrogen Ground Power Unit at Groningen Airport Eelde. Available at: https://www.groningenairport.nl/en/news/development-of-hydrogen-ground-power-unit-at-groningen-airport-eelde (Accessed: 5 February 2023).
10. Glanz, S., & Schönauer, A. L. (2021). Towards a low-carbon society via hydrogen and carbon capture and storage: Social acceptance from a stakeholder perspective. Journal of *Sustainable Development of Energy, Water and Environment Systems*, 9(1), 1–18.
11. Goedkoop, M., Oele, M., de Schryver, A., Vieira, M., & Hegger, S. (2008). SimaPro database manual methods library. *PRé Consultants, The Netherlands*, 22-25.
12. Helmers, E., Leitão, J., Tietge, U., & Butler, T. (2019). CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: Assessing the climate benefit of the European "diesel boom". *Atmospheric Environment*, 198, 122-132.
13. IRENA (2022) Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward. Abu Dhabi: International Renewable Energy Agency. Available at: www.irena.org/publications.
14. Nielsen, E. (2020). In house production drastically reduces CO2 emissions. Retrieved from: https://blog.alpla.com/en/blog/company-economy/house-production-drastically-reduces-co2-emissions/10-20 Accessed on: 19th of January 2023.

15. Papadis, E., & Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector. *Energy*, 205, 118025.
16. Qyyum, M. A., Dickson, R., Shah, S. F. A., Niaz, H., Khan, A., Liu, J. J., & Lee, M. (2021). Availability, versatility, and viability of feedstocks for hydrogen production: Product space perspective. *Renewable and Sustainable Energy Reviews*, 145, 110843.
17. Statista. (2022). Hours of sunshine in the Netherlands 1990-2021. https://www.statista.com/statistics/1012949/hours-of-sunshine-in-the-netherlands/ Accessed on 10-11-2022 https://www.statista.com/statistics/276629/global-co2-emissions/ Accessed on 1st of January 2022.
18. Testa, E., Giammusso, C., Bruno, M., & Maggiore, P. (2014). Analysis of environmental benefits resulting from use of hydrogen technology in handling operations at airports. *Clean Technologies and Environmental Policy*, 16(5), 875-890.
19. Wu, M., Wu, Y., He, J., Xu, M., & Zhang, T. (2022). ScienceDirect Barrier identification , analysis and solutions of hydrogen energy storage application in multiple power scenarios based on improved DEMATAL- ISM approach. *International Journal of Hydrogen Energy*, 47(71), 30329–30346.
20. Wulf, C., & Kaltschmitt, M. (2018). Hydrogen supply chains for mobility—environmental and economic assessment. *Sustainability*, 10(6), 1699.
21. Wulf, C., Reuß, M., Grube, T., Zapp, P., Robinius, M., Hake, J. F., & Stolten, D. (2018). Life Cycle Assessment of hydrogen transport and distribution options. *Journal of cleaner production*, 199, 431-443.
22. Xiang, Y., Cai, H., Liu, J., & Zhang, X. (2021). Techno-economic design of energy systems for airport electrification: A hydrogen-solar-storage integrated microgrid solution. *Applied energy*, 283, 116374.

Appendix A. Replacing diesel-powered GPUs with hydrogen-powered GPUs - A study investigating the environmental impact of those GPUs and their supply chains

Abstract

This research aims to study the environmental impact of a hydrogen Ground Power Unit (GPU) powered by an on-site solar power plant. The reason for studying this is that the emissions within the aviation industry have to decrease. GPUs are responsible for 10% of the total emissions in the aviation industry. Therefore, improving GPUs, such that the emissions will be reduced, will be a positive development for this industry. Life cycle assessment (LCA) analysis is used to get an insight into the Global Warming Potential (GWP) of the hydrogen GPU supply chain compared to the d-GPU supply chain. Groningen Airport Eelde is used as a case, and using scenario development, multiple supply chain sizes are studied. Other impact categories, such as human health and resource scarcity, are also considered. The LCA consists of the whole supply chain from production using photovoltaic (PV) panels, electrolysis, storage, and, eventually, the GPU. The GWP of the hydrogen GPU is lower than the GWP of the d-GPU. Additionally, the GWP of the hydrogen supply chain is also lower than the GWP of the diesel supply chain. However, the solar park and hydrogen storage are points of improvement for the hydrogen supply chain. To conclude, replacing d-GPUs with hydrogen GPUs helps reduce CO_2 emissions. However, further research into hydrogen storage and PV panels can help further reduce those emissions. Due to the scenario developments, this research is useful for small-scale and large-scale airports considering using a hydrogen GPU. Additionally, parts of this research can be helpful for other industries using hydrogen, such as the automotive industry, in producing and installing infrastrure for hydrogen vehicle.

1. Introduction

Ground power units (GPUs) are a significant source of carbon emissions in the airport sector (Testa et al., 2014). The application of the GPUs is to supply energy to aeroplanes while they are on the ground (Baxter et al., 2018). Mobile GPUs usually have a diesel engine-powered generator (Selema et al., 2019). However, environmental sustainability increases the need for emission-free solutions in every sector, including the aviation industry (Ellaban et al., 2014). Furthermore, the expectation is that transportation through the air will increase in the coming years, which enlarges the need for equipment with low environmental impact (Testa et al., 2014). Accordingly, substituting d-GPUs with renewable sources can reduce greenhouse gas emissions (Testa et al., 2014).

Two options are considered to replace the d-GPU, a battery GPU and a hydrogen GPU (Hoelzen et al., 2022). However, the battery GPU is out of the research scope because the capacity of a battery GPU is insufficient for large aeroplanes and aeroplanes connected to a GPU for a couple of hours (Eisenhut et al., 2021). In Contrast, hydrogen GPUs can be a solution for the aviation industry. Hydrogen is an energy carrier and can be generated in different ways (Qyyum et al., 2021). To use hydrogen in the aviation industry, infrastructure for transportation or a local production facility is needed to power an airport with hydrogen (Barke et al., 2020). Importantly, building this infrastructure and transporting the hydrogen also contributes to emissions within this sector (Wulf et al., 2018). Therefore, to map the environmental impact of a GPU, it is essential to not only focus on the usage phase of the unit. The whole life cycle from production to disposal has to be considered, as all the side activities (Ceinkaya et al., 2012). The production facilities and the needed infrastructure are all part of the impact of a hydrogen GPU (Góralczyk, 2003). Life cycle assessment (LCA) analysis is a method that tries to map the environmental impact of a system in multiple stages. Those general LCA stages are raw material extraction, production, usage, and disposal (Wulf & Kaltschmitt, 2018).

The LCA of the hydrogen GPU compared to the LCA of the d-GPU gave an overview of the difference in environmental impact between them. Apart from reducing emissions in the usage stage, the emissions during transportation, manufacturing, and eventually disposal must be reduced (Ceinkaya et al., 2012). In literature, multiple LCA analyses related to hydrogen and renewable energy sources are performed. For example, Wulf & Kaltschmitt (2018) did an LCA of hydrogen used in electric vehicles. Barke et al. (2020) conducted an LCA in the aviation industry, focusing on aircraft. Another LCA was performed for the aviation sector by Siddiquin & Dincer (2021), who conducted an LCA of different fuels for the aviation sector. At last, a comparative LCA performed by Kawamoto et al. (2019) compared an electrical motor with a diesel motor. However, an LCA of a hydrogen GPU still needs to be performed.

In this research, the focus lies on the hydrogen GPUs and the supply chain needed to power them. In addition, the LCA will help to better understand how much CO_2 emission will be reduced if a hydrogen GPU is used instead of a d-GPU. The research question, therefore, is:

Using LCA, what is the environmental impact of a hydrogen GPU and its supply chain? How significant are the emissions compared to a d-GPU?

For this research, the scale of the airport and, thereby, the number of PV panels, the capacity of the electrolyser and storage were required, as well as the materials and processes needed to produce those components. The LCA performed in this research indicates the size of the reduction of the global warming potential (GWP) if hydrogen GPUs are used instead of d-GPUs. In particular, this research is helpful for airports willing to change to hydrogen GPUs. In addition, the results of the LCA will help in identifying potential research areas for improving the GWP of the hydrogen supply chain.

The next section of this research focusses on a literature review in the aviation industry regarding LCA, renewable energy sources, hydrogen production, and GPUs. Furthermore, in the methodology section, the LCA will be elaborated on in more detail as the data collection methods used. Additionally, the GWP of the diesel and hydrogen supply chains and individual components of those supply chains will be presented. Lastly, recommendations for decreasing the environmental impact of the hydrogen supply chain will be given.

2. Literature overview

The transportation sector is currently dominated by fossil fuels (Siddiqui & Dincer, 2021). In particular, the aviation sector produces 2-3 % of worldwide carbon emissions (Hoelzen et al., 2021; Papadis & Tsatsaronis, 2022). Solutions for reducing CO_2 emissions in the aviation industry include efficiency improvements, operation improvements, switching to green fuels, and regulatory measures (Papadis & Tsatsaronis, 2020). The aviation sector grew in the last decade by almost 5% per year, making CO_2 reduction increasingly critical (Lai et al., 2022). Increasing fuel efficiency and reducing the number of flights are two factors via which the most significant decreases in the short term in emissions can be reached (Yu et al., 2022). However, most people are still eager to travel by plane and unwilling to sacrifice this for the environment (Dube & Nhamo, 2019). This unwillingness makes it unlikely that flight movements will decrease in the coming years (Dube & Nhamo, 2019). Replacing conventional fuels with more sustainable fuels will reduce emissions (Yu et al., 2022). Sustainable aviation fuel is already generated and used in the airport sector (Dube & Nhamo, 2019). However, only enough sustainable aviation fuel is available to power 2% of the aviation industry (Dube & Nhamo, 2019). The prospect is that this amount will not increase significantly in the short term. Therefore, the focus on emission reduction in the aviation industry has to shift to other factors (Yu et al., 2022). The GPUs are responsible for 10% of the total aviation emissions and produce similar emissions as the aeroplanes (Dube & Nhamo, 2019; Balli & Calliskan, 2022). Therefore, focusing on reducing GPU emissions could be a way to reduce the emissions in the aviation industry in the short term (Balli & Calliskan, 2022). Currently, if mobile GPUs are used, they run on diesel and are used to power aeroplanes while they are on the ground (Rivera et al., 2022; Yusuf et al., 2022). This section will discuss the characteristic of the hydrogen GPU and the d-GPU. Subsequently, the supply chain components needed to power these GPUs are addressed.

2.1 Ground Power Units

A GPU unit supplies external electric power to the aeroplane. When a plane arrives at an airport, those units are transported and connected to the aircraft (Rivera et al., 2022). Figure 2.1 shows a drawing of a GPU. The unit size is approximately 2.5 meters by 1.4 meters by 1.3 meters (Mobile Ground Power Units, 2022). An advantage of a GPU unit is that the aeroplane's motor can be turned off, reducing the noise produced by the engine (Jensen et al., 1998). Another advantage of the GPU is related to costs; using a GPU, energy can be converted more efficiently than burning fuel in a jet (Rivera et al., 2022). Additionally, this leads to less air contamination (Rivera et al., 2022). The power of a GPU can be generated via an internal combustion engine or through electrical frequency converters (Rivera et al., 2022).

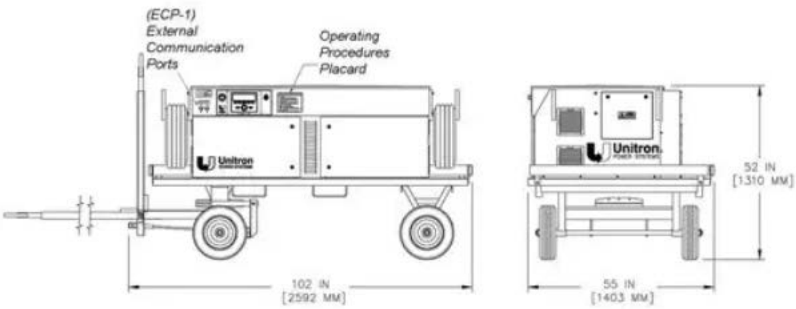

Figure 2.1 A schematic representation of a mobile GPU and its corresponding size (Mobile Ground Power Unit, 2022).

2.1.1 Diesel Ground Power Unit

A GPU consists of a power converter, which is a generating set for a d-GPU. (Borup et al., 2004). A generating set consists of a generator together with a diesel engine (Borup et al., 2004). The combustion of diesel fuel leads to the generation of electrical power (Padhara, 2018). **Figure 2.2** overviews the d-GPU's three major components and input and output. The GPU consists of a diesel engine, a diesel storage tank and a DC/AC converter (Borup et al., 2004). The volumetric density of diesel is high, resulting in relatively small GPUs. Therefore, those can be placed close to the aeroplane (Selema et al., 2019). Another advantage of the d-GPU is its long lifetime and high reliability (Selema et al., 2019). However, the emissions from those diesel engines are high (Ihara & Tanaka, 2016). Diesel engines mainly produce CO_x and NO_x emissions (Padhra, 2018).

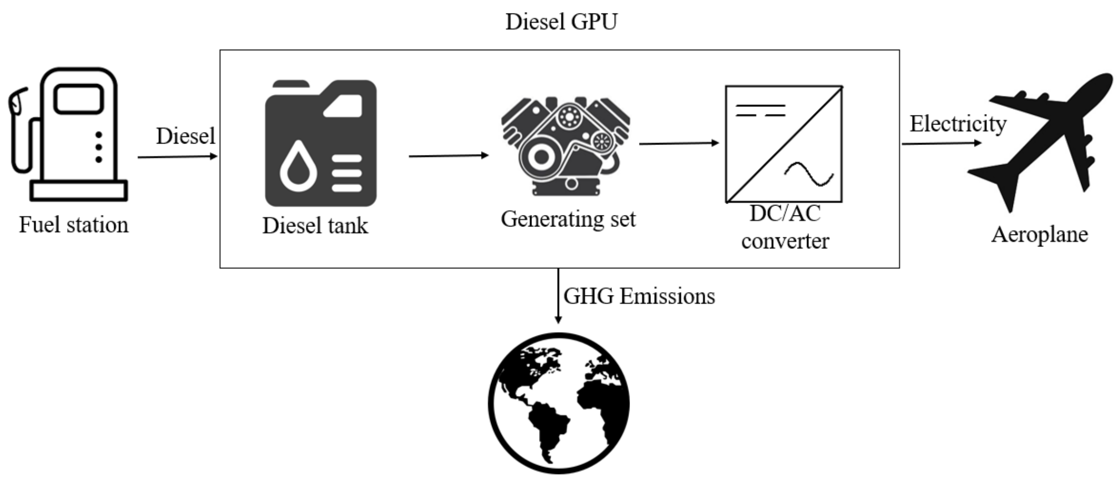

Figure 2.2 A schematic overview of the d-GPU

The supply chain of a d-GPU starts with the oil winning. From there, transportation trucks transport the diesel towards the fuel station at the airport. The d-GPUs will be fueled from this fuel station and can be used to power aeroplanes. An overview of the supply chain is given in Figure 2.3.

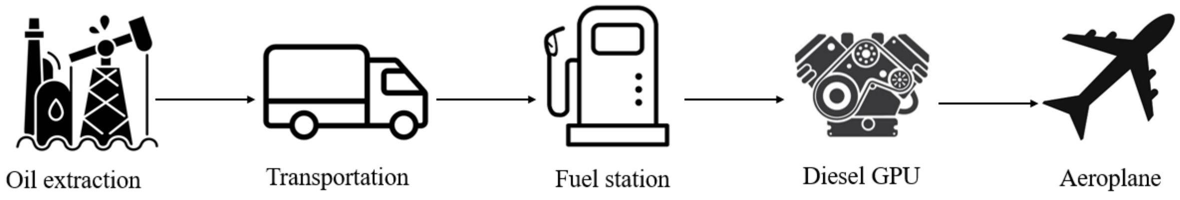

Figure 2.3 The supply chain of the d- GPU

2.1.2 Hydrogen Ground Power Unit

In a hydrogen GPU, the diesel unit is replaced by a power unit, which is a fuel cell driven by hydrogen. The fuel cell inside the GPU generates electricity from hydrogen and oxygen, with water as a reaction product (Stern, 2018). Therefore, fuel cells are pollution-free and can be used for large-scale applications (Ellitzur et al., 2017; Stern, 2018). However, due to the low volumetric density of hydrogen, large or multiple hydrogen tanks are required to deliver sufficient energy (Ellitzur et al., 2017). Figure 2.4 depicts an overview of the main components of the hydrogen GPU and its input and output. The GPU consists of a hydrogen tank that supplies hydrogen to the fuel cell. The electricity generated within the fuel cell will be converted from direct current (DC) to alternating current (AC) and provided to the aeroplane (Company A, 2022a; Borup et al., 2021). A battery connected to the fuel cell keeps it running, like a car battery in a hydrogen car. The fuel cell will refill the battery (Company A, 2022a). A cooling system ensures that the fuel cell is not overheated (Company A, 2022a). A hydrogen supply chain must be installed to have sufficient hydrogen at the airport for powering the GPUs (Hoelzen et al., 2022). This supply chain can be installed at the airport for on-site production, or hydrogen can be produced off-site and transported to the airport (Yang & Ogden, 2007). The coming section will discuss different aspects of the hydrogen supply chain.

2.1.2a Usage of hydrogen

The advantages of fuel cells compared to d-GPUs are the soundlessness and, more importantly, the lack of carbon emissions in their usage phase. Water and heat are the by-products of the electrical reaction in the fuel cells (Baroutaji et al., 2019). Proton exchange membrane fuel cells (PEMFCS) and solid oxide fuel cells (SOFC) are the fuel cells of interest for this research (Delpierre et al., 2021). PEMFCs produce hydrogen at low temperatures, between 60 and 120 degrees Celsius, and SOFCs produce hydrogen at high temperatures, between 550 and 950 degrees Celsius (Renouard-Vallet et al., 2010; Malik et al., 2021). The advantages of PEMFC compared to SOFC are higher efficiency, lower weight, and better suitability for small-scale applications (Malik et al., 2021). The advantage of SOFC is that it does not require an entire clean stream of water and that the power density of SOFC is better than that of PEMFC (Fernandes et al., 2018; Malik et al., 2021). Due to the higher efficiency of PEMFC, those fuel cells are considered in this research.

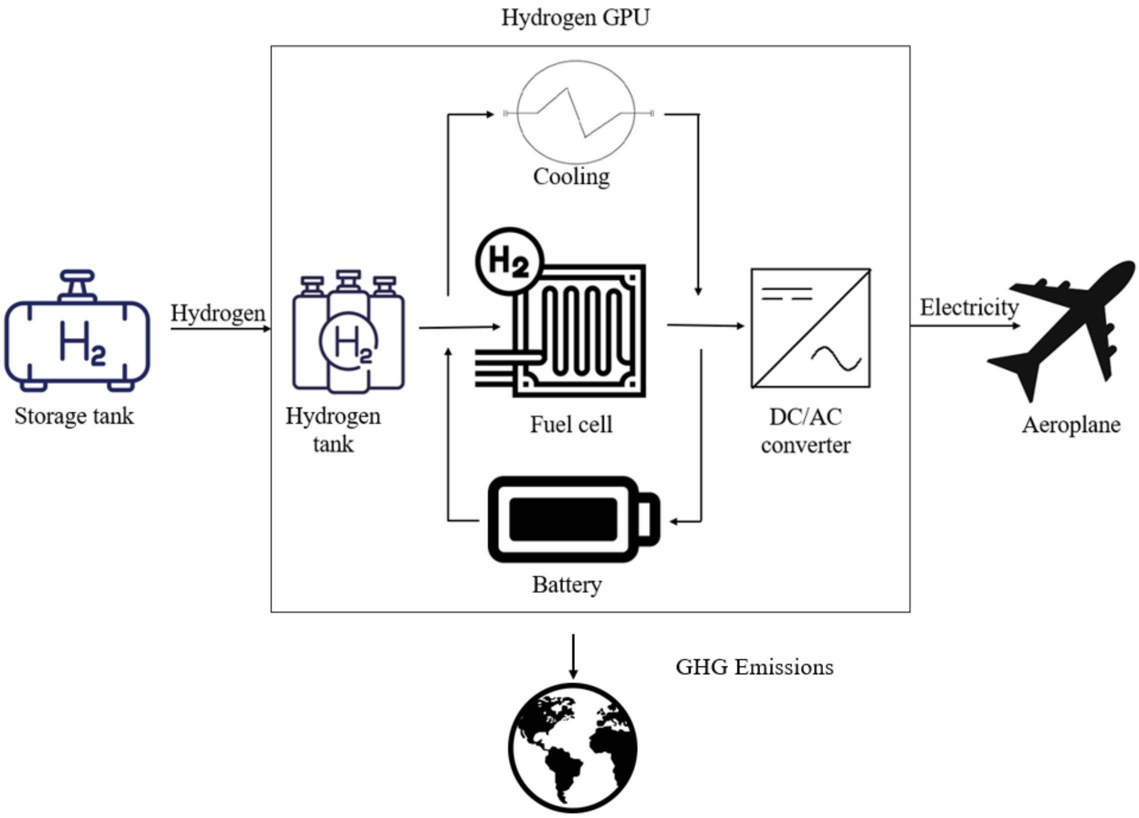

Figure 2.4 a schematic overview of a hydrogen ground power unit

2.2 The supply chain of a hydrogen GPU at an airport

Figure 2.5 depicts the supply chain of the hydrogen GPU. The hydrogen supply chain starts with generating renewable energy. Next, hydrogen is produced using an electrolyser and the generated renewable energy. This will be stored in large storage tanks, and will be connected to a fuelling station. Subsequently, the fuelling station will supply hydrogen to the GPU. Lastly, the GPU will supply the aeroplane with electricity.

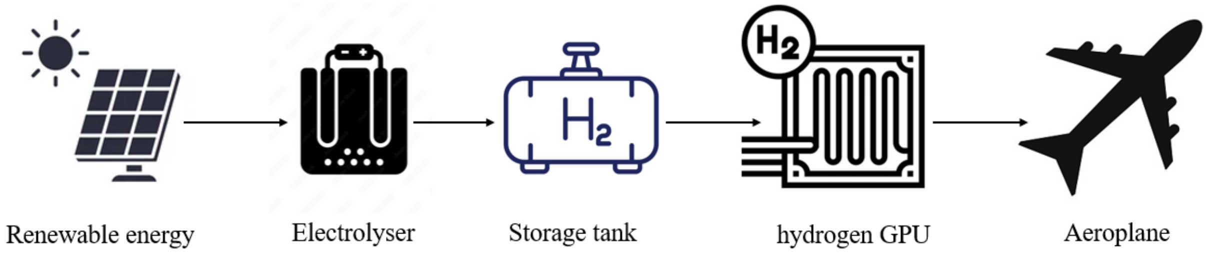

Figure 2.5 The supply chain for the hydrogen GPU

2.2.1 Hydrogen production

Multiple mechanisms exist to produce hydrogen: electrolysis, thermal splitting, and gasification (Stern, 2018). The method depends on the energy source. Therefore, only some methods are suitable for the production of green hydrogen. An overview of the different energy sources and the corresponding process for hydrogen production is given in Table 2.1 (Ellban et al., 2014; Qyyum et al., 2021). The table shows that the three main energy sources are fossil fuels, nuclear power, and renewable energy (Qazi et al., 2019). Renewable energy sources can be split into five kinds: biofuels including biomass, solar energy, wind energy, hydropower, and geothermal energy (Bhandari et al., 2014; Fontes & Feires, 2018). Hydrogen is an energy carrier often used as a storage method for electrical energy. It is, therefore, often used in combination with solar energy and wind energy, as those types of renewable energy need energy storage to manage supply and demand (Qyyum et al., 2021).

The primary process of green hydrogen production is water electrolysis with electricity generated through renewable energy sources (Hoezen et al., 2021; Bhandari et al., 2014). Production of green hydrogen is without CO_2 emission. Generating hydrogen from coal and natural gas emits carbon dioxide, nitrogen oxides, sulphate aerosols, and other particulates, which is unwanted for an emission-free airport (Papadis & Tsatsaronis, 2022; Eisenhut, 2021). Producing hydrogen from biomass also has CO_2 emissions and is not the preferred method for replacing diesel (Ortega Alba & Manana, 2016). Using nuclear energy at airports is in most countries not allowed due to potential risks (Lloyd, 2012). Considering renewable energy sources that do not emit CO_2, Solar and wind energy are the most suitable for on-site hydrogen production (Fontes & Feires, 2018). However, there are limitations on placing large obstacles on an airport; therefore, wind energy is not a widely used renewable energy option for airports (Ortega Alba & Manana, 2016). Leading to solar energy generated from PV panels being the primary production source of renewable energy for airports (Xiang et al., 2019; Fontes & Feires, 2018). Airports are an ideal location for PV panels, as they are large and shading-free (Ortega

Alba & Manana, 2016). The panels can be stored on the rooftop of the airports or in open fields near the airport (Xiang et al., 2019; Fontes & Feires et al., 2018).

PV panels can convert sunlight into DC electricity (Saravanan & Babu, 2017). This generated energy needs to be used directly, or it needs to be stored in a storage system through hydrogen generation or batteries (Venkateswari & Sreejith, 2019). A drawback of PV panels is their low efficiency and seasonal character (Venkateswari & Sreejith, 2019). The most common PV panel is crystalline silicon (Gerbinet et al., 2014; Asim et al., 2012). However, other PV panels are also available (Bagher et al., 2015). Different types of PV panels can be classified based on two criteria (Bagher et al., 2015). The first classification can be based on the number of light-absorbing material layers (Bagher et al., 2015). One layer of absorbing material is known as single-junction PV panels, and multiple layers as multi-junction PV panels (Friedman, 2010). Multi-junction PV panels have a higher efficiency than single-junction PV panels (Friedmann, 2010). However, the downside is that extra materials are used for the additional light-absorbing layers (Bagher et al., 2015). The second classification is the materials used for PV panels. The first generation of PV panels is the widely used crystalline silicon PV panel (Bagher et al., 2015). The second-generation PV panels are amorphous silicon panels. Those panels use fewer construction materials. However, the efficiency is lower than the first-generation panels (Bagher et al., 2015). The third-generation PV panels are not yet commercially available. In those panels, organic materials are used. The prospects are that those panels can be generated at a lower cost and with higher efficiency (Bagher et al., 2015). The multi-junction silicon PV panels are considered in this research, as those panels have the highest efficiency of the commercially available panels. As PV panels have to be produced, emissions and other environmental impacts during the production of those PV panels have to be considered if the supply chain of the hydrogen GPU is studied.

Table 2.1 Energy sources and hydrogen production methods.

Energy source	Renewable	Description	Hydrogen production
Natural gas	No	Natural gas originates from the Earth's surface and consists of remains of plants and animals (Hubert, 1949).	Steam reforming (Qyyum et al., 2021)
Coal	No	Coal is an organic material from thousands of years ago. Energy is generated by heating coal and steam (Hubert, 1949).	Gasification with CO_2 (Qyyum et al., 2021)
Biomass energy	Yes	Biomass is organic material from plants and trees. It can be converted into heat, electricity, and liquid fuels (Ellabban et al., 2014).	Gasification without CO_2 (Qyyum et al., 2021)
Wind energy	Yes	Wind energy is generated through windmills and wind turbines. It uses the kinetic energy of air (Ellaban et al., 2014).	Electrolysis (Qyyum et al., 2021)
Solar energy	Yes	Solar energy is energy generated by the sun. The generation can be done with PV cells or thermal systems (Ellabban et al., 2014).	Electrolysis (Qyyum et al., 2021)
Hydro power	Yes	Hydropower, in other words, water power, produces electricity by relying on lakes and rivers' potential and kinetic energy (Li et al. 2018).	Electrolysis (Tarnay, 1985)
Geo-thermal Energy	Yes	Geothermal Energy relies on the extraction of heat from the interior of the Earth. Hot fluids from the interior are subtracted at the surface and used to generate electricity (Barbier, 2002).	Electrolysis (Ghazvini et al., 2019)
Nuclea	No	Nuclear energy can be generated by splitting the	Thermal splitting (Qyyum

r sources		Uranium atom (Yildiz & Kazimi, 2005).	et al., 2021)

2.2.2 Storage of hydrogen

Hydrogen in gas form has a low mass density, 0.089 kg/m3 (Ellitzur et al., 2017). Therefore, storing hydrogen on a large scale is complicated as it requires large amounts of space (Yusuf et al., 2022; Yanxing et al., 2019). Storage of hydrogen is possible in multiple phases: as gas, as pure liquid, as liquid organic hydrogen carriers, and in its solid state (Yanxing et al., 2019). An example of a liquid organic hydrogen carrier is ammonia, and a solid state is metal hydrides (Hoezen et al., 2021; Qyyum et al., 2021). There are three techniques for storing hydrogen; see Table 2.2. Firstly, hydrogen liquefication can be done by cooling the hydrogen to a temperature of 20 K or equivalently -253,15 ◦C (Hoezen et al., 2021; Barthelemy et al., 2016). Liquefication will increase the density of hydrogen to 71 kg/m3 (Ellitzur, 2017). However, the liquefaction process is highly energy-intensive and costly (Papadis & Tsatsaronis, 2022; Hoelzen et al., 2022). According to Hoelzen et al. (2022), 31% of the total costs from the hydrogen supply chain are caused by the liquefaction of the hydrogen. Secondly, hydrogen can also be stored in hydrides. The material used for hydride storage is highly relevant, as hydrogen has to enter the material and form hydrides. Temperature regulation within the storing process is essential. The temperature has to switch between favourable for absorption and desorption (Barthelemy et al., 2016). Thirdly, the least expensive and most mature option is compressed hydrogen storage (Staffel et al., 2018; Ellitzur et al., 2017; Barthelelmey et al., 2016). However, a significant downside is that hydrogen is stored under high pressure and requires large storage capacities (Ellitzur et al., 2017).

There are multiple storage methods for compressed hydrogen. Hydrogen is stored in salt caverns, large-scale storage tanks, and small-scale storage bottles (Wulf et al., 2018; Elburry et al., 2021). Salt cavern storage is used for large-scale centralised storage (Wulf et al., 2018). Storage tanks and bottles are used for decentralised storage (Elburry et al., 2021). Storage bottles are more suitable for storage inside applications, and storage tanks are used for storage facilities (Staffel et al., 2018). Therefore, the storage method considered in this research will be hydrogen storage in tanks. Metals used for storage are stainless steel, aluminium, and copper alloys. The materials should be carefully selected to prevent leakage (Elburry et al., 2021). Additionally, hydrogen can permeate some materials and decrease their strength, eventually leading to failure (Elburry et al., 2021).

2.2.2a Fuelling station

To fill the GPU, the hydrogen storage facility has to be connected to a hydrogen fuelling station (Wulf & Kaltschmitt, 2012). The main components of a hydrogen fuelling station are a gas compressor, a dispenser, and a hydrogen storage tank (Haskel, n.d.). Hydrogen is often stored at pressures of 350 bar or 700 bar (Wulf & Kaltschmitt, 2012). Wulf and Kaltschmitt (2012) discuss a fuelling station that is in operation in Hamburg. This station consists of three storage tanks, a storage tank with low pressure, a storage tank with medium pressure and a storage tank with high pressure (Wulf & Kaltschmitt, 2012). The medium-pressure storage tank is used for excess hydrogen, such that this hydrogen can be sold or used later (Wulf & Kaltschmitt, 2012). However, most hydrogen fuelling stations store all hydrogen under the same pressure (Apostolou & Xydis, 2019).

Table 2.2 An overview of the hydrogen storage methods.

	Compressed hydrogen (Barthelemey et al., 2016)	**Liquid hydrogen** (Barthelemey et al., 2016)	**Hydride storage** (Barthelemey et al., 2016)
Mechanisms	Hydrogen is stored under high pressure; by compressing the hydrogen, the density of hydrogen increases. Energy is needed for the compression.	Hydrogen is cooled to a temperature of 20K. Hydrogen becomes liquid and has a higher density than gaseous hydrogen. The cooling of hydrogen requires energy.	Hydrogen molecules dissociate first and then are absorbed in the material, and hydrogen forms hydrides with the material.
Volumetric density	Medium	High	High
Temperature	Filling: 338 - 358 K Emptying: 233 - 213 K	20 K	Heat management for desorption and adsorption reactions important

2.2.3 Transportation

Production on-site or off-site is an essential characteristic of transportation because on-site production asks for the transportation of hydrogen from storage to the application, and those distances are small (Yang & Ogden, 2007). For off-site production, possible modes of transportation are trucks, ships, trains, or pipelines (Hoezen et al., 2021). Pipeline transportation is the preferred transportation option for large-scale hydrogen transportation (Staffel et al., 2018). However, the investment costs are high. Therefore, on a smaller scale, compressed hydrogen gas and liquified hydrogen are preferred (Qyyum et al.,2021; Staffel et al., 2018). In particular, compressed hydrogen tube trailers can be used (Staffel et al., 2018).

2.3 Contribution

This research contributes because it is the first to perform an LCA of the entire supply chain for an on-site production facility. Appendix 1 shows an overview of LCAs done in comparable research directions. LCAs of electrolysers, storage tanks, and fuel cells are performed (Agostini et al., 2018; Benitez et al., 2018; Evangelisti et al., 2017; Koj et al., 2017; Kawamoto et al., 2019). Those research can be used as input for performing the LCA of the entire fuel cell. Another gap in literature that this research addresses is that an LCA of a hydrogen GPU still needs to be done.

3. Methodology

3.1 Research design

A hydrogen GPU's supply chain was compared to a d-GPU's supply chain. The environmental impacts of all components within those supply chains were considered to evaluate those supply chains. On those analyses, recommendations and improvements for further research were given. The LCA was performed according to ISO14040 and ISO14044 (ISO 14040, 2006; ISO14044, 2018). SimaPro 9.4 was used as software, in which the Ecoinvent 3 database was used for the LCA models (Hjellvik, 2021). The materials needed for the LCA were collected via literature research consisting of articles that performed similar LCAs of one of the supply chain components. In addition, interviews with company representatives were conducted for data collection. In Appendix 2, an overview of the interviewed companies is given.

3.2 Life cycle assessment

In LCA, the impact of systems and products is analysed from the production stage towards the disposal stage (ISO 14040, 2006). A life cycle model should include every phase of the life cycle; this consists of the raw material extraction, transport, production phase, usage phase, and disposal stage (Masoni et al., 2011). An LCA indicates the impact on natural resources and the number of polluting emissions (Masoni et al., 2011). The primary purpose of the LCA performed in this research is decision making, whether a hydrogen supply chain is better than a diesel supply chain in terms of environmental impact. An LCA is an appropriate method to answer the research question, as the environmental impact is the result of the analysis. Via this method, multiple products or supply chains can be compared with each other (Thies et al., 2019). This study also considered the environmental impact if the number of aeroplanes leaving airport Eelde increases (Camilles et al., 2013). Therefore, this research used a consequential LCA to answer the research question.

3.2.1 Goal and scope definition

This research focused on the supply chain of a d-GPU and a hydrogen GPU. So the two systems studied have a function to supply energy for the GPUs used at airports. The functional unit was the supply chain needed to power a ground power unit for one year. The components within the supply chain have different lifetimes. Therefore, the environmental impact throughout the whole lifetime of the element was divided by the element's lifetime which gave the environmental impact for one year. Appendix 3 provides an overview of the components and their corresponding lifetime. For example, a solar park has a lifetime of 30 years, so the environmental impact of the solar park was divided by

30 to get the environmental impact in one year. A critical part of the life cycle was the disposal phase. The studied GPU is new, and little is known about its recycling, recovery and disposal. In SimaPro, a general waste and recovery scenario can be selected. Due to the unknown disposal phase, this general waste scenario was chosen for the supply chain.

With the LCA results, the d-GPU's environmental impact was compared with the environmental effects of the hydrogen GPU. Next, the diesel and hydrogen supply chain LCAs were compared. Lastly, the individual parts of the hydrogen supply chain were studied to better understand the environmental impact of the separate components. The LCA model of the hydrogen and d-GPUs and their supply chain are presented in Figure 3.1 and Figure 3.2, respectively.

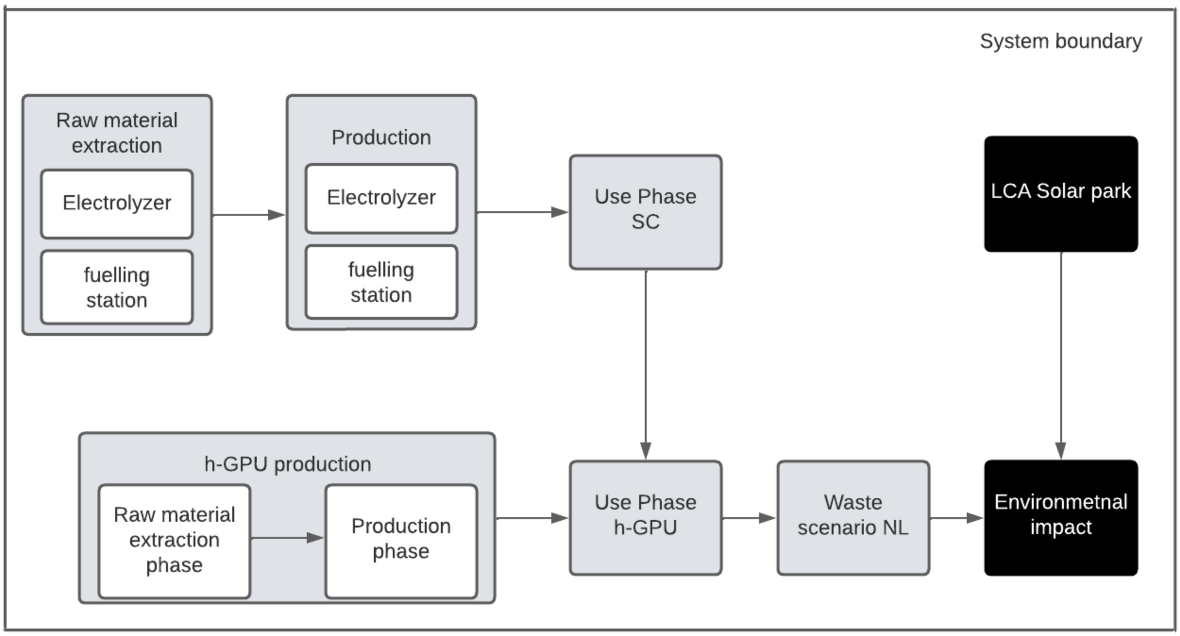

Figure 3.1 The LCA model for the hydrogen GPU.’

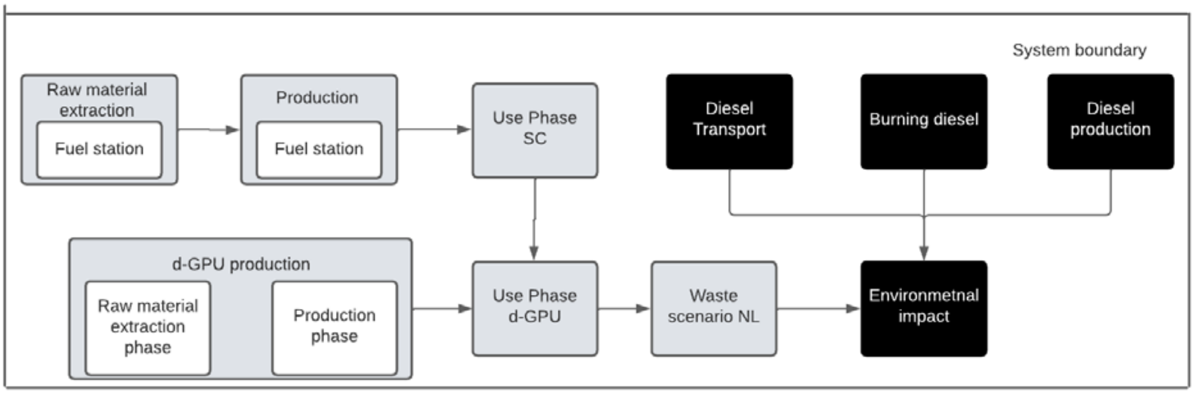

Figure 3.2 The LCA model for the d-GPU.

3.2.2 Inventory analysis

A list of all materials was needed for every component of the supply chains. This data was collected using a literature study of previously performed LCAs, interviews with experts and producers, and data provided by them. Unstructured interviews were conducted, as the main reason for interviewing was to collect data about the materials, the production process, and the usage phase. Additional information was provided by the Ecoinvent database included in SimaPro 9.4. LCAs of some components were already present in this database and could be used for this research. Appendix 4 presents an overview of all materials, processes and products put into SimaPro 9.4.

3.2.3 Impact assessment and interpretation

An LCA focuses on environmental impact, which can be grouped into impact categories (Curran, 2015). Emissions within those categories could be studied separately (Goedkoop, 2008). This study determined the studied impact categories according to what is mainly used in related articles. Appendix 5 gives an overview of the impact categories in related LCA studies. Based on Appendix 5, this research focused primarily on the global warming potential (GWP). Additionally, the ReCiPe method was used to indicate the emissions in other impact categories.

The final stage of the study was the interpretation of the results. The results of the LCA had to align with the defined goal and scope of the LCA. Based on those results, recommendations were made to reduce the environmental impact of the hydrogen supply chain.

3.3 Scenario analysis

In this study, five scenarios were developed. Those scenarios were generated based on the number of flights leaving per day. The amount of hydrogen and the corresponding infrastructure needed based on this number. The scenarios are one flight, three flights, five flights, ten flights, and fifteen flights leaving per day. The energy is produced with a solar park, an electrolyser is responsible for the hydrogen production, and the hydrogen is stored at a fuelling station. The base scenarios are developed based on information provided by Groningen Airport Eelde (GAE). More flights leaving GAE impacts the entire supply chain as more flights lead to more hydrogen, more storage capacity, a larger electrolyser capacity, and a more extensive solar park. For the diesel supply chain, comparable scenarios were developed. The diesel supply chain consists of diesel production, transport, diesel storage, the diesel GPU, and the burning of diesel.

3.4 Validation and transparency

The output of the LCA will be validated by recontacting interviewees and reviewing other comparable LCAs to see if the output matches. In addition, a list of all the materials and processes specified in SimaPro will be provided to ensure transparency.

3.5 Case description

This study used GAE for a case study. GAE is a small-scale airport with, on average, two commercial aeroplanes leaving per day in the summer (Company E, 2022). However, in winter, this number decreased towards, on average, four flights a week (Company E, 2022). GAE aims to increase the number of flights (Company E, 2022). Another aim of GAE is to have emission-free ground power equipment by 2030 (Wal, 2030). A hydrogen supply chain will be installed to achieve this zero-emission goal. GAE wants to produce onsite hydrogen through PV panels and an electrolyser (Company E, 2022). A fuelling station will be built to store and supply the hydrogen to the GPUs (Company E, 2022).

At GAE, Company C installed a solar park. This solar park generates renewable energy for hydrogen production. The solar park has a capacity of 21.9 MW and consists of 63,196 PV panels (Company C, 2022). The solar park will also be used for applications other than GPUs (Company E, 2022). Therefore, only some of the solar park will be used as input for the LCA of the hydrogen GPU supply chain. The same holds for the electrolyser; the capacity of the electrolyser installed at GAE will be bigger than the electrolyser needed for the ground power unit.

4. Scenario development

The following scenarios are researched:

- Scenario 1: one flight a day is connected to a GPU
- Scenario 2: three flights a day are connected to a GPU
- Scenario 3: five flights a day are connected to a GPU
- Scenario 4: ten flights a day are connected to a GPU
- Scenario 5: fifteen flights a day are connected to a GPU

4.1 Hydrogen supply chain

GAE produces renewable energy through a solar park and aims to connect this solar park to an electrolyser for hydrogen production. This hydrogen can power the ground power units through a fuelling station (Company E, 2022). Therefore, the hydrogen supply chain of GAE consists of a solar park, electrolyser, fuelling station and a GPU. However, generating an autonomous grid for an on-site supply chain is not feasible due to laws and regulations within the Netherlands (Company C, 2022). Therefore, the solar park and the electrolyser must be connected to the grid.

The following assumptions and calculations were performed to develop the hydrogen supply chain for the five scenarios. According to Company B (2022), most flights are connected to a GPU for between one and two hours. Therefore, this research assumed that an aeroplane is, on average, connected to a GPU for one and a half hours. Additionally, 10 kg of hydrogen is needed to power the GPU for one hour (Company A, 2022a). Consequently, on average, 15 kg of hydrogen is required for one aeroplane connected to a GPU. The fuel cell inside the GPU also needs oxygen; this oxygen reacts with hydrogen. Oxygen is a byproduct of electrolysis; it is assumed that the oxygen generated in the electrolyser can be used in the GPU.

Sufficient hydrogen has to be produced to power the GPUs. Therefore, the capacity of the electrolyser has to be suitable to produce this amount. According to Company D (2022), the amount of hydrogen produced is linear with the capacity of the electrolyser. For example, a 1 MW electrolyser can produce 400 kg of hydrogen daily (Company D, 2022). Within the performed LCA, it was assumed that the size of the electrolyser cell stack is related to the capacity of the electrolyser. The balance of plants (BOP), consisting of all the components that support the electrolysis, is not linearly related to the capacity of the electrolyser (Company D, 2022). In other words, the BOP are all the components that are not part of the cell stack. Assumed was that the BOP from the electrolyser has the same size in every scenario.

$$electrolyzer\ output\ per\ day\ \ \frac{1000\ kW}{400\ kg} = 2.5\frac{kW}{kg}\ per\ day$$

$$2.5\ \frac{kW}{kg}\ per\ day\ x\ 15\ kg\ H_2 = 37.5\ kW\ capacity\ electrolyzer$$

Thus, a 2.5 kW electrolyser is needed to produce 1 kg of H2 per day. Linearity was assumed; thus, a 37.5 kW electrolyser is required to make 15 kg of H2 per day. To produce 1 kg of hydrogen, an electrolyser needs 53 kW of electricity (Levene et al., 2007). Again, linearity was assumed.

$$15\ kg\ of\ H_2\ x\ 53\ kW\ electricity = 795\ kW\ of\ electricity\ needed\ per\ day$$

An electrolyser needs DC for the electrolysis (Company C, 2022). However, the electricity supplied by the grid is AC (Company C, 2022). Therefore, the electricity provided by the grid has to be converted to direct current. The energy loss for this conversion is 8% (Mikaylov et al., 2012).

$$\frac{795\ kW}{92\ \%}x\ 100\% = 864\ kW\ energy\ needed\ from\ the\ grid$$

The output of 21.9 MWp means that the entire solar park can generate 21.9 MWh during a peak. The solar park produces DC (Company C, 2022). Before the energy from the solar park can be given to the electricity grid, the solar energy has to be converted to an alternating current (Company C, 2022). This conversion again leads to an energy loss of 8% (Mikhaylov et al., 2012).

$$\frac{864\ kW}{92\ \%}\ x\ 100\% = 939\ kWh\ needed\ per\ day\ from\ the\ solar\ park$$

The total number of sun hours in the Netherlands in 2021 was 1726 (Statista, 2022). Meaning that the average sun hours per day in the Netherlands was 4.7 hours. If 939 kW of electricity is needed per day, the capacity of the solar park has to be:

$$\frac{939\ kWh}{4.7\ hours} = 200\ \ kWh\ capacity\ solar\ park$$

Due to soil on solar panels, in practice, less than the maximum peak capacity of solar parks is feasible (Company C, 2022). This leads to a reduction in efficiency of approximately 15% (Zahidee et al., 2016). Additionally, the percentages of the installed solar park at GAE that had to be used for the scenarios, were calculated based on this new capacity.

$$21900\ kWp\ x\ 0.85 = 18615\ kWh$$

$$\frac{200\ \ kWh\ supply\ chain\ GPU}{18615\ kWh\ solar\ park\ GAE} = 1.1\ \%$$

The produced hydrogen has to be stored. On days with fewer sun hours, the hydrogen from the storage will be used to power the GPU. On days with more sun hours, the hydrogen will be stored. Company C provided quarterly energy data from a solar park with a capacity of 4.5 MWp (Company C, 2022). This solar park is adjusted for sizes corresponding to the solar park of the five scenarios. Calculations regarding this solar park are attached in Appendix 6. This solar park also generates less energy than under ideal conditions due to dirt on the PV panels.

$$4500\ kW\ x\ 0.85 = 3825\ kW$$

$$\frac{200\ kW}{3825\ kW} = 5.2\ \%\ of the\ provided\ data$$

Based on this data, the amount of hydrogen generated in one day was calculated. This calculation was done by adding up all the generated electricity in one day and dividing it by 53 kW, which is the electricity needed to produce 1 kg of hydrogen. The output is the amount of hydrogen generated in kilograms per day. For Scenario 1, the maximum amount of generated hydrogen was 31 kg in one day. Every day the GPUs are used, and thus, hydrogen will be used; the generation and usage of hydrogen is a daily cycle. Therefore, the storage capacity has to be sufficient to store the maximum amount of hydrogen generated in one day. This results in a hydrogen storage capacity of 31 kg for scenario 1.

The supply chains for the scenarios considered in this research are presented in Table 4.1. For hydrogen production, 8.9 litres of water is needed (Gerloff, 2021). The functional unit of the LCA is one year. Therefore, the corresponding amount of hydrogen and water for a whole year is given in Table 4.2.

Table 4.1 Hydrogen supply chains for the five scenarios

Scenario:	H2 per day	Capacity electrolyser	Electricity needed from the grid	Capacity solar panels	Percentage of the solar farm GAE	Capacity Storage
1 flight a day	15 kg	37.5 kW	864 kW	200 kW	1.1 %	31 kg
3 flights a day	45 kg	112,5 kW	2592 kW	599 kW	3.2 %	92 kg
5 flights a day	75 kg	187,5 kW	4321 kW	999 kW	5.4 %	153 kg
10 flights a day	150 kg	375 kW	8641 kW	1998 kW	10.7 %	305 kg
15 flights a day	225 kg	562.5 kW	12962 kW	2998 kW	16.1 %	457 kg

Table 4.2 the amount of hydrogen per day and year per scenario.

Scenario:	H2 per day	H2 per year	H2O per year
1 flight a day	15 kg	5475 kg	40953 kg
3 flights a day	45 kg	16425 kg	122859 kg
5 flights a day	75 kg	27375 kg	204765 kg
10 flights a day	150 kg	54750 kg	409530 kg
15 flights a day	225 kg	82125 kg	614295 kg

4.2 Diesel supply chain

The supply chain for the d-GPU consists of diesel production and diesel storage in a fuelling station. This fuelling station will be used to power the d-GPU. It is assumed that the diesel will be transported from a central point within the Netherlands towards GAE. The transport from production towards the central point is out of the scope of this research. The amount of diesel used per year in this research compared to the yearly diesel consumption in the Netherlands is negligible, As in 2020, 12 billion litres of diesel were used in the Netherlands (CBS, 2020).

The density of hydrogen in kilograms is 2.79 times higher than the energy density of diesel (Milojević, 2016). If 15 kg of hydrogen is required per day, 42 kg of diesel is needed. One kg of diesel has an energy capacity of 42.7 MJ (World Nuclear, n.d.).

$$15\ kg\ of\ H_2\ x\ 2.79 = 42\ kg\ diesel$$

$$42\ kg\ of\ diesel\ x\ 42.7\ MJ = 1793\ MJ\ per\ day$$

$$1793\ MJ\ x\ 365\ days = 654591\ MJ\ per\ year$$

The 42 kg of diesel is calculated based on the expectation that 15 kg of hydrogen is used by a plane when connected to a hydrogen GPU (Company A, 2022a). To validate these results, diesel consumption reported for a generator set with a capacity of 105 kW were used. According to FW power (n.d.), an 80 kW diesel generator set uses 25 litres of diesel per hour, and a 120 kW diesel generator set uses 32 kW an hour. Additionally, 1 litre of diesel weighs 0.84 kilograms (Martinez, 1995). So assuming linearity between 80 and 120 kW, the diesel consumption of a 105 kW diesel generator set will be:

$$\frac{32\ l - 25\ l}{120\ kW - 80\ kW}\ x\ (105\ kW - 80\ kW) = 6\ litres$$

$$25 + 6\ litres = 31\ litres\ of\ diesel\ per\ hour$$

$$31\ x\ 1.5\ = 46.5\ litres\ of\ diesel\ per\ 1.5\ hour$$

$$46.5\ x\ 0.84 = 39\ kg\ of\ diesel$$

$$\frac{39\ kg\ of\ diesel}{2.79} = 14\ kg\ of\ hydrogen$$

This calculation shows that 39 kg of diesel is needed to power the aeroplane. In the hydrogen GPU, it was assumed that some hydrogen is used to let the system run; this was assumed for the diesel GPU as well. Therefore, this research used 42 kg of diesel instead of 39 kilograms of diesel.

The diesel used at GAE will not be produced on-site. Instead, the diesel would be supplied to the airports by truck. Assumed was that the diesel would be supplied once per week. Therefore, the storage capacity has to be sufficient to store seven days of diesel demand. The maximum amount of diesel transported via truck is 1500 litres. However, it is common to transport 1000 litres of diesel at once (ETL, n.d.). One thousand litres of diesel equals 840 kg of diesel. Assumed was that the distance driven by the truck per week was 195 km, representing the middle of the Netherlands toward GAE.

$$42\ kg\ x\ 7\ days = 294\ kg\ of\ diesel\ per\ week$$

$$0.294\ ton\ x\ 195\ km = 57.33\ tkm$$

$$57.33\ tkm\ x\ 52\ weeks = 2981.16\ tkm$$

An overview of the amount of diesel per day, year and capacity of storage is presented in Table 4.3.

Table 4.3 An overview of the five scenarios and the corresponding diesel demand, storage size, and transport kilometres.

Scenario:	Diesel per day	Diesel per year	Diesel per year (MJ)	Capacity storage	Transport per year
1 flight a day	42 kg	15330 kg	654591 MJ	294 kg	2981,16 tkm
3 flights a day	126 kg	45990 kg	1963773 MJ	882 kg	8963,76 tkm
5 flights a day	210 kg	76650 kg	3272955 MJ	1470 kg	14905,8 tkm
10 flights a day	420 kg	153300 kg	6545910 MJ	2940 kg	14905,8 tkm
15 flights a day	630 kg	229950 kg	9818865 MJ	4410 kg	44717,4 tkm

4.3 Ground Power Units

The components of a hydrogen GPU are a PEM fuel cell, a battery, a cooler and a converter (Company A, 2022b). Additionally, two hydrogen storage cylinders of each 5 kg will be connected to the h-GPU. One tank can be refuelled while the GPU is running. The hydrogen will be stored under a pressure of 350 bar (Company A, 2022a). Company A is currently developing an h-GPU for GAE with a fuel cell of 120 kW. Of this 120 kW, 105 kW of power is supplied to the aeroplane, and the remaining 15 kW is used for cooling (Company A, 2022a). This research expects that the lifetime of the h-GPU will be the same as the lifetime of the d-GPU. Therefore, the lifetime will be between 20 and 25 years (Company A, 2022a).

The d-GPU consists of a generator set and a diesel engine that supplies power to the aeroplane (Company B, 2022). The generator set is connected to a converter (Company B, 2022). Additionally, inside a d-GPU, there will be a diesel storage tank with a capacity of 290 litres (Company E, 2022).

5. Results

5.1 Diesel vs hydrogen GPU

In Figure 5.1 and Table 5.1, the GWP of the d-GPU was compared with the hydrogen GPU. Appendix 7 shows the GWP of the d-GPU and h-GPU separately. One year of using the d-GPU had a GWP of 41,170 kg CO_2-eq. Whereby the generating set contributes the most to the GWP. One year of using the hydrogen GPU had a GWP of 3,900 kg CO_2-eq. The power unit, the fuel cell, was also contributing the most to the hydrogen GPU. However, this contribution was 14 times lower than the d-GPU's power unit. The materials used for the converter and the packaging of both GPUs are the same. Therefore, the GWP of those components was the same. Another remark is that the storage tank is the only component of the hydrogen GPU with a higher GWP than the corresponding component in the d-GPU. The hydrogen GPU storage tank has a GWP of more than three times higher than the diesel storage tank.

Table 5.1 GWP of the different components of the d-GPU compared with the GWP of the components of the hydrogen GPU.

d-GPU			h-GPU		
	Unit	**GWP (x1000)**		**Unit**	**GWP (x1000)**
generating set	kg CO_2-eq	40.47	fuel cell	kg CO_2-eq	2.89
diesel storage	kg CO_2-eq	0.06	storage	kg CO_2-eq	0.19
converter	kg CO_2-eq	0.40	converter	kg CO_2-eq	0.40
packaging	kg CO_2-eq	0.20	packaging	kg CO_2-eq	0.20
waste management	kg CO_2-eq	0.04	battery	kg CO_2-eq	0.12
total	kg CO_2-eq	41,17	waste management	kg CO_2-eq	0.11
			total	kg CO_2-eq	3.90

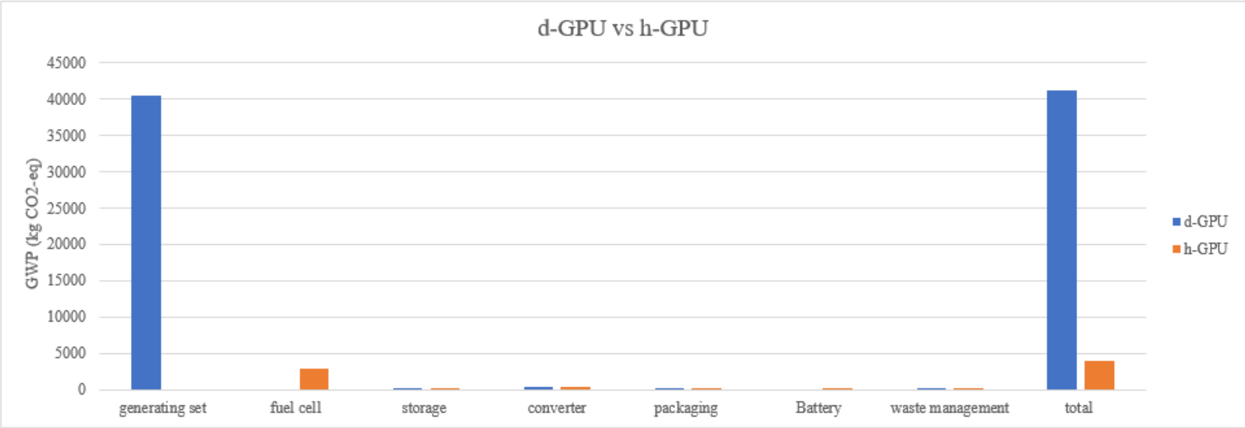

Figure 5.1 The GWP of the separate components of the d-GPU (blue) and hydrogen GPU (orange)

5.2 Diesel vs hydrogen supply chain

As described in the section – scenario development, five different scenarios were considered in this research. For each scenario, the GWP was generated. The total GWP for the supply chain consists of the production phase of all components, the usage phase and the disposal of all components. The burning of diesel in the d-GPU and water usage in the hydrogen GPU were given separate inputs in the supply chain. The functional unit comprises one year; the GWP is the GWP for one year of the supply chain. In Table 5.2 and Figure 5.2, the supply chain of the d-GPU was compared with the supply chain of the h-GPU for each scenario. Appendix 7 presents the diesel and hydrogen scenarios in separate figures.

Table 5.2 the global warming potential of one year for the d-GPU and the h-GPU.

		GWP	
	unit	d-GPU (x10,000)	h-GPU (x10,000)
Scenario 1	kg CO_2-eq	36.40	1.17
Scenario 2	kg CO_2-eq	109.06	3.01
Scenario 3	kg CO_2-eq	182.43	4.90
Scenario 4	kg CO_2-eq	362.49	9.51
Scenario 5	kg CO_2-eq	543.65	14.20

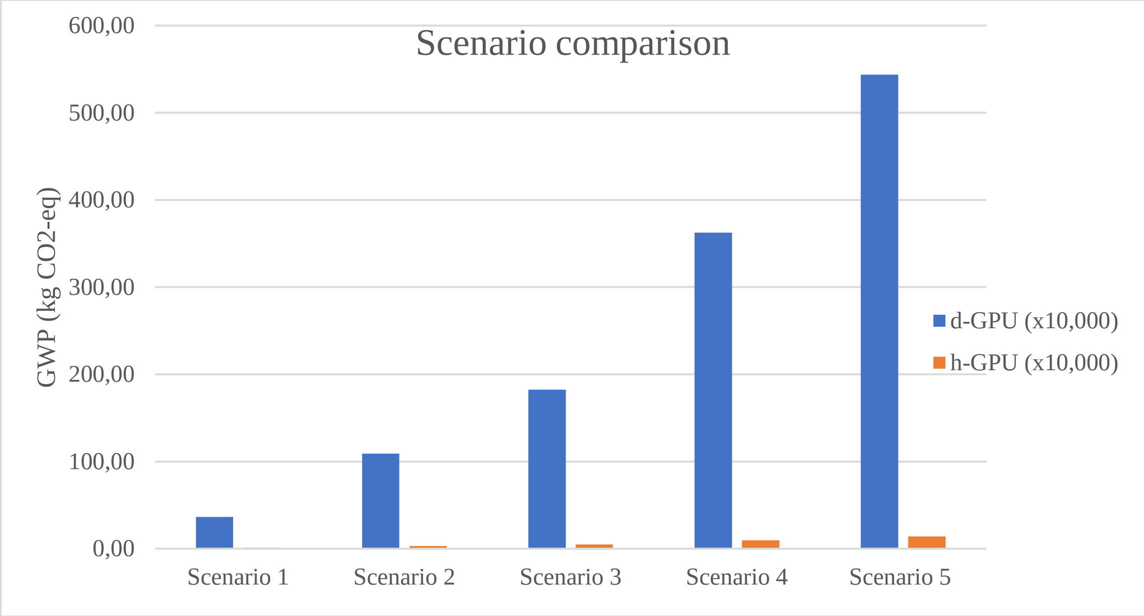

Figure 5.2 An comparison in global warming potential between the d-GPU and the h-GPU.

Compared to a d-GPU, the supply chain of a hydrogen GPU had a lower GWP in every scenario. In the first scenario, the GWP of the diesel supply chain was almost 31.1 times higher than the GWP of the hydrogen supply chain. In the fifth scenario, the hydrogen supply chain was more than 38.3 times more favourable than the diesel supply chain. The GWP of the hydrogen supply chain was increasing less than linear with the number of flights leaving per day. Consequently, the GWP per flight was less if more flights were leaving GAE, and thus a larger supply chain is installed.

The GWP of the diesel supply chains was almost increasing linearly with the number of flights. In scenario 1, one flight a day is leaving GAE, and the global warming potential of the entire supply chain is 364,000 kg CO_2-eq. In scenario 5, 15 flights a day leave GAE, and the GWP was almost 15 times bigger than in scenario 1. Nearly every component, except the d-GPU, in the diesel supply chain, increased linearly if the number of flights increased. This was because more trucks were transported per week to the airport, the storage capacity increased, and more diesel was used. The only component that stayed the same was the GPU itself; in scenarios one and five, one GPU was used to power all the aeroplanes.

For the hydrogen supply chain, the increase in GWP is significantly less than linear with the number of flights leaving per day. Therefore, if more flights leave per day, the hydrogen supply chain becomes more favourable than the diesel supply chain. The solar park and the hydrogen storage were increasing linearly with the number of flights, as more hydrogen had to be stored and more PV panels were needed to produce sufficient energy. However, the electrolyser and the GPU were not increasing linearly. The electrolyser consists of components that together form the BOP of the electrolyser. Those materials were not increasing when the capacity of the electrolyser increased.

To better understand which supply chain components contribute the most to the GWP, scenario 3 was considered and studied in more detail. Scenario 3 was chosen because this is the most realistic scenario for GAE. Currently, two flights a day are leaving GAE; they want to expand in the coming years. Therefore, it is plausible that five flights a day will leave GAE. Figure 5.3 and Table 5.3 present an overview of the GWP of the separate components of the diesel and hydrogen supply chain. Appendix 7 shows the same figure as Figure 5.3. However, the h-GPU and the d-GPU are separated into two figures.

Table 5.3 Comparison of the GWP of the diesel supply chain components and the hydrogen supply chain components

d-GPU			**h-GPU**		
	Unit	**GWP (x10.000)**		**Unit**	**GWP (x10.000)**
diesel production	kg CO_2-eq	3.45	solar park	kg CO_2-eq	3.88
fueling station	kg CO_2-eq	0.004	electrolyser	kg CO_2-eq	0.29
d-GPU	kg CO_2-eq	0.16	fueling station	kg CO_2-eq	0.65
transport	kg CO_2-eq	143.23	h-GPU	kg CO_2-eq	0.02
burning diesel	kg CO_2-eq	31.33	Water usage	kg CO_2-eq	0.06
waste management	kg CO_2-eq	4.00	waste management	kg CO_2-eq	0.01
total	kg CO_2-eq	182.43	total	kg CO_2-eq	4.90

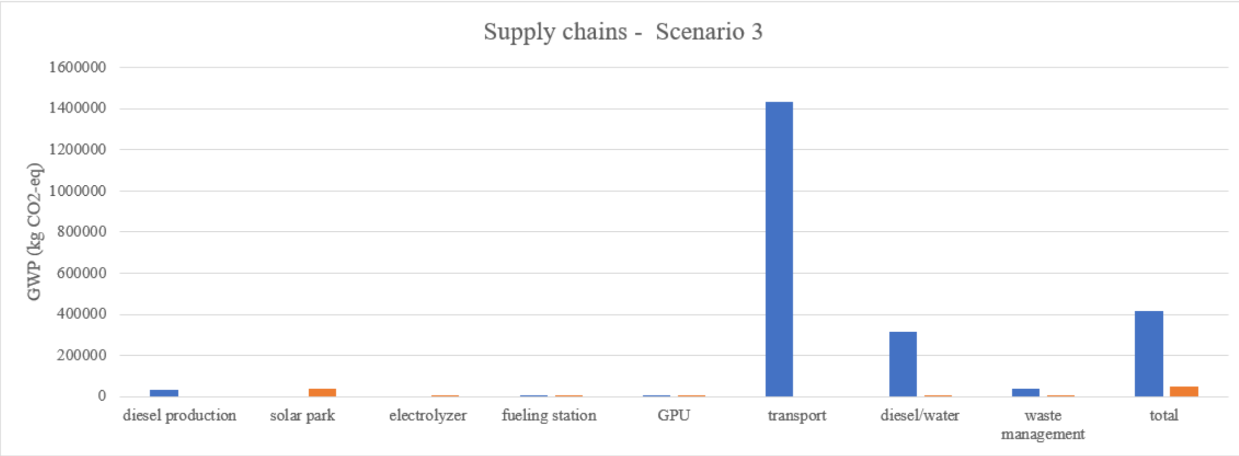

Figure 5.3 the GWP of the diesel supply chain (blue) components and the hydrogen supply chain (orange) components compared

Within the d-GPU supply chain, transport had the highest impact on the GWP. Transportation of diesel towards the airport had a GWP that is more than 29 times higher than the total GWP of the entire hydrogen supply chain. Burning diesel had the second-highest GWP; this amount was more than six times higher than the GWP of the entire hydrogen supply chain. The production of diesel and waste management scenario had similar GWPs. Those were at least a factor of ten smaller than the GWP of burning diesel and a factor of hundred than the diesel transport. However, they individually had approximately the same GWP as the entire hydrogen supply chain. For the hydrogen supply chain, the solar park had the highest GWP. The solar park contributed 79% to the total GWP of the entire supply chain. The GWP of the solar park was higher than the GWP of the diesel production facility. Other components that contributed to the GWP of the hydrogen supply chain are the fuelling station and the electrolyser. Therefore, those components and their materials will be studied in more detail.

This model's solar park consists of the components: the PV panels, the electric installation, the mounting system and an inverter. Table 5.4 gives an overview of the contribution of the different components to the total GWP of the solar park. The main contributor to the GWP was the production and installation of PV panels. The PV panel contributes 95.7% to the total GWP of the solar park. The other components of the solar park contribute to the remaining 4.3%.

Table 5.4 The components of the solar park and their contribution to the global warming potential

	Unit	GWP (x10,000)
solar panel	kg CO_2-eq	3.714
electric installation	kg CO_2-eq	0.066
mounting system	kg CO_2-eq	0.001
inverter	kg CO_2-eq	0.099
total	kg CO_2-eq	3.879

The hydrogen storage tank had the highest environmental impact on the fuelling station regarding GWP. This is because hydrogen must be stored under high pressure, so composite fibres are needed to strengthen the material (Barthelemey et al., 2016). The carbon fibres had the most considerable impact on the GWP of all materials used for the fuelling station. An overview of all the materials and their contribution to the GWP is given in Appendix 8. The storage method was the main difference between a hydrogen GPU and a diesel GPU. Hydrogen has to be stored under high pressure, and diesel does not. Therefore, the GWP of the hydrogen fuelling station was higher than the GWP of the diesel fuelling station. This can also be seen in Table 5.5.

Table 5.5 The components of the fuelling station and their contribution to the global warming potential.

	Unit	GWP (x1000)
Storage	kg CO_2-eq	6.35
dispenser	kg CO_2-eq	0.06
compressor	kg CO_2-eq	0.05
total	kg CO_2-eq	6.46

An electrolyser consists of multiple components with approximately the same GWP, as seen in Table 5.6. However, the cell stack had a higher GWP than the other components, as this part is more than two times higher than the other components. Additionally, the cell stack is the only component of the electrolyser that increased linearly with the capacity of the electrolyser. The others category includes a purifier, deoxidiser, alkali pump, dryer, and gas separator.

Table 5.6 The components of the electrolyser and their contribution to the global warming potential.

	Unit	**GWP (x1000)**
stack	kg CO_2-eq	1.10
heat exchanger	kg CO_2-eq	0.20
cooling	kg CO_2-eq	0.10
tubing and cables	kg CO_2-eq	0.29
fundament	kg CO_2-eq	0.08
compressor	kg CO_2-eq	0.29
control panel	kg CO_2-eq	0.13
tank	kg CO_2-eq	0.36
transformer	kg CO_2-eq	0.21
other	kg CO_2-eq	0.16
total	kg CO_2-eq	2.92

5.3 Results ReCiPe method

The GWP was considered in most research, as seen in Appendix 9. However, in some research next to the GWP, other impact categories were considered, such as ozone depletion, land use, water consumption, and resource scarcity (Garrain et al., 2021). Figures 5.4 and 5.5 show the impact on these categories of the components of the diesel supply chain and the hydrogen supply chain from scenario 3, respectively.

The transportation of diesel contributed the most in every impact category. The burning of diesel is the second most contributing in almost every impact category. Especially the contribution of burning diesel is relatively high in the following categories: ozone formation and fine particulate matter. Diesel production contributes significantly in most categories, including freshwater eutrophication, fossil resource scarcity, and ionising radiation. The contribution of the d-GPU and the gas station is, according to Figure 5.4, negligible in every category.

In every impact category, the solar park is the most polluting of the hydrogen supply chain. Except in the categories of freshwater eutrophication and marine eutrophication, water consumption contributed or had an equal contribution. In the impact categories of human carcinogenic and mineral resources, the electrolyser contributed a similar amount as the solar park.

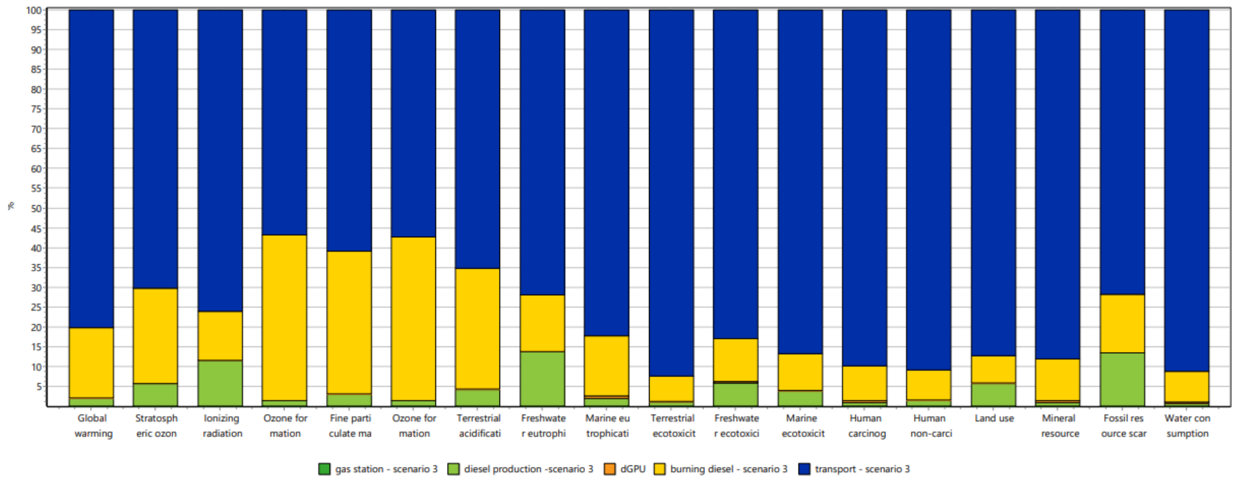

Figure 5.4 The effect of the diesel supply chain on other impact categories. In particular, the contribution of separate parts of the supply chain to each category.

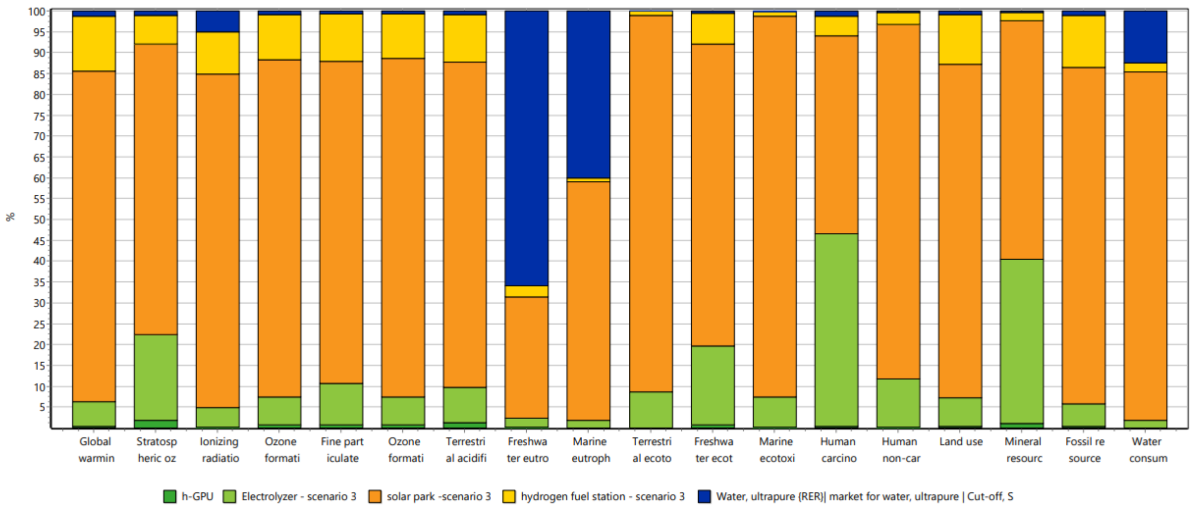

Figure 5.5 The effect of the hydrogen supply chain on other impact categories. In particular, the contribution of separate parts of the supply chain to each category.

6. Discussion

This research aims to give an advice over the replacement of a d-GPU by a hydrogen GPU. Comparing the hydrogen GPU with a d-GPU, the GWP of the d-GPU throughout its entire life cycle is 41,170 kg CO_2-eq, which is 10.4 times larger than the GWP of the hydrogen GPU. Consequently, the hydrogen GPU has a GWP throughout its life cycle of 3,900 kg CO_2-eq. Based on the GWP, the hydrogen GPU is preferred over the d-GPU. Additionally, based on the results of this research, the difference between the GWP of a d-GPU and a hydrogen GPU is mainly due to the generating set inside the d-GPU. The d-GPU contributes 98.3% to the total GWP. This high contribution is primarily due to the electricity used during the production of the generating set (Klemann, 2020). Therefore, using renewable energy resources to produce the generating set will positively impact the GWP of those d-GPUs. The storage capacity is an advantage of the d-GPU compared to the hydrogen GPU. The d-GPU has a storage capacity of 290 litres, which equals almost six flights. Compared to the hydrogen GPU with a storage capacity of 10 kg, which is enough to power 0.67 flights. Thus, the hydrogen GPU must be refuelled more often than the d-GPU.

In every scenario, the diesel supply chain for a d-GPU has a higher GWP than the hydrogen supply chain for a hydrogen GPU. In scenario 1, the hydrogen supply chain is 31.1 times more favourable; in scenario 5, the hydrogen supply chain is 38.3 times more favourable. If more flights leave GAE, the hydrogen supply chain becomes even more optimistic than the diesel supply chain. This is mainly due to the production and storage scale. For instance, the electrolyser and the fuelling station's BOP do not increase if the capacity of those components is increased (Mori et al., 2021). Consequently, the GWP per flight will be lower if more flights leave. Centralised hydrogen production and storage can be a solution, as large-scale production is more favourable (Seo et al., 2020). As well as that, when it is stored on a large-scale, salt caverns can be used (Malachowska et al., 2022). The salt cavern must be connected to a compressor to make the hydrogen applicable for GPUs (Malochowska et al., 2022). However, fewer materials for storage can be used (Malochowska et al., 2022). Appendix 8 shows that the storage tank is the main contributor to the fuelling station. Therefore, increasing the production capacity of the electrolyser and the hydrogen storage and considering centralised storage could lead to a decrease in the GWP of the hydrogen supply chain.

Focusing on the choice of materials and the number of materials used during production is another way to reduce the GWP of the hydrogen supply chain. The solar park contributes 79% to the total GWP of the hydrogen supply chain. The PV panels considered are multi-junction silicon panels. However, the literature review of this research mentions the development of organic PV panels;

according to the LCA performed by Tsang et al. (2016), considering the environmental impact of those PV panels, organic PV panels are preferred over silicon PV panels. Once those panels are commercially available, replacing the silicon crystalline PV panels with organic PV panels can be a way to reduce the GWP. Reconsidering the materials used in electrolysers could also help in reducing the GWP. Rare earth metals increase electrode activity in electrolysers (Santos et al., 2013). Consequently, mining those materials lead to higher impacts on human carcinogenic toxicity and scarcity of mineral resources categories (Pagano et al., 2015). Therefore, it is essential to weigh the positives of rare materials, such as higher performance, against the negatives, such as human toxicity and resource scarcity.

Increasing the lifetime of the supply chain components leads to a lower GWP per year if the GWP throughout the entire lifetime stays the same (Gerbinet, 2014). Currently, the lifetime of crystalline silicon PV panels is 30 years. However, as discussed by Company C (2022), after 30 years, the panels are still able to generate electricity. At the moment, the panels will be removed after 30 years because the licence is expired. If PV panels are used for more than 30 years, the amount of CO_2 per kWh will be less. High-pressure storage tanks currently have a lifetime of 15 years, which is short compared to the relatively short lifetime of other components (Wulf & Kaltschmitt, 2012). According to Zhang et al. (2019), the liner controls the high-pressure tanks' lifetime. The liner is made of aluminium, and its primary application is to prevent hydrogen from leaking (Zhang et al., 2019). Increasing the performance of the aluminium liner will decrease the chance of leaking and thereby increase the lifetime of the high-pressure storage vessels. Therefore, if the performance of the aluminium liner is increased, the lifetime will be increased, leading to a lower GWP per year of the fuelling station.

Not only the performance of materials can be increased to lower the GWP, but the performance of the supply chain components can also be increased. Especially if the focus lies on increasing the efficiency of those parts (Gerbinet et al. 2014). Zieminkska-Stolarska et al. (2021) propose using concentrated PV panels instead of crystalline silicon PV panels as those panels have almost three times higher efficiency. Increasing the efficiency of the PV panels will mean more electricity generated by the PV panel. However, those concentrated PV panels use additional materials (Zieminska-Stolarska et al., 2021). Therefore, it is essential to check whether the extra used materials weigh up to the extra efficiency and thus, indeed, lead to a lower GWP. Considering the electrolyser, the expectation is that the efficiency of the electrolyser will increase during the coming years (Zeng et al., 2022). An alkaline electrolyser's efficiency is 73%, which means that 27% of renewable energy generated by the solar park is lost (Zayat et al., 2020). If this efficiency is higher, more hydrogen can be generated with the same amount of renewable electricity. This means that fewer solar panels have to be connected to the electrolyser.

The recycling and reusing of materials from the hydrogen supply chain can reduce the GWP of the supply chain components (Gerbinet et al., 2014). However, in a few years, a considerable amount of PV panels, electrolysers and fuel cells will reach the end of life and needs to be disposed of. Consequently, this disposal needs to be an essential research topic; as limited is known about the disposal of these components (Chowdhury et al., 2022). Accordingly, Maani et al. (2020) propose structuring the research concerning removing those materials. First, the environmental impact of every material used in one of the products needs to be assessed. Then, the material with the highest environmental impact needs to get prioritised, and the product must be designed so that most of that specific metal can be recycled. For instance, silver is a metal with a high environmental impact and is present in solar parks. Therefore, solar parks must be designed so that most of the silver can be recovered. This will reduce the environmental impact of production because instead of extracting new raw materials, recycled materials will be used (Maani et al., 2020).

Lastly, improving laws and regulations could positively impact the GWP. Due to laws and regulations, it is currently in the Netherlands not feasible to create an autonomous grid. Therefore, the solar park and the electrolyser are connected to the grid instead of directly connected (Company C, 2022). This leads to conversion losses, as the grid uses AC and the electrolyser and solar park use DC (Company C, 2022). The AC/DC and DC/AC converters have a loss of approximately 8% (Borup et al., 2021). Consequently, more than 15% of electricity is lost. Therefore, creating an autonomous grid leads to fewer solar panels needed and thereby lowers the GWP of the hydrogen supply chain.

6.1 Cost assessment

Appendix 10 presents a cost assessment of the investment and usage costs of the five scenarios. The costs per year for the hydrogen supply chain are significantly higher than the costs per year for the diesel supply chain. The difference in the five scenarios is, respectively: €137,269, €134,088, €131,407, €123,691, and €116,418. Especially the hydrogen fuelling station is expensive (Reuß et al., 2017). An increase in lifetime will also lead to lower yearly costs, as the investment costs can be divided by more years. Another expensive element is purchasing ultrapure water (ReAgent Chemical Service Ltd, 2022). This water is needed for the electrolyser. A solution for this could be to collect the water generated by the fuel cell and use this water as input for the electrolyser. This will lead to less purchasing costs of water.

If Emission Trade System (ETS) prices are considered, the cost gap between the hydrogen and diesel supply chains becomes less. For every ton of CO_2-eq, currently, 85 euros is fined (Trading Economics, n.d.). However, ETS costs only consider the emissions produced in its sector. For this research, these are the emissions from the airport itself. In this case, the burning of diesel, fining the burning of diesel, the costs gap for the five scenarios will be, respectively: €131,998, €118,107, €104,321, €70,396, €36,518. If the airport is transporting diesel, transport emissions must also be considered for the ETS prices. In this case, the hydrogen supply chain is less expensive than the diesel supply chain in scenarios 3, 4, and 5. The difference between the diesel and hydrogen costs are, respectively: €107,773, €45,687, -€17,344, -€171,259, -€326,432. The larger the airport, thus, the more planes leaving the airport, the smaller the cost gap between the hydrogen and diesel supply chain. This also supports the production of hydrogen and storage on a larger scale.

6.2 Implications of research

This research has multiple implications. Firstly, LCA analyses of various components of the hydrogen and diesel supply chains are conducted. By providing a material, process and product list, the LCAs can be replicated and used for other studies. Secondly, this research highlights components within those supply chains that highly impact the GWP and other impact categories. These results help provide leading points of improvement and, thereby, focal points for additional research. Thirdly, For the aviation sector, this research shed light on how much more environmentally friendly the hydrogen supply chain is compared with the diesel supply chain. A hydrogen supply chain is a possible solution to reduce CO_2 emissions within the aviation sector. An on-site hydrogen supply chain could be an option for large-scale airports as GWP and investment costs per flight are lower. It could be a solution for small-scale airports to look into centralised production and storage. Fourthly, this research also has implications for other industries, such as the automotive industry and other industries which need to consider hydrogen instead of diesel. Lastly, an on-site hydrogen supply chain could be a good solution for GAE because the solar park, which has the highest GWP of all the hydrogen supply chain components, is already installed. The second most polluting component is the fuelling station; this station can be built together with other industries, such as the automotive industry. Combining this, the hydrogen storage scale will be bigger, leading to less GWP per stored amount of hydrogen.

6.3 Limitations

This research considered average values; the number of sun hours per day and the time an aeroplane is connected to a GPU unit. The capacity of the solar park is calculated based on 4.7 sun hours per day. However, the amount of sun hours will fluctuate seasonally. This research did not account for the seasonality production of solar energy. A suggestion for follow-up research would be to simulate the sun hours and account for seasonality. The same holds for the average hours a GPU is connected to an aeroplane since the time each aeroplane needs to be connected to the GPU also differs, which leads to a differentiation in the hydrogen demand. Lastly, the storage facility did not account for seasonal solar production either. The storage is large enough to store all the hydrogen produced in one day. However, if multiple days with a high number of sun hours occur, the storage capacity needs to be increased. This principle also applies to the winter, as the storage capacity will run out of hydrogen if multiple days with low sun hours occur. One possible solution is to have a larger storage tank. However, this inevitably brings an additional impact on the environment. Another solution would be to buy additional hydrogen in the winter and sell hydrogen in the summer. The supply chain to accompany this will also cause an additional impact on the environment.

This research did not consider which sizes and capacities of electrolysers and storage tanks are produced. It only considered how much was needed for the supply chain. Airports using a hydrogen supply chain probably will use hydrogen for more applications than for the hydrogen GPU. Therefore, the capacities of the solar park, electrolyser and storage tanks have to be bigger to be sufficient for the entire airport. However, this research only focused on the supply chain of the GPU and therefore only considered the impact of the supply chain, which corresponds with the capacities mentioned in this research.

The battery-electric GPU is not considered in this research, as the energy-storing capacity of those units is insufficient (Eisenhut et al., 2021). Company B (2022) proposed a hybrid situation to replace d-GPUs. The solution proposes battery electric GPUs for small aeroplanes and hydrogen GPUs for large aeroplanes. The reasoning behind this solution is the price of the hydrogen GPUs. Hydrogen GPUs, especially fuel cells, are more expensive than electric motors (Ajanovic & Haas, 2021). Depending on the size of the airport, this could be a suitable solution as this would imply that more than one GPUs need to be purchased.

6.4 Further research

Replacing diesel with hydrogen is a relatively new topic; therefore, there are multiple areas in which further research is required. At first, improving the efficiency of hydrogen supply chain components such as the solar park and the electrolyser. Furthermore, the choice of material has a large impact on the environment. Therefore, replacing polluting materials with less polluting ones might be a good solution. This direction requires more research, mainly focusing on the fuelling station and electrolyser. Thereby laying the focus on the fuelling station and the electrolyser. Lastly, research into the disposal of solar parks, electrolysers, fuel cells, and high-pressure storage tanks leads to recycling more materials and, therefore, appropriate research directions.

6.5 Validation

This research is validated by contacting companies about the results and using the Ecoinvent database as much as possible. This database is often checked on reliability (Ecoinvent, n.d.). The database is used for the solar park, diesel production, generating set, and parts of the fuelling station. For the parts which are not present in SimaPro, companies are contacted. For example, the material inputs of the electrolyser were checked by an employee from Company D. All essential parts or materials were present, according to this employee. The information for the hydrogen GPU is gathered from literature and in contact with Company A. However, the exact materials are unknown due to confidentiality reasons. Additionally, a contact person from GAE was contacted again after performing the research. The prospects of 5 flights leaving per day were confirmed in this meeting.

7. Conclusion

This study performed an LCA of the hydrogen supply chain, diesel supply chain and the separate components of those supply chains. The two supply chains are compared with each other. In almost every impact category, the diesel supply chain is more polluting than the hydrogen supply chain. Therefore, the conclusion can be drawn that, purely focusing on the environmental impact, the hydrogen GPU and its supply chain is more environmentally friendly than the d-GPU and its supply chain. The primary focus is directed towards the GWP of both supply chains. To indicate how much more favourable the hydrogen supply chain is, the GWP of each supply chain is compared with the GWP of human beings, flights, and passenger cars. Considering scenario 3, five flights leaving GAE per day, the hydrogen supply chain has a GWP of 49,000 kg CO_2-eq per year and the diesel supply chain has a GWP of 18,243,000 kg CO_2-eq per year. To compare, a human has a GWP of 4,470 kg CO_2-eq per year (Statista, 2022), meaning that the hydrogen supply chain equals almost 11 humans and the diesel supply chain 4,081 humans. Another comparison, driving a diesel passenger car has a GWP of 0.178 kg CO_2-eq per km. Consequently, the GWP of the hydrogen supply chain equals 275 thousand kilometres, and a diesel supply chain equals 102 million kilometres (Helmers et al., 2019). Lastly, the hydrogen supply chain has the same GWP of 14.8 flights from Vienna to Rio, and the diesel supply chain has the same GWP of 5,510 flights (Nielsen, 2020). Consequently, from these numbers, it is safe to conclude that powering the GPUs with hydrogen instead of diesel will lead to a lower environmental impact.

The PV panels are the most polluting of the hydrogen supply chain, mainly due to the production of the panels themselves. New generation PV panels could lead to lower environmental impact as fewer materials are used, and the efficiency will be higher. For the electrolyser and the fuelling station, larger-scale production positively impacts the GWP. As the materials used do not increase linearly with the capacity. Lastly, the fuel cell inside the GPU contributes the most to the GWP. However, this contribution is far less than the contribution of the generating set inside the d-GPU.

Overall, purely looking at the GWP of the diesel supply chain compared to the hydrogen supply chain, the hydrogen GPU and its supply chain is a good solution to reduce the environmental impact in the aviation industry.

References

Abarzadeh, M., & Kojabadi, H. M. (2016). A static ground power unit based on the improved hybrid active neutral-point-clamped converter. *IEEE Transactions on Industrial Electronics*, *63*(12), 7792-7803.

Aggarwal, V. (2022, 29 November). Solar panel output: How much energy does a solar panel produce? EnergySage Blog. Accessed on 7th of December 2022. Via: https://news.energysage.com/what-is-the-power-output-of-a-solar-panel/

Agostini, A., Belmonte, N., Masala, A., Hu, J., Rizzi, P., Fichtner, M., ... & Baricco, M. (2018). Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units. *Applied Energy, 215*, 1-12.

Air products (n.d). Fueling Stations. https://www.airproducts.com/equipment/hydrogen-fueling-stations Accessed on: 12th of December 2022.

Ajanovic, A., & Haas, R. (2021). Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. *International journal of hydrogen energy, 46*(16), 10049-10058.

Apostolou, D., & Xydis, G. (2019). A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renewable and Sustainable Energy Reviews*, *113*, 109292.

Asim, N., Sopian, K., Ahmadi, S., Saeedfar, K., Alghoul, M. A., Saadatian, O., & Zaidi, S. H. (2012). A review on the role of materials science in solar cells. *Renewable and Sustainable Energy Reviews*, *16*(8), 5834-5847.

Balli, O., & Caliskan, H. (2022). Environmental impact assessments of different auxiliary power units used for commercial aircraft by using global warming potential approach. *Environmental Science and Pollution Research*, *29*(58), 87334-87346.

Bagher, A. M., Vahid, M. M. A., & Mohsen, M. (2015). Types of solar cells and application. *American Journal of optics and Photonics*, *3*(5), 94-113. ‘

Baratto, F., & Diwekar, U. M. (2005). Life cycle assessment of fuel cell-based APUs. *Journal of Power Sources*, *139*(1-2), 188-196.

Barbier, E. (2002). Geothermal energy technology and current status: an overview. *Renewable and sustainable energy reviews*, *6*(1-2), 3-65.

Barke, A., Thies, C., Melo, S. P., Cerdas, F., Herrmann, C., & Spengler, T. S. (2020). Socio-economic life cycle assessment of future aircraft systems. *Procedia* CIRP, 90, 262-267.

Barthélémy, H., Weber, M., & Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, *42*(11), 7254-7262.

Baroutaji, A., Wilberforce, T., Ramadan, M., & Olabi, A. G. (2019). A comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. Renewable and sustainable energy reviews, 106, 31-40.

Baxter, G., Srisaeng, P., & Wild, G. (2018). Sustainable airport energy management: The case of kansai international airport. *International Journal for Traffic & Transport Engineering*, *8*(3).

Benitez, A., Wulf, C., de Palmenaer, A., Lengersdorf, M., Röding, T., Grube, T., ... & Kuckshinrichs, W. (2021). Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank. *Journal of cleaner production*, *278*, 123277.

Benveniste, G., Pucciarelli, M., Torrell, M., Kendall, M., & Tarancon, A. (2017). Life Cycle Assessment of microtubular solid oxide fuel cell based auxiliary power unit systems for recreational vehicles. *Journal of Cleaner Production*, *165*, 312-322.

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis–a review. *Journal of cleaner production*, *85*, 151-163.

Borup, U., Nielsen, B. V., & Blaabjerg, F. (2004). Compensation of cable voltage drops and automatic identification of cable parameters in 400 Hz ground power units. *IEEE Transactions on Industry Applications*, *40*(5), 1281-1286.

Bridgestone Mobility Solutions B.V. (n.d.). Webfleet. https://www.webfleet.com/nl_nl/webfleet/blog/hoeveel-diesel-verbruikt-een-vrachtwagen-per-kilometer/ Accessed on 25th of January

Burkhardt, J., Patyk, A., Tanguy, P., & Retzke, C. (2016). Hydrogen mobility from wind energy–A life cycle assessment focusing on the fuel supply. *Applied energy*, *181*, 54-64.

Camillis, C. D., Brandão, M., Zamagni, A. & Pennington, D., 2013. Sustainability assessment for future-oriented scenarios: a review of data modelling approaches in Life Cycle Assessment - Towards recommendations for policy making and business strategies, Italy: European Commision - Joint Research Centre, Institute for Environment and Sustainability

CBS (2020) - diesel verbruik in nederland. Retrieved from: https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/uitstoot-en-brandstofverbruik/brandstofverbruik-wegvervoer Accessed on 1st of January

Cetinkaya, E., Dincer, I., & Naterer, G. F. (2012). Life cycle assessment of various hydrogen production methods. *International journal of hydrogen energy*, *37*(3), 2071-2080.

Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., ... & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews, 27*, 100431.

Curran, M., 2015. Life Cycle Assessment Student Handbook. United Stated of America: Scrievener Publishing LCC

Delpierre, M., Quist, J., Mertens, J., Prieur-Vernat, A., & Cucurachi, S. (2021). Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *Journal of Cleaner Production*, *299*, 126866.

Dorp, J., (2022, November 15). Groningen Airport Eelde. Mail conversation.

Dube, K., & Nhamo, G. (2019). Climate change and the aviation sector: A focus on the Victoria Falls tourism route. *Environmental Development*, *29*, 5-15.

EBTL. (n.d.). Deiselvervoer door niet-ADR voertuigen. https://www.ebtl.nl/adr-advies/adr-wet-en-regelgeving/dieselvervoer-door-niet-adr-voertuigen/ Accessed on 20th of December.

Ecoinvent (n.d.) Retrieved from: https://ecoinvent.org/the-ecoinvent-database/ Accessed on: 22nd of December

eGPU (2022). *eGPU*. ITW GSE. https://itwgse.com/products/power/itw-gse-7400-egpu/

Eisenhut, D., Moebs, N., Windels, E., Bergmann, D., Geiß, I., Reis, R., & Strohmayer, A. (2021). Aircraft requirements for sustainable regional aviation. *Aerospace*, *8*(3), 61.

Elberry, A. M., Thakur, J., Santasalo-Aarnio, A., & Larmi, M. (2021). Large-scale compressed hydrogen storage as part of renewable electricity storage systems. *International journal of hydrogen energy*, *46*(29), 15671-15690.

Elia, J. A., Baliban, R. C., Floudas, C. A., Gurau, B., Weingarten, M. B., & Klotz, S. D. (2013). Hardwood biomass to gasoline, diesel, and jet fuel: 2. Supply chain optimization framework for a network of thermochemical refineries. *Energy & fuels*, *27*(8), 4325-4352.

Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and sustainable energy reviews*, *39*, 748-764.

Elitzur, S., Rosenband, V., & Gany, A. (2017). On-board hydrogen production for auxiliary power in passenger aircraft. *International Journal of Hydrogen Energy*, *42*(19), 14003-14009.

Evangelisti, S., Tagliaferri, C., Brett, D. J., & Lettieri, P. (2017). Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. *Journal of cleaner production*, *142*, 4339-4355.

Fernandes, M. D., Andrade, S. D. P., Bistritzki, V. N., Fonseca, R. M., Zacarias, L. G., Gonçalves, H. N. C., ... & Matencio, T. (2018). SOFC-APU systems for aircraft: A review. *International Journal of Hydrogen Energy*, *43*(33), 16311-16333.

Fontes, C. H. D. O., & Freires, F. G. M. (2018). Sustainable and renewable energy supply chain: A system dynamics overview. Renewable and Sustainable Energy Reviews, 82, 247-259.

Friedman, D. J. (2010). Progress and challenges for next-generation high-efficiency multijunction solar cells. *Current Opinion in Solid State and Materials Science*, *14*(6), 131-138.

FW Power (n.d.). Diesel Generator Fuel Consumption Chart in Litres. https://fwpower.co.uk/wp-content/uploads/2018/12/Diesel-Generator-Fuel-Consumption-Chart-in-Litres.pdf. Accessed on 28th of December 2022.

Garraín, D., Banacloche, S., Ferreira-Aparicio, P., Martínez-Chaparro, A., & Lechón, Y. (2021). Sustainability Indicators for the Manufacturing and Use of a Fuel Cell Prototype and Hydrogen Storage for Portable Uses. *Energies*, *14*(20), 6558.

Gerloff, N. (2021). Comparative Life-Cycle Assessment Analysis of Power-to-Methane Plants Including Different Water Electrolysis Technologies and CO2 Sources While Applying Various Energy Scenarios. *ACS Sustainable Chemistry & Engineering*, *9*(30), 10123-10141.

Gardiner, M., & Satyapal, S. (2009). DOE Hydrogen and Fuel Cells Program Record 9013: Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs. *US Department of Energy: Washington, DC*.

Gerbinet, S., Belboom, S., & Léonard, A. (2014). Life Cycle Analysis (LCA) of photovoltaic panels: A review. *Renewable and Sustainable Energy Reviews*, *38*, 747-753.

Geurts, E. (2022, March 18). Flinke impuls voor Hydrogen Valley Airport in Noord-Nederland. Alles Over Waterstof. https://allesoverwaterstof.nl/flinke-impuls-voor-hydrogen-valley-airport-in-noord-nederland/

Ghazvini, M., Sadeghzadeh, M., Ahmadi, M. H., Moosavi, S., & Pourfayaz, F. (2019). Geothermal energy use in hydrogen production: A review. *International Journal of Energy Research*, *43*(14), 7823-7851.

Girardi, P., Gargiulo, A., & Brambilla, P. C. (2015). A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. *The International Journal of Life Cycle Assessment*, *20*(8), 1127-1142.

Goedkoop, M., Oele, M., de Schryver, A., Vieira, M., & Hegger, S. (2008). SimaPro database manual methods library. *PRé Consultants, The Netherlands*, 22-25.

Góralczyk, M. (2003). Life-cycle assessment in the renewable energy sector. *Applied Energy*, *75*(3-4), 205-211.

GroenLeven. (2022). Zonnepark Groningen Airport Eelde. groenleven.nl. https://groenleven.nl/projecten/zonnepark-groningen-airport-eelde/ Accessed on 10-11-2022.

Guanxi (n.d.). Portable Diesel Generator. https://www.ultimatewasher.com/generators/portable-diesel-generators.htm Accessed on 13th of December 2022.

Hamburger Hochbahn AG Zemships.
http://www.zemships. eu/de/technologie/wasserstofftankstelle/index.php. Retrieved October 13, 2011.

Haskel. (n.d). How does a hydrogen Refuelling station Work. Retrieved December 1, 2022, from https://www.haskel.com/en-us/blog/how-does-a-hydrogen-refuelling-station-work#:~:text=A%20regular%20HRS%20consists%20of,type%20of%20vehicle%20being%20refuelled.

Helmers, E., Leitão, J., Tietge, U., & Butler, T. (2019). CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: Assessing the climate benefit of the European “diesel boom”. *Atmospheric Environment*, *198*, 122-132.

HII Group Asia. (2022, May 7). Aircraft Ground Power Unit, 60 KVA GPU, 90 KVA GPU. Hydraulics International (Asia). https://hiigroupasia.com/aircraft-ground-power-unit/ Accessed on: 13th of December 2022

Hjellvik, S. (2021). SimaPro Flow Tutorial. https://simapro.com/wp-content/uploads/2021/03/Flow-Tutorial.pdf

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*.

Hoeksema, A.J. (2022, November, 29).Groningen Airport Eelde. Mail conversation.

Hubbert, M. K. (1949). Energy from fossil fuels. *Science*, *109*(2823), 103-109.

Ihara, T., & Tanaka, K. (2016). Electricity management for persuing green and resilient airport in case of disaster: Including renewable energy sources, batteries, and diesel generators. In *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)* (pp. 1-4). IEEE.

ISO 14040, 2006. SVENSK STANDARD SS-EN ISO 14040:2006, Stockholm: Swedish Standards Institute

ISO 14044, 2018. SVENSK STANDARD SS-EN ISO 14044:2006/A1:2018, Stockholm: Swedish Standard Institute

Jensen, U. B., Rasmussen, M. P., Mortensen, T., Blaabjerg, F., & Pedersen, J. K. (1998, October). A new control method for 400 hz ground power units for airplanes. In *Conference Record of 1998 IEEE Industry Applications Conference. Thirty-Third IAS Annual Meeting (Cat. No. 98CH36242)* (Vol. 2, pp. 1469-1476). IEEE.

Kawamoto, R., Mochizuki, H., Moriguchi, Y., Nakano, T., Motohashi, M., Sakai, Y., & Inaba, A. (2019). Estimation of CO2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA. *Sustainability, 11*(9), 2690.

Keçeci, M., Colpan, C. O., & Karakoç, T. H. (2022). Reducing the fuel consumption and emissions with the use of an external fuel cell hybrid power unit for electric taxiing at airports. *International Journal of Hydrogen Energy*.

Klöpffer, W. (1997). Life cycle assessment. *Environmental Science and Pollution Research*, *4*(4), 223-228.

Kolk, P. (2022, November 25). KLM equipment service. Interview

Koj, J. C., Wulf, C., Schreiber, A., & Zapp, P. (2017). Site-dependent environmental impacts of industrial hydrogen production by alkaline water electrolysis. *Energies*, *10*(7), 860.

Kromwijk, S., (2022) Groenleven, mail conversation on 9-11-2022.

Lahnaoui, A., Wulf, C., Heinrichs, H., & Dalmazzone, D. (2019). Optimizing hydrogen transportation system for mobility via compressed hydrogen trucks. International journal of hydrogen energy, 44(35), 19302-19312.

Lai, Y. Y., Christley, E., Kulanovic, A., Teng, C. C., Björklund, A., Nordensvärd, J., ... & Urban, F. (2022). Analysing the opportunities and challenges for mitigating the climate impact of aviation: A narrative review. Renewable and Sustainable Energy Reviews, 156, 111972.

Landorf, M. (n.d.). Onground Diesel & Petrol Storage Tanks. https://www.sltanks.com.au/onground.html Accessed on 13th of December 2022.

Levene, J. I., Mann, M. K., Margolis, R. M., & Milbrandt, A. (2007). An analysis of hydrogen production from renewable electricity sources. *Solar energy*, *81*(6), 773-780.

Lloyd, D. G. (2012). Transport of radioactive materials: Safety aspects. Journal of Radiological Protection, 32(3), 369-379. doi:10.1088/0952-4746/32/3/369

Li, X. Z., Chen, Z. J., Fan, X. C., & Cheng, Z. J. (2018). Hydropower development situation and prospects in China. *Renewable and Sustainable Energy Reviews*, *82*, 232-239.

Lombardi, L., Tribioli, L., Cozzolino, R., & Bella, G. (2017). Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA. *The International Journal of Life Cycle Assessment*, *22*(12), 1989-2006.

Lucas, A., Neto, R. C., & Silva, C. A. (2013). Energy supply infrastructure LCA model for electric and hydrogen transportation systems. *Energy*, *56*, 70-80.

Maghami, M. R., Hizam, H., Gomes, C., Radzi, M. A., Rezadad, M. I., & Hajighorbani, S. (2016). Power loss due to soiling on solar panel: A review. *Renewable and Sustainable Energy Reviews*, *59*, 1307-1316.

Małachowska, A., Łukasik, N., Mioduska, J., & Gębicki, J. (2022). Hydrogen storage in geological formations—The potential of salt caverns. *Energies*, *15*(14), 5038.

Malik, V., Srivastava, S., Bhatnagar, M. K., & Vishnoi, M. (2021). Comparative study and analysis between Solid Oxide Fuel Cells (SOFC) and Proton Exchange Membrane (PEM) fuel cell– A review. *Materials Today: Proceedings*, *47*, 2270-2275.

Manutan B.V. (n.d.). Mobiel bevoorradingsstation diesel - 600 L | Manutan. https://www.manutan.nl/nl/mnl/mobiel-bevoorradingsstation-diesel-600-l-a065950?gclid=Cj0KCQiA4uCcBhDdARIsAH5jyUmYHYvH7Z1k4NyS1jX4zMg7RYR-WSQcxtc2yEhC14iGp7Jf3icuOwIaAnfBEALw_wcB Accessed on 13th of December 2022.

Martinez, I. (n.d.). Fuel properties. Retrieved from: http://webserver.dmt.upm.es/~isidoro/bk3/c15/Fuel%20properties.pdf Accessed on 18th of January 2023.

Masoni, P., Zamagni, A., Bode, M., Finkbeiner, M., & Chomkhamsri, K. (2011). Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies. *Rapport, nD3, 3*, 109.

May, T. (2022, October 5). Netherlands: Hydrogen Refuelling Station to Be Built at Groningen Airport Eelde. Airport Industry-News. https://airportindustry-news.com/netherlands-hydrogen-refuelling-station-to-be-built-at-groningen-airport-eelde/

MetDeZon. (2020). Afmetingen zonnepanelen? Formaat van een zonnepaneel. https://www.zonnepanelen.nl/kennis/afmetingen-zonnepanelen/ Accessed on: 12th of December 2022.

Milojević, S. (2016). Reconstruction of existing city buses on diesel fuel for drive on Hydrogen. *Applied Engineering Letters*, *1*(1), 16-23.

Mikhaylov, K., Tervonen, J., & Fadeev, D. (2012). Development of Energy Efficiency Aware Applications Using Commercial Low Power Embedded Systems. 10.5772-38171.

Mlakar, N., Lotrič, A., Sekavčnik, M., & Mori, M. (2022). The influence of degradation effects in proton exchange membrane fuel cells on life cycle assessment modelling and environmental impact indicators. *International Journal of Hydrogen Energy*.

Mobile Ground Power Unit (2022). *Unitron Power System*. Aero Expo. https://www.aeroexpo.online/prod/unitron-power-systems/product-169030-11915.html

Noteboom, P. (2022, December 23). Groenleven. Interview

Moolla, R., Curtis, C. J., & Knight, J. (2015). Occupational exposure of diesel station workers to BTEX compounds at a bus depot. *International journal of environmental research and public health*, *12*(4), 4101-4115.

Mori, M., Stropnik, R., Sekavčnik, M., & Lotrič, A. (2021). Criticality and life-cycle assessment of materials used in fuel-cell and hydrogen technologies. *Sustainability, 13*(6), 3565.

Muteri, V., Cellura, M., Curto, D., Franzitta, V., Longo, S., Mistretta, M., & Parisi, M. L. (2020). Review on life cycle assessment of solar photovoltaic panels. *Energies, 13*(1), 252.

Nanaki, E. A., & Koroneos, C. J. (2012). Comparative LCA of the use of biodiesel, diesel and gasoline for transportation. *Journal of Cleaner Production*, *20*(1), 14-19.

Nederland prijzen van diesel,. (n.d.). GlobalPetrolPrices.com. https://nl.globalpetrolprices.com/Netherlands/diesel_prices/ Accessed on: 21st of January

Nielsen, E. (2020). In house production drastically reduces CO2 emissions. Retrieved from: https://blog.alpla.com/en/blog/company-economy/house-production-drastically-reduces-co2-emissions/10-20 Accessed on: 19th of January 2023.

Oechies, A. (2022a, October, 27). Holthausen. Visit to Holthausen.

Oechies , A. (2022b, November, 16) Holthausen. Mail conversation

Ortega Alba, S., & Manana, M. (2016). Energy research in airports: A review. *Energies*, *9*(5), 349.

Padhra, A. (2018). Emissions from auxiliary power units and ground power units during intraday aircraft turnarounds at European airports. *Transportation Research Part D: Transport and Environment*, *63*, 433-444.

Pagano, G., Guida, M., Tommasi, F., & Oral, R. (2015). Health effects and toxicity mechanisms of rare earth elements—Knowledge gaps and research prospects. *Ecotoxicology and environmental safety*, *115*, 40-48.

Papadis, E., & Tsatsaronis, G. (2020). Challenges in the decarbonization of the energy sector. *Energy*, *205*, 118025.

Pehnt, M. (2001). Life-cycle assessment of fuel cell stacks. *International Journal of Hydrogen Energy*, *26*(1), 91-101.

Perez-Gallardo, J.R., Azzaro-Pantel, C., Astier, S., 2017. A multi-objective framework for assessment of recycling strategies for photovoltaic modules based on life cycle assessment. Waste and Biomass Valorization 0, 0. doi:https://doi.org/10.1007/s12649- 017-9878-0.

Qazi, A., Hussain, F., Rahim, N. A., Hardaker, G., Alghazzawi, D., Shaban, K., & Haruna, K. (2019). Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions. *IEEE access*, *7*, 63837-63851.

Qyyum, M. A., Dickson, R., Shah, S. F. A., Niaz, H., Khan, A., Liu, J. J., & Lee, M. (2021). Availability, versatility, and viability of feedstocks for hydrogen production: Product space perspective. *Renewable and Sustainable Energy Reviews*, *145*, 110843.

ReAgent Chemical Services Ltd. (2022). *Buy Ultrapure Water Online | UK Chemical Suppliers*. ReAgent Chemical Services. https://www.chemicals.co.uk/ultrapure-water Accessed on: 25th of January

Reddi, K., Elgowainy, A., Rustagi, N., & Gupta, E. (2017). Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen. *International Journal of Hydrogen Energy*, *42*(34), 21855-21865.

Renouard-Vallet, G., Saballus, M., Schmithals, G., Schirmer, J., Kallo, J., & Friedrich, K. A. (2010). Improving the environmental impact of civil aircraft by fuel cell technology: concepts and technological progress. *Energy & Environmental Science*, *3*(10), 1458-1468.

Reuß, M., Grube, T., Robinius, M., & Stolten, D. (2019). A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany. *Applied Energy*, *247*, 438-453.

Rinawati, D. I., Keeley, A. R., Takeda, S., & Managi, S. (2021). A systematic review of life cycle assessment of hydrogen for road transport use. *Progress in Energy*.

Rivera, M., Faundez, D., Kolar, J., Wheeler, P., Besoaín, F., & Riveros, J. A. (2018). A New Ground Power Unit (GPU) Supply for Aircraft Applications. In *2018 IEEE Biennial Congress of Argentina (ARGENCON)* (pp. 1-6). IEEE.

Roos, B. (2018). *'Zonneparken: hoge opbrengsten maar ook hoge kosten' | Vereniging van accountants en belastingadviesbureaus (VLB)*. https://vlb.nl/zonneparken-hoge-opbrengsten-maar-ook-hoge-kosten-2/ Accessed on: 21st of January

Santos, D. M. F., Sequeira, C. A. C., Macciò, D. A. N. I. E. L. E., Saccone, A. D. R. I. A. N. A., & Figueiredo, J. L. (2013). Platinum–rare earth electrodes for hydrogen evolution in alkaline water electrolysis. *International journal of hydrogen energy*, *38*(8), 3137-3145.

Saravanan, S., & Babu, N. R. (2017). Analysis and implementation of high step-up DC-DC converter for PV based grid application. *Applied Energy, 190*, 64-72.

Shumaker, R. (2022). *How Much Does It Cost to Own a Gas Station Franchise? - Biz2Credit*. https://www.biz2credit.com/blog/how-much-cost-gas-station-franchise/ Accessed on 21st of January

Selema, A., Osheba, D. S., Tahoon, S. M. R., & El-Shanawany, M. M. (2019). Design and analysis of a three-phase brushless flux switching generator for aircraft ground power units. *IET Electric Power Applications*, *13*(2), 154-161.

Seo, S. K., Yun, D. Y., & Lee, C. J. (2020). Design and optimization of a hydrogen supply chain using a centralized storage model. *Applied energy*, *262*, 114452.

Siddiqui, O., & Dincer, I. (2021). A comparative life cycle assessment of clean aviation fuels. *Energy*, *234*, 121126.

Simons, A., & Bauer, C. (2015). A life-cycle perspective on automotive fuel cells. *Applied Energy*, *157*, 884-896.

Sinha, P., & Brophy, B. (2021). Life cycle assessment of renewable hydrogen for fuel cell passenger vehicles in California. *Sustainable Energy Technologies and Assessments*, *45*, 101188.

Skoon Energy. (2022, 12 augustus). 1.5kWh battery - Beaver. https://www.skoon.world/energy-solutions/1-5kwh-battery-beaver/ Accessed on 16th of December 2022.

Smit, R., Weeda, M., & De Groot, A. (2007). Hydrogen infrastructure development in The Netherlands. *International Journal of Hydrogen Energy*, *32*(10-11), 1387-1395.

Sopian, K., Cheow, S. L., & Zaidi, S. H. (2017, September). An overview of crystalline silicon solar cell technology: Past, present, and future. In AIP Conference Proceedings (Vol. 1877, No. 1, p. 020004). AIP Publishing LLC.

Staffell, I., Scamman, D., Abad, A. V., Balcombe, P., Dodds, P. E., Ekins, P., ... & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, *12*(2), 463-491.

Statista. (2022). Hours of sunshine in the Netherlands 1990-2021. https://www.statista.com/statistics/1012949/hours-of-sunshine-in-the-netherlands/ Accessed on 10-11-2022. https://www.statista.com/statistics/276629/global-co2-emissions/ Accessed on 1st of January 2022.

Tarnay, D. S. (1985). Hydrogen production at hydro-power plants. *International Journal of Hydrogen Energy*, *10*(9), 577-584.

Testa, E., Giammusso, C., Bruno, M., & Maggiore, P. (2014). Analysis of environmental benefits resulting from use of hydrogen technology in handling operations at airports. *Clean Technologies and Environmental Policy*, *16*(5), 875-890.

Thies, C., Kieckhäfer, K., Spengler, T. S., & Sodhi, M. S. (2019). Operations research for sustainability assessment of products: A review. *European Journal of Operational Research*, *274*(1), 1-21.

TRADING ECONOMICS. (n.d.). *EU Carbon Permits - 2023 Data - 2005-2022 Historical - 2024 Forecast - Price - Quote*. https://tradingeconomics.com/commodity/carbon

Tsang, M. P., Sonnemann, G. W., & Bassani, D. M. (2016). Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Solar Energy Materials and Solar Cells*, *156*, 37-48.

Ultimate Washer (n.d.). Portable Diesel Generator. https://www.ultimatewasher.com/generators/portable-diesel-generators.htm Accessed on 13th of December 2022

US EPA. (n.d.). Science Inventorory https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHEERL Accessed on 1st of January 2023

Valley Airport in Europe. New Energy Coalition. https://www.newenergycoalition.org/en/groningen-airport-eelde-and-new-energy-coalition-collaboration-first-hydrogen-valley-airport-in-europe/

Vet, B. (2022, December, 7). Demcon. Mail conversation.

Wal, T. van der. (2022, January 27). Groningen Airport Eelde and collaboration: first Hydrogen

Wang, Y., Diaz, D. F. R., Chen, K. S., Wang, Z., & Adroher, X. C. (2020). Materials, technological status, and fundamentals of PEM fuel cells–a review. *Materials today*, *32*, 178-203.

World bank. (n.d.). Putting a price on carbon with an ETS. https://www.worldbank.org/content/dam/Worldbank/document/Climate/background-note_ets.pdf Accessed on: 25th of January 2023

World Nuclear. (n.d.). Heat values of various fuels. Retrieved from: https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx Accessed at: 18th of January 2023.

Wulf, C., Reuß, M., Grube, T., Zapp, P., Robinius, M., Hake, J. F., & Stolten, D. (2018). Life Cycle Assessment of hydrogen transport and distribution options. *Journal of cleaner production*, *199*, 431-443.

Wulf, C., & Kaltschmitt, M. (2012). Life cycle assessment of hydrogen supply chain with special attention on hydrogen refuelling stations. *International Journal of Hydrogen Energy*, *37*(21), 16711-16721.

Wulf, C., & Kaltschmitt, M. (2018). Hydrogen supply chains for mobility—environmental and economic assessment. *Sustainability*, *10*(6), 1699.

Xiang, Y., Cai, H., Liu, J., & Zhang, X. (2021). Techno-economic design of energy systems for airport electrification: A hydrogen-solar-storage integrated microgrid solution. *Applied energy*, *283*, 116374.

Yang, C., & Ogden, J. (2007). Determining the lowest-cost hydrogen delivery mode. International Journal of Hydrogen Energy, 32(2), 268-286.

Yang, Z., Wang, B., & Jiao, K. (2020). Life cycle assessment of fuel cell, electric and internal combustion engine vehicles under different fuel scenarios and driving mileages in China. *Energy*, *198*, 117365.

Yanxing, Z., Maoqiong, G., Yuan, Z., Xueqiang, D., & Jun, S. (2019). Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen. *International Journal of Hydrogen Energy*, *44*(31), 16833-16840.

Yildiz, B., & Kazimi, M. S. (2006). Efficiency of hydrogen production systems using alternative nuclear energy technologies. *International Journal of Hydrogen Energy*, *31*(1), 77-92.

Yu, J., Shao, C., Xue, C., & Hu, H. (2020). China's aircraft-related CO2 emissions: decomposition analysis, decoupling status, and future trends. *Energy Policy*, *138*, 111215.

Yusaf, T., Fernandes, L., Abu Talib, A. R., Altarazi, Y. S., Alrefae, W., Kadirgama, K., ... & Laimon, M. (2022). Sustainable aviation—hydrogen is the future. *Sustainability*, *14*(1), 548.

Zaihidee, F. M., Mekhilef, S., Seyedmahmoudian, M., & Horan, B. (2016). Dust as an unalterable deteriorative factor a↵ecting PV panels eciency: Why and how. Renewable and Sustainable Energy Reviews, 65, 12671278.https://doi.org/10.1016/ j.rser.2016.06.068

Zayat, B., Mitra, D., & Narayanan, S. R. (2020). Inexpensive and efficient alkaline water electrolyzer with robust steel-based electrodes. *Journal of The Electrochemical Society*, *167*(11), 114513.

Zeng, L., Zhao, Z., Lv, F., Xia, Z., Lu, S. Y., Li, J., ... & Guo, S. (2022). Anti-dissolution Pt single site with Pt (OH)(O3)/Co (P) coordination for efficient alkaline water splitting electrolyzer. *Nature communications*, *13*(1), 1-9.

Zhang, M., Lv, H., Kang, H., Zhou, W., & Zhang, C. (2019). A literature review of failure prediction and analysis methods for composite high-pressure hydrogen storage tanks. *International Journal of Hydrogen Energy*, *44*(47), 25777-25799.

Zhao, G., Kraglund, M. R., Frandsen, H. L., Wulff, A. C., Jensen, S. H., Chen, M., & Graves, C. R. (2020). Life cycle assessment of H2O electrolysis technologies. *International Journal of Hydrogen Energy*, *45*(43), 23765-23781.

Appendix

Appendix 1: Literature overview

Table A 1.1: An overview of the discussed topics in literature

	Hydrogen Supply chain				**Hydrogen GPU**		**Diesel GPU**	**Methods**
	PV panels	**Electrolyser**	**Hydrogen storage**	**Fuelling station**	**h-GPU**	**Fuel cell**	**d-GPU**	**LCA**
Barke et al. (2020)								✓
Barthelemy et al. (2016)			✓	✓				✓
Bhandari et al. (2014)	✓							✓
Delpierre et al. (2021)		✓						✓
Eisenhut et al. (2021)					✓	✓		

Elberry et al. (2022)	✓	✓	✓					
Elitzur et al. (2017)			✓					
Fontes & Feires (2018)	✓							✓
Hoelzen et al. (2022)					✓	✓	✓	
Ihara & Tanaka (2016)					✓	✓	✓	
Kececi et al. 2022)						✓		✓
Rivera et al. (2022)					✓	✓		
Siddiquin & Dincer (2021)								✓
Staffel et al. (2018)	✓	✓	✓	✓		✓		
Wulf & Kaltschmitt (2018)	✓	✓	✓			✓		✓
Wulf & Kaltschmitt (2012)			✓	✓				✓
Agostini et al. (2018)		✓				✓		✓
Benitez et al. (2021)			✓					✓
Evangelisti et al. (2017)						✓		✓

Simons & Bauer (2015)						✓		✓
Kawamoto et al. (2019)						✓		✓
Koj et al. (2017)		✓						

Appendix 2: All inputs in Simapro 9.4

Hydrogen Supply Chain

Table A… gives an overview of all the materials, processes, and producte used as input in SimaPro 9.4. For every material, process or product, the Cut-off,S method is selected. As well that the following sequence as selection method was chosen:

1. {NL}
2. {Europe without Switzerland}
3. {RER}
4. {GLO}
5. {RoW}

The first column of the Table shows the materials, processes, or products chosen in SimaPro. The second column shows the quantity that was given as input for Simapro. The third column shows the quantity for the different scenarios. The fourth column shows the component's lifetim, and thus with which number the total emissions were divided.

For example, the electrolyser, all the separate parts of the electrolyser were first specified in SimaPro. After which, those materials are combined into a complete electrolyser. Lastly, the scenarios were specified, and the third column was used to specify the scenario-specific quantities within those scenarios.

Table A 2.1: Input parameters for SimaPro 9.4, representing the hydrogen supply chain.

Solar park			
Photovoltaic panel, multi-Si wafer (RER)| production| Cut-off,S	103009,48 m^2	Scenario 1: 0.011 p Scenario 2: 0.032 p	For one year: divided by 30

Inverter, 500 kW {RER}| production| Cut-off, S	38,4 p	Scenario 3: 0.54 p Scenario 4: 0.107 p Scenario 5: 0.161 p	
Photovoltaic mounting system, for 570 kWp open ground module {GLO}| market for | Cut-off, S	38.4 p		
Photovoltaic, electric installation for 570 kWp module open ground {GLO}| market for photovoltaics, electric installation for 570 kWp module, open ground| Cut-off, S	38,4 p		
Electrolyser			
<u>Alkali-resistant rotary pump</u>			
Polypropylene, granulate {RER}| production | Cut-off, S	3 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Injection moulding {RER}| processing | Cut-off, S	3 kg		
<u>Buffer tank</u>			
Steel, chromium steel 18/8, hot rolled {RER}| production | Cut-off, S	511 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Sheet rolling, chromium steel {RER}| processing | Cut-off, S	511 kg		
Welding, arc, steel {RER}| processing | Cut-off, S	29 m		
<u>Control panel</u>			
Electronics, for control units {RER}| production| Cut-off, S	100 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
<u>Diaphragm for diaphragm compressor</u>			

Cast iron {RER}| production | Cut-off, S	600 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Ethylene glycol {RER}| production| Cut-off, S	7 kg		
Reinforcing steel {RER}| production| Cut-off, S	1300 kg		
Steel, chromium steel 18/8, hot rolled {RER}| production| Cut-off, S	405 kg		
Sheet rolling, steel {RER}| processing | Cut-off, S	400 kg		
Sheet rolling, chromium steel {RER}| processing| Cut-off, S	405 kg		
<u>Frequency converter diaphragm compressor</u>			
Aluminium, wrought alloy {GLO}| market for | Cut-off, S	60 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Copper {GLO}| market for | Cut-off, S	45 kg		
Reinforcing steel {RER}| production | Cut-off, S	180 kg		
Tube insulation, elastomere {GLO}| market for | Cut-off, S	15 kg		
Wire drawing, copper {RER}| processing| Cut-off, S	45 kg		
<u>Fundament</u>			
Concrete, 35 MPa {ROW}| concrete production 35 MPa, Cut-off, S	7.7 m^3	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
<u>Gas separator</u>			
Reinforcing steel {RER}| production | Cut-off, S	80 kg	Scenario 1: 1p Scenario 2: 1p	For one year: divided by 25

Sheet rolling, steel {RER}| processing | Cut-off, S	80 kg	Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	
<u>Heat exchanger</u>			
Steel, chromium steel 18/8 {GLO}| market for| Cut-off, S	929.1 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Sheet rolling, chromium steel {RER}| processing| Cut-off, S	929.1 kg		
<u>Hydrogen dryer and deoxidizer</u>			
Glass fibre {RER}| production | Cut-off, S	464.6 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Reinforcing steel {RER}| production| Cut-off, S	696.8 kg		
Steel, Chromium steel 18/8, hot rolled {RER}| production | Cut-off, S	232.3 kg		
Sheet rolling, steel {RER}| processing | Cut-off, S	696.8 kg		
Sheet rolling, chromium steel {RER}| processing | Cut-off,S	232.3 kg		
<u>Pumps and coolers</u>			
Cast iron {RER}| production | Cut-off, S	116.1 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Reinforcing steel {RER}| production| Cut-off, S	209.1 kg		
Sheet rolling, steel {RER}| processing| Cut-off, S	209.1 kg		
<u>Stack</u>			
Steel, chromium steel, 18/8 {GLO}| market for| Cut-off, S	20194.4 kg	Scenario 1: 0.0375 p Scenario 2: 0.1125 p Scenario 3: 0.1875 p Scenario 4: 0.375 p	For one year: divided by 25
Polysulfone {GLO}| market for| Cut-off, S	48.8 kg		

Zirconium oxide {GLO}| market for| Cut-off, S	73.0 kg	Scenario 5: 0.5625 p	
Nickel, class 1 {GLO}| market for| Cut-off, S	2884.9 kg		
Tetrafluorethylene {RER}| production | Cut-off, S	144.2 kg		
Sheet rolling, chromium steel {GLO}| market for| Cut-off, S	20194.4 kg		
<u>Steel tank for KOH</u>			
Steel chromium steel 18/8 {GLO}| market for | Cut-off, S	851 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Sheet rolling, chromium steel {RER}| processing | Cut-off, S	851 kg		
<u>Transformer and rectifier</u>			
Copper {GLO}| market for | Cut-off, S	100 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Reinforcing steel {RER}| production | Cut-off, S	600 kg		
Aluminium, wrought alloy {GLO}| market for| Cut-off, S	200 kg		
Tube insulation, elastomere {GLO}| market for | Cut-off, S	100 kg		
Sheet rolling, aluminium {RER}| processing| Cut-off, S	100 kg		
Sheet rolling, steel {RER}| processing | Cut-off, S	600 kg		
Wire drawing, copper {RER}| processing| Cut-off, S	200 kg		
<u>Tubing and cables</u>			
Copper {GLO}| Market for | Cut-off, S	371.7 kg	Scenario 1: 1p Scenario 2: 1p	For one year: divided by 25

Steel, chromium steel 18/8 {GLO}| market for| Cut-off, S	929.1 kg	Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	
Tube insulation, elastomere {GLO}| market for | Cut-off, S	92.9 kg		
Sheet rolling, chromium steel {RER}| processing | Cut-off, S	929.1 kg		
Wire drawing, copper {RER}| processing | Cut-off, S	371.7 kg		
<u>Water cooling plant</u>			
Reinforcing steel {RER}| production | Cut-off, S	836.2 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Sheet rolling, steel {RER}| processing | Cut-off, S	836.2 kg		
<u>Water purifier and feed tank</u>			
Reinforcing steel {RER}| production | Cut-off, S	232.3 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Polyethylene, low density, granulate {RER}| production | Cut-off, S	464.6 kg		
Sheet rolling, steel {RER}| processing | Cut-off, S	232.3 kg		
Extrustion, plastic pipes {RER}, extrustion, plastic pipes | Cut-off, S	464.6 kg		
Water			
Water, ultrapure {RER}| market for, ultrapure | Cut-off, S	-	Scenario 1: 40953 kg Scenario 2: 122859 kg Scenario 3: 204765 kg Scenario 4: 409530 kg	-

		Scenario 5: 614295 kg	
Fuelling station			
High pressure storage (per 10 kg)			
Steel chromimum steel 18/8 {GLO}| market for | Cut-off, S	9.0 kg	Scenario 1: 3.1 p Scenario 2: 9.2 p Scenario 3: 15.3 p Scenario 4: 30.5 p Scenario 5: 45.7 p	For one year: divided by 15
Steel, low-alloyed {GLO}| market for | Cut-off, S	9.0 kg		
Aluminium wrought alloy {GLO}| Cut-off, S	6 kg		
Epoxy resin {ROW}| epoxy resin production | Cut-off, S	30.6 kg		
Carbon fibre reinforced plastic, injection moulded {GLO}| carbon fibre reinforced plastic, injection moulded| Cut-off, S	71.4 kg		
Sheet rolling, chromium steel {GLO}| market for | Cut-off, S	9 kg		
Sheet rolling, aluminium {GLO}| market-for, Cut-off, S	6 kg		
Sheet rolling. Steel {GLO}| market for | Cut-off, S	9 kg		
Dispenser			
Steel, low-alloyed {GLO}| market for | Cut-off,S	100 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 15
Aluminium, wrought alloy {GLO}| aluminium ingot, primary to market | Cut-off, S	30 kg		
Synthetic rubber {RER}| production | Cut-off, S	5 kg		
Sheet rolling, steel {GLO}| market for| Cut-off, S	100 kg		

Sheet rolling, chromium steel {GLO}| market for, Cut-off, S	30 kg		
Compressor			
Air compressor, screw-type ccompressor 4kW {RER}| production | Cut-off,S	1 p	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 15
Hydrogen GPU			
Fuel cell – bipolar plates (per 1kW)			
Graphite {RER}| production | Cut-off, S	0.1435 kg	Scenario 1: 120 p Scenario 2: 120 p Scenario 3: 120 p Scenario 4: 120 p Scenario 5: 120 p	For one year: divided by 25
Phenolic resin {RER}| production | Cut-off, S	0.2869 kg		
Injection moulding {RER}| processing | Cut-off,S	0.4304 kg		
Fuel cell – BOP			
Reinforcing steel {GLO}| market for | Cut-off,S	24 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Aluminium, primary, cast alloy slab from continuous casting {GLO}| market for | Cut-off, S	6 kg		
Steel, Chromium steel 18/8 {GLO} | market for | Cut-off,S	3.6 kg		
Polyethylene, high density, granulate {RoW}| production | Cut-off,S	3.6 kg		
Polyphenylene sulfide {GLO}| production| Cut-off,S	18 kg		
Ethylene glycol {RoW}| production| Cut-off,S	12 kg		
Synthetic rubber {GLO}| market for | Cut-off,S	3.6 kg		

Electronics, for control units {GLO}| market for | Cut-off,S	4.8 kg		
<u>Fuel cell – catalyst layer (per 1kW)</u>			
Platinum {GLO}| market for | Cut-off,S	0.00015 kg	Scenario 1: 120 p Scenario 2: 120 p Scenario 3: 120 p Scenario 4: 120 p Scenario 5: 120 p	For one year: divided by 25
Carbon black {GLO}| market for | Cut-off,S	0.00023 kg		
Tetrafluorethylene {RoW}| production | Cut-off,S	0.000011 kg		
Sulfuric acid {GLO}| market for | Cut-off,S	0.000008 kg		
Ethllyene glycol {RoW} | production | Cut-off,S	0.000019 kg		
Water, ultrapure {RER}| water production, ultrapure | Cut-off,S	0.000188 kg		
Cobalt {GLO}| market for | Cut-off,S	0.00003 kg		
Acetic acid, without water, in 98% solution state {RoW}| oxidation of butatne | Cut-off,S	0.05 kg		
Selective coat, stainless steel sheet, black chrome {GLO}| market for | Cut-off,S	0.24 m2		
Thermoforming of plastic sheets {RoW}| processing | Cut-off,S	0.08554 kg		
<u>Fuel cell – end plates</u>			
Aluminium, primary, cast alloy slab from continuous casting {GLO}| market for | Cut-off,S	4.8 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Steel, chromium steel 18/8 {GLO}| market for | Cut-off,S	3.96 kg		
<u>Fuel cell – GDL + MDL (per 1 kW)</u>			

Carbon black {GLO}| market for | Cut-off,S	0.00301 kg	Scenario 1: 120 p Scenario 2: 120 p Scenario 3: 120 p Scenario 4: 120 p Scenario 5: 120 p	For one year: divided by 25
Carbon fibre reinforced plastic, injection moulded {GLO}| carbon fibre reinforced plastic, injection moulded| Cut-off,S	0.051 kg		
Tetrafluorethylene {RER}| production | Cut-off,S	0.009 kg		
Thermoforming of plastic sheets {GLO}| market for | Cut-off,S	0.0631 kg		
<u>Fuel cell – membrane (per 1kW)</u>			
Tetrafluorethylene{RER}| production | Cut-off,S	0.0109 kg	Scenario 1: 120 p Scenario 2: 120 p Scenario 3: 120 p Scenario 4: 120 p Scenario 5: 120 p	For one year: divided by 25
Sulfuric acid {GLO}| market for| Cut-off,S	0.0081 kg		
Titanium dioxide {RER}| market for | Cut-off,S	0.0019 kg		
Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off,S	0.0215 kg		
<u>Battery</u>			
Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Cut-off,S	15 kg		
<u>H2 storage</u>			
Aluminium, primary, cast alloy slab from continuous casting {GLO}| market for| Cut-off,S	2.05 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Steel, stainless 304, scrap\kg\GLO	0.5 kg		
Epoxy resin {RER}| epoxy resin production | Cut-off,S	1.2 kg		
Carbon fibre reinforced plastic, injection moulded {GLO}| carbon	1.7 kg		

fibre reinforced plastic, injection moulded | Cut-off,S			
<u>Converter</u>			
Converter, for electric passenger car {GLO}| market for| Cut-off,S	10 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
<u>Housing</u>			
Steel, low-alloyed {GLO}| market for | Cut-off,S	104 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25

Diesel Supply Chain

Table A… gives an overview of all the materials, processes, and products that are used as input in SimaPro 9.4. For every material, process or product, the Cut-off,S method is selected. As well that the following sequence as selection method was chosen:

6. {NL}
7. {Europe without Switzerland}
8. {RER}
9. {GLO}
10. {RoW}

The first column of the Table shows the materials, processes, or products chosen in SimaPro. The second column shows the quantity that was given as input for Simapro. The third column shows the quantity for the different scenarios. The fourth column shows the component's lifetime and thus with which number the total emissions were divided.

For example, for the diesel, all the separate parts of the GPU were first specified in SimaPro. After which, those materials are combined into a complete GPU. Lastly, the scenarios were specified, and the third column was used to specify the scenario-specific quantities within those scenarios.

Table A.2.2: Input parameters for SimaPro 9.4, representing the diesel supply chain.

Diesel production			
Diesel {Europe without Switzerland}| diesel production, petroleum refineary operation | Cut-off,S	-	Scenario 1: 15330 kg Scenario 2: 45990 kg Scenario 3: 76650 kg Scenario 4:153300 kg Scenario 5:229950 kg	-
Transport			
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | Cut-off,S	-	Scenario 1: 57.33 tkm Scenario 2: 172.38 tkm Scenario 3: 286.65 tkm Scenario 4: 573.3 tkm Scenario 5: 859.95 tkm	-
Fueling station			
<u>Storage</u>			
Steel, low-alloyed {GLO}| market for | Cut-off,S	-	Scenario 1: 33.49 kg Scenario 2: 100.46 kg Scenario 3: 167.44 kg	For one year: divided by 30

		Scenario 4: 334.88 kg Scenario 5: 502.32 kg	
Dispenser			
Steel, low alloyed {GLO}| market for | Cut-off,S	100 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 30
Aluminium, wrought alloy {GLO}| aluminium ingot, primary, to market | Cut-off,S	30 kg		
Synthetic rubber {RER}| production | Cut-off,S	5 kg		
Sheet rolling, steel {GLO}| market for | Cut-off,S	100 kg		
Sheet rolling, steel {GLO}| market for | Cut-off,S	100 kg		
Sheet rolling, aluminium {GLO}| market for | Cut-off,S	30 kg		
Diesel GPU			
Generating set			
Diesel-electric generating set, 18.5 kW {GLO}| production | Cut-off,S	5 p	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Storage			
Polyethylene, low density, granulate {GLO}| market for| Cut-off,S	26 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Converter			

Converter, for electric passenger car {GLO}| market for | Cut-off,S	10 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
<u>Housing</u>			
Steel, low alloyed {GLO}| market for | Cut-off,S	104 kg	Scenario 1: 1p Scenario 2: 1p Scenario 3: 1p Scenario 4: 1p Scenario 5: 1p	For one year: divided by 25
Burning diesel			
Diesel, burned in diesel-electric generating set, 18.5 kW {GLO}| diesel, burned in diesel-electric generating set, 18.5 kW | Cut-off,S	-	Scenario 1: 654591 MJ Scenario 2: 1963773 MJ Scenario 3: 3272955 MJ Scenario 4: 6545910 MJ Scenario 5: 9818865 MJ	-

Appendix 3: Impact categories

Table A 3.1: An overview of the impact categories considered in other LCA research

	Impact category	Unit	References	Count
ReCiPe method	Global warming potential	Kg CO_2-eq	Agostini et al. (2018); Benitez et al. (2021); Bhandari & Trudewind (2014); Burkhart et al. (2016); Centinkaya et al. (2012); Yang et al. (2020); Evangelisti et al. (2017); Cooney et al. (2013); Wulf & Kaltschmitt (2012); Lucas et al. (2013); Pehnt (2001); Simons & Bauer (2015); Benveniste et al., (2017); Lombardi et al. (2017); Girandi et al. (2015); Mori et al. (2021); Girandi et al. (2015); Nanaki & Koroneos (2021)	17
	Stratospheric ozone depletion	Kg CFC11 eq	Lombardi et al. (2017); Girandi et al. (2015); Garrain et al. (2021); Beveniste et al. (2017); Rinawati et al. (2021); Cooney et al. (2013)	6
	Ionizing radiation	kBq Co-60 eq	Lombardi et al. (2017); Girandi et al. (2015); Garrain et al. (2021)	4
	Ozone formation Human health	Kg NOx eq	Lombardi et al. (2017); Gerloff (2021); Girandi et al. (2015); Rinawati et al., (2021)	
	Fine particulate matter formation	Kg PM2.5 eq	Benitez et al. (2021); Lombardi et al. (2017); Girandi et al. (2015); Wulf & Kaltschmitt (2012); Rinawati et al. (2021); Garrain et al. (2021)	6
	Ozone formation Terrestrial ecosystems	Kg NOx eq	Lombardi et al. (2017); Girandi et al. (2015); Rinawati et al. (2021)	3
	Terrestrial acidification	Kg SO2 eq	Benitez et al. (2021); Benveniste et al., (2017); Burkhardt et al. (2016); Lombardi et al. (2017); Girandi et al. (2015); Cooney	13

			et al. (2013) ; Wulf & Kaltschmitt (2012); Pehnt (2001); Simons & Bauer (2015); Mori et al. (2021); Evangelisti et al. (2017); Garrain et al. (2021); Rinawati et al. (2021); Cooney et al. (2013)	
	Freshwater eutrophication	Kg P eq	Benveniste et al., (2017); Lombardi et al. (2017); Girandi et al. (2015); Wulf & Kaltschmitt (2012)	4
	Marine eutrophication	Kg N eq	Benveniste et al. (2017); Lombardi et al. (2017); Garrain et al. (2021); Wulf & Kaltschmitt (2012); Rinawati et al. (2021); Cooney et al. (2021)	6
	Terrestrial ecotoxicity	Kg 1,4-DCB	Burkhardt et al. (2016); Lombardi et al. (2017); Girandi et al. (2015); Cooney et al. (2013); Mori et al. (2021)	5
	Freshwater ecotoxicity	Kg 1,4-DCB	Burkhardt et al. (2016); Lombardi et al. (2017); Garrain et al. (2021); Girandi et al. (2015); Nanaki & Koroneos (2012); Mori et al. (2021)	6
	Marine ecotoxicity	Kg 1,4-DCB	Benveniste et al. (2017); Lombardi et al. (2017); Girandi et al. (2015); Nanaki & Koroneos (2012); Mori et al. (2021); Cooney et al., (2013)	6
	Human carcinogenic toxicity	Kg 1,4-DCB	Barrato & Diwekar (2005); Benitez et al. (2021); Burkhardt et al. (2016); Lombardi et al. (2017); Evangelisti et al. (2017); Garrain et al. (2021); Gerloff (2021); Girandi et al. (2015); Cooney et al. (2013); Wulf & Kaltschmitt (2012); Rinawati et al. (2021); Nanaki & Koroneos (2012); Mori et al. (2021)	13

	Human non-carcinogenic toxicity	Kg 1,4-DCB	Benitez et al. (2021); Burkhardt et al. (2016); Lombardi et al. (2017); Evangelisti et al. (2017); Garrain et al. (2021); Gerloff (2021); Girandi et al. (2015); Cooney et al. (2013); Wulf & Kaltschmitt (2012); Rinawati et al. (2021); Mori et al. (2021)	11
	Land use	M2a crop eq	Lombardi et al. (2017); Garrain et al. (2021); Girandi et al. (2015); Mori et al. (2021)	4
	Mineral resource scarcity	Kg Cu eq	Lombardi et al. (2017); Garrain et al. (2021); Girandi et al. (2015); Agostini et al. (2018)	4
	Fossil resource scarcity	Kg oil eq	Lombardi et al. (2017); Garrain et al., (2021); Girandi et al. (2015); Nanaki & Koroneos (2012); Agostini et al. (2018)	5
	Water consumption	M3	Lombardi et al. (2017); Garrain et al. (2021); Girandi et al. (2015)	3
	Abiotic depletion	Kg Sb eq	Mori et al. (2021); Agostini et al. (2018); Evangelisti et al. (2017); Rinawati et al. (2021); Girandi et al. (2015); Beveniste et al. (2017)	6
	Eutorphication	Kg SO2 eq	Mori et al. (2021); Girandi et al., (2015); Garrain et al. (2021); Nanaki & Kokolores (2012)	4
	Ozone layer depletion	Kg CFC-11 eq	Mori et al. (2021)	1
	Marine sediment ecotoxicity	Kg 1,4-DB eq	Mori et al. (2021)	1
	Freshwater sediment ecotoxicity	Kg 1,4-DB eq	Mori et al. (2021)	1

	Average European	Kg NOx-eq	Mori et al. (2021)	1
	Average European	Kg SO2-eq	Mori et al. (2021)	1
	Photochemical oxidation	Kg C2H4 eq	Mori et al. (2021); Evangelisiti et al. (2017); Benitez et al. (2021); Beveniste et al. (2017); Garrain et al. (2021); Simons & Bauer (2015); Rinawati et al. (2021); Wulf & Kaltschmitt (2012)	8
	Malodorous air	M3 air	Mori et al. (2021); Girandi et al. (2015)	2
	Equal benefit incremental reactivity	Kg formed O3	Mori et al. (2021)	1
	Max incremental reactivity	Kg formed O3	Mori et al. (2021)	1
	Max Ozone incremental reactivity	Kg formed O3	Mori et al. (2021)	1
	Energy demand	MJ	Benveniste et al. (2017); Lucas et al. (2013); Rinawati et al. (2021); Girandi et al. (2015)	4
	Acute hazard index	ppm	Barrato & Diwekar (2005)	1

Appendix 4: Calculations data solar park

The provided data by Company C is data of 4.5 MWp east-west solar park. Quarterly data in kWh is given for each day in the year 2020. Adding up all the quarterly data per day gives the total amount of generated energy per day in kWh.

$$4500\ kW\ x\ 0.85 = 3825\ kW$$

$$\frac{200\ kW}{3825\ kW} = 5.2\ \%\ of the\ provided\ data$$

The 200 kW of energy is needed from the solar park in the first scenario. The 3825 kW is the adjusted solar park's adjusted capacity, considering practice the conditions are not ideal. The percentages for the other scenarios are provided in Table A… The generated energy is divided by 53 to get the amount of hydrogen that could be produced per day. From Table A… it can be seen that sometimes there is excess hydrogen, and some days there is a hydrogen shortage.

Table A 4.1: Overview of the scenarios together with the provided data of the 4.5 MWp solar park

Scenarios	Capacity needed	Percentage	Hydrogen needed	The smallest amount of hydrogen	The largest amount of hydrogen
Scenario 1	200 kW	5.2%	15 kg	0.427 kg	30.23 kg
Scenario 2	599 kW	15.7%	45 kg	1.29 kg	91.27 kg
Scenario 3	999 kW	26.1%	75 kg	2.15 kg	152.31 kg
Scenario 4	1998 kW	52.2%	150 kg	4.31 kg	304.62 kg
Scenario 5	2998 kW	78.4 %	225 kg	6.45 kg	456.92 kg

Appendix 5: Diesel and hydrogen figures separately

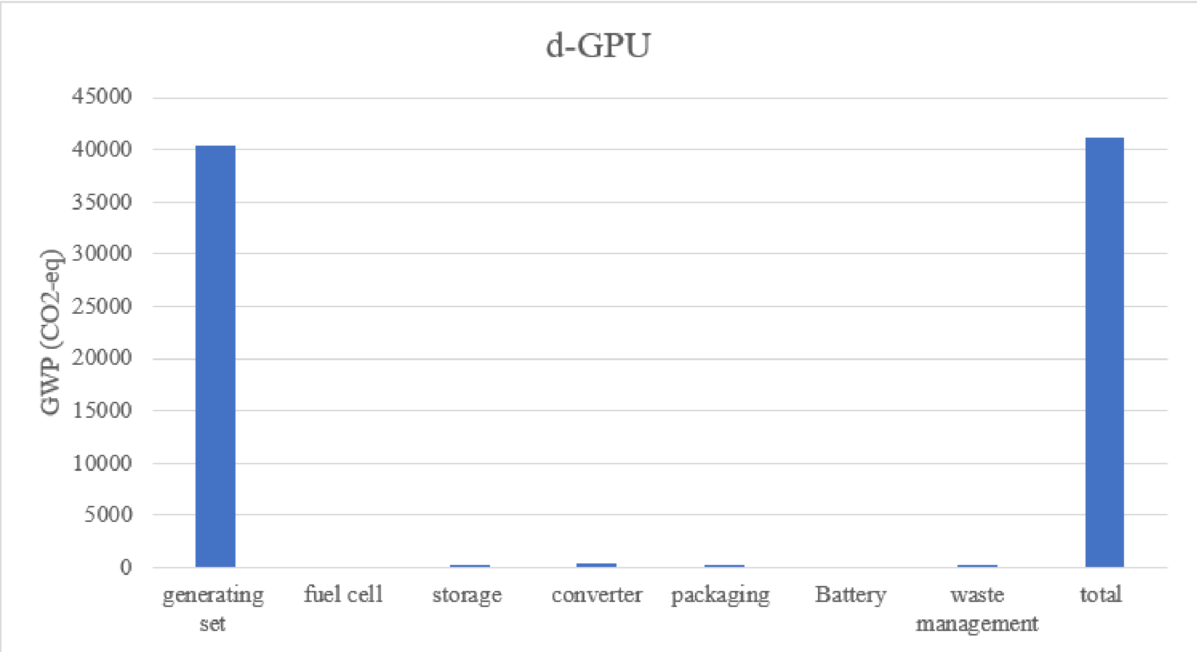

Figure A 5.1. The GWP of components of a d-GPU.

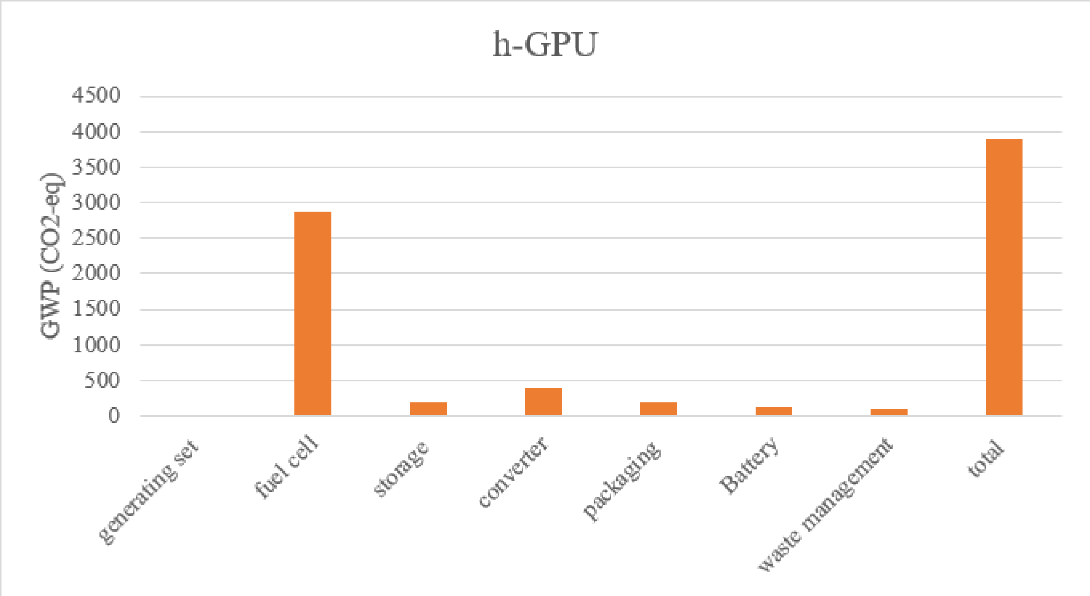

Figure A 5.2. The GWP of components of a hydrogen GPU.

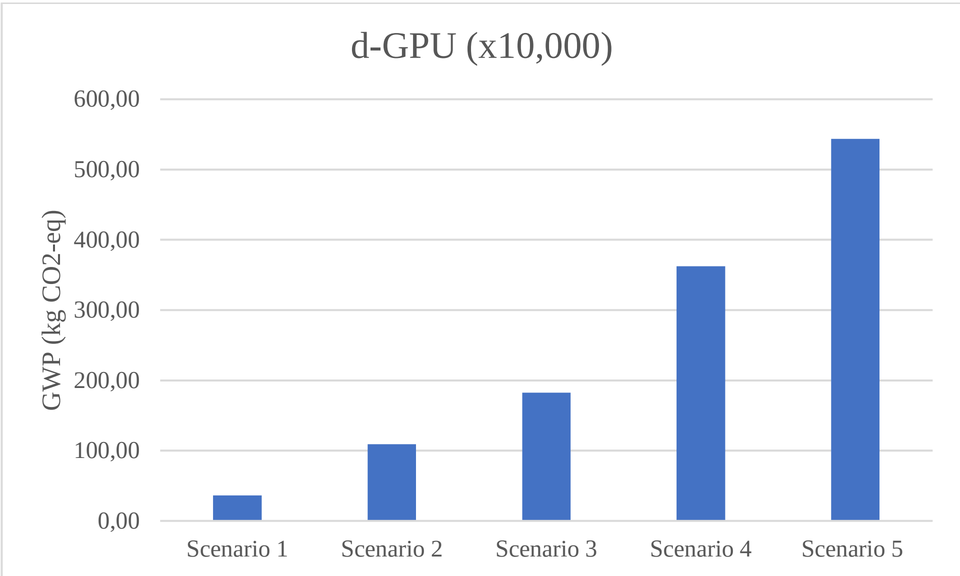

Figure A 5.3. GWP of the diesel supply chain for the five scenarios

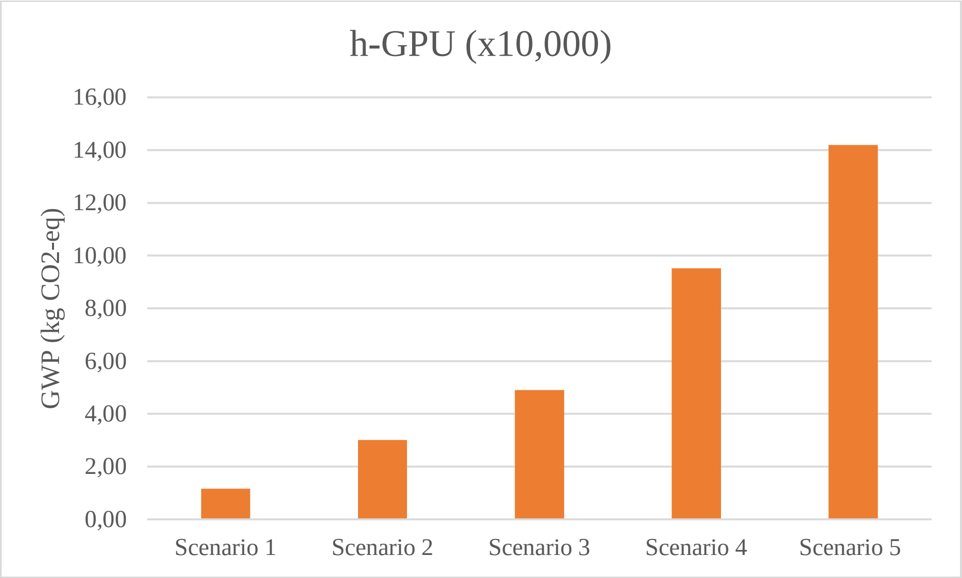

Figure A 5.4. GWP of the hydrogen supply chain for the five scenarios

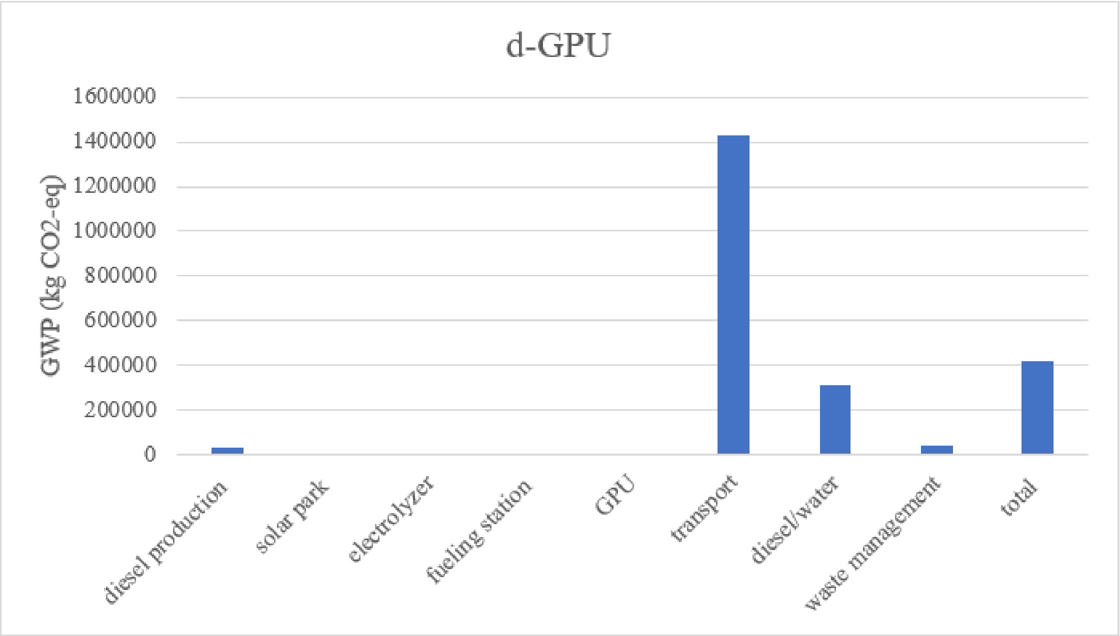

Figure A 5.5. The GWP of the diesel supply chain

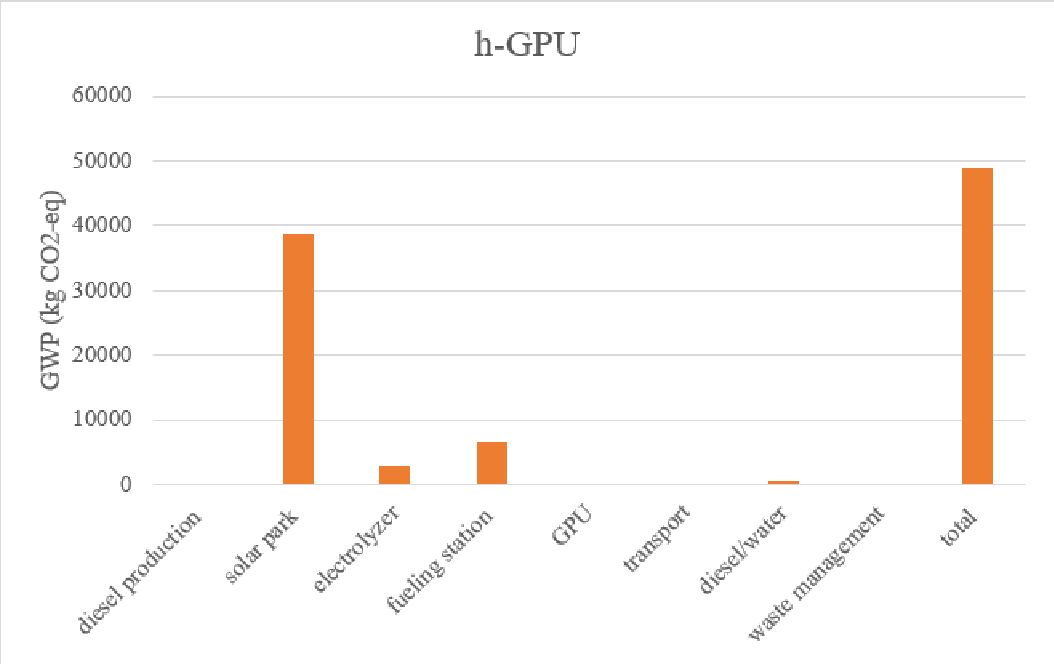

Figure A 5.6. The GWP of the hydrogen supply chain

Appendix 6: fuelling station

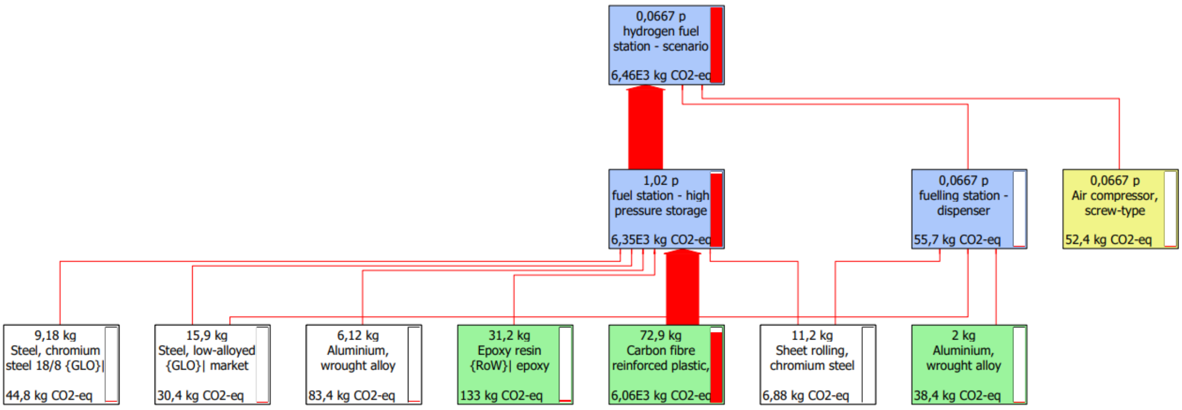

Figure A 6.1. Overview of the contribution of materials, processes and products to the fuelling station

Appendix 7: ReCiPe method

Table A 7.1: ReCiPe method of scenario 3 for the diesel supply chain

Impact category	Unit	Total	Diesel fuelling station	Diesel production	d-GPU	Burning diesel	Transport

Global warming	kg CO2 eq	1.78E+06	3.89E+01	3.52E+04	1.68E+03	3.15E+05	1.43E+06
Stratospheric ozone depletion	kg CFC11 eq	1.22E+00	9.00E-06	6.98E-02	4.87E-04	2.95E-01	8.58E-01
Ionizing radiation	kBq Co-60 eq	1.67E+04	1.18E-01	1.92E+03	6.68E+00	2.09E+03	1.27E+04
Ozone formation, Human health	kg NOx eq	1.15E+04	9.97E-02	1.49E+02	4.42E+00	4.82E+03	6.52E+03
Fine particulate matter formation	kg PM2.5 eq	3.57E+03	7.67E-02	1.04E+02	3.69E+00	1.29E+03	2.18E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.18E+04	1.03E-01	1.59E+02	4.50E+00	4.86E+03	6.74E+03
Terrestrial acidification	kg SO2 eq	7.52E+03	1.47E-01	3.11E+02	8.18E+00	2.29E+03	4.90E+03
Freshwater eutrophication	kg P eq	2.43E+02	2.27E-03	3.33E+01	1.18E-01	3.49E+01	1.75E+02
Marine eutrophication	kg N eq	5.17E+00	7.64E-04	1.01E-01	3.50E-02	7.81E-01	4.25E+00
Terrestrial ecotoxicity	kg 1,4-DCB	1.10E+07	1.27E+02	1.15E+05	1.70E+04	6.96E+05	1.02E+07
Freshwater ecotoxicity	kg 1,4-DCB	1.52E+03	1.11E-01	8.88E+01	4.00E+00	1.67E+02	1.26E+03
Marine ecotoxicity	kg 1,4-DCB	7.91E+03	2.29E-01	2.95E+02	1.66E+01	7.35E+02	6.86E+03
Human carcinogenic toxicity	kg 1,4-DCB	3.54E+04	7.10E+00	3.07E+02	1.47E+02	3.13E+03	3.18E+04
Human non-carcinogenic toxicity	kg 1,4-DCB	4.63E+05	1.56E+01	5.97E+03	1.45E+03	3.50E+04	4.21E+05
Land use	m2a crop eq	6.37E+04	6.78E-01	3.66E+03	3.63E+01	4.45E+03	5.56E+04

Mineral resource scarcity	kg Cu eq	7.17E+03	1.18E+00	6.49E+01	3.56E+01	7.43E+02	6.32E+03
Fossil resource scarcity	kg oil eq	6.60E+05	8.81E+00	8.86E+04	3.82E+02	9.67E+04	4.74E+05
Water consumption	m3	4.35E+03	2.94E-01	3.02E+01	1.28E+01	3.37E+02	3.97E+03

Table A 7.2: ReCiPe method of scenario 3 for the hydrogen supply chain

Impactcategory	**Unit**	**Total**	**h-GPU**	**Electrolyser**	**Solar park**	**Hydrogen fuelling station**	**Water**	**Waste scenario**
Global warming	kg CO2 eq	1.58E+05	1.54E+02	2.97E+03	3.95E+04	6.59E+03	5.89E+02	1.08E+05
Stratospheric ozone depletion	kg CFC11 eq	1.34E-01	4.98E-04	5.56E-03	1.89E-02	1.84E-03	2.98E-04	1.07E-01
Ionizing radiation	kBq Co-60 eq	3.90E+02	7.89E-01	1.75E+01	2.96E+02	3.75E+01	1.86E+01	2.02E+01
Ozone formation, Human health	kg NOx eq	1.94E+02	9.52E-01	8.63E+00	1.04E+02	1.41E+01	1.07E+00	6.54E+01
Fine particulate matter formation	kg PM2.5 eq	1.26E+02	9.11E-01	1.11E+01	8.72E+01	1.28E+01	8.50E-01	1.36E+01
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.01E+02	9.76E-01	8.91E+00	1.10E+02	1.43E+01	1.09E+00	6.58E+01
Terrestrial acidification	kg SO2 eq	2.64E+02	2.88E+00	1.94E+01	1.78E+02	2.59E+01	2.06E+00	3.53E+01

Freshwater eutrophication	kg P eq	1.80E+01	2.73E-02	2.91E-01	4.08E+00	3.69E-01	9.21E+00	4.03E+00
Marine eutrophication	kg N eq	6.24E+00	1.76E-03	5.42E-02	1.83E+00	3.12E-02	1.28E+00	3.04E+00
Terrestrial ecotoxicity	kg 1,4-DCB	1.51E+06	1.20E+03	1.24E+05	1.32E+06	1.49E+04	1.02E+03	5.16E+04
Freshwater ecotoxicity	kg 1,4-DCB	5.18E+02	5.05E-01	1.46E+01	5.59E+01	5.63E+00	4.85E-01	4.41E+02
Marine ecotoxicity	kg 1,4-DCB	1.69E+03	1.56E+00	7.69E+01	9.67E+02	1.22E+01	1.39E+00	6.29E+02
Human carcinogenic toxicity	kg 1,4-DCB	3.30E+03	8.40E+00	9.43E+02	9.72E+02	9.63E+01	2.54E+01	1.26E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	6.40E+04	9.49E+01	5.33E+03	3.93E+04	1.41E+03	1.34E+02	1.77E+04
Land use	m2a crop eq	1.70E+03	4.22E+00	1.06E+02	1.23E+03	1.81E+02	1.52E+01	1.64E+02
Mineral resource scarcity	kg Cu eq	8.06E+02	8.07E+00	3.01E+02	4.37E+02	1.60E+01	2.26E+00	4.12E+01
Fossil resource scarcity	kg oil eq	1.46E+04	4.20E+01	7.05E+02	1.06E+04	1.64E+03	1.48E+02	1.45E+03
Water consumption	m3	2.14E+03	1.36E+00	3.37E+01	1.59E+03	4.14E+01	2.39E+02	2.31E+02

Appendix 8: Cost assessment

Table A 8.1: The hydrogen supply chain and its investment and usage costs

Hydrogen component	Costs	Lifetime	Costs per year
Solar park	€800,000 per hectare (Roos, 2018)	30 years (Company C, 2022)	€26,667 per year per hectare
Electrolyser	€500 per kW (Reuß et al., 2019)	25 years (Evangelisti et al., 2017)	€2 per year per kW
Fuelling station	€1,700,000 (Reuß et al., 2017)	15 years (Wulf & Kaltschmitt 2012)	€113,333 per year
Hydrogen GPU	€200,000 per GPU (Oechies, 2022a)	25 years (Oechies, 2022a)	€25,000 per year
Ultrapure water	€696.26 per 1000 litres (ReAgent Chemical Service Ltd, 2022)	-	-

Table A 8.2: The diesel supply chain and its investment and usage costs

Diesel component	Costs	Lifetime	Costs per year
Purchasing diesel	€1.90 per liter (Nederland prijzen van diesel, n.d.) €0.51 per km (Bridgestone Mobiliy Solution BV, n.d.)	-	-
Truck	€160.000 (Reuß et al., 2017)	8 years (Reuß et al., 2017)	€8,000 per year
Fuelling station	€250.000 (Schumaker, 2022)	30 years (Moolla et al., 2015)	€8.333 per year
Diesel GPU	€85,000 (Kolk, 2022)	25 years (Oechies, 2022a)	€3,400 per year

Table A 8.3: The amount of diesel used per year in litres per scenario

	Amount of diesel per year
Scenario 1	42 kg/0.85 = 49.4 l 49.4 l * 365 days = 18,035 l
Scenario 2	126/0.85 = 148.2 l 148.2 * 365 days = 54,106 l
Scenario 3	210/0.85 = 247.1 l 247.1 * 365 = 90,177 l
Scenario 4	420/0.85 = 494.1 l 494.1*365 = 180,353 l
Scenario 5	630/0.85=741.2 l 741.2*365=270,529 l

Table A 8.4: Cost calculations for the hydrogen and diesel supply chain

Scenario	Hydrogen	Diesel
Scenario independent costs	€133,333 + €25,000 = €158,333	€8,000 + €8,333 + €3,400 = €19,733
Scenario 1	0.22 hectare * €26,667 = €5,866.74 37,5 kW * €2 = €75 €696.26 * 40.953 = €28,513.94	2981.16 tkm * €0.51 = €1,520.39 18035 l * €1.90 = €34,266.50
Total scenario 1	€192,788.68	€55,519.89
Scenario 2	0.64 hectare * €26,667 = €17,066.88 112.5 kW * €2 =225 €696.26 * 122.859 = €85,566.87	8963.76 tkm * €0.51 = €4,571.52 54106 l * €1.90 = €102,801.40
Total scenario 2	€261,191.75	€127,105.92
Scenario 3	1.08 hectare * €26,667 = €28,800.36 187.5 kW * €2 = €375 €696.26 * 204.765 = €142,569.68	14905.8 tkm * €0.51 = €7,601.96 90177 l * €1.90 = €171,336.30
Total scenario 3	€330,078.04	€198,671,26
Scenario 4	2.14 hectare * €26,667 = €57,067.38 375 kW * €2 = €750 €696.26 * 409.530 = €285,139.36	29811.6 tkm * €0.51 = €15,203.92 180353 l * €1.90 = €342,670.70
Total scenario 4	€501,289.74	€377,607.62
Scenario 5	3.22 hectare * €26,667 = €85,867.74 526.5 kW * €2 = €1,053 €696.26 * 614.295 = €427,709.04	44717.4 tkm * €0.51 = €22,805.87 270529 l * €1.90 = €541,005.10
Total scenario 5	€672,962.78	€556.543.97

According to Trading Economics (n.d.), a ton of CO_2-eq is €85. This is a price that has to be paid over the emissions during their production process. For the airport, this is the emissions of the aeroplanes and the ground support equipment. Not of the production of this equipment. Therefore, for the scope of this research, the CO2 emitted as the cause of the burning of diesel is considered for these prices. If the transport of diesel is kept inhouse by the airport, than the emissions of transport have to be considered as well and also be considered for the ETS prices.

Table A 8.5: Cost gaps and the calculated ETS costs for the five scenarios

	Burning diesel (tons CO_2-eq)	**Burning diesel + transport (tons CO_2-eq)**	**Cost difference hydrogen and diesel**
Scenario 1	62 * €85 = €5,270	347 * €85 = €29,495	€137,268.79
Scenario 2	188 * €85 = €15,980	1,040 * €85 = €88,400	€134,087.73
Scenario 3	315 * €85 = €26,775	1,750 * €85 = €148,750	€131,406.73
Scenario 4	627 * €85 = €53,295	3,470 * €85 = €294,950	€123,691.12
Scenario 5	940 * €85 = €79,900	5,210 * €85 = €442.850	€116,418.81

Appendix B. Economic Effects of Sustainable Energy Supply at Regional Airports: The Transformation Towards Hydrogen Ground Power Units (h-GPUs) at Groningen Airport Eelde

Abstract

Objective: The aviation industry faces growing pressure to reduce its enormous carbon emissions. The transition towards a sustainable energy supply is needed for the airports to decarbonize, whereby hydrogen is a high potential to reach carbon neutrality. However, high initial investment costs for green hydrogen form an obstacle to the implementation of hydrogen at airport operati The primary source of emission is caused by powering the aircraft during turnaround times by diesel ground power units (d-GPUs). Therefore, this study aims to determine the costs and benefits of acquiring a hydrogen fuel cell-powered ground power unit (h-GPU) at a regional airport and compare it to a traditional GPU.

Methodology: This is achieved using an economic model and simulation, including energy consumption costs, capital expenditures, and operational expenditures, based on real-life data and expert knowledge. The simulation is based on the energy demand of an h-GPU and the supply provided by the solar park, hydrogen storage tank, and grid. The baseline is expanded by three scenarios to enlarge the understanding of costs and benefits. Also, a sensitivity analysis is conducted on the electricity cost of PV, diesel price, and carbon emission cost.

Findings: The study found that the GPU is economically more profitable than the h-GPU in the baseline scenario. However, in the scenario where demand is doubled, the h-GPU provides a market opportunity, as its NPV exceeds the NPV of the GPU. Implementing the carbon emission tax and doubling the demand, further increased the market opportunity for the h-GPU. In the scenario with increased demand, the hydrogen unit costs decrease from €5.97/kg to €3.80/kg by the economics of scale.

Conclusion: Ultimately, implementing h-GPU at regional airports presents promising opportunities, increasing the potential to become a regional hydrogen hub. Increasing the hydrogen implementation in ground support equipment (GSE) of airports will further increase the viability and reduce the unit production costs of hydrogen. However, further developments are needed to make this economically visible for larger airports and foreign countries that depend more on outside energy sources.

Keywords: green hydrogen fuel cell, renewable energy, regional airport, cost and benefit, simulation model

1. Introduction

The European Union is making significant efforts to attain climate neutrality by 2050 in response to the damaging effects of greenhouse gas (GHG) emissions on the environment (European Commission, 2021). To reach this goal, electrification, energy efficiency, and the utilization of renewable energy sources (RES) are estimated to achieve roughly 70% of the necessary reductions in carbon dioxide (CO_2) emissions toward a net-zero energy system (IRENA, 2022). However, full decarbonization will necessitate the integration of hydrogen as a critical component (IRENA, 2022). Hydrogen can be produced from renewable sources like solar and wind energy, and while RES can be generated globally, their cost-effectiveness can vary depending on location (IRENA, 2022). Additionally, hydrogen has several advantages, including being transported via existing gas pipelines and ships, stored in salt caverns, used locally, and converted into electricity by fuel cells (FC) (Farahani *et al.*, 2020). These characteristics make hydrogen a valuable energy carrier for countries that rely on imports of fossil fuels (Dunn, 2002; Staffell et al., 2019).

The aviation industry presents unique challenges in reducing CO_2 emissions (Morrow, Hochard, and Francfort, 2007). This sector accounts for approximately 5% of global GHG emissions (Lai *et al.*, 2022). Moreover, the industry's dependency on fossil fuels and its anticipated growth that exceeds the average growth rate of other sectors only exacerbate the problem (Gonzalez-Garay *et al.*, 2022). Therefore, there is an increasing demand for adopting renewable power sources and environmentally friendly technologies within the industry (Baroutaji *et al.*, 2019). For the aviation industry to decarbonize, the transition towards biofuels and hydrogen is deemed crucial by the Intergovernmental Panel on Climate Change (IPPC, 2021).

Even though the fuel consumption of aircraft is the most significant contributor to carbon emissions in the aviation industry, this study focuses on the early implementation of electrifying airports. The integration of hydrogen resources and electrification into airport energy systems is seen as a solution for mitigating carbon emissions (Kılkış and Kılkış, 2017; Zhao *et al.*, 2022). During aircraft turnaround times, ground support equipment (GSE) is utilized for loading, cleaning, repositioning, and taxiing aircraft (Greer, Rakas, and Horvath, 2020). The primary source of carbon emissions at airports is the power supply for aircraft, which can be provided either through an auxiliary power unit (APU) on the plane or through an external d-GPUs (Padhra, 2018). It is imperative to find a carbon-neutral alternative for powering aircraft during these times to meet decarbonization targets. Transitioning to hydrogen ground power units (h-GPUs) is essential for reaching the net-zero emissions goal by 2030. Moreover, such a transition would allow airports to become regional hydrogen hubs and reduce their dependence on congested national grids.

Despite its numerous benefits in the energy sector, the global dissemination of hydrogen faces several challenges that impede its implementation. One obstacle to producing hydrogen from RES is the high initial investment costs associated with the required technology, such as electrolyzers, fuel cells, hydrogen storage tanks (HST), and refueling equipment (Zhou and Searle, 2022). Moreover, the growth of the clean hydrogen industry faces additional constraints from regulatory restrictions and the slow advancement of hydrogen infrastructure developments (IEA, 2019). In contrast to these challenges, the International Energy Agency (IEA, 2019) projects that the cost of producing hydrogen from RES could decrease by 30% by 2030 due to declining costs of renewable energy technologies and the scaling up of hydrogen production.

For airports to reach their carbon-neutral targets, decision-makers must evaluate the necessary investment costs for the transition. Given that the most significant carbon emissions at airports occur during aircraft ground power operations, assessing the cost implications of transitioning to hydrogen for this purpose is essential. This study aims to contribute to the implementation of hydrogen at airports by examining the economic effects of the transformation at a regional airport in the Northern Netherlands. The findings of this study will be valuable to policymakers and airport managers in making informed and well-rounded decisions. The research question of this study is: What are the costs and benefits of transforming towards a h-GPU for airports?

To answer the question and achieve the objective of this study, a cost assessment is conducted that analyzes the total costs associated with establishing a h-GPU. Moreover, the net present value (NPV) for GPU and h-GPU are compared to evaluate the economic feasibility of transforming to a h-GPU. A simulation model is developed to estimate the energy consumption and distribution based on the hydrogen demand of aircraft. For this instance, Groningen Airport Eelde has been selected due to its aspiration to be recognized as Europe's first Hydrogen Valley Airport and its efforts towards achieving this goal (GAE, 2021). In addition, to gain a more comprehensive understanding of the system under investigation, the study expanded the baseline scenario by incorporating three scenarios: (A) doubled demand, (B) carbon emission tax, and (C) doubled demand and carbon emissions tax. Furthermore, a sensitivity analysis is conducted on the key parameters to assess their impact.

The result shows that in all scenarios, the total costs and revenues for the h-GPU are higher than the GPU. Specifically, when demand is doubled, transitioning towards an h-GPU becomes economically feasible, as the NPV of the h-GPU is found to be 22% higher than that of the GPU. Furthermore, when demand is doubled and a carbon emission tax is implemented, the market opportunity for h-GPU further increases. Because the hydrogen unit cost decreases from €5.96 per kg to €3.80 per kg due to economics of scale and contributes to the increase in NPV for the h-GPU. In contrast, the NPV of the GPU decreases due to the implementation of a carbon emission tax.

The paper continues with an extensive literature review in chapter 2 to provide background information on the research topic. Chapter 3 explains the methodology used to conduct a cost assessment, and chapter 4 describes the simulation model and provides an overview of the scenarios. The results are presented in chapter 5 and are discussed in chapter 6. Lastly, the conclusions are drawn in chapter 7.

2. Literature Review

In the first part of this section, previous research conducted on hydrogen is reviewed. Firstly, the focus will be on the hydrogen infrastructure, which consists of hydrogen production, storage, transportation, and end-use. Thereafter, the hydrogen implementation at airports is investigated, and the focus will be on the sustainable energy supply of the GPU, such as hydrogen fuel cells or battery storage systems (BSS). Furthermore, the financial aspect of hydrogen implementations at airports is discussed. In the final part, the research gap is identified, and the contribution of this paper is elaborated.

2.1. Hydrogen Infrastructure

Due to the undeniable environmental effects of burning fossil fuels, there is an increasing demand for renewable energy sources (RES) as part of the energy transition to combat the climate crisis. (Dawood, Anda and Shafiullah, 2020; Yue *et al.*, 2021). Hydrogen is a promising energy source for the energy transition. The transition from a fossil fuel-based economy towards a clean hydrogen future is globally known as the hydrogen economy (Dawood, Anda, and Shafiullah, 2020) Hydrogen-based fuel-cell technologies provide solutions to reduce environmental pollution, as they provide more efficient production of energy from fuel compared to the traditional systems (Testa *et al.*, 2014). Additionally, hydrogen is a carbon-free fuel at the point of use, as it permits the contamination of emissions such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and hydrocarbons (HC_s) (Testa *et al.*, 2014; Bicer and Dincer, 2017; Baroutaji *et al.*, 2019; Staffell *et al.*, 2019; Dawood, Anda and Shafiullah, 2020; Siddiqui and Dincer, 2021). So, hydrogen has a vital position in the energy transition as it diminishes emissions since pure water is the sole spinoff from the electricity production from hydrogen when produced by fuel cells (Yue *et al.*, 2021).

2.1.1. Production

Hydrogen is not an energy source but an energy carrier; however, it can be converted to use as an energy source. Even though pure hydrogen is hardly a separate element, it can easily be discovered with other elements. For example, hydrogen occurs naturally in water with a combination of oxygen and in various hydrocarbon fuels, plants, and animals in combination with carbon (Dunn, 2002). There are different ways to produce hydrogen. As discussed in Siddiqui and Dincer (2021), hydrogen can be produced by either a conventional production route or a renewable energy-based route, whereby the latter includes wind, solar, hydropower, or geothermal energy resources. To signify hydrogen as a clean energy carrier, it is essential to investigate the environmental effects during its life cycle (Acar and Dincer, 2020; Dawood, Anda, and Shafiullah, 2020; Siddiqui and Dincer, 2021).

A color-coding model distinguishes hydrogen based on the used production technologies (Schlund, Schulte, and Sprenger, 2022). Dawood, Anda, and Shafiullah (2020) and Osman et al. (2022) have disclaimed the color coding model and its correlation with clean hydrogen since it only considers the type of energy and technologies used during the production process. The color-coding model mainly differentiates three types of hydrogen: grey, green, and blue. Generally, grey hydrogen is assumed to be generated using fossil fuels (Osman et al., 2022), such as natural gas steam reforming (Papadis and Tsatsaronis, 2020). Next, green hydrogen is identified as hydrogen produced from renewable energy resources (Yue et al., 2021). The electricity generated from solar panels or wind farms is used in a water electrolyzer to produce hydrogen (Dawood, Anda, and Shafiullah, 2020; Hoelzen et al., 2022). Subsequently, blue hydrogen refers to hydrogen generated from natural gas, at which approximately 90% of the carbon is captured with the support of carbon capture and storage (CCS) (Dawood, Anda, and Shafiullah, 2020; Yue et al., 2021).

2.1.2 Storage and Transportation

Another aspect of the hydrogen infrastructure is storage and transportation. Hydrogen energy storage (HES) is prominent in balancing energy supply and demand, which is especially important for time scale fluctuations and seasonal changes (Reuß et al., 2017; Dawood, Anda, and Shafiullah, 2020). Furthermore, Zini and Dalla Rosa (2014) explain that it is possible to sell excess energy to the grid during high electricity prices due to the advantages of having HES with a RES power plant. Farahani et al. (2020) show that the electricity imbalance between supply and demand during peak moments could be solved by fuel cell electric vehicles (FCEVs), whereby the energy system of office buildings would become more flexible, reliable, and cheaper. Their research also reveals that 20% to 30% of the energy supply comes from storage in a renewable energy system. Hydrogen storage has different ways, whereas physical and chemical storage are the main categories (Baroutaji et al., 2019; Nazir et al., 2020a). Currently, hydrogen is commonly stored in the pressurized gas state, for example, above ground in metallic tanks, cylinders, spherical vessels, or underground, such as in salt caverns or depleted gas and oil reservoirs. (Haghi, Raahemifar, and Fowler, 2018; Baroutaji et al., 2019; Nazir et al., 2020a).

Furthermore, hydrogen in liquid form can be stored in cryogenic tanks, and hydrogen in a solid state can be stored in metal hydrides (Baroutaji *et al.*, 2019). The choice of storage type depends on various factors, including the end-use, geographical limitations, volume, transportation, safety regulations, and installation costs. Each storage form has advantages and disadvantages (Schrotenboer *et al.*, 2022). Also, transportation choice varies depending on similar factors, including hydrogen state, storage form, end-use, distance, and scale. Nazir et al. (2020a) discuss the transportation options for large-scale hydrogen applications, including vessel tanks, trucks, and pipelines. Hassan et al. (2021) emphasize the crucial procedure of determining the optimal sizes of components in a HES, including electrolyzers, fuel cells, and hydrogen storage tanks (HST). The technical and financial limitations in hydrogen storage and transportation are significant drawbacks in developing the hydrogen economy and will be explored further in the subsequent section of the chapter.

2.1.3. End-use

Subsequently, the produced and stored hydrogen is used for multiple sources. According to Wulf et al. (2018), the advantage of generating hydrogen from renewable energy is the provided possibilities within the mobility sector for FCEV and the allowance for storage of electricity surplus. Among other things, hydrogen can be used in the built environment, for example, as heating and electricity, whereas in the industry, it is mainly used as a chemical feedstock (Staffell *et al.*, 2019; Schrotenboer *et al.*, 2022). For instance, Xie et al. (2021) investigated the economic feasibility of powering a data center with hydrogen. Ehret and Bonhoff (2015) and Acar and Dincer (2020) examined the viable implementations of hydrogen fuel for transportation systems.

Furthermore, González-Garay et al. (2019) provided a critical analysis of producing green methanol by using green hydrogen. Testa et al. (2014) explored reducing airport air pollution by transforming it towards h-GSE vehicles. Although hydrogen can be used for various applications, as mentioned, the focus in this paper will be on the potential of hydrogen as a power source, such as electricity, in the transportation sector. The main scope of this study is on the implementation of hydrogen fuel cells at the airport's ground vehicles to provide power to aircraft, specifically the ground power units (GPU), which will be further explained in section 2.3.1.

2.2. Limitations of Hydrogen

The businesses focussing on hydrogen innovation could be perceived as taking part in both organization transformation and system building of the sustainability-orientated innovation (SOI) framework. But there are several challenges, including shifting mindset, collaboration with other industry stakeholders, and creditability requirements, to name a few (Network for Business Sustainability, 2012). One of the main challenges of hydrogen is financial limitations. For example, the hydrogen (storage) system costs are higher than the battery (storage) systems; however, with current research and developments, there is increasing potential to make hydrogen systems competitive by 2030 (Glenk and Reichelstein, 2019; Nazir et al., 2020a; Hassan et al., 2021). Also, the various hydrogen production methods have consequences for production costs (Papadis and

Tsatsaronis, 2020), making hydrogen production more expensive than fossil fuels (Testa et al., 2014; Acar and Acar, and Dincer, 2020). Consequently, the barriers for the mobility sector are the economic feasibility of FCEV and sufficient hydrogen infrastructure (Nazir et al., 2020b) . Another limitation of a hydrogen economy is the indistinct public view on hydrogen (Schmidt and Donsbach, 2016), which negatively influences various stakeholders' trust in hydrogen systems.

2.3. Hydrogen at Airports

Implementing hydrogen and fuel cell technologies in the aviation industry has promising potential (Testa *et al.*, 2014; Baroutaji *et al.*, 2019; Siddiqui and Dincer, 2021; Xiang *et al.*, 2021). Decarbonization of the aviation industry has attained increasing attention, as it currently accounts for over 2.5% of global CO_2 emissions (Kroyan *et al.*, 2022). However, this percentage increases further when airport operations and construction are considered (Greer, Rakas, and Horvath, 2020; Gonzalez-Garay et al., 2022). The decarbonization of airports is especially important to reduce GHG emissions and achieve the goals outlined in the Paris Agreement to limit global temperature rise to 1.5°C above pre-industrial levels (UNFCCC, 2015; Haghi, Raahemifar and Fowler, 2018; Barke *et al.*, 2020).

Numerous studies have been executed about implementing hydrogen within the energy system of the aviation industry as a solution for decarbonization and achieving zero emissions (Xiang *et al.*, 2021; Hoelzen *et al.*, 2022). Accordingly, Xiang et al. (2021) examined the advantages of a techno-economic analysis of the airport electrification system integrated with a hydrogen solar storage energy system. Specifically, the paper observed the benefits of implementing, among other things, electric vehicles (EV), photovoltaic energy (PV), the battery storage system (BSS), and electric auxiliary power unit (APU) of airplanes as a micro-grid solution at airports. The APU of the aircraft is used during the turnaround time when the plane is being prepared for its next flight at the gate. During this turnaround time, passengers, cabin crew, and cargo are unloaded from the plane, and the APU powers the electrical system of the airplane to supply power for the lighting and the air conditioning of the aircraft, as well as support the main engines of the aircraft with starting up (Padhra, 2018; Baroutaji et al., 2019; Salihu, Lloyd and Akgunduz, 2021). Subsequently, research reveals that the APU is a predominant emission emitter with a relatively high usage duration and fuel consumption rate (Padhra, 2018; Baroutaji *et al.*, 2019). Therefore, alternative ways for powering the APU are examined. For example, Boeing and Airbus are exploring the possibilities of converting the traditional diesel engine-powered APU to hydrogen fuel cells (Baroutaji *et al.*, 2019).

2.3.1. Ground Power Units

An alternative way to power an aircraft during turnaround times is using external power suppliers, such as a remote stand-ground power unit (GPU) (Xiang *et al.*, 2021) or electrical contact stands (Padhra, 2018). When the airplane is at a contact stand, passengers can board through a boarding bridge, and when the aircraft is at a remote stand, the passengers need to be carried to the location by bus (Xiang *et al.*, 2021). So, in the contact stand, the aircraft can be powered by energy from the airport, usually located under the boarding bridge (Padhra, 2018; Xiang *et al.*, 2021). But this limits the usage on a broader scale when aircraft are not parked near the terminal. Whereas GPUs can supply energy to aircraft at remote stands since they are mobilized fuel cell vehicles and are an alternative for contact stands. The GPU has the advantage of reducing costs as the power can be converted efficiently and cheaply on the ground and eliminate the adverse side effects of the APU, such as noise and air contamination (Rivera *et al.*, 2018). By extending the usage of GPUs prior to departure, the use of APUs will be minimized (Padhra, 2018). When the GPUs are transitioned to be powered by renewable energy sources, there will be an emission reduction (Destination 2050, 2021). Therefore, airports are increasing the implementation of hydrogen in their energy systems and ground operations using fuel cells, including ground support equipment (GSE) and GPUs (Testa *et al.*, 2014). GSEs are, among other things, used for repositioning, loading, and cleaning parked airplanes (Greer, Rakas, and Horvath, 2020). GPUs are traditionally powered by fossil fuels such as diesel engines; however, new technologies make it feasible to produce hydrogen ground power units (h-GPUs) powered by fuel cells (Testa *et al.*, 2014). Research revealed that the primary emission sources at airports are caused during turnarounds when the airplane is powered by either an APU or a d-GPU (Padhra, 2018). Therefore, the direct solution for decarbonized airports is the transition towards sustainable energy powered by either control stands, remote stand h-GPUs, or battery-powered e-GPUs. Each option has its advantages and disadvantages. The limitations of the h-GPU are related to the challenges of the hydrogen infrastructure. A challenge of the e-GPU is increasing the dependency of the airport on the grid, hence increasing the energy costs (Xiang *et al.*, 2021). Another challenge of e-GPU is the need for ample battery storage and long charging times to supply energy to aircraft. With the increasing potential of hydrogen in the aviation industry and hydrogen infrastructure, a h-GPU is more applicable for wide-body aircraft. An e-GPU is more beneficial for small-sized aircraft with fewer flight hours. The following explains the financial factors of hydrogen implications at airports.

2.3.2. Economic Aspects of Hydrogen at Airports

As aforementioned, the main barrier to the hydrogen economy is the economic limitations of hydrogen production and infrastructure. For example, research reveals that the production costs of green hydrogen and the system capital cost are currently uncompetitive due to the inefficiency and consequently increasing operations and maintenance costs (OMC) for fuel cell systems and electrolyzer systems (Qyyum *et al.*, 2021; Yue *et al.*, 2021; Terlouw *et al.*, 2022). Testa et al. (2014) emphasize that there is a need for an accurate cost analysis when a new technology is commercially applied. Additionally, according to Terlouw et al. (2022), a life cycle analysis and overall cost assessments are generally accepted to identify the environmental and economic trade-offs of HES. Therefore, airports need to consider the transformation towards h-GPUs financially. Even though limited research is conducted about the financial aspects of a h-GPU, there are cost assessment studies evaluating hydrogen production and FCEVs.

For example, Terlouw et al. (2022) examined the hydrogen production costs using water electrolyzers and RES. They concluded that green hydrogen could compete with grey hydrogen since natural gas prices have recently increased. Glenk and Reichelstein (2019) revealed that gaseous green hydrogen is economically feasible for small and medium-scale applications and will become competitive for industrial-scale supply in a decade. Hoelzen et al. (2022) revealed that a supply of low-cost green liquid hydrogen infrastructure is required for the economic feasibility of hydrogen aviation fuel, which was conducted by a cost assessment on direct operating costs (DOC). Research also covers the economic feasibility of hydrogen-powered buildings, using hydrogen fuel cells and solar energy, with a net present cost analysis using a simulation by Singh, Baredar, and Gupta (2017) or a life cycle cost analysis (LCC) (Xie *et al.*, 2021). Farahani et al. (2020) simulated the cost of components for using hydrogen FCEVs connected to the grid for an office building. Research by Oldenbroek, Verhoef, and van Wijk (2017) concluded that FCEVs and RES are cost-effective and reliable energy systems for renewable energy-based city areas , where FCEVs can provide power by vehicle-to-grid facilities. Research about passenger cars revealed that the total cost of ownership (TCO) of FCEV is significantly higher compared to all other vehicles (Ahmadi and Kjeang, 2017; Cox *et al.*, 2020).

Furthermore, Testa et al. (2014) compared the costs of a d-GPU and h-GPU. Their findings indicate that h-GPUs are more costly than GPUs, despite advancements in PEM fuel cell technology and the production of gaseous hydrogen via electrolyzer and steam methane reforming at airports. While their study provides a cost comparison between GPUs and h-GPUs, the use of steam methane reforming for hydrogen production limits its potential for decarbonizing airport operations.

2.4. Contribution

The literature review, as demonstrated in Table 2.1, reveals a lack of research comparing the costs of a d-GPU and a green h-GPU, considering economic benefits over their lifetime. This study aims to fill this research gap by examining the economic viability of substituting a d-GPU with a sustainable h-GPU at airports. To achieve this objective, a comprehensive cost analysis will compare the two systems and explore the benefits of using a GPU and a h-GPU. This study will build on the work of Xiang et al. (2021), by focussing on the electrification of energy systems and zero emission operations at airports, by delving deeper into the costs associated with operating a GPU and a h-GPU. By incorporating green hydrogen for the h-GPU, the analysis will expand on the research of Testa et al. (2014), providing a novel comparison between the cost of a d-GPU and a h-GPU. It will provide valuable insights to stakeholders in the long term by contributing to the literature on hydrogen systems at airports, as highlighted by Hoelzen et al. (2022). As the results of this investigation can provide valuable insights for decision-makers and investors, allowing for informed decisions based on a comprehensive understanding of the potential consequences and benefits. The contribution could best be summarized as follows:

- This study will undertake a comprehensive economic analysis to evaluate the cost and benefits of a GPU and a h-GPU, considering hydrogen production using solar energy and grid electricity with an alkaline electrolysis process.
- To gain a deeper understanding of the impact of various factors on the costs and benefits of GPU and h-GPU, a simulation study will be performed based on flight frequencies and exploring three different scenarios. A sensitivity analysis will also be conducted to identify the key parameters that influence the model results, building upon the research of Xiang et al. (2021).
- The research will be conducted at a regional airport in North Netherlands and incorporate insights from relevant experts to provide practical recommendations for decision-makers in the airport industry.

Table 2.1 Literature Review Table

Articles	*Hydrogen*	*GPU*	*h-GPU*	*FC(EV)*	*Cost Analysis*
Testa et al. (2014)	✓ (grey)	✓	✓	✓	✓
Bicer and Dincer (2017)	✓				
Gonzalez-Garay et al. (2022)	✓				
Greer, Rakas and Horvath (2020)		✓			
Wulf et al. (2018)	✓			✓	
Baroutaji et al. (2019)	✓			✓	
Acar and Dincer (2020)	✓			✓	
Hoelzen et al. (2022)	✓				✓
Ehret and Bonhoff (2015)	✓				
Xiang et al. (2021)	✓			✓	✓
Farahani et al. (2020)	✓			✓	✓
Staffell et al. (2019)	✓			✓	
Dawood, Anda and Shafiullah (2020)	✓			✓	
Siddiqui and Dincer (2021)	✓				
Nazir et al. (2020b)	✓			✓	
Padra (2018)			✓		
González-Garay et al. (2019)	✓				✓
Zini and Dakka Rosa (2014)	✓			✓	
Salihu, Lloyd and Akgunduz (2021					✓
Papadis and Tsatsaronis (2020)	✓				
Yue et al. (2021)	✓			✓	✓
Rivera et al. (2018)		✓			
Dunn (2002)	✓			✓	✓
Haghi, Raahemifar, and Fowler (2018)				✓	✓

Terlouw et al. (2022)	✔				✔
Nazir et al. (2020a)	✔				✔
Hassan et al. (2021)	✔			✔	✔
Qyyum et al. (2021)	✔			✔	✔
Reuß et al. (2017)	✔			✔	✔
Schrotenboer et al. (2022)	✔				✔
Glenk and Reichelstein (2019)	✔				✔
Oldenbroek, Verhoef and van Wijk (2017)	✔			✔	✔
Cox et al. (2020)	✔			✔	✔
Singh, Baredar, and Gupta (2017)	✔			✔	✔
Ahmadi and Kjeang (2017)	✔			✔	✔
Xie et al. (2021)	✔			✔	✔
Apaydin (2022)	✔ (green)	✔	✔	✔	✔

3. Methodology

In this section, we will first discuss the research design and then the data collection process. We will also explore the selection of parameters for the cost and benefits model. At this stage, we will provide detailed explanations of the input variables and experimental variables to provide a comprehensive understanding of the research methodology.

3.1. Research Design

A cost and benefits analysis will be employed in this study since this analysis is mainly well-suited for determining the net present value (NPV) of energy devices, such as PV systems (Singh, Baredar and Gupta, 2017; Xiang *et al.*, 2021; Guo and Xiang, 2022). To provide a holistic understanding of the costs associated with the implementation of h-GPUs in an airport setting, various cost components must be considered, such as investment costs for equipment, energy, operation, and maintenance cost.

A simulation is developed in Python to analyze the utilization of a h-GPU in a regional airport setting, by using hydrogen generated from solar energy or electricity purchased from the grid and an electrolyzer. The simulation model reveals the energy consumption and production, which are subsequently used in the cost assessment, similarly to the studies of Zini and Dalla Rosa (2014) and Singh, Baredar, and Gupta (2017). The developed simulation model is presented in chapter 4. In the baseline modelthe demand is determined by the existing flight schedule. The baseline scenario is extended with three scenarios and are presented below:

- In scenario A, demand has doubled in size.
- In scenario B, a carbon tax is introduced on the emitted carbon.
- In scenario C, demand has doubled, and a carbon tax is implemented on the emitted carbon.

3.2. Case Selection

Groningen Airport Eelde (GAE) aims to become the first Hydrogen Valley Airport in Europe, located in the Northern Netherlands and Europe's first Hydrogen Valley (GAE, 2021). With external stakeholders such as the Province of Drenthe and Holthausen Clean Technology, the airport developed a project to transform a GPU into a h-GPU that will be powered using solar energy from the installed solar park or using grid electricity. Green hydrogen will be locally produced by an alkaline electrolyzer and stored as a gas in a trailer till HST, as these facilities will be established in the future. The installed solar park, with a capacity of 21.9 MWp at standard test conditions, is owned by Groenleven and is directly connected to the grid. GAE is unique as it will use green hydrogen and local produce, distribute, and store it (GAE, 2022a). GAE has a limited presence in commercial flights offering at most one flight per day during the summer of 2023 (GAE, 2022b), but with its generated energy, the airport can become a regional hydrogen hub.

3.3. Model Development

To calculate the costs and revenues associated with the transition to h-GPUs at a regional airport, the following assumptions are presented in the model:

1. The project life cycle is 25 years.
2. The model assumes the installed solar park is connected to the grid and electrolyzer, potentially eliminating conversion losses. Because, emerging technologies are expected to drive the formulation of new legislation for the aviation industry, permitting the direct connection of the solar park with the electrolyzer in the future. It is worth noting that while the efficiency of converting grid electricity of alternating current (AC) to direct current (DC) typically ranges between 95% and 98%, however the model does not incorporate losses associated with this conversion process (Park *et al.*, 2020).
3. Given the solar park installation, the PV's capital cost is not factored into the cost analysis. Instead, only the capital costs associated with the absent hydrogen infrastructure equipment are considered. Nevertheless, the expenses related to the operations and maintenance of all energy equipment are included.
4. The surplus hydrogen generated is sold directly to local consumers at market price through a refueling station yet to be established. The surplus solar electricity is sold back to the grid.
5. Due to the restricted understanding of hydrogen application in airport settings and the associated safety apprehensions, aviation regulations limit the refueling of hydrogen fuel cells in the proximity of aircraft. Hence, it is presumed that the h-GPU is charged to meet the anticipated demand ahead of an aircraft's arrival.
6. Demand is based on the current flight schedule of the regional airport for 2023. An increase in flight frequencies is handled in scenarios.

To assess the financial feasibility of investing in h-GPU for regional airports, this study aims to calculate the NPV of the investment and compare it to the conventional GPU. Several costs are associated with operating an h-GPU, including capital expenditures (CapEx) for energy devices such as the d-GPU, h-GPU, HST, and electrolyzer. Additionally, there are annual operational expenditures (OpEx) which is made up maintenance cost and COE. The cost of energy (COE) depends on the demand for hydrogen, electricity, and diesel, which varies based on the type of GPU utilized. Table 3.1 explains the parameters used in the equation of the model.

Table 3.1 Financial Parameters

Parameters	*Descriptions*
N	Project life cycle and service time of the energy devices (25 years)
y	Year in the life cycle
r	Discount rate
i	Energy devices: GPU, h-GPU, HST, electrolyzer, and PV
$CapEx_{y,i}$	Annual capital expenditures for the energy device i, excluding PV, in year y
$OpEx_{y,i}$	Annual operational expenditures for energy device i, in year y
COE_y	Annual cost of energy for hydrogen, electricity, and diesel in year y
$R_y^{electricity}$	Annual revenue generated from selling excess of solar energy in year y
$R_y^{hydrogen}$	Annual revenue generated from selling excess of hydrogen in year y

The annual total cost (TC_y) is the sum of the discounted CapEx, OpEx, and COE, adopted from (Testa *et al.*, 2014; Xiang *et al.*, 2021; Zhao *et al.*, 2022), and the calculation of the (TC_y) is expressed as follows:

$$TC_y = \sum_{y=0}^{N} \frac{CapEx_{y,i}}{(1+r)^y} + OpEx_{y,i} + COE_y \qquad [1]$$

The calculation of the annual COE, noted as COE_y h-GPU is done by multiplying the annual hydrogen consumption by the current hydrogen unit cost, plus the yearly electricity consumption from the grid multiplied by the electricity unit cost (Zhou and Searle, 2022). Additionally, COE for the GPU is calculated by multiplying the annual diesel consumption by the diesel price. The energy consumption of hydrogen, electricity, and diesel is obtained from the simulation model.

The model is developed by considering revenue generation by selling excess energy. The annually generated revenue (REV_y) is calculated by using Equation [2] (Jovan and Dolanc, 2020):

$$REV_y = R_y^{electricity} + R_y^{hydrogen} \qquad [2]$$

where $R_y^{electricity}$ is the revenue from electricity, which is calculated by multiplying the annual excess of PV energy by the electricity selling price. Revenue from selling hydrogen, $R_y^{hydrogen}$, is only applicable to the h-GPU project, and the excess of hydrogen is multiplied by subtracting the hydrogen market price and the unit cost of hydrogen (Jovan and Dolanc, 2020).

Additionally, the net present value (NPV) of the investments is calculated by using equation [3] (Nicita *et al.*, 2020; Jang *et al.*, 2022):

$$NPV = -\text{CapEx} + \sum_{y=0}^{N} \left(\frac{REV_y - OpEx_y}{(1+r)^y} \right) \qquad [3]$$

In the equation, $CapEx$ refers to the total capital expenditures, (REV_y) represents the annual revenues generated, and $OpEx_y$ stands for the annual operational expenditures of all energy devices.

The hydrogen production cost per kg (H_{2_cost}) is calculated by using Equation [4] (Jovan and Dolanc, 2020).

$$H_{2\_cost} = \frac{CapEx + OpEx_{PV,EL,HST}}{total\ H2\ production} + \frac{OpEx_{HGPU}}{H2\ consumption} \qquad [4]$$

$$+ electric\ energy\ price \left(\frac{€}{kWh} \right) * hydrogen\ production\ power\ consumption \left(\frac{kWh}{kg} \right)$$

3.4. Input Data Collection and Analysis

This section discusses the general framework of the airport supply and demand to describe the present structure of the model. The airport's general layout is illustrated in Figure 3.1, which depicts the airport's energy supply and demand system. According to the figure, energy is sourced from the grid and/or PV and utilized by the terminal for daily operations and by the h-GSEs. The utilization of the h-GSEs depends on flight frequencies, whereas the energy production of the solar park is subject to variations in solar irradiance and temperature. Additionally, obtaining energy from the grid incurs financial costs, and emissions produced require the imposition of a carbon tax. The PV is connected to the electrolyzer to prevent energy losses. The microgrid transforms the electricity obtained from the national grid and PV to the terminal for daily operations or transfers the national grid electricity to the electrolyzer to produce hydrogen.

Quantitative data for this research was gathered from various sources such as academic literature, public documents, reports, and interviews with relevant individuals at the regional airport and its external stakeholders. The energy capacities and the economic data of the energy devices are shown in Table 3.2. A discount rate of 7% has been set, which is within the typical range of discount rates for hydrogen production systems, according to Terlouw et al. (2022). By combining these data sources, we could conduct a comprehensive analysis of the (H)GPUs energy usage.

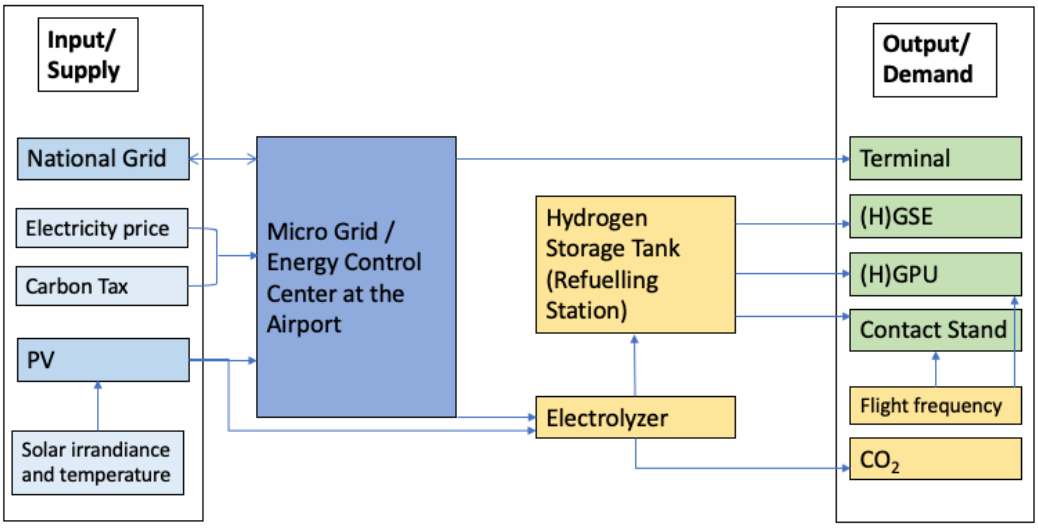

Figure 3.1 Airport Energy Supply and Demand Layout (adopted from Xiang et al., 2021)

Table 3.2 Economic characteristics of energy devices

Energy device	Capacity	Efficiency rates	Capex	OpEx/year	Lifetime (years)
PV	21,900 kW			€7.76 / kW (Xiang et al., 2022)	25 (Xiang et al., 2022)
Electrolyzer	1,000 kW	0.72 (Yue et al., 2021)	€1,000 / kw (Yue et al., 2021)	4% of CapEx (Haghi et al., 2018)	25 (Xiang et al., 2022)
HST	35 kg	0.72 (Yue et al., 2021)	€ 1297.2 / kg (Haghi et al., 2018)	0.5% of CapEx (Haghi et al., 2018)	25 (Xiang et al., 2022)
h-GPU	120 kW	0.6 (Yue et al., 2021)	€ 200,000	€10.64 / kW (Xiang et al., 2022)	25 (Oechies, 2022)
GPU	290 l	-	€ 85,000	€2,000 (Hoeksema, 2022)	25 (Oechies, 2022)

Note: discount rate = 7%, exchange rate: 1$ = €0.92 on 19-01-2013

Finally, qualitative data in the form of expert insights are gathered through interactions and interviews with industry experts and visits to relevant stakeholders.

The generated solar energy, energy demand, commodity prices, and carbon emission tax are explained in detail in the following subsections.

3.4.1. Photovoltaic System Modelling

GAE has an installed solar park with 63,196 solar panels generating a maximum of 21.9 MW electricity at standard test conditions (STC) (GAE, 2023). The forecasted solar irradiance and temperature for the upcoming 25-year period have been calculated using the rolling average of the historical data obtained from KNMI (2023). These are needed to estimate the expected electricity output from the PV system. To accurately assess the hourly electricity generation from the PV system during the project, the following PV system model has been adopted from Xiang et al. (2021):

$$P_{t,pv}^{out} = N_{pv} P_{STC} \frac{I_t}{I_{STC}} \left[1 + \alpha\left(T_{t,c} - T_{c,STC}\right)\right] \quad [5]$$

where the cell temperature (T_c) is calculated using the following equation (Zouine *et al.*, 2019):

$$T_c = T_a + \frac{G_g}{800}(T_{NOCT} - 20) \quad [6]$$

The parameters of the models are described in Table 3.3. Additionally, it should be noted that under the STC, the cell temperature is 25°C, and the irradiance is 1000 W/m^2 (Xiang et al.,2021), and a panel's average operating cell temperature is 46°C (Zouine et al., 2019).

In addition, the rated power of a PV panel can be calculated by dividing the maximum capacity of the solar park by the number of PV panels.

3.4.2. Hydrogen Ground Power Unit Energy Demand

The electricity consumption of aircraft influences the annual hydrogen demand for the (H)GPU during their turnaround time. In the previous year, the GPU, possessing a 290-liter capacity, reportedly consumed around 1800 liters of diesel (Dorp, 2022). Based on the flight schedule of the current year, the estimated number of flights is 263 per year (GAE, 2022b), presented in Table 3.4. The demand for electricity arises solely on days when commercial flights are scheduled, at 3 pm. With an aircraft turnaround time of 60 minutes, the demand for diesel per aircraft is estimated to be approximately 6.84 l/h (Hoeksema, 2022; Rijkens, 2022). Furthermore, it has been noted that the h-GPU can provide up to 105 kW of power to an aircraft, as 15 kW is required for its cooling system, with a total capacity of 120 kW (Oechies, 2022). Additionally, the energy density of diesel stands at approximately 10.7 kW/l, whereas hydrogen is estimated to have a density of around 33.33 kWh/kg (Jovan and Dolanc, 2020; Eefting, 2022). Hydrogen production involves a power consumption of about 50 kWh/kg (Jovan and Dolanc, 2020).

Based on the provided data from GAE, electricity demand per turnaround is 73.18 kW, which is consistent with the range of energy demand of 39 to 107 kW for different aircraft classes reported by Testa et al. (2014). With the efficiency loss of the h-GPU, this leads to a hydrogen consumption of 3.67 kg per turnaround time, which is in line with the values provided by Testa et al. (2014), where different aircraft types require hydrogen in the range of 0.7371 kg, 2.3789 kg, and 5.7973 kg.

Table 3.3 Parameters for PV system model

Parameters	Description
$P_{t,pv}^{out}$	PV power output in kw at time t
N_{pv}	Number of PV panels
P_{STC}	Rated power of PV panel at standard text conditions in kW
I_t	Solar radiation intensity in W/m^2 at time t
I_{STC}	Solar irradiance intensity at standard text conditions in W/m^2
α	Temperature coefficient of power
$T_{t,c}$	PV cell temperature in °C at time t
$T_{c,STC}$	PV cell temperature under standard text conditions in °C
T_a	Ambient temperature
G_g	Plane module irradiance
T_{NOCT}	Normal operating cell temperature

Table 3.4 Flight Schedule

Day	Airline	Destination	Start date	End date
Monday	TUI	Grand Canaria	2022-12-26	2023-12-24
Friday	TUI	Grand Canaria	2022-12-30	2023-12-24
Saturday	Transavia	Ostersund	2022-12-24	2023-03-18
Saturday	TUI	Mallorca	2023-07-15	2023-09-20
Tuesday	Corendon	Antalya	2023-04-01	2023-10-31
Thursday	Corendon	Antalya	2023-04-01	2023-10-31
Saturday	Corendon	Antalya	2023-04-01	2023-10-31
Sunday	Blue Islands	Channel Islands	2023-04-22	2023-08-14
Sunday	Corendon	Crete	2023-04-23	2023-10-29

3.4.3 Commodity Prices

Currently, in the Netherlands, the green hydrogen market price is around 9.60 €/kg and 17.2 €/kg, and it will decrease to values between 2.4 €/kg and 8.5 €/kg in 2040. The hydrogen market price is set to 17 €/kg in 2023, which is linearly decreasing to 2.7 €/kg in 2040, and it is assumed that it will remain constant in the years after 2040 (Terlouw et al. 2022). The excess hydrogen is sold to local consumers at the market price of green hydrogen through a refuel station.

Additionally, diesel and electricity prices fluctuate depending on various factors such as war, natural gas, and oil prices. When grid electricity is required, it will be purchased at the current electricity price of 0.495 €/kWh in the Netherlands as of March 2023 (Energievergelijk, 2023). When there is an excess of electricity, it is sold to the grid. According to the model of solar power generation, when there is an abundance of sun, electricity prices tend to be lower. Therefore, the model assumes a selling price of 0.01 €/kWh for electricity. Because electricity depends on the electricity market's volatility, electricity price remains constant during the project cycle time (Xiang *et al.*, 2021). The same holds for the diesel price, which remains constant at 1.766 €/liter during the project cycle time (ANWB, 2023). To investigate the effect of these prices and validate these assumptions, sensitivity analyses are conducted on the electricity and diesel prices in section 5.5.

3.4.5. Carbon Emission and Tax

The annual CO_2 emission of a d-GPU used for 1.5 hours daily is 36.4 kg (x10,000), meaning that the hourly CO_2 emission of a d-GPU is estimated as 664.84 kg CO_2/h (Nuhn, 2023). To evaluate the carbon emissions from the diesel consumption of the GPU, we calculate the annual emissions by multiplying the hourly carbon emission rate by the total number of operational hours per year (Padhra, 2018). In the Netherlands, the Dutch Emission Authority declared the CO_2 tax is €55.94/ton CO_2 in 2023 and will annually increase by €11.55/ton CO_2 (NEA, 2021).

4. Case Setting

4.1 Experimental design

A discrete event simulation (DES) model has been developed to estimate the energy consumption and production for the h-GPU. The simulation is constructed using Python and based on the flowchart depicted in Figure 4.1.

The simulation model begins with checking the availability of the hydrogen demand within a given hour. If demand exists, the available inventory of h-GPUs is evaluated to determine whether it can meet the demand. When the h-GPU supply is sufficient to meet demand, and adequate solar energy is available, the system converts the solar energy into hydrogen. The remain of excess hydrogen is sold at the market price. When the h-GPU inventory is insufficient to meet hydrogen demand, the system sources additional power from the PV system, HST, or grid to meet the demand. However, if the solar energy and HST are insufficient to meet the demand, the system purchases electricity from the grid to produce the required hydrogen. Once the demand is met, the system checks for surplus hydrogen. Then, surplus hydrogen is used to refuel the HST, and the excess hydrogen can be sold. The simulation runs continuously for 25 years. Additionally, when there is no demand for hydrogen, but solar irradiance is available, the system converts the solar energy into hydrogen and sells it for the market price. If the excess solar energy exceeds the electrolyzer's capacity, the system sells the excess electricity to the national grid. The simulation is developed by considering the h-GPU and HST at full capacity, and the inventory for these devices is updated at the end of each hour. The simulation model is subject to the following constraints:

$$S_{H2GPU,\,t} \leq 0 \qquad [7]$$

$$120\ kW \geq HGPU_{INV,\,t} \geq 0 \qquad [8]$$

$$HST_{MAX} \geq HST_{INV,\,t} \geq 0 \qquad [9]$$

Constraint [7] ensures that the hydrogen supply to the h-GPU remains positive, while constraint [8] establishes the inventory level of the h-GPU. Similarly, constraint [9] determines the inventory level of the HST. The simulation generates information on the amount of hydrogen obtained and utilized from the PV system, HST, and grid for each time frame. In addition, the simulation reports any surplus energy, which is subsequently used to calculate the revenue generated from selling excess energy in subsequent scenarios. Table 4.1 provides descriptions of the variables used in the simulation.

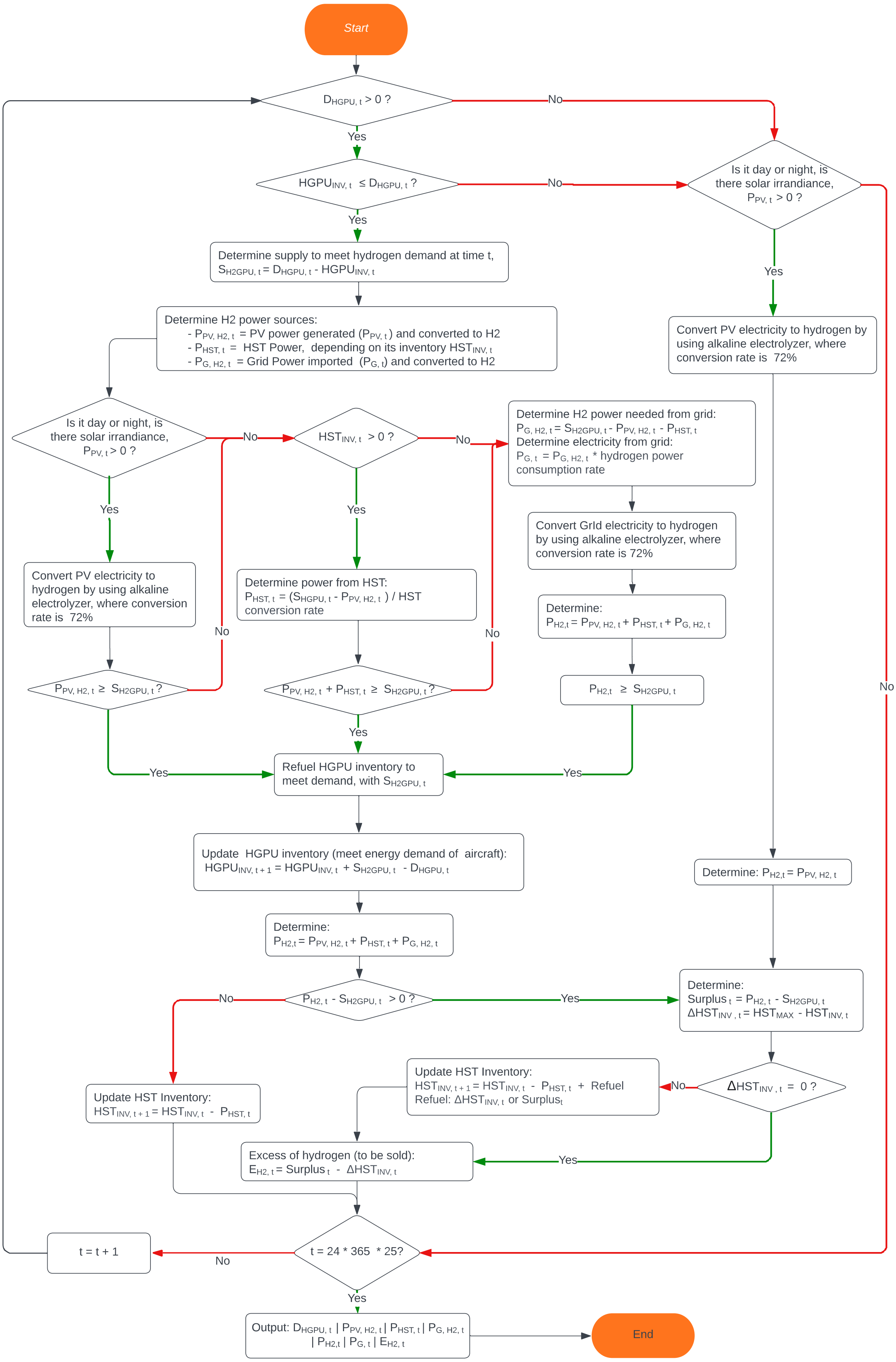

Figure 4.1 Flowchart for The Hydrogen Demand and Supply Flow for Remote Stand Aircrafts

Table 4.1 Flowchart simulation variables

Variables	Description
$\Delta HST_{INV, t}$	Difference between HST capacity and HST inventory level in kg at time t
$D_{HGPU, t}$	Aircraft hydrogen demand from HGPU in kg at time t
$E_{H2, t}$	Excess of hydrogen amount in kg at time t
$HGPU_{INV, t}$	Hydrogen inventory level of HGPU in kg at time t
$HGPU_{INV, t+1}$	Hydrogen inventory level of HGPU in kg at time t + 1
$HST_{INV, t}$	HST inventory level in kg at time t
$HST_{INV, t+1}$	HST inventory level in kg at time t + 1
HST_{MAX}	Maximum capacity of HST in kg
$P_{G, H2, t}$	Power of hydrogen from grid-supplied to HGPU in kg at time t
$P_{G, t}$	Electricity power imported from the grid in kW at time t
$P_{H2,t}$	Production of hydrogen by PV, HST, and grid in kg at time t
$P_{HST, t}$	Power of hydrogen from HST supplied to HGPU in kg at time t
$P_{PV, H2, t}$	Power of hydrogen by PV supplied to HGPU in kg at time t
$P_{PV,t}$	Generated power by PV in kg at time t
$S_{H2GPU, t}$	Supply of hydrogen from energy devices for HGPU in kg at time t
$Surplus_t$	Surplus of hydrogen after fulfilling demand in kg at time t

4.2. Scenarios

To achieve a comprehensive understanding of the system under investigation and to observe the impacts of different parameters, it is essential to undertake scenario analyses and evaluate the consequences of these scenarios. The base case model will be enlarged to achieve this aim with three additional scenarios. A summary of these scenarios can be found in Table 4.2. Then, a detailed explanation of each scenario is discussed in the next section.

Table 4.2 Overview of Scenarios

	Demand	**CO_2 Tax**
Baseline	*Based On The Current Flight Frequency*	*No*
Scenarios		
A (Doubled Demand)	Based On The Doubled Flight Frequency	No
B (CO_2 Tax)	Based On The Current Flight Frequency	Yes
C (Doubled Demand And CO_2 Tax)	Based On The Doubled Flight Frequency	Yes

4.2.1. Baseline

The baseline scenario aims to investigate the potential economic advantages of the hydrogen transition of h-GPU, based on the present annual flights. The base case and all scenarios examine the selling of surplus energy generated through hydrogen and solar power utilization. By selling the excess energy, the h-GPU project has the potential to generate revenue that can offset its costs, making its execution more economically viable (Terlouw *et al.*, 2022). This approach can motivate airport management to make a comprehensive investment decision by comparing the NPVs of the traditional GPUs and h-GPU projects.

4.2.2. Scenario A: Doubled Demand

The scenario is developed based on increased demand, a prevalent phenomenon in the aviation industry. Because of the complex and dynamic environments in airports, fluctuations in flight schedules are continually subject to changes. Consequently, this scenario examines the impact of an expanded flight schedule on the NPV of (H)GPU. This scenario investigates the effects of doubling the current annual flights and projecting this trend into the future years.

4.2.3 Scenario B: Carbon Emission Tax

The third scenario involves the implementation of a CO_2 tax only for the use of the GPU to consider the carbon emission costs. Since h-GPU does not emit carbon emissions. This scenario expands on equation [1], as presented in Section 3.3, by incorporating an additional cost component for carbon emissions, denoted as, $C_y^{emission}$. Given the significant contribution of the aviation industry to GHG emissions and subsequent climate change, there is a pressing need to reduce emissions through policy measures such as carbon taxes. Implementing such taxes incentivizes companies and industries to prioritize sustainability considerations in their decision-making processes (Rijksoverheid, 2021), as directed by the National Climate Agreement in the Netherlands (Papadis and Tsatsaronis, 2020;

Rijksoverheid, 2022). Accounting for the costs of carbon emissions is crucial in providing a comprehensive understanding of the economic impacts of the (H)GPU. (Testa *et al.*, 2014; Padhra, 2018; Zhao *et al.*, 2022). It is crucial to align with the objectives of the Dutch government to promote net zero emission targets.

4.2.4. Scenario C: Doubled Demand and Carbon Emission Tax

The last scenario under investigation involves examining the impacts of augmenting flight frequencies through a twofold increase in demand alongside the imposition of a CO_2 tax on the GPU. The frequent changes in flight schedules are significant as they indicate the potential realities of the aviation industry. In addition, implementing a CO_2 tax presents a sustainable pathway to mitigate carbon emissions, and analyzing its effects on flight demand is critical to inform sustainable policy-making.

5. Results

This section established the cost and benefits model of transitioning towards utilizing (H)GPUs at airports. The analysis begins with an examination of the base case. Thereafter, the results of the three scenarios will be analyzed, followed by the sensitivity analysis of critical parameters.

5.1 Baseline

In the base case, among other things the sum of the total cost for the traditional GPU and the transformation for the h-GPU are compared. Additionally, it should be noted that hydrogen supply chain of GPU is included in this research. The result of the cost assessment is depicted in Figure 5.1. The analysis shows that the total capital investment required for the h-GPU project is €200.000 which is higher than the €85,000 required for the d-GPUs project. Additionally, including in the hydrogen infrastructure equipment, the total capital investment amounts to €1.2 million. The maintenance cost for h-GPU, and d-GPU are, €32 thousand, and €50 thousand, respectively. Notably, maintenance cost of the h-GPU is lower than that of the d-GPU, which is consistent with the previous research conducted by Eefting (2022). When analyzing the operating expenses of the hydrogen supply chain, it amounts to €5.25 million. Moreover, the cost of energy for the h-GPU is €143 thousand, which is also higher than the €79 thousand required for the GPU. As a result, the total cost for the transition to h-GPU is €6.67 million. This expected cost difference has been a factor that has contributed to the prolonged postponement of the transition toward hydrogen technology.

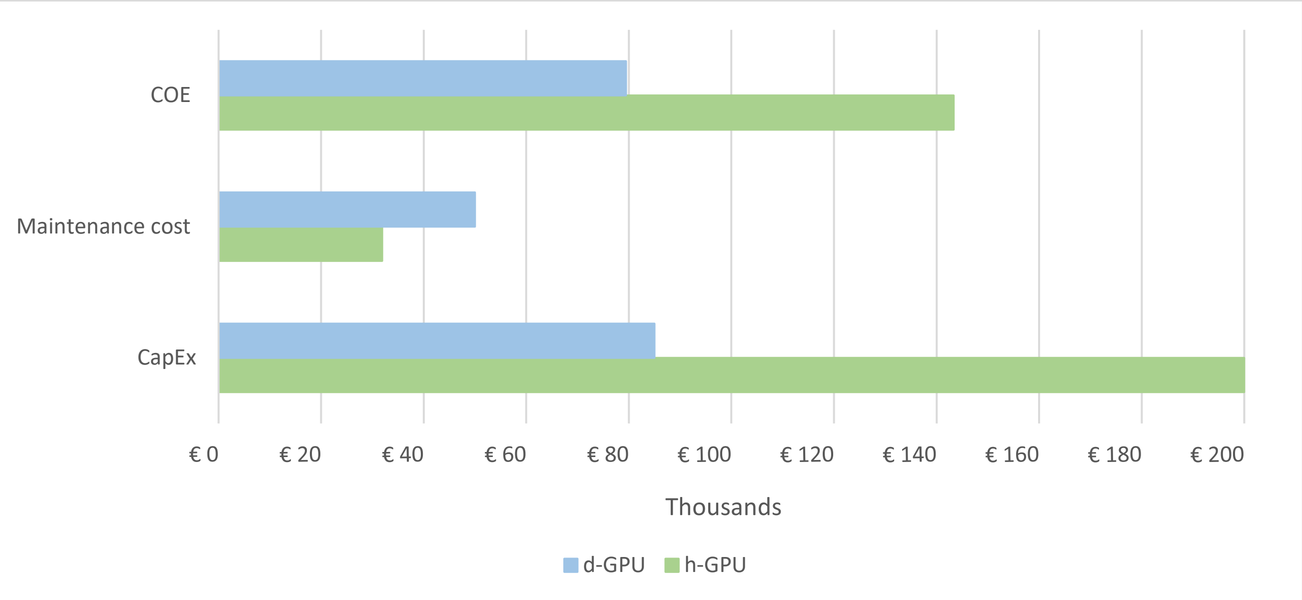

Figure 5.1 Cost Assessment of the d-GPU and h-GPU

Figure 5.2 illustrates the relative contribution of maintenance cost and COE of GPUs within the OpEx. The COE accounts for the majority of the OpEx for both the h-GPU (82%) and the d-GPU (61%). Maintenance cost of the h-GPU corresponds to 18% of the OpEx, while the maintenance cost of the d-GPU corresponds to 39% of the OpEx. The difference in these cost proportions is primarily attributable to the higher hydrogen unit cost than diesel unit cost. The findings indicate that while the h-GPU may have higher energy costs, it requires less maintenance costs during its lifetime than the GPU.

(a) (b)

Figure 5. Portion of maintenance cost and COE within the OpEx (a: h-GPUs, b: d-GPUs)

The h-GPU project presents an opportunity for the airport to expand its revenue streams beyond electricity sales by including hydrogen sales. According to the analysis, hydrogen sales account for 46% of the total revenue, with electricity sales accounting for the remaining 54% for the h-GPU. The annual excess of energy for the h-GPU project is 80 thousand kg. The model indicates a hydrogen product cost of €5.97 per kg in 2023, decreasing slightly over time. However, the current market price for selling hydrogen is around €17 per kg, declining at a higher rate than the hydrogen product cost. As a result, it is essential to note that the revenue generated by hydrogen sales may decrease throughout the project's lifetime. As depicted in Figure 5.3, from 2035 onwards, the revenues are insufficient to cover costs, leading to a loss for h-GPU. The total cumulative revenue for the h-GPU and GPU is €8.3 million and €5.5 million, respectively. h-GPU and GPU are €8.3 million and €5.5 million, respectively.

Although the h-GPU generates more revenue than the GPU, the net present value (NPV) of the h-GPU is lower than that of the GPU, indicating that the GPU is more economically advantageous. Specifically, the NPVs of the h-GPU and GPU are approximately €1.2 million and €2.7 million, respectively, indicating a difference of 55%. The findings show that hydrogen sales contribute significantly to the total revenue of the h-GPU project.

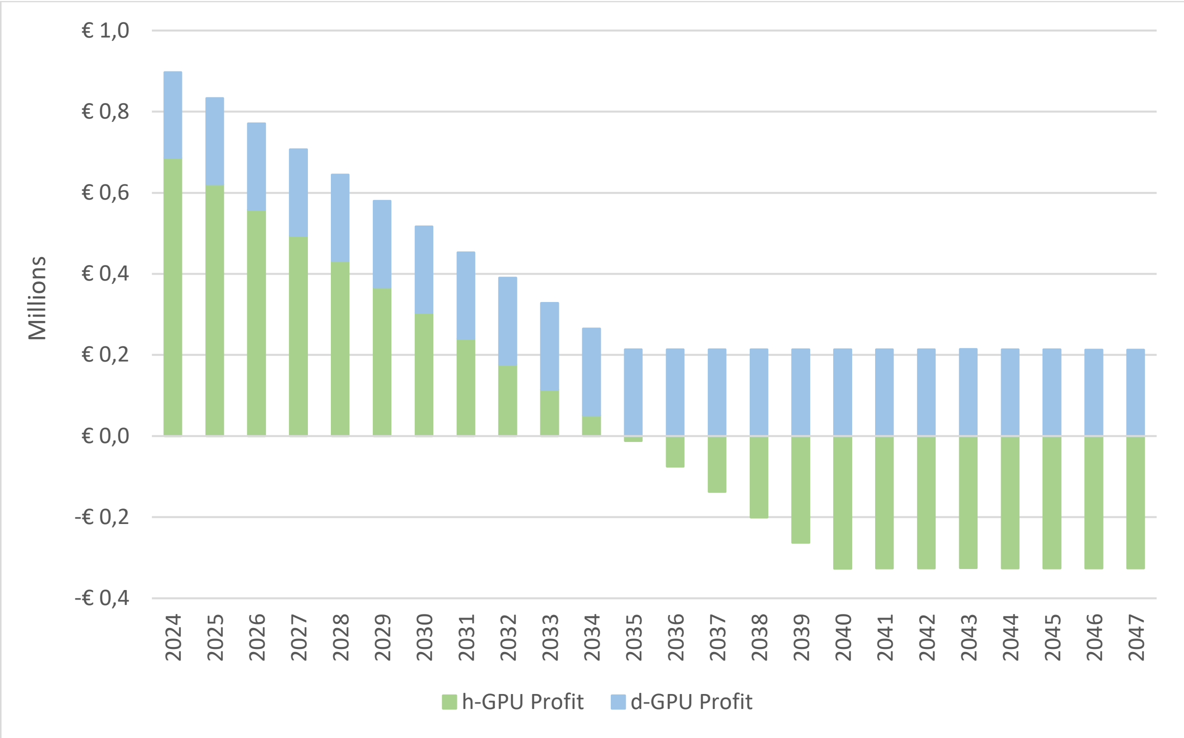

Figure 5.3 Annual Profit of h-GPU and GPU

5.2. Scenario A: Doubled Demand

In this scenario, the frequency of flights has increased, leading to a twofold rise in demand. The cost of hydrogen production has decreased by 36%, now reaching €3.80 per kg. The increased demand and the fuel cost per unit influence the energy cost. The GPU has observed a doubling in energy costs, whereas, for the h-GPU, the increase was only 28%. This indicates that, for energy costs of the h-GPU, the effect of the increasing demand is partly mitigated by the declining unit cost of hydrogen.

Additionally, the revenue from selling hydrogen also benefits from the decrease in hydrogen costs per kg and is slightly influenced by a 1% decline in hydrogen excess. This led to revenue generated from selling hydrogen surging by 50%. The effect of the increasing COE on the total cost is neglectable, with 1% due to the small portion of the COE in the total cost.

Figure 5.4 depicts the cumulative total costs, total revenues, and present values for the h-GPUs. The figure reveals that the total costs for the h-GPU have linearly increased, whereas the revenues have increased at a higher rate than the total cost. However, it can be observed that the increase of revenue for the h-GPU slowed down after around 2035; this is due to the decreasing difference between the hydrogen production cost and the hydrogen selling price throughout the project lifetime.

In contrast, to scenario A, the total revenue generated by the h-GPU is higher than that of the GPU, amounting to €12.4 million and €5.5 million, respectively. As a result, the NPV of the h-GPU has increased to €3.2 million, while that of the GPU has marginally decreased by 3% to €2.7 million. The observed increase in flight frequencies represents a realistic trend, thereby highlighting the likelihood of these results. The realization of a 22% higher NPV by the h-GPU indicates its potential for market opportunity in these circumstances.

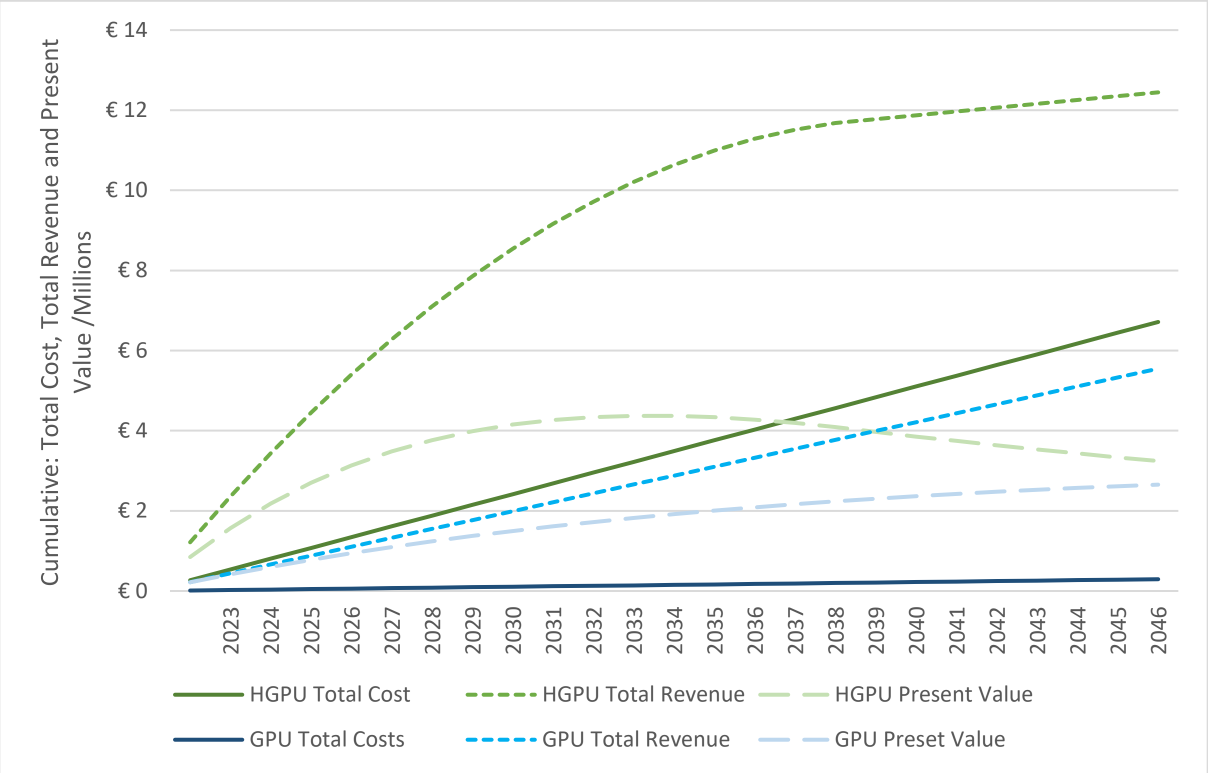

Figure 5.4 Cumulative Total Cost, Cumulative Total Revenue, and Cumulative Present Value for h-GPU and GPU

5.3. Scenario B: Carbon Emission Tax

The third scenario evaluates the effect of implementing a carbon emission tax. In the model, carbon emission arises due to the diesel consumption of the GPU. The GPU emits 664.84 kg CO_2 per hour, meaning the annual carbon emission is 175 thousand kg CO_2. Currently, in the Netherlands, the carbon emission tax is €55.94/ton CO_2 and is estimated to increase annually by €11.55/ton CO_2. As depicted in Figure 5.5, the carbon emission costs increased by implementing an increasing carbon emission tax, whereas the present value decreased. This led to a four-time increase in the total costs and a reduction in NPV of 12% for the GPU, reaching €2.4 million.

In contrast, the NPV for the h-GPU remained at €1.2 million. It means that the difference between the NPVs has decreased, where the NPV of the GPU is 49% higher than that of the h-GPU. However, the further change in NPVs with a carbon emission tax and increased demand is elaborated in the following scenario.

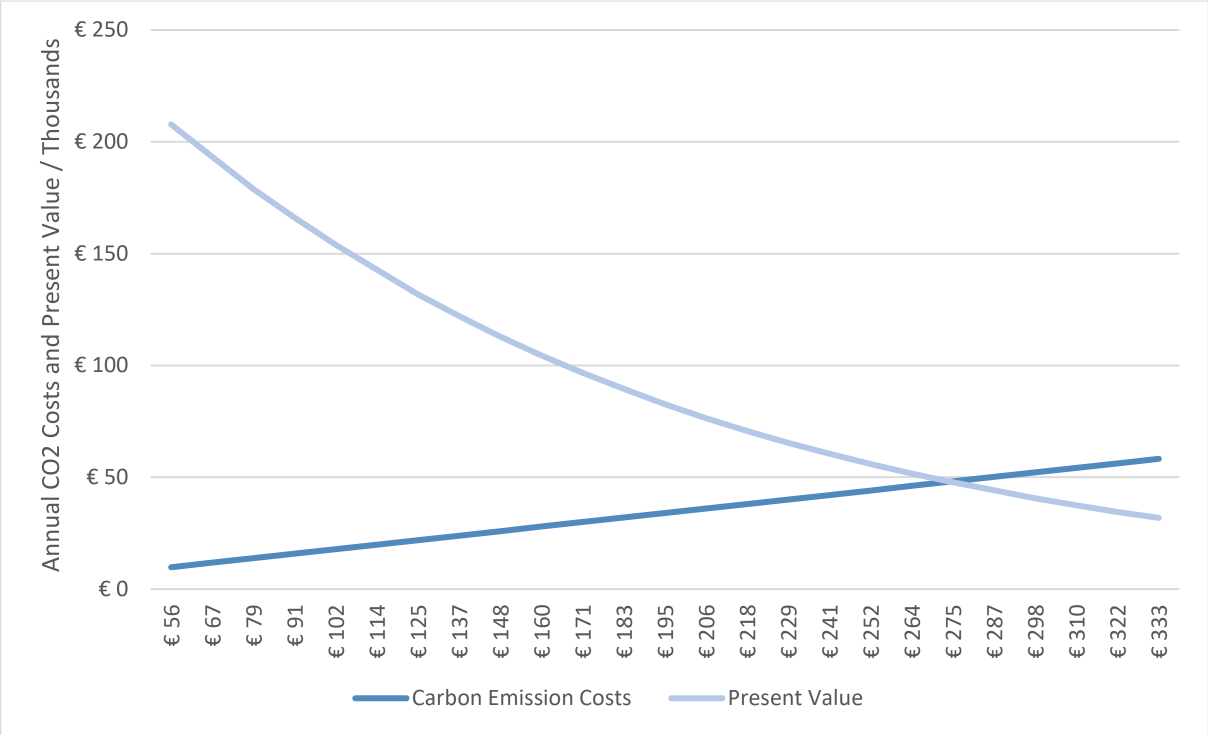

Figure 5.5 Effect of the Carbon Emission Tax on Carbon Emission Costs and Present Value of the GPU

5.4. Scenario C: Doubled Demand and Carbon Emission Tax

In the final scenario, the circumstances on the h-GPU are identical to Scenario A, as only the increase in demand impacts the NPVs. In this case, there is a decrease in unit hydrogen production cost from €5.97 to €3.80 per kg. A significant increase in total cost with a higher increase in total revenue led to an increase in NPV to €3.2 million.

However, increasing demand and implementing a carbon emission tax severely affect the total cost of GPU. Due to increased demand, the cost of energy for the GPU increased. Additionally, due to the implementation carbon emission tax, the carbon emission costs increased, leading to an increase in total cost for the GPU.

Accordingly, as shown in Figure 5.6, the h-GPU has a higher NPV than the GPU in Scenario A and C, indicating a market opportunity in these cases. Specifically, it can be observed that the difference between the NPVs is highest in scenario D, at 63%. Additionally, it can be indicated that a carbon emission tax by governments has a severe impact on NPV when demand is increased compared to the base scenario's demand. The combined scenario of implementing carbon emission tax and increased demand show that increasing demand is realistic and provides an opportunity for the airport.

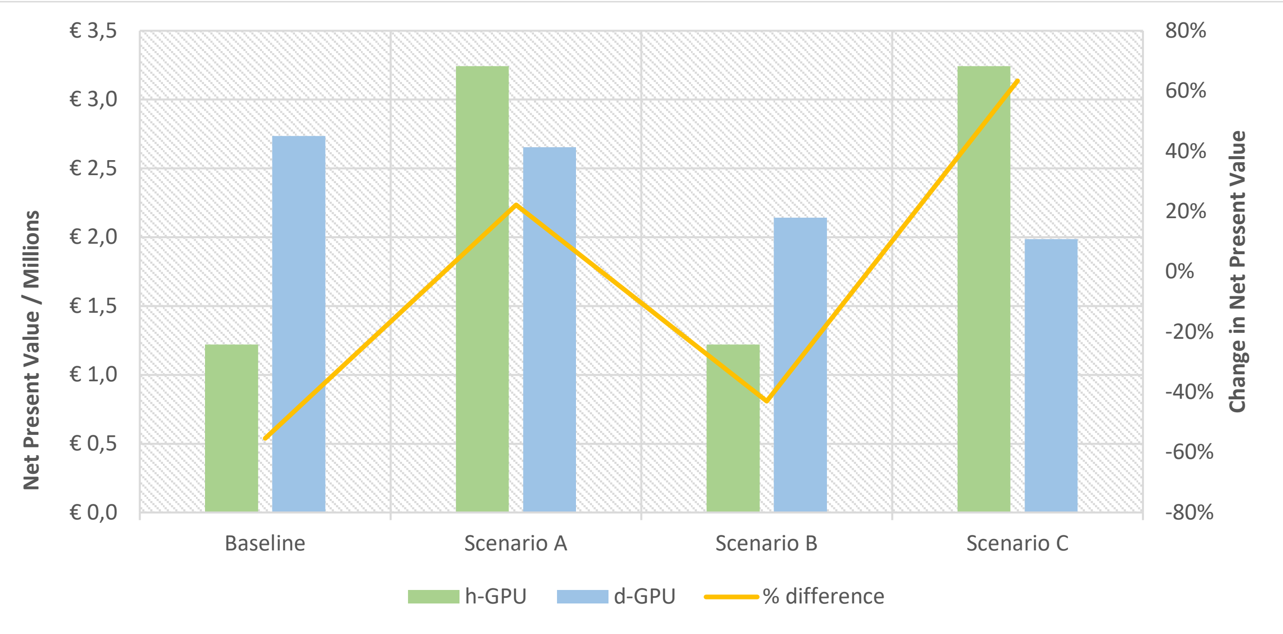

Figure 5.6 The NPV for h-GPU and GPU for all Scenarios

6. Sensitivity Analysis

Sensitivity analysis has been conducted based on critical parameters such as the price of electricity used by electrolyzer, diesel price, and carbon emission tax in the results of the base scenario.

6.1. Price of Electricity Used by Electrolyzer

Hydrogen is produced by the electrolyzer using electricity from the PV solar park. Figure 5.7 demonstrates a direct correlation between an increase in the unit cost of electricity derived from the PV solar park and a corresponding rise in the cost of producing hydrogen, establishing that the cost of locally generated hydrogen is directly linked to the cost of PV electricity. The results show that the system under investigation can sufficiently produce hydrogen to meet demand without requiring additional electricity from the grid since the level of HST is sufficient to meet demand when there is no solar energy to produce hydrogen. It is worth noting that the inventory of the HST is refuelled exclusively with solar energy, which is available when the PV solar park generates electricity. However, if the system were to require additional hydrogen beyond what can be produced by the PV solar park, it would need to purchase electricity from the grid, which currently costs 0.495 €/kWh. This would increase the unit cost of hydrogen.

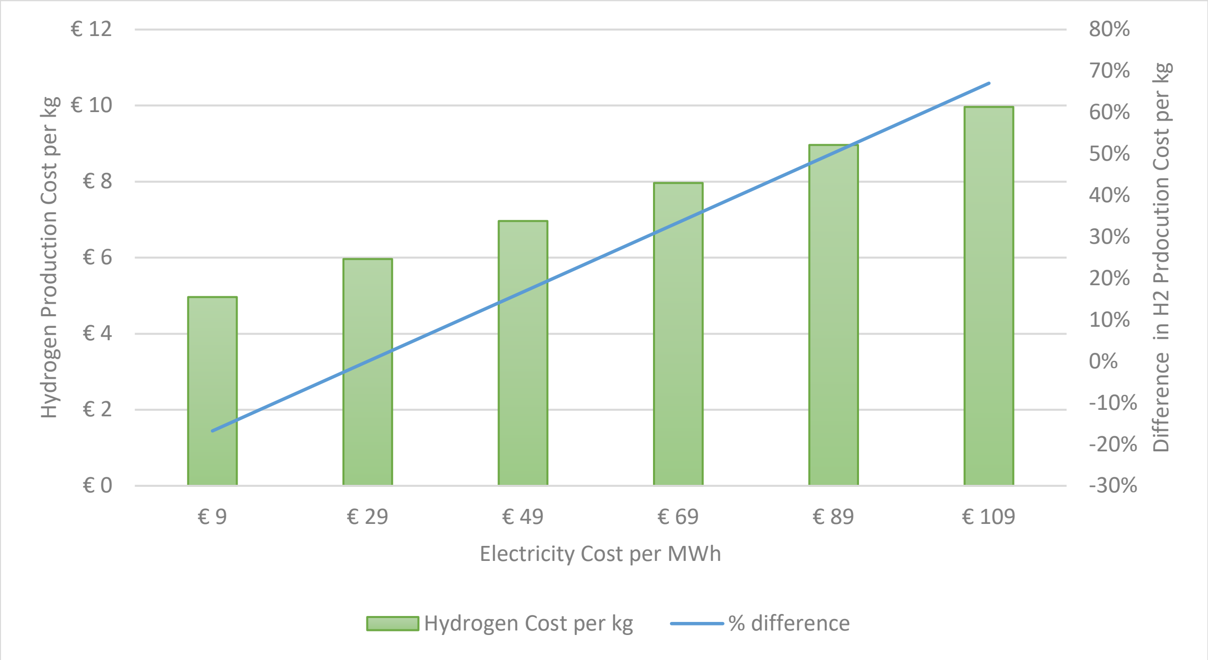

Figure 5.7 Sensitivity Analysis on Hydrogen Production Cost per kg

6.2. Diesel Price

The diesel price was assumed to be constant at €1.766/liter in the model. However, the diesel price can vary due to several factors. Figure 5.8 provides an overview of the impact of a lower and higher diesel price per liter on the annual profit of the GPU. The results show that as the unit diesel price increases, the total costs increase correspondently. However, the effect of diesel prices on the annual profit is minor, as generated revenues balance the rise in energy costs. Consequently, the impact on the profitability of the GPU is negligible.

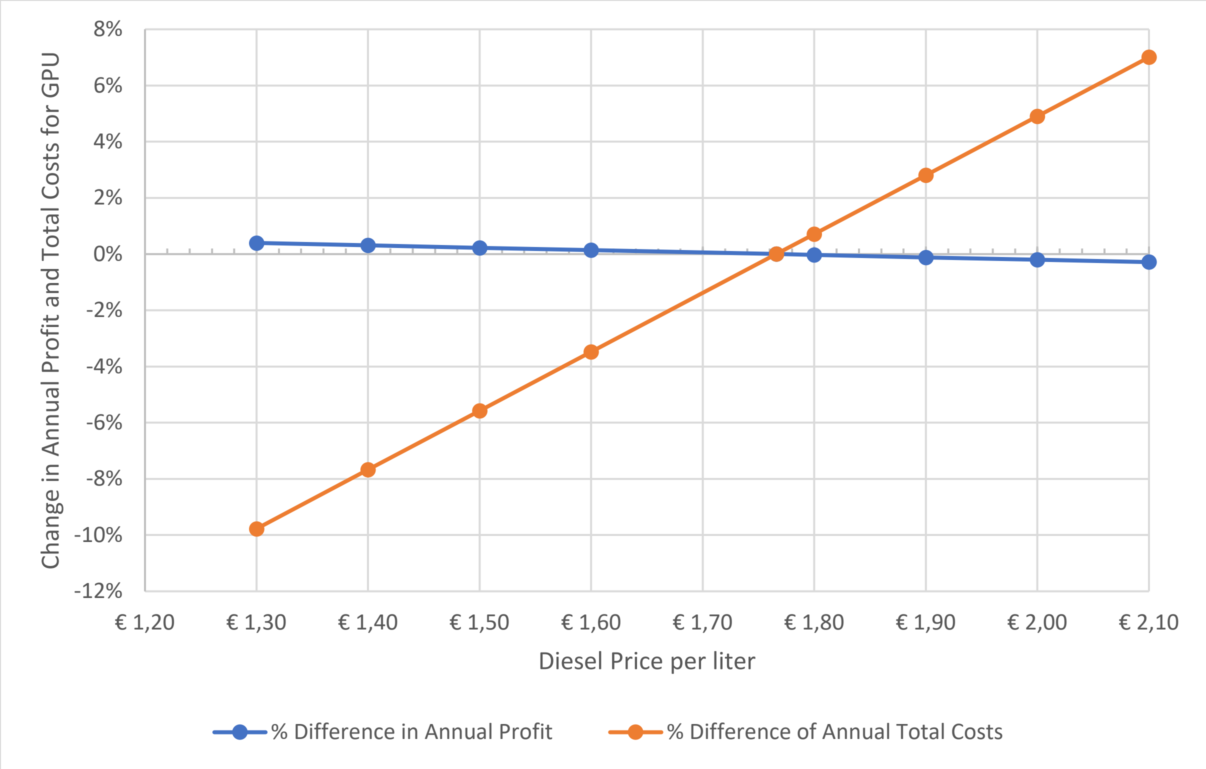

Figure 5.8 Sensitivity Analysis of the Change in Diesel Price on Annual Profit and Annual Total Costs

6.3. Carbon Emission Tax

In the Netherlands, the CO_2 tax is based on the declaration of the Dutch Emission Authority, which determined that the CO_2 tax will increase to €11.55/ton CO2 annually. A sensitivity analysis was performed to assess the impact of a higher annual increase in the CO_2 tax on the NPV of GPU. Figure 5.8 indicates that as the annual carbon emission tax rate increases, the NPV decreases gradually. When the yearly increase of the CO_2 tax per ton increased from €11.55 to €30, the NPV decreased by 15%. Thus, it can be concluded that the impact of increased CO_2 tax significantly impacts the NPV of the GPU.

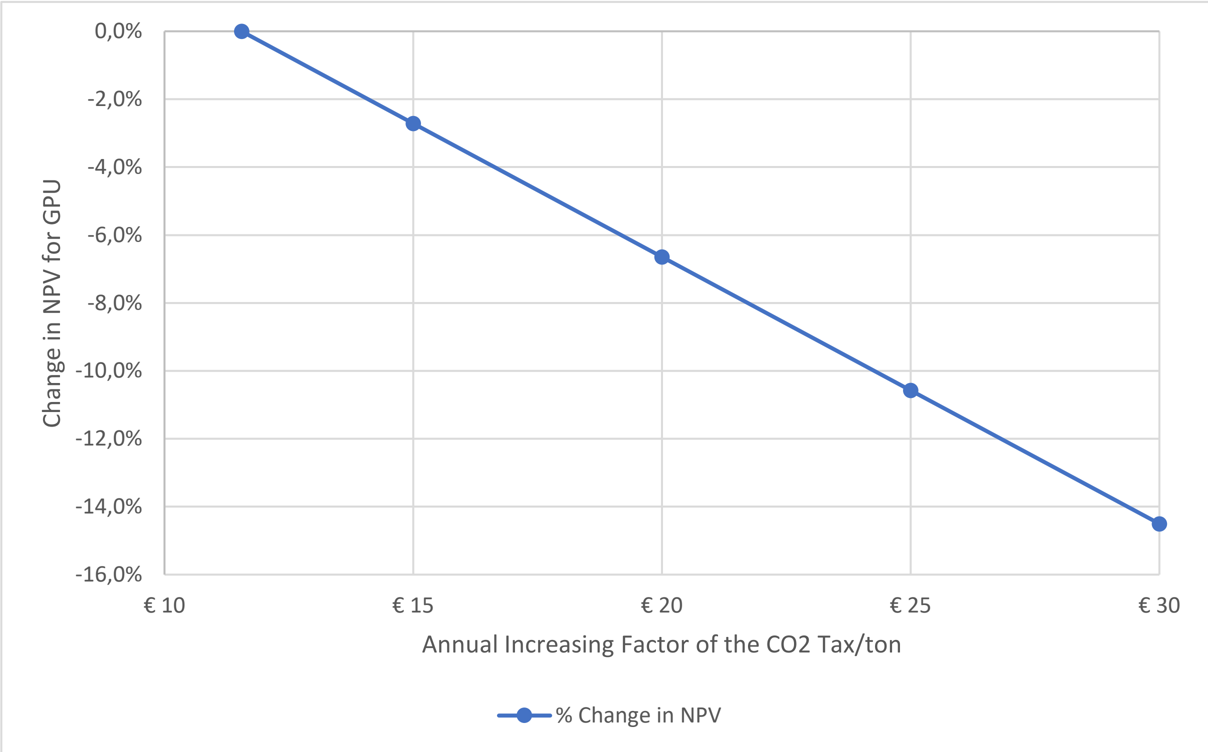

Figure 5.8 Sensitivity Analysis of Increasing annual Carbon Emission Tax on NPV of the GPU

7. Discussion

This research aims to evaluate the costs and benefits of transitioning to a h-GPU in the airport. The cost assessment model is developed based on estimating energy production and consumption in the simulation model. In this discussion section, the results from the cost assessment and benefits model will be thoroughly analyzed and interpreted. The outcomes of the base scenario and three different scenarios will be examined and evaluated to determine the most feasible decision for acquiring a h-GPU in the airport. Additionally, the results of this study are compared to existing literature and national and international reports to provide further insights and valuable practical implementation for the transition to h-GPU in regional airports.

The findings of the study present that the total costs of the h-GPU is more than that of a GPU in all cases since the capital investment costs of the h-GPU are higher than the GPU. This is caused by the high infrastructure cost for hydrogen. The result of the study indicates that the operational expenses are higher for the GPU because of the higher maintenance cost of the GPU, and energy costs are higher in the h-GPU compared to the GPU. When it comes to the evaluation of the revenues for GPU, it can be observed that the revenues for the h-GPU are higher than revenues for the GPU since the h-GPU earns revenue from selling both hydrogen and solar energy. In all scenarios, the NPV for both h-GPU and GPU is positive, meaning that the returns outweigh the high costs for both h-GPUs. The NPV of the GPU is higher than that of the h-GPU in the baseline scenario and when the carbon emission tax is implemented in scenario (B). However, in scenario (A), when the demand is doubled, and the combining scenario (C), which is based on the doubled demand and considering of carbon emission tax, the NPV of h-GPU is higher than the GPU. Thus, it suggests that increasing demand provides a market opportunity for the transition to hydrogen in the airport. However, when the demand is doubled, the unit cost of hydrogen decreases from €5.97 per kg to €3.80 per kg, increasing the revenue from selling hydrogen. Because the difference between the current hydrogen market price of €17 per kg and the unit hydrogen cost will increase as the unit hydrogen production cost decreases, thus, it provides higher revenues for h-GPU to cover the total costs and to make a higher profit, which in turn leads to a 22% higher NPV compared to the GPU. Additionally, in scenario (C), the NPV of the h-GPU has advantages over the d-GPU because the difference between the NPVs of h-GPU and GPU is further increased to 63% when the carbon emission tax is implemented by the increased demand.

Testa et al. (2014) examined the reduction in air pollution by using grey hydrogen for the GSEs at airports. Thus, they conducted a cost analysis on the GPU and h-GPU to evaluate the direct and indirect emissions for the production and consumption of hydrogen and diesel. This research also found the total cost of the h-GPU as €6.67 million. In alignment with this, Testa et al. (2014) have predicted the future life cycle costs of the h-GPU as €6.67 million in the next 10-15 years.

Yue et al. (2021) state that at an average electricity cost of €30 per MWh, the hydrogen production cost is €5.21 per kg. Similarly, in the baseline scenario with an average electricity cost of €29 per MWh for using solar energy, the hydrogen unit cost was found to be €5.97 per kg, which is higher than the current hydrogen unit cost of €4 per kg (IRENA, 2022; Janzow, Koch Blank and Tatarenko, 2022). Moreover, it can be observed that the hydrogen unit cost decreased to €3.80 when the demand increased by double, eventually reaching the hydrogen unit cost of €4 per kg.

Furthermore, Xiang et al. (2021) aimed to minimize the cumulative annual costs for an airport, including a hydrogen energy system. The study emphasizes that integrating hydrogen, solar park, and hydrogen storage tank technologies presents a promising solution for the energy requirements of future airports. This cost-effective and eco-friendly solution reduces annual energy costs and GHG emissions. In contrast with this study, this study specifically focuses on evaluating the costs for the h-GPU and GPU. As a result, although its net present value is lower than that of the GPU in the baseline scenario, the h-GPU can be considered a cost-effective alternative compared to the GPU considering the combined scenario, which applies carbon tax and demand increase.

This study highlights the surplus energy of hydrogen and electricity and the potential for revenue generation due to moderate operational hours and energy consumption. In the baseline scenario, the yearly hydrogen excess is about 80 thousand kg. Groningen has twenty hydrogen buses (Rijksoverheid, 2019) with a capacity of 37 kg (Shell, 2021). These buses could refuel 108 times a year at the refuel station of the airport, providing a revenue stream for the airport.

The simulation model assumes that no energy is lost when electricity is transported between the energy devices. Because the solar park, hydrogen storage, electrolyzer, and fuel cell can change power via autonomous distributed control systems that rely on direct current (DC)(Xiang *et al.*, 2021). Energy losses of about 1% may occur when electricity is transmitted through appropriate cables of specific applications (Vaicys et al., 2022; thus, this loss is not considered in the model.

The sensitivity analysis showed that the hydrogen unit cost is sensitive to changes in the electricity cost of the PV, which is in line with Xiang et al. (2021). When the model requires grid electricity to produce hydrogen, the hydrogen unit cost will be higher than the baseline scenario. For example, when 10% of demand is supplied by the grid, the hydrogen unit cost will increase from €5.97 to €7.96 per kg. Subsequently, this will lead to a negative NPV of €974 thousand, meaning that the total revenues will not be able to outweigh the total costs for the h-GPU. In such a case, importing the deficient hydrogen from outside suppliers would be more cost-efficient.

Additionally, a sensitivity analysis is conducted on the diesel price. The diesel price appears to impact the total costs significantly. Still, as generated revenues balance the rise in energy costs, the impact on the annual profit is neglectable for the regional airport. This aligns with a survey conducted by Shell, where decision-makers from the construction and fleet industries indicated that operating costs would decrease by at least 10% per month when fuel is managed more effectively (Shell, no date). This emphasizes the significant effect of the energy cost on the total costs for both the unit cost of hydrogen and diesel.

Moreover, the system is highly sensitive to changes in carbon emission tax. As the CO_2 tax increases, the NPV of the GPU significantly increases, which is in accordance with research by Xiang et al. (2021). When the demand is increased, and there is a carbon emission tax, the influence of a carbon emission tax results in a lower net present value for the GPU compared to theh-h-GPU. Which provides a market opportunity for the h-GPU.

7.1. Scalability

The results of this study apply to (regional) airports that possess specific characteristics, such as the availability of land to install a solar park of 21MW capacity requiring 20 hectares (Groenleven, no date). Moreover, there should be a local demand for hydrogen to generate revenue from excess energy, and the airport should have the potential to serve as a regional hydrogen hub. Groningen Airport Eelde is part of the Hydrogen Valley, which benefits from the built ecosystem. The Hydrogen Valley focuses on the large-scale production of green hydrogen and the storage, transport, and distribution of hydrogen (New Energy Coalition, no date).

Furthermore, managers at larger airports must consider the substantial demand for hydrogen due to more scheduled flights. Due to the higher demand, the hydrogen unit cost will decrease, providing an opportunity for larger airports. Additionally, the development of a hydrogen hub in the surrounding region of the airport will benefit the airport. For instance, in the future, the Port of Rotterdam can become a hydrogen trade hub (IRENA, 2022) and might support energy demand at Schiphol airport

Additionally, it should be noted that this study's outcomes only apply to foreign airports situated in regions with favorable conditions for utilizing solar energy. Installing a solar park may not be practical or cost-effective in some locations, and implementing a wind park may be more advantageous (IRENA, 2022). Additionally, diesel, electricity, and hydrogen prices may vary across countries due to different policies and regulations. As a result, the cost evaluation of foreign airports may not be fully aligned with the results presented in this study.

7.2. Opportunities

For regional airports, implementing hydrogen provides the potential to become hydrogen trade hubs in their respective regions. By economics of scale, the unit cost per kg hydrogen will decrease to €4 per kg and align with industrial expectations (IRENA, 2022; Janzow, Koch Blank and Tatarenko, 2022), as shown in scenario A, where the demand was doubled. Moreover, the airports could benefit from transforming more ground support equipment to hydrogen to reduce hydrogen unit costs by the economics of scale.

As the technology for hydrogen infrastructure advances, investment costs are expected to decline. For example, a combination of lower electricity costs, reduced capital expenditure on electrolyzer, increased efficiency, and optimized electrolyzer operation can reduce green hydrogen production costs by up to 85% in the long term (IRENA, 2022). Moreover, additional revenue could be realized by commercializing oxygen, a byproduct of hydrogen production.

In addition, new sustainable energy solutions, such as hydrogen solar panels, are being developed and will continue to drive down costs in the future. A hydrogen solar panel is designed to efficiently convert atmospheric water vapor directly into green hydrogen (H2 Platform, 2022). These significant investments are expected to be funded by government institutions, as there is still a lack of clear business plans. Governments could also encourage investment in sustainability through tax incentives or subsidies, which is essential for decision-making (Schrotenboer et al., 2022). For instance, in the Netherlands, there is a tax incentive for investments that replace fossil fuels (IRENA, 2020).

Furthermore, nations like the United Arab Emirates are investing substantially in green energy, intending to become leading global suppliers (IRENA, 2022). This presents an opportunity for airports which are unable to produce green hydrogen locally to consider importing as a cost-effective alternative.

7.3. Barriers

As the literature review highlights, the high investment costs are the primary factor behind the slow adoption of hydrogen technology. But, the transition towards h-GPU has a benefit on the operational costs because of lower maintenance costs of the h-GPU compared to GPU. Most of the total costs are attributed to capital and operating expenditures. This indicates that the cost difference between the h-GPU and GPU is primarily driven by the high investment costs associated with the hydrogen infrastructure. Additionally, the relatively high price of hydrogen compared to diesel further contributes to the cost difference between the two vehicles.

Investing in hydrogen, particularly h-GPUs, aims to reduce the carbon footprint and mitigate the environmental impacts. The process of converting hydrogen back to electricity results in the release of water, which may be considered wasteful, especially in regions where water scarcity is a significant concern. The consequences of this water usage and its impact on the costs must be regarded as it might increase the cost difference between the h-GPUs. Furthermore, the model assumed that PV-generated energy was directly connected to the electrolyzer. However, aviation regulations prohibit such a direct connection, and the solar energy must be converted to the national grid before being connected to the electrolyzer. This results in more conversion losses and raises questions about the carbon footprint of the hydrogen energy obtained from the PV system and its impact on the overall costs for the h-GPU.

Moreover, the lack of familiarity with hydrogen technology and regulations has led to restrictions on refueling h-GPUs, near aircraft to mitigate potential hazards. Therefore, h-GPU losses time and energy by riding to the refuel station. Stakeholders are investing in hydrogen research with the expectation that the outcomes will lead to lifting restrictions in the future. However, research about cost comparisons between hydrogen and diesel GSEs has been discouraged by some stakeholders because they do not see value in a study in which they could predict that hydrogen would remain more expensive (Kolk, 2023). Additionally, it was revealed that employees at Schiphol Airport faced challenges in adapting to novel technologies and control panels of new vehicles (Kolk, 2023). This resulted in a reluctance to transition away from older equipment (Kolk, 2023), ultimately renderng the investment in the contact stand and e-GPU financially unfeasible.

7.4. Implications

Based on the results and analysis of the opportunities and barriers associated with implementing hydrogen technology at airports, particularly the h-GPU, several practical recommendations can be made to local and public government agencies, policymakers, and airport managers. These recommendations will play a crucial role in furthering the development and implementation of hydrogen technology at airports.

Initially, it is imperative for government entities to invest in technological advancements in hydrogen to reduce the high investment costs associated with this technology. Governments can support these investments by implementing tax incentives, subsidies, loans, and grant programs. This will not only promote investment in RES but also support the attainment of decarbonization goals (IRENA, 2020).

Airport managers also have an essential role in fostering the adoption of technological advancements in the airport industry. By providing employee training programs, airport managers can equip them with the necessary skills and knowledge to effectively embrace technological changes in their work environment.

Finally, new regulations must be established to ensure the generated hydrogen is carbon-neutral and minimize conversion loss. These regulations should facilitate the direct connection of solar energy to the electrolyzer, contributing to the attainment of net-zero emissions objectives at airports.

8. Conclusion

The objective of this study was to examine the transition to hydrogen energy at airports, with a focus on evaluating the economic feasibility of implementing a h-GPU compared to a traditional GPU. To achieve this purpose, a cost analysis was conducted using a simulation model to determine the energy consumption and distribution costs. The simulation model is developed by considering the energy demands of aircrafts and the potential for solar and grid energy generation to produce hydrogen on an hourly basis. The baseline and the three scenarios were analyzed to examine the variations and indicate impact on the comparison between the GPUs and h-GPUs. In order to observe effects of the key factors which are electricity price, carbon tax and diesel price changes on the profit of h-GPUs, sensitivity analyses was carried out.

The results showed that in the baseline scenario, the GPU has a higher NPV comparing with the h-GPU. However when demand is doubled, in scenario A, the transition to h-GPU creates a market opportunity as the NPV of h-GPU surpasses the NPV of the GPU. Additionally, the economic feasibility of the h-GPU further increases in the combined scenario when demand is doubled and a carbon emission tax is implemented, where the NPV of the h-GPU becomes 63% higher than that of the GPU. The unit cost of hydrogen drops from €5.97/kg to €3.80/kg, with an increase in NPV for h-GPU. The cost for the GPU increases due to the implementation of the carbon emission, causing for a lower NPV. Additionally, the sensitivity analysis of the carbon emission tax revealed a significant impact on the total cost of the GPU. Furthermore, the sensitivity analysis demonstrates a direct correlation between an increase in the unit cost of electricity derived from the PV solar park and a corresponding rise in the cost of producing hydrogen. Finally, sensitivity analysis of diesel price shows that an change in diesel price has a significant impact on the total cost of the GPU.

As a conclusion, it can be said that the implementing a h-GPU at a regional airport has a market opportunity when considering increased demand and emission cost. Therefore, to achieve decarbonization targets, it will be economically feasible to transition to h-GPU for regional airports when demand increases.

This study has some limitations that could be addressed in future research to enhance the realism of the model. Because, the model was subject to certain simplification as a result of time limitations. Specifically, one of the limitation of this study is that the demand of h-GPU will consider the current flight schedule throughout a 25-year period. Therefore, scenario A where the demand increases has been developed. In this study, real data were used, but since there are not many studies in the literature, the data collection stage can be considered as one of the limitations of the study.

Moreover, the model operates on the assumption of a static selling price of €0.01 per kWh and a fixed purchase price. While, in reality the cost of electricity can vary hourly. Refuelling strategies and a scenario analysis incorporating PV outages and energy distribution loss could also be considered. Furthermore, additional GSEs applicable to convert to hydrogen, such as an aircraft tractor and de-icing vehicle, could be incorporated to the model to provide economic of scale at the airport.

References

Acar, C. and Dincer, I. (2020) 'The potential role of hydrogen as a sustainable transportation fuel to combat global warming', *International Journal of Hydrogen Energy*, 45(5), pp. 3396–3406. Available at: https://doi.org/10.1016/j.ijhydene.2018.10.149.

Ahmadi, P. and Kjeang, E. (2017) 'Realistic simulation of fuel economy and life cycle metrics for hydrogen fuel cell vehicles', *International Journal of Energy Research*, 41(5), pp. 714–727. Available at: https://doi.org/10.1002/er.3672.

ANWB (2023) *Dieselprijzen Europa*. Available at: https://www.anwb.nl/vakantie/reisvoorbereiding/dieselprijzen-europa (Accessed: 24 January 2023).

Barke, A. *et al.* (2020) 'Socio-economic life cycle assessment of future aircraft systems', in *Procedia CIRP*. Elsevier B.V., pp. 262–267. Available at: https://doi.org/10.1016/j.procir.2020.01.096.

Baroutaji, A. *et al.* (2019) 'Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors', *Renewable and Sustainable Energy Reviews*, 106, pp. 31–40. Available at: https://doi.org/10.1016/j.rser.2019.02.022.

Bicer, Y. and Dincer, I. (2017) 'Life cycle evaluation of hydrogen and other potential fuels for aircrafts', *International Journal of Hydrogen Energy*, 42(16), pp. 10722–10738. Available at: https://doi.org/10.1016/j.ijhydene.2016.12.119.

Cox, B. *et al.* (2020) 'Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios', *Applied Energy*, 269. Available at: https://doi.org/10.1016/j.apenergy.2020.115021.

Dawood, F., Anda, M. and Shafiullah, G.M. (2020) 'Hydrogen production for energy: An overview', *International Journal of Hydrogen Energy*. Elsevier Ltd, pp. 3847–3869. Available at: https://doi.org/10.1016/j.ijhydene.2019.12.059.

Destination 2050 (2021) *Destination 2050 A Route To Net Zero European Aviation NLR-Royal Netherlands Aerospace Centre SEO Amsterdam Economics*. Available at: https://www.destination2050.eu (Accessed: 15 November 2022).

Dorp (2022) 'Groningen Airport Eelde. Mail conversation.'

Dunn, S. (2002) *Hydrogen futures: toward a sustainable energy system*, *International Journal of Hydrogen Energy*. Available at: www.elsevier.com/locate/ijhydene.

Eefting, J. (2022) *Hydrogen Ecosystem Design at a Small Regional Airport: Groningen Airport Eelde's Road to Net-Zero Emissions | Master Thesis, MSc Supply Chain Management*.

Ehret, O. and Bonhoff, K. (2015) 'Hydrogen as a fuel and energy storage: Success factors for the German energiewende', *International Journal of Hydrogen Energy*, 40(15), pp. 5526–5533. Available at: https://doi.org/10.1016/j.ijhydene.2015.01.176.

Energievergelijk (2023) *Stroomprijs*. Available at: https://www.energievergelijk.nl/energieprijzen/stroomprijs (Accessed: 12 March 2023).

European Commission (2021) *2050 long-term strategy*, *Climate Action*. Available at: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (Accessed: 10 September 2022).

Farahani, S.S. *et al.* (2020) 'Hydrogen-based integrated energy and mobility system for a real-life office environment', *Applied Energy*, 264. Available at: https://doi.org/10.1016/j.apenergy.2020.114695.

GAE (2021) *Groningen Airport Eelde becomes the first Hydrogen Valley Airport in Europe*. Available at: https://www.groningenairport.nl/en/news/groningen-airport-eelde-becomes-the-first-hydrogen-valley-airport-in-europe (Accessed: 20 November 2022).

GAE (2022a) *Development of hydrogen Ground Power Unit at Groningen Airport Eelde*. Available at: https://www.groningenairport.nl/en/news/development-of-hydrogen-ground-power-unit-at-groningen-airport-eelde (Accessed: 5 February 2023).

GAE (2022b) *Vluchtschema's*. Available at: https://www.groningenairport.nl/voor-reizigers/vluchten (Accessed: 10 November 2022).

GAE (2023) *Zonnepark Groningen Airport Eelde*. Available at: https://www.groningenairport.nl/over-groningen-airport-eelde/de-organisatie/duurzaamheid/zonnepark (Accessed: 24 January 2023).

Glenk, G. and Reichelstein, S. (2019) 'Economics of converting renewable power to hydrogen', *Nature Energy*, 4(3), pp. 216–222. Available at: https://doi.org/10.1038/s41560-019-0326-1.

González-Garay, A. *et al.* (2019) 'Plant-to-planet analysis of CO2-based methanol processes', *Energy and Environmental Science*, 12(12), pp. 3425–3436. Available at: https://doi.org/10.1039/c9ee01673b.

Gonzalez-Garay, A. *et al*. (2022) 'Unravelling the potential of sustainable aviation fuels to decarbonise the aviation sector', *Energy and Environmental Science*, 15(8), pp. 3291–3309. Available at: https://doi.org/10.1039/d1ee03437e.

Greer, F., Rakas, J. and Horvath, A. (2020) 'Airports and environmental sustainability: A comprehensive review', *Environmental Research Letters*. IOP Publishing Ltd. Available at: https://doi.org/10.1088/1748-9326/abb42a.

Groenleven (no date) *Zonnepark Groningen Airport Eelde*. Available at: Zonnepark Groningen Airport Eelde (Accessed: 15 March 2023).

Guo, Y. and Xiang, Y. (2022) 'Cost–benefit analysis of photovoltaic-storage investment in integrated energy systems', *Energy Reports*, 8, pp. 66–71. Available at: https://doi.org/10.1016/j.egyr.2022.02.158.

H2 Platform (2022) *Waterstofpanelen klaar voor productie*. Available at: https://opwegmetwaterstof.nl/waterstofpanelen-klaar-voor-productie/ (Accessed: 9 February 2023).

Haghi, E., Raahemifar, K. and Fowler, M. (2018) 'Investigating the effect of renewable energy incentives and hydrogen storage on advantages of stakeholders in a microgrid', *Energy Policy*, 113, pp. 206–222. Available at: https://doi.org/10.1016/j.enpol.2017.10.045.

Hassan, I.A. *et al.* (2021) 'Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. Available at: https://doi.org/10.1016/j.rser.2021.111311.

Hoeksema, AJ. (2022) 'Groningen Airport Eelde. Phone conversation.'

Hoelzen, J. *et al.* (2022) 'Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps', *International Journal of Hydrogen Energy*. Elsevier Ltd, pp. 3108–3130. Available at: https://doi.org/10.1016/j.ijhydene.2021.10.239.

IEA (2019) *The Future of Hydrogen, seizing today's opportunities*.

IPPC (2021) *WG III contribution to the Sixth Assessment Report List of corrigenda to be implemented*.

IRENA (2020) *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.50C Climate Goal*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction.

IRENA (2022) *Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward*. Abu Dhabi: International Renewable Energy Agency. Available at: www.irena.org/publications.

Jang, D. *et al.* (2022) 'Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies', *Energy Conversion and Management*, 258. Available at: https://doi.org/10.1016/j.enconman.2022.115499.

Janzow, N., Koch Blank, T. and Tatarenko, O. (2022) *Strategic Advantages of Green Hydrogen Imports for the EU, RMI*. Available at: https://rmi.org/insight/strategic-advantages-of-green-hydrogen-imports-.

Jovan, D.J. and Dolanc, G. (2020) 'Can green hydrogen production be economically viable under current market conditions', *Energies*, 13(24). Available at: https://doi.org/10.3390/en13246599.

Kılkış, B. and Kılkış, Ş. (2017) 'New exergy metrics for energy, environment, and economy nexus and optimum design model for nearly-zero exergy airport (nZEXAP) systems', *Energy*, 140, pp. 1329–1349. Available at: https://doi.org/10.1016/j.energy.2017.04.129.

Kolk, P. (2023) 'Interview by A. Apaydin and A. Nuhn, 25 November'. Remote, 25 November.

Kroyan, Y. *et al.* (2022) 'Modeling the impact of sustainable aviation fuel properties on end-use performance and emissions in aircraft jet engines', *Energy*, 255. Available at: https://doi.org/10.1016/j.energy.2022.124470.

Lai, Y.Y. *et al.* (2022) 'Analysing the opportunities and challenges for mitigating the climate impact of aviation: A narrative review', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. Available at: https://doi.org/10.1016/j.rser.2021.111972.

Morrow, K., Hochard, D. and Francfort, J. (2007) *Cost Benefit Analysis Modeling Tool for Electric vs. ICE Airport Ground Support Equipment-Development and Results*.

Nazir, H., Muthuswamy, N., Louis, C., Jose, S., Prakash, J., Buan, M.E., *et al.* (2020a) 'Is the H2 economy realizable in the foreseeable future? Part II: H2 storage, transportation, and distribution', *International Journal of Hydrogen Energy*. Elsevier Ltd, pp. 20693–20708. Available at: https://doi.org/10.1016/j.ijhydene.2020.05.241.

Nazir, H., Muthuswamy, N., Louis, C., Jose, S., Prakash, J., Buan, M.E.M., *et al.* (2020b) 'Is the H2 economy realizable in the foreseeable future? Part III: H2 usage technologies, applications, and challenges and opportunities', *International Journal of Hydrogen Energy*. Elsevier Ltd, pp. 28217–28239. Available at: https://doi.org/10.1016/j.ijhydene.2020.07.256.

NEA (2021) *Tarieven CO2-heffing, Nederlandse Emissieautoriteit*. Available at: https://www.emissieautoriteit.nl/onderwerpen/tarieven-co2-heffing (Accessed: 5 February 2023).

Network for Business Sustainability (2012) *Innovating for sustainability: A guide for executives*. London, Canada: Network for Business Sustainability. Available at: www.nbs.net/knowledge (Accessed: 15 November 2022).

New Energy Coalition (no date) *Hydrogen Valley*. Available at: https://www.newenergycoalition.org/hydrogen-valley/ (Accessed: 15 March 2023).

Nicita, A. *et al.* (2020) 'Green hydrogen as feedstock: Financial analysis of a photovoltaic-powered electrolysis plant', *International Journal of Hydrogen Energy*, 45(20), pp. 11395–11408. Available at: https://doi.org/10.1016/j.ijhydene.2020.02.062.

Nuhn, A. (2023) *Msc Thesis Supply Chain Management Replacing diesel-powered GPUs with hydrogen-powered GPUs-A study investigating the environmental impact of those GPUs and their supply chains*.

Oechies, A. (2022) 'Company visit to Holthausen Clean Technology'.

Oldenbroek, V., Verhoef, L.A. and van Wijk, A.J.M. (2017) 'Fuel cell electric vehicle as a power plant: Fully renewable integrated transport and energy system design and analysis for smart city areas', *International Journal of Hydrogen Energy*, 42(12), pp. 8166–8196. Available at: https://doi.org/10.1016/j.ijhydene.2017.01.155.

Osman, A.I. *et al.* (2022) 'Hydrogen production, storage, utilisation and environmental impacts: a review', *Environmental Chemistry Letters*. Springer Science and Business Media Deutschland GmbH, pp. 153–188. Available at: https://doi.org/10.1007/s10311-021-01322-8.

Padhra, A. (2018) ‘Emissions from auxiliary power units and ground power units during intraday aircraft turnarounds at European airports’, *Transportation Research Part D: Transport and Environment*, 63, pp. 433–444. Available at: https://doi.org/10.1016/j.trd.2018.06.015.

Papadis, E. and Tsatsaronis, G. (2020) ‘Challenges in the decarbonization of the energy sector’, *Energy*. Elsevier Ltd. Available at: https://doi.org/10.1016/j.energy.2020.118025.

Park, C.Y. *et al.* (2020) ‘Inverter efficiency analysis model based on solar power estimation using solar radiation’, *Processes*, 8(10), pp. 1–19. Available at: https://doi.org/10.3390/pr8101225.

Qyyum, M.A. *et al.* (2021) ‘Availability, versatility, and viability of feedstocks for hydrogen production: Product space perspective’, *Renewable and Sustainable Energy Reviews*, 145. Available at: https://doi.org/10.1016/j.rser.2021.110843.

Reuß, M. *et al.* (2017) ‘Seasonal storage and alternative carriers: A flexible hydrogen supply chain model’, *Applied Energy*, 200, pp. 290–302. Available at: https://doi.org/10.1016/j.apenergy.2017.05.050.

Rijkens, W.H. (2022) ‘Groningen Airport Eelde. Mail conversation.’

Rijksoverheid (2019) *Vijftig nieuwe waterstofbussen in het openbaar vervoer*. Available at: https://www.rijksoverheid.nl/actueel/nieuws/2019/11/20/vijftig-nieuwe-waterstofbussen-in-het-openbaar-vervoer (Accessed: 2 February 2023).

Rijksoverheid (2021) *CO2-heffing voor industrie*. Available at: https://www.rijksoverheid.nl/onderwerpen/milieubelastingen/co2-heffing-voor-industrie (Accessed: 6 February 2023).

Rijksoverheid (2022) *Aanscherping CO2-heffing industrie*. Available at: https://www.rijksoverheid.nl/onderwerpen/belastingplan/klimaat/co2-heffing (Accessed: 6 February 2023).

Rivera, M. *et al.* (2018) *A New Ground Power Unit (GPU) Supply for Aircraft Applications*.

Salihu, A.L., Lloyd, S.M. and Akgunduz, A. (2021) ‘Electrification of airport taxiway operations: A simulation framework for analyzing congestion and cost’, *Transportation Research Part D: Transport and Environment*, 97. Available at: https://doi.org/10.1016/j.trd.2021.102962.

Schlund, D., Schulte, S. and Sprenger, T. (2022) ‘The who’s who of a hydrogen market ramp-up: A stakeholder analysis for Germany’, *Renewable and Sustainable Energy Reviews*, 154. Available at: https://doi.org/10.1016/j.rser.2021.111810.

Schmidt, A. and Donsbach, W. (2016) 'Acceptance factors of hydrogen and their use by relevant stakeholders and the media', *International Journal of Hydrogen Energy*, 41(8), pp. 4509–4520. Available at: https://doi.org/10.1016/j.ijhydene.2016.01.058.

Schrotenboer, A.H. *et al.* (2022) 'A Green Hydrogen Energy System: Optimal control strategies for integrated hydrogen storage and power generation with wind energy', *Renewable and Sustainable Energy Reviews*, 168. Available at: https://doi.org/10.1016/j.rser.2022.112744.

Shell (2021) *Waterstofbussen Groningen en Drenthe* . Available at: https://www.shell.nl/energie-en-innovatie/waterstof/waterstofbussen.html (Accessed: 2 February 2023).

Shell (no date) *Reducing total cost of ownership*. Available at: https://www.shell.com/business-customers/commercial-fuels/reducingtco.html (Accessed: 9 February 2023).

Siddiqui, O. and Dincer, I. (2021) 'A comparative life cycle assessment of clean aviation fuels', *Energy*, 234. Available at: https://doi.org/10.1016/j.energy.2021.121126.

Singh, A., Baredar, P. and Gupta, B. (2017) 'Techno-economic feasibility analysis of hydrogen fuel cell and solar photovoltaic hybrid renewable energy system for academic research building', *Energy Conversion and Management*, 145, pp. 398–414. Available at: https://doi.org/10.1016/j.enconman.2017.05.014.

Staffell, I. *et al.* (2019) 'The role of hydrogen and fuel cells in the global energy system', *Energy and Environmental Science*. Royal Society of Chemistry, pp. 463–491. Available at: https://doi.org/10.1039/c8ee01157e.

Terlouw, T. *et al.* (2022) 'Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment', *Energy and Environmental Science* [Preprint]. Available at: https://doi.org/10.1039/d2ee01023b.

Testa, E. *et al.* (2014) 'Analysis of environmental benefits resulting from use of hydrogen technology in handling operations at airports', *Clean Technologies and Environmental Policy*, 16(5), pp. 875–890. Available at: https://doi.org/10.1007/s10098-013-0678-3.

UNFCCC (2015) *Paris Agreement United Nations*.

Vaicys, J. *et al.* (2022) 'Efficiency evaluation of the dual system power inverter for on-grid photovoltaic system', *Energies*, 15(1). Available at: https://doi.org/10.3390/en15010161.

Wulf, C. *et al.* (2018) 'Life Cycle Assessment of hydrogen transport and distribution options', *Journal of Cleaner Production*, 199, pp. 431–443. Available at: https://doi.org/10.1016/j.jclepro.2018.07.180.

Xiang, Y. *et al.* (2021) 'Techno-economic design of energy systems for airport electrification: A hydrogen-solar-storage integrated microgrid solution', *Applied Energy*, 283. Available at: https://doi.org/10.1016/j.apenergy.2020.116374.

Xie, Y. *et al.* (2021) 'Economic analysis of hydrogen-powered data center', *International Journal of Hydrogen Energy*, 46(55), pp. 27841–27850. Available at: https://doi.org/10.1016/j.ijhydene.2021.06.048.

Yue, M. *et al.* (2021) 'Hydrogen energy systems: A critical review of technologies, applications, trends and challenges', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. Available at: https://doi.org/10.1016/j.rser.2021.111180.

Zhao, H. *et al.* (2022) 'Resilience Assessment of Hydrogen-Integrated Energy System for Airport Electrification', *IEEE Transactions on Industry Applications*, 58(2), pp. 2812–2824. Available at: https://doi.org/10.1109/TIA.2021.3127481.

Zhou, Y. and Searle, S. (2022) *Caost of renewable hydrogen produced onsite at hydrogen refueling stations in europe*. Available at: www.theicct.orgcommunications@theicct.org.

Zini, G. and Dalla Rosa, A. (2014) 'Hydrogen systems for large-scale photovoltaic plants: Simulation with forecast and real production data', *International Journal of Hydrogen Energy*, 39(1), pp. 107–118. Available at: https://doi.org/10.1016/j.ijhydene.2013.10.076.

Zouine, M. *et al.* (2019) 'Mathematical models calculating PV module temperature using weather data: Experimental study', in *Lecture Notes in Electrical Engineering*. Springer Verlag, pp. 630–639. Available at: https://doi.org/10.1007/978-981-13-1405-6_72.

Appendix C. Stakeholder Collaboration in an Airport Hydrogen Ecosystem: Investigation of Barriers and Design Advice- Case study at Groningen Airport Eelde

Abstract

Research problem and objective: Hydrogen is a promising energy vector that can reduce airport emissions. However, many barriers impede the commercialization and adoption of hydrogen technology. Stakeholder involvement is critical in developing a local hydrogen ecosystem because stakeholders are needed to provide technologies and establish demand. Nevertheless, stakeholders often have conflicting objectives that airports should manage. This paper aims to investigate stakeholder roles, expectations, and barriers. Moreover, the paper provides design advice for managers and policymakers.

Method: A case study at Groningen Airport Eelde is carried out. Sixteen industry experts are interviewed to explore in-depth insights into a hydrogen airport ecosystem.

Results: The paper identified diverse economic, technical, political, social & environmental barriers that impede hydrogen development and deployment. Stakeholder experience uncertainties, but the future is promising. Furthermore, social acceptance is controversial, but sustainability practices and appropriate communication help to gain support. The paper contributes to a better understanding of the challenges to overcome to develop and deploy an airport hydrogen ecosystem.

Conclusion: Hydrogen cannot compete with fossil fuels, but this is expected to change by 2040. Moreover, hydrogen has notable advantages for airports and their stakeholders. This paper provides practitioners with guidance for designing an airport hydrogen ecosystem. Moreover, the paper can contribute to developing infrastructure and policy plans. It is challenging to realize a feasible business model. Therefore, government support is essential to foster market development and mitigate uncertainty.

1. Introduction

Combatting climate change requires decarbonization of the global energy system. The objective of the Paris Agreement is to limit the increase of the global average temperature below 2 degrees Celsius. Therefore, rapid emission reduction is needed to achieve net-zero goals in the second half of the century (United Nations, 2015). A transformation of energy vectors and industrial practices is required. The transport sector plays a crucial role in reaching a low-carbon society. The prediction is that the aviation sector will grow faster than other sectors' average growth. Moreover, the aviation sector relies heavily on fossil fuels (European Commission, 2017). Consequently, it is challenging to achieve zero-emission targets.

Ground support equipment (GSE) accounts for a significant share of airport emissions (Nambisan et al., 2000; Schürmann et al., 2007). GSE is used to service airport ground handling. There are various kinds of GSE, such as ground power units (GPUs) and refueling trucks (Baroutaji et al., 2019). Electrification of final energy demand and decarbonization of power supply is crucial to achieving zero-emission goals. This is especially true for the transportation industry (Fragkos et al., 2017). Hydrogen can be used to realize this because hydrogen fuel cells can generate electricity to power equipment. In addition, hydrogen is suitable for storing renewable energy (Zhang et al., 2016), and its high power density is an advantage to power equipment. Hydrogen and fuel cell technology are suitable for various kinds of GSE. Therefore, hydrogen can be the future of energy supply in the aviation industry. However, significant challenges limit the adoption of hydrogen technology (Baroutaji et al., 2019).

Developed countries explore sustainable and efficient pathways to realize zero carbon footprint through the hydrogen economy. A hydrogen economy can be attained through the large-scale integration of renewable energies and intermittent power generation with the production of green hydrogen (Nazir et al., 2020). There is increasing interest in improving the air quality around airports. Fuel cell devices have potential in different GSE applications, such as shuttles and refueling trucks (Staffell et al., 2019). Furthermore, fuel cells are suitable to power other transport vehicles. In Tokyo, some of the passenger buses between Tokyo center and Tokyo airport are hydrogen fuel cell or battery hybrid driven (Toyota, 2011).

Stakeholder involvement is crucial in addressing the environmental sustainability of airports (Greer et al., 2020). This study focuses on the landside part. Integrating hydrogen into the energy system might be disruptive for established stakeholders. New parties enter the market, and current business models and stakeholder roles are challenged. However, stakeholder engagement and consensus are essential in the development of the market (Schlund et al., 2022). Barke et al. (2020) investigated socioeconomic sustainability in aviation, especially for aircraft. Stakeholder groups, like airlines and airport operators, often have diverging preferences and objectives. These conflicting objectives can make it challenging to develop sustainable aircraft systems (Barke et al., 2020). Research about stakeholders and the sustainability of the landside component is lacking. This is especially true for stakeholders in an airport hydrogen ecosystem.

An airport can be a focal firm and facilitator in developing a local hydrogen ecosystem. However, this role should be further explored (Hoelzen et al., 2022). Xiang et al. (2021) state that an airport can generate electricity independent of the grid with a hydrogen-solar-storage integrated energy system. Kamphuis (2022) identified stakeholder categories, opportunities, and barriers to implementing an airport hydrogen energy system. However, more in-depth and extended stakeholder analysis is needed to gain further deployment insights (Kamphuis, 2022). For small airports, demand from nearby industries is essential for the feasibility of the ecosystem (Eefting, 2022). The development of hydrogen energy systems is in its infancy stage. Many barriers hinder the commercialization and large-scale application of hydrogen technologies (Wu et al., 2022). This paper will focus on hydrogen development and commercialization at the landside airport component. Therefore, the report aims to answer the following research questions:

What are stakeholder cooperation possibilities and expectations for an airport hydrogen ecosystem? What are the barriers and design recommendations?

A case study at Groningen Airport Eelde will answer these questions. This is a small airport in the north of the Netherlands. The airport is in the middle of Europe’s first Hydrogen Valley, also called the HEAVENN project. The airport focuses on sustainability and develops a hydrogen ecosystem (Groningen Airport Eelde, 2022; HEAVENN, 2022). Industry experts will be interviewed to gain insights into collaboration possibilities, expectations, and barriers.

The paper contributes to the literature about stakeholders and sustainability of the landside airport component, especially regarding stakeholders in an airport hydrogen ecosystem. Also, the results give more insights into airport net-zero hydrogen practices. These insights contribute to a better understanding of hydrogen application and demand creation at small airports. Hydrogen demand is low in the current early transition stage. Therefore, collaboration with regional industries and institutions is essential to create demand and make the transition economically feasible. Furthermore, the paper provides learning points and design recommendations for airport managers, policymakers, and stakeholders. This can support them in the transition to a hydrogen ecosystem.

The paper is structured in the following way: Section two reviews the current literature. Section three explains the methodology used in this research. Section four will show the results. Section five provides a discussion of the results. Finally, the paper concludes in section six.

2. Literature review

In this section, the existing literature will be reviewed. First, hydrogen and its supply chain are explained. After that, the relevant airport applications are illustrated. Then follows further explanation about stakeholders and barriers inhibiting hydrogen deployment. Finally, the section concludes with the contributions of this paper.

Hydrogen is a promising element to meet sustainable future energy demand (Elam et al., 2003) because hydrogen applications can mitigate the global temperature increase. Hydrogen is an essential component in the energy transition as a feedstock and an energy carrier (El-Emam & Khamis, 2019). Due to its carbon-free nature and high energy content, hydrogen is considered an eco-friendly alternative to fossil fuels (DeLuchi, 1989; Ellabban et al., 2014; Momirlan & Veziroglu, 2005). Hydrogen can be used in different ways. Therefore, it can fulfill the market needs regarding renewable energy sources. Moreover, it can reduce annual CO2 emissions, and hydrogen technology can create 30 million new jobs in 2050 (Mathiesen et al., 2015). For example, hydrogen can power over 400 million cars, 15-20 million trucks, and 5 million buses by 2050. This is 20-25% of the transport and shipping industry (Mostafaeipour et al., 2016). However, a lot needs to be done to achieve a developed hydrogen economy. Well-established hydrogen energy systems based on sustainable resources, production methods, and end-use options, including storage and distribution, are required. Commercial hydrogen economies are essential for reducing global warming. However, current research revealed various limitations regarding the feasibility of hydrogen production and applications. Some examples are storage complications and expensive production (Qyyum et al., 2021).

2.1 Hydrogen Supply Chain

Hydrogen production can occur at large centralized or small decentralized facilities (Hoelzen et al., 2022). The advantage of decentralized onsite production is that it reduces transportation problems (Li et al., 2020). The fundamental hydrogen infrastructure includes production, storage, delivery, and end-use applications (DOE, 2002). There are different pathways and sources to produce hydrogen, carbon sources such as gas and coal, renewable sources such as water and biomass, and nuclear sources (Qyyum et al., 2021). Currently, hydrogen is mainly produced from fossil fuels, which is not sustainable and is called grey hydrogen (Zhang et al., 2016). Renewable sources include biomass processing, biofuel reforming, water electrolysis, and thermochemical cycles (Hydrogen Production Processes, 2021). Electrolysis is the essential carbon-neutral technique used in most sustainable hydrogen production. However, electrolysis is more expensive and complex than the other techniques mentioned (Qyyum et al., 2021).

A developed hydrogen economy requires cost-effective transmission and distribution. Challenges occur due to low density, high diffusivity, and safety issues. Different options for hydrogen transmission and distribution include compressed gaseous hydrogen trailers (CGH2), liquefied hydrogen trucks (LH2), liquid organic hydrogen carriers (LOHC), and pipelines. The economic feasibility of the transport and storage option depends on volumes and delivery distances. Significant capital investments are required to develop distribution infrastructures (Qyyum et al., 2021). Storage terminals are vital in the network because they buffer against demand and seasonal fluctuations. The transportation method depends on the form of hydrogen and whether production is centralized or decentralized. Liquid hydrogen can be transported on trucks, trains, or ships. Gaseous hydrogen can be transported with pipelines, tube trailers, or railway tube wagons (Li et al., 2020). Transport of liquid hydrogen is less expensive per volume than gaseous hydrogen. However, high liquefication costs make liquid hydrogen only feasible for medium-order quantities and long-distance scenarios (Yang et al., 2006).

Hydrogen can be used in various ways, for example, as a feedstock to replace current fossil fuels and for heating in buildings and industry (Detz et al., 2019). Moreover, fuel cells can power cars and are promising for heavy transport and public transportation (IEA, 2015; Navas-Anguita et al., 2020). Fuel cells are needed to convert the hydrogen energy for end-use chemically. Electricity generation in a fuel cell is a promising method because of its high efficiency, low to zero emissions, scalability, durability, and quiet operation (Das et al., 2017). Several fuel cells have been developed for a variety of applications. However, some issues must be solved before fuel cells can effectively replace current applications. These challenges include cost reduction, increased durability and reliability, material safety, convenient system sizes, and improved heat recovery systems (Qyyum et al., 2021).

2.2. Airport applications

This paragraph will discuss the application of hydrogen technology at airports. Hydrogen is considered the future of energy generation in the aviation industry. There are various potential aviation applications where hydrogen and fuel cell technology can be used (Baroutaji et al., 2019). Fuel cells can generate electricity to power equipment, and hydrogen is suitable for storing green energy (Zhang et al., 2016). Moreover, the high power density of hydrogen is an advantage to powering heavy airport equipment (Baroutaji et al., 2019). Xiang et al. (2021) investigated a hydrogen-solar-storage integrated energy system for airport electrification. Their case studies found hydrogen integration's economic, technical, and environmental benefits. The findings show a total annual cost decrease of 41.6% and an emission reduction of 67.29%. Moreover, the proposed system provides long-term economic and environmental benefits in the project lifecycle.

Fuel cell devices have received attention due to their potential to power Ground Support Equipment (GSE) and other vehicles operating at airports (Staffell et al., 2019). GSE is used to service airport ground operations. Airports have various types of GSE, such as ground power units (GPUs), refueling trucks, passenger shuttles, the air start unit of the engine, air conditioning units, cargo loaders, baggage tractors, pushback trucks, and trolleys (Baroutaji et al., 2019). GSE is a source of pollution at airports and their surroundings. Conventionally GSE is powered by diesel engines. Fuel cell electric vehicles (FCEV) can achieve pollution reduction. Research shows that emissions can be reduced by 25-50%, depending on the equipment's power level. These emissions can be further reduced by employing renewable energy sources (Testa et al., 2014).

The Department of Energy in the USA announced that 250 million US dollars would be used to deploy fuel cells for baggage vehicles at airports (DOE, 2012). Medium-size fuel cell-powered forklifts have been tested in airports such as Toronto, Pearson, Hamburg, and Munich (McConnell, 2010). Fuel cells can operate for more than eight hours without refueling, which is an advantage over traditional batteries (Fuel Cells Bull, 2015).

2.3. Stakeholders

This paragraph will elaborate on stakeholder involvement. Stakeholder involvement is essential to enhance the environmental sustainability of an airport. Historically, an airport's airside and landside components have been managed by different stakeholders (Greer et al., 2020). In particular, for small airports, demand from nearby industries is essential for the economic feasibility of the ecosystem (Eefting, 2022). Furthermore, the role of an airport as a focal firm and facilitator of a local hydrogen ecosystem should be further investigated (Hoelzen et al., 2022).

The growth of the hydrogen market is in a critical phase, which requires the engagement and coordination of many heterogeneous stakeholders. Schlund et al. (2022) carried out a stakeholder analysis of the German hydrogen market. The findings reveal stakeholder motives relevant to developing an airport hydrogen ecosystem. Integration of hydrogen into the energy system could have a disruptive impact on established stakeholders. Business models are questioned, and new stakeholders enter the market. This creates new partnerships among potential stakeholders and causes new conflicts. As a result, uncertainty among potential stakeholders in the future hydrogen market is high. However, engagement and consensus are essential in market development (Schlund et al., 2022).

Barke et al. (2020) analyzed socioeconomic sustainability in aviation, specifically for aircraft. Evaluating novel and renewable aircraft systems requires the assessment of various sustainability indicators and considering different stakeholder groups. Stakeholder groups, like airlines and airport operators, often have diverging preferences and objectives. These conflicting objectives can make it challenging to derive recommendations for developing sustainable aircraft systems. Therefore, airports should find ways to deal with the contradictory objectives of stakeholders (Barke et al., 2020). However, research about stakeholders and the sustainability of the landside component is lacking.

Previous research identified relevant stakeholders for the hydrogen industry. Enevoldsen et al. (2014) classified stakeholders. They categorized ten groups of stakeholders for the Danish hydrogen electrolysis industry. A stakeholder analysis of the hydrogen market in Germany derived 49 stakeholder groups (Schlund et al., 2022). Kamphuis (2022) analyzed stakeholders for an airport hydrogen ecosystem. Combined with the studies of Enevoldsen et al. (2014) and Schlund et al. (2022), 21 stakeholder categories for an airport hydrogen ecosystem are derived (Kamphuis, 2022). However, transformation to new technology and infrastructure often provokes protests from the population. Therefore, it is crucial to understand societal positions and conflicts to achieve social acceptance (Glanz & Schönauer, 2021). Therefore, this paper will also include the civilians around the airport. The stakeholder categories used for this paper can be found in table 3.1.

2.4. Barriers inhibiting hydrogen deployment

Many barriers hinder hydrogen application and commercialization. This paragraph will elaborate on that topic. According to Shakeel et al. (2017), commercializing renewable energy technology requires a mix of technical, market, and regulatory factors. If one of those is missing, adopting a technology becomes difficult. In addition, Kamphuis (2022) identified barriers that impede the development and deployment of an airport hydrogen energy system. These barriers are high capital investments, the need for more trained and qualified employees, and the shortage of safety codes and standards.

There are different ways to distinguish conflicting criteria and barriers. According to Ahmad et al. (2021), criteria can be grouped into social, environmental, economic, and technical categories. Rosso et al. (2014) distinguish environmental, economic, technical, and socio-politic aspects. Wu et al.

(2022) distinguish four types of barriers: economic, technological, policy, environmental & social. Some examples of barriers will be summed up. Economic barriers include high initial investment costs, high conversion costs, and carbon tax. Technological barriers include immature technology, low energy conversion efficiency, lack of professionals, and hydrogen safety. Policy barriers include a lack of regulations and standards, incomplete subsidy mechanisms, complicated regulatory procedures, and a lack of demonstration projects. Environment and social barriers include pollution in hydrogen production, limited financing channels, and social acceptance. Eliminating or reducing the different barriers contributes to the large-scale application (Wu et al., 2022). So, hydrogen energy systems face several barriers that must be conquered to make hydrogen a competitive energy carrier (Elam et al., 2003).

2.5. Contributions

This chapter covered the relevant literature about a hydrogen airport ecosystem and its stakeholders. Table. 2.1 shows that several studies have been done about the hydrogen supply chain and hydrogen aviation applications. There are various ways to produce and deploy hydrogen. Since hydrogen is promising for GSE (Baroutaji et al., 2019; Staffell et al., 2019; Testa et al., 2014), this paper will focus on the landside airport component. Table 2.1 shows that several studies about stakeholders have been done. However, these studies are not about the landside stakeholders in an airport hydrogen ecosystem. This research explores potential stakeholder roles and barriers inhibiting hydrogen deployment. The role of an airport in developing a local hydrogen ecosystem should be further investigated (Hoelzen et al., 2022). Stakeholder involvement is essential (Greer et al., 2020) but challenging due to conflicts and changing business models (Schlund et al., 2022).

Nowadays, many barriers hinder the commercialization and application of hydrogen technologies (Wu et al., 2022). Kamphuis (2022) identified stakeholders, barriers, and opportunities for deploying an airport hydrogen energy system. Table 2.1 shows that various papers found barriers and opportunities for hydrogen deployment, but only some case studies have been conducted. Case studies can provide in-depth exploration in real life context (Karlsson, 2016). Therefore, this paper will perform an in-depth stakeholder analysis, including society's views, which is essential to achieve social acceptance (Glanz & Schönauer, 2021). The results will give insights into the development of an airport hydrogen ecosystem. Moreover, the paper provides learning points and design advice for airport managers, policymakers, and stakeholders.

Table 2.1 Overview of topics investigated by previous studies

	Hydrogen Supply Chain	GSE	Aviation	Stakeholders	Barriers and opportunities	Case study
Article						
Barke et al., 2020			✓	✓		
Baroutaij et al., 2019		✓	✓		✓	
Greer et al., 2020			✓	✓	✓	
Hoelzen et al., 2022	✓		✓		✓	
Nazir et al., 2020	✓				✓	
Qyyum et al., 2021	✓				✓	
Schlund et al., 2022	✓			✓		✓
Staffel et al., 2019	✓	✓			✓	
Testa et al., 2014		✓				
Wu et al., 2022				✓	✓	
Xiang et al., 2021	✓		✓			✓
Glanz & Schönauer, 2021				✓		

3. Methodology

In this section, the research methodology will be justified and explained.

3.1. Research design

This paper provides a stakeholder analysis for Groningen Airport Eelde. It explores stakeholder collaboration possibilities and expectations for an airport hydrogen ecosystem. Literature states that an airport can be a facilitator for developing a local hydrogen energy system (Hoelzen et al., 2022), and stakeholder involvement is crucial (Greer et al., 2020). There are various potential aviation applications where hydrogen and fuel cell technology can be used (Baroutaji et al., 2019). However, many barriers hinder the commercialization and large-scale application of hydrogen technologies. These barriers can be categorized as economic, technological, policy, environmental & social (Wu et al., 2022). First, this paper will explore stakeholder roles and expectations for an airport hydrogen energy system. Second, it will identify barriers and derive design advice for hydrogen deployment. Therefore, the report aims to answer the following research questions:

What are stakeholder cooperation possibilities and expectations for an airport hydrogen ecosystem? What are the barriers and design recommendations?

A case study at Groningen Airport Eelde will answer these questions. This is a small airport in the North of the Netherlands. Here a hydrogen-solar-storage integrated energy system for airport electrification will be developed. Sixteen semi-structured interviews with representatives from different stakeholder categories will be held. The representatives have the expertise and represent a company or a government organization. Twenty-two stakeholder categories (see table 2) for an airport hydrogen ecosystem are derived from earlier studies (Enevoldsen et al., 2014; Glanz & Schönauer, 2021; Kamphuis, 2022; Schlund et al., 2022). The interview protocols can be found in Appendix B. Two protocols are used, one for businesses and one for organizations representing society. This is because society has other interests and less knowledge about hydrogen.

The research follows a single case study approach. The development of an airport hydrogen ecosystem is novel. Moreover, large-scale hydrogen deployment is immature. Therefore, the study is explorative and aims to build theory (Karlsson, 2016). A case study is highly appropriate because it implies a contemporary phenomenon in real life context. Moreover, there is a small theoretical basis (Yin, 2018). The phenomenon will be studied in a natural setting, increasing practitioner validity. Furthermore, a single case study allows for an in-depth exploration (Karlsson, 2016).

Table 3.1 Stakeholder categories and their definitions (Enevoldsen et al., 2014; Glanz & Schönauer, 2021; Kamphuis, 2022; Schlund et al., 2022)

Stakeholder	Definition
Airport	The airport as an infrastructure provider
Airlines	The airlines can be hydrogen consumers
Electricity TSO and DSO	Electricity transmission and distributor systems companies
Electricity utilities	Utilities along the electricity value chain who perform different activities along the electricity value chain (excluding municipal utilities)
Energy cooperatives	Cooperatives such as civil wind farms or other energy cooperatives
Energy service companies	Providers of a wide range of energy solutions, for instance, planning or engineering power generation and energy supply (not part of the value chain)
Ground handling companies	Ground handling refers to a range of services on the ground
GSE maintenance companies	Providers that perform GSE maintenance
Hydrogen exchange	Hydrogen exchange, could be integrated into existing energy exchanges
Hydrogen technology provider	Manufacturers and providers of special equipment for hydrogen technologies. Independent of the value chain (for example, fuel cells, storage equipment, electrolyzers, compressors, pipelines, and liquefaction plants)
Natural gas industry	Natural gas industry in the broad sense (for example. gas exploration, extraction, import, and trading)
NGOs, civil society, and trade groups	Stakeholders opposing or promoting the electricity industry toward collaboration with the hydrogen industry
Gas TSO and DSO	Gas transmission and distributor systems operators
Politics	European/ Federal/ State/ Local politics. It also includes targeted policies (for example, climate policy, regulation, and development policy)
Project developers	Project developers as service providers (for example, developers of renewable energy projects)
Public companies	Public companies are companies in whole or majority state ownership. They often have the purpose of regional promotion of social or economic areas
RES plant operators	Operators of renewable energy plants such as photovoltaic, hydro, wind, and biomass
Research and development	Private and public research organizations, such as universities
Storage operator	Operators of the hydrogen storage facilities
Industrial sector	The industrial sector can be a hydrogen consumer
Transport sector	The transport sector can be a hydrogen consumer
Society	People living around the airport and associations of people representing residents

3.2. Case and interviewee selection

Groningen Airport Eelde has the ambition to become Europe's most sustainable airport. The airport is in the middle of Europe's first Hydrogen Valley, also called the HEAVENN project. The HEAVENN project started in the Northern Netherlands to show the techno-economic feasibility and environmental advantage of deploying a hydrogen energy system (HEAVENN, 2022). The airport develops a full-scale hydrogen ecosystem involving the production of green hydrogen, distribution, and utilization. An existing 22MW solar park with 63.00 solar panels is located at the airport. The electrolyzer will produce green hydrogen, and a hydrogen refueling station will enable hydrogen on and off-site distribution. Furthermore, the airport strongly focuses on innovation, sustainability, and education. An example is the developing electric flying infrastructure (Groningen Airport Eelde, 2022).

Interviewees are selected from various backgrounds and stakeholder categories, contributing to the study's validity and data triangulation (Karlsson, 2016). For example, stakeholders can be hydrogen fuel cell equipment manufacturers, fuel station operators, government representatives, society representatives, and other parties in the hydrogen supply chain and energy sector.

3.3. Data collection

Semi-structured interviews will be held in November and December of 2022. An overview of the interviewees can be found in table 3.2. The interview questions (Appendix B) consist of open-ended and follow-up questions that encourage interviewees to provide more detailed answers (Adams, 2015). The interviews were recorded and transcribed shortly after they took place to ensure sufficient memory of the interview. In addition, company visits, presentations, emails, websites, and company documents gather complementary data. This contributes to validity and secures data triangulation (Karlsson, 2016; Yin, 2018).

3.4. Data analysis

The interviews were analyzed and coded using Atlas.ti. The transcripts can be found in the appendix. Codes were both based on theory and data. Data reduction is done by only assigning codes to relevant data for this research. First-order codes emerged during data analysis. These initial codes are reduced and refined by merging codes with the same meanings. Second-order codes are based on grouped first-order codes and concepts from literature, such as different barriers. In the last step, these codes were aggregated into dimensions (Karlsson, 2016). Finally, 57 initial codes emerged, followed by 11 second-order codes and two dimensions.

4. Results

In this section, the findings of the analyzed interviews will be presented. The structure will follow the coding trees displayed in Tables 4.1 and 4.2. Coding trees with example quotes and quantities can be found in Appendix A.

Table 4.1 Coding tree 1

First order code	Second order code	Dimension
Current hydrogen role	Current hydrogen economy	Stakeholder collaboration and expectations
Current renewable energy		
Energy supplier role		
Hydrogen Northern Netherlands		
Little renewable energy		
Figure out hydrogen future	Future hydrogen economy	
Future energy mix		
Import hydrogen from abroad		
Mainly direct electrification		
Promising hydrogen future		
Specific applications		
Uncertain future		
Collaboration with partners	Stakeholder collaboration	
New parnerships		
Different organisations needed		
Competition parties	Stakeholder conflicts	
Different objectives stakeholders		
No conflicts		
Airport role	Hydrogen airport ecosystem	
Business opportunity		
Decentralized system		
Economic benefits		
Grid capacity		
Grid connection		
Hydrogen demand		
Succes depending on scale		
Zero emmission target		
Electric GSE	Ground support equipment	
Ground support equipment		
Hydrogen GSE		

Table 4.2 Coding tree 2

First order code	Second order code	Dimension
Business model hydrogen	Economic barriers	Barriers inhibiting hydrogen deployment and recommendations
Diesel cheaper		
High hydrogen price		
High investment costs		
No viable business model		
Subsidies		
Availability	Technological barriers	
Hydrogen infrastructure		
Technology excists		
Research and knowledge		
Technical staff and skills		
Technology development		
Missing stimulating policy	Political and regulatory barriers	
Policy not consistant and slow		
Regulation		
Permits		
Hinder environment	Social and environmental barriers	
Inform public		
Positive for environment		
Safe and responsible		
Resistance airport		
Safe distance people		
Safety concerns		
Social acceptance		
Social support hydrogen		
Support airport		
Ranking barriers	Ranking barriers	

4.1. Stakeholder roles and views

This part will cover the first research theme and the related research question. Various stakeholder roles and views are further explained.

4.1.1. Current hydrogen economy

The result reveals that hydrogen development and deployment are in the early stages. Some organizations are involved in one or more hydrogen projects in the Northern Netherlands. Many organizations are engaged in the HEAVENN project (organizations A F, H, I, J, L, M). Organization D is co-designer and developer of the HEAVENN project. They have a role in technical coordination and in developing business models. It is a complex project that interconnects deployment projects. Interviewee I: *''HEAVENN is a glue that connects projects and creates an entire ecosystem. An airport is valuable in the project because it provides different applications and business models''*. Organization A is involved in several research projects, and some are already running. They have several small electrolyzers and currently building a large central one. Interviewee A: *''I currently work on a research project in Emmen, developing an innovation and research facility in renewable energy and electrolysis. Also, I am working on mapping the hydrogen demand in the region''*. In Oosterwolde, organization E manages a hydrogen project in which an electrolyzer is connected to a solar park, comparable to the airport project.

The organizations are in different stages of hydrogen application. Some are thinking about it; some are developing applications, and others are already deploying them. Interviewee K: *''Currently, we do nothing with hydrogen. We have 3300 solar panels on our roof and looking to the next step. For example, last year, we bought a boiler that could be additionally fired with hydrogen''*. For organization C, hydrogen is currently a by-product. However, they realized that hydrogen has more potential and wanted to focus on further development. Hydrogen is deployed in transport and associated refueling stations. Interviewee J: *''We are pioneering with several hydrogen refueling stations. The experience is that it works; that is the most important thing. Experimentation and selling it to customers give valuable lessons to improve''*. In Groningen and Drenthe, some public transport buses and taxis are fuelled by hydrogen. Currently, 32 buses and five taxis. Here are issues to overcome. For example, breakdowns of refueling stations (organization L and M). Interviewee M: *''Availability of refueling is critical. If busses cannot drive, a part of the timetable fails''*.

Hydrogen is also used in the chemical industry. However, this is not green hydrogen. Organisation E states that there is currently a lot of grey hydrogen, which is less expensive than green hydrogen. The high energy prices make it more costly to produce green hydrogen. Organization A states that the amount of renewable energy is a significant problem. Interviewee A: *''we have too little renewable energy, which is a big problem. If that supply increases, the hydrogen price will fall''*.

4.1.2. Future hydrogen economy

The results reveal that most organizations think the future of hydrogen is promising but uncertain. Hydrogen will play a key role, especially in the Northern Netherlands. Some specific challenges and applications will be difficult to solve with another solution or technology. The gas situation is changing due to problems with earthquakes. Digging for natural gas in this region will not be an option anymore. Therefore, we need a replacement, from an energy and economic point of view. Hydrogen will play a role in the energy system, but it will take time (organization I). Between now and ten years, a lot will change. More will follow if large companies and industries switch to hydrogen (organization D). Organization G: *''Hydrogen is beautiful, and I hope the airport can play a positive role. In the end, if it works out, we all gain something''*. However, the future of hydrogen is also uncertain (organization A, J).

Interviewee J: *''No one knows what will happen in the future. There are many hydrogen forms, and everyone is looking at what form works best for what application''*. We do not yet have the answer to many questions, such as where to apply it at an airport. Interviewee B2: *''Should we build super large or small electrolyzers? For what applications is hydrogen best suited?''*. You must pioneer and determine if hydrogen is appropriate for the organization at a certain point in the future. This also depends on the development of batteries and regulations regarding emission reduction. For example, at a particular moment, diesel could no longer be allowed at the airport (organization B).

We must look carefully at the role of hydrogen in de energy mix. It is risky to make hydrogen for things that can be much better electric. For example, newly built hydrogen-powered houses or hydrogen-powered passenger cars. Interviewee A: *''I see it as a risk that we use hydrogen as a sort of panacea for everything. This will create resistance for hydrogen pilots, and we throw away much energy''*. The majority will be direct electrification. This also holds for aviation applications. If possible, you can fly electrically or make a GPU electrically. This is much more efficient (organization A). Interviewee E: *''Hydrogen is the big loser per turnover step. This makes it expensive energy. I am skeptical about using hydrogen while you can also use batteries''*. In the future energy mix, we can use hydrogen as energy storage. Wind- and sun energy gives high fluctuations. Hydrogen can be produced at peak times and later be used. This makes it necessary for the energy mix (organization C).

Hydrogen can be used for applications too heavy for batteries or direct electrification (organization A, B, D, L, M). At airports, some vehicles cannot be electric. For example, a vehicle that sprays high-temperature liquids makes planes ice-free. Also, some heavy kerosine transport trucks and pushback trucks. Sometimes those vehicles must drive long distances with heavy aircraft or do not have time to load (organization B). It is also a solution for the transportation sector. Trucks, buses, taxis, and machinery that are heavy and must drive long distances can be powered by hydrogen. Usually, these vehicles must be constantly deployable (organization D). Battery electricity is only sometimes feasible for taxis because the range is too short. Also, cabs must fill up quickly and move on (organization L). Hydrogen is also suitable for regional buses that need a sizeable autonomous range. There are also few opportunities to recharge in rural areas (organization M).

Furthermore, hydrogen can be a solution in specific situations. For example, when the electricity grid is overloaded and cannot supply. Also, applications where hydrogen as feedstock is essential and niche markets where it is not profitable to install an entire power network (organization A, D).

Lastly, several organizations expect future hydrogen importation from abroad. Interviewee A: ''*We expect a lot from the import of hydrogen and are looking to different opportunities. Like liquid hydrogen transport from Australia by boat*''. Production can also occur in Australia or Africa because solar panels generate more energy there. Then Import terminals should be developed. Furthermore, production could happen in the North Sea (organization C, F).

4.1.3. Stakeholder collaboration

The results reveal that stakeholders see the importance of collaboration. This corresponds with the expectation. New partnerships are emerging. Particularly cooperation between research and industry is essential. Interviewee I: ''*We are part of that and work closely with the university*''. It is essential to highlight that collaboration is vital in large and small industries. Large companies can provide capital, experience, and large-scale infrastructure. On the other hand, small companies and entrepreneurs are crucial for innovating new technologies (organization I). Interviewee K: ''*I notice that smaller companies mainly look at big companies like the airport and us. Most companies here are too small to develop major initiatives*''. Collaboration is necessary and logical because a new sector must be developed—an entire supply chain from production to end-user. Partnerships are even created with competitors. Manager A: ''*We develop an electrolyzer demo together with a competitor in de electricity market*'' (organization A).

Recently companies starting to collaborate at the business park next to the airport. Companies are also looking at how they can use hydrogen, for example, in heating and transport. Before, there was no cooperation, but now companies realize they need help with the energy transition and want to make it together. The municipality launched a project here on energy-neutral business parks. This project resulted in a business association cooperating. Interviewee G: ‘’*We managed to find funding for an energy consultant there. He can analyze possibilities and costs. Entrepreneurs realize that it is not possible alone, financially it is also such a big task*’’. Currently, hydrogen is difficult to implement. It is new, and nobody knows what to expect (organization G). The government is also supporting local collaboration. Companies should pick up different elements of the hydrogen supply chain. In all those elements, parties can play a role. The government is essential in giving permissions and making development and deployment possible. Interviewee H: ‘’*What you want is that companies in that industrial park sit together to solve it locally. It is about the development of those value chains. Therefore, you also must define all those subsidy instruments on the supply chain level*’’. If there is a collaboration, companies can apply for a significant subsidy (Organisation H).

Companies at the airport business park are looking at what to do with energy and how the airport can be involved. There are large transport companies that that willing to participate in innovative pilots. Interviewee K: ‘’*As entrepreneurs, we sat together to see how we could help each other. We have a lot of solar panels and the airport too. What can we do with that energy?*’’. The energy goes into the grid now, but the network is overloaded. In the future local decentralized networks could be a solution. Then companies can be local suppliers of energy. The business park could be autonomous of the grid in a collaborative setting with solar panels, hydrogen, and other sources. Currently, legalization does not allow this (organization G, K).

4.1.4. Stakeholder conflicts

The results reveal that conflicts are controversial. Most organizations notice few conflicts and focus on collaboration. Interviewee I: ‘’*I would not call it conflicts. Different parties have different motivations and objectives. There are challenges to align those, but I would not say conflicts*’’. Interviewee G: ‘’*Instead of conflicts, you see movements of collaboration*’’. There are different interests but no conflicts. There is healthy completion that is just beginning (organization A, I).

However, reaching a consensus about responsibilities can be challenging. For example, the airport wants to avoid being responsible for technology development. The airport is only a facilitator for stakeholders. For hydrogen technology providers, it is a risk to invest and to be accountable. Organization D: ‘’*At airports are strict laws regarding safety. It is not allowed to experiment with hydrogen GSE near aircraft. We can develop hydrogen GSE, but we do not want to be responsible* *for safety certificates''*. Realizing infrastructure, such as an electrolyzer and refueling station, requires stakeholder action. These conflicts make it challenging to move on (organization D, J).

Furthermore, organizations notice conflicts between airport and society. These conflicts are not about renewable energy and hydrogen but nuisance from the airport. People complain about noise and pollution. Furthermore, they complain that the airport is not profitable and costs too much society money (organization G, O).

4.1.5. Hydrogen airport ecosystem

The results reveal that parties are willing to cooperate in the zero-emission hydrogen airport ecosystem at Groningen Airport Eelde. Many stakeholders collaborate in this project (organizations B, C, D, E, F, H, J). However, parties are critical of the system's success, for example, due to the lack of demand. The airport is a hub where various parties settle. Therefore, the airport facilitates parties to come together and trigger hydrogen usage (organization A, J). The airport is small, but this can be valuable from a research point of view. At a small airport is room for experimentation. It is less busy, and the investments will be smaller. Ultimately these hydrogen ecosystems could be applied to bigger airports (organization D). Interviewee E: *''The airport has released a playfield where different parties can do their thing''*. Different businesses can share knowledge and work together on hydrogen development. Interviewee C: *''This project is an interesting business opportunity because we want to take our residual product seriously and sell it. Also, we like to participate in innovative environmentally friendly projects*''. The ambition of the airport is to create a business park. It would be interesting if companies there invested and continued with hydrogen (organization G).

It is noticeable that organizations are critical of the project's business model. The specific applications of the project have much value, but there are also challenges. The main challenge is to be able to develop a business model that is acceptable to the stakeholders involved. Fortunately, the refueling station can help with that (organization I). The success of the project will be dependent on the scale of demand. A decentralized network can be valuable, but for production with electrolyzers, you need a specific scale to make it feasible. Large-scale production is more interesting because the price per molecule is lower. Electrolyzers become interesting from 10 MW on. This supply cannot be used at this airport. Therefore, other parties who use hydrogen are needed. This could be logistical parties, taxi companies, and other traffic. A demand model for the refueling station is required to estimate volumes (organization A, J).

Interviewee A: *''The success depends on the volume needed at the airport. I wonder which parties will use the refueling station there because it is not a logical location to create a hydrogen hub''*. It would be favorable a multi-fuel station. Interviewee J: *‘’At the moment, the business case is not great. Adding multiple fuels can mitigate this, but this is dependent on location and demand’’.*

Several large transport companies in the area could use hydrogen as fuel. A large transport company (Faber Bloementransport) next to the airport is interested in hydrogen trucks, especially with a filling point nearby. Another nearby company is interested in using hydrogen for heating (organization H, K). A taxi company that drives hydrogen cars is also willing to use the station. Interviewee L: *‘’If we can refuel in more places, our employability will increase’’*. Public transport buses could be filled there, but limited bus lines pass by the airport. Also, the hydrogen price is too high to drive the extra distance to the refuel station (organization L, M).

Switching from fossil fuels to green hydrogen contributes to the zero-emission goal of the airport ecosystem. Currently, most hydrogen is grey and blue, which is not zero-emission. Green electricity is needed if the whole chain becomes zero emission. The solar park at the airport will ensure that it is green hydrogen. Interviewee J: *‘’In mobility are only two net-zero options: battery electric and hydrogen fuel cells’’*. Another advantage of green solar electricity is that it can be easily applied in a fuel cell (organization D, J). Interviewee F: *‘’The first parties want to deliver green hydrogen on a large scale around 2024-2025. Currently, it happens on a smaller scale’’.*

Several organizations state that a decentralized hydrogen ecosystem brings grid capacity and connection challenges. Such a network should be legally and appropriately organized. Currently, the airport has a grid connection, and the solar park has a grid connection. The solar park is a separate company; the solar power goes directly into the grid. This is legally and economically the easiest way to organize the system. In the future, the electrolyzer can have a contract with the solar field, or it can also be powered from the grid. It will probably be a separate company that owns the electrolyzer. Legally they both should have a connection to the grid. The principle of a potential battery will be the same (organization E). Companies at the nearby business park are considering an off-grid decentralized network with the airport. However, legally this is not allowed currently (organization G, K). Interviewee K: *‘’Energy suppliers also are not interested in returning all energy because the grid is overloaded. Instead, we could directly supply our neighbor. The future lies in local initiatives, but the law is still against us’’.*

4.1.6 Ground support equipment

The ground support equipment is currently mainly powered by diesel. This should be changed to directly electric or hydrogen-electric to reach zero-emission goals. The results reveal that most GSEs can be battery electric. Section 4.1.2 of the report explains that hydrogen is promising for some specific vehicles. One of them is a GPU. GPUs are one of the biggest emitters of airports. Making them zero-emission has several challenges. A GPU currently has a large diesel tank that can run 24 hours daily. This will not be possible with an electric GPU because of the charging time. However, an electric GPU is more expensive than a d-GPU, and a hydrogen one is even more expensive. Moreover, it is not even for sale yet. The Dutch airport Schiphol also has electric fixed power units (FPUs). Then a GPU is not necessary anymore. However, there are too few cables, and everything gets hot at high occupation. Furthermore, the power cable of an FPU is much heavier, which is a disadvantage for employees. The expectation for the future is that for big aircraft, FPUs will be used and for small aircraft, battery electric or hydrogen GPUs (organization B).

Interviewee B1: *‘’We now have the policy first electric, and if there is no other choice than hydrogen’’*. Combining electricity and hydrogen means creating two infrastructures at the airport. The electricity network needs more capacity, and a hydrogen fuelling station is required. Electric GPUs and hydrogen GPUs have both advantages and disadvantages. Electric GPUs need to be brought to the charger and back all the time. This costs time and makes it more expensive. Also, their capacity is not big enough for big aircraft. Hydrogen GPUs could be filled at the location. However, hydrogen GPUs need to be developed and tested. This requires collaboration with the technology provider and training of mechanics. Hydrogen GPUs can also be used when the network is overloaded. Interviewee B2: *‘’We think there will be insufficient electric energy; with hydrogen, we have a plan B’’* (organization B). Technically it would be possible to convert all GSE into electricity or hydrogen. However, airport safety regulations are strict. Legally, it is impossible to convert everything now because of strict safety regulations at airports. Therefore, hydrogen GSE should be tested to receive safety certifications (organization D).

4.2. Barriers

This part will mainly cover the second research question. This question is about the different barriers inhibiting successful hydrogen deployment.

4.2.1. Economic barriers

The results reveal that hydrogen deployment involves high investment and operational costs. Often companies must choose between diesel, electric, and hydrogen. Interviewee B1: *‘’If we compare the costs for a new transport vehicle: diesel €45.000, electric €75.000, hydrogen €180.000. Tell me which one you choose’’*. So, battery electricity is the cheapest zero-emission option. The price difference between battery electricity and hydrogen is significantly significant. Lastly, equipment is currently barely available on the market. Companies cannot buy things that are not being produced. Interviewee

M: *''We cannot buy 50 hydrogen buses because they do not exist''* (organization B, L, M). Also, it is an investment in an uncertain factor. Companies do not know if hydrogen will get off the ground and when. Investments are needed, but it is uncertain if you will get them back. Currently, companies are highly dependent on subsidies. However, large companies can also take responsibility and take the first step. Interviewee K: *''Companies start working on it when subsidies are provided, but you must be intrinsically motivated to make the first step as a company. Not always dependent on subsidies alone''* (organization G, K).

Furthermore, the chicken-and-egg problem is also essential here. Companies will not invest if there is no infrastructure, like refueling stations. Interviewee F: *''Should there first be production or demand? It is like electric cars; you need charging stations''* (organization F).

The operational costs are also high due to the high hydrogen price. This makes hydrogen both expensive in OPEX and CAPEX. Hydrogen can become cheaper if production increases. Moreover, the supply of renewable energy must increase. This is a matter of supply and demand (organization A, L). Interviewee A: *''Comparable to solar panels ten years ago. They were twice as expensive because the supply chain was not as large as now''*. Currently, there is more grey hydrogen, which is cheaper. Interviewee L: *''We can refuel at a chemical company. Their hydrogen is residual material, which makes it cheaper''*. It is a problem that hydrogen costs are not acceptable to compete with fossil fuels. It is not possible to escape diesel, especially for long distances. Some hydrogen vehicles are doable, but an entire fleet cannot be profitable (organization L). Governments have a significant role here. Without subsidies, the price will never drop (organization F).

The high prices make it hard to develop an economically viable business model. Companies cannot complete a business case for a green electrolysis project. It will take years to achieve this (organization E, H). Interviewee A: *''I think most hydrogen projects are not viable. Certainly not without subsidies and often even with subsidies. This is the most important barrier''*. Investors require an acceptable business model. Currently, it is a challenge to get investors. Moreover, getting subsidies is very challenging (organization I). Grants are essential for development. Interviewee D: *''If you contribute to zero-emission, you can subsidize up to 100 percent''*. Subsidies help to accelerate and create a kind of new industrial revolution. Therefore, the government should revise the subsidy system (organization D). Also, it will be valuable for smaller companies if there are local subsidies instead of EU-subsidy (organization L).

4.2.2. Technical barriers

The results reveal that hydrogen infrastructure, knowledge, and skills must be improved. There are different hydrogen technologies well developed. For example, the chemical industry has produced and used hydrogen for decades. However, the integration of these technologies is a challenge. It is about systems engineering and integration. That has yet to be done at this scale. Particularly not for energy and transport applications. It is challenging to produce and deliver it to many parties (organizations A, I).

In the future, two infrastructures should be created at airports. Both for electric and h-GSE (organization B). The same goes for the whole energy network. Interviewee D: ''*It will take time before gas network operators and energy suppliers will start big infrastructure projects*''. The gas network operator is willing to build infrastructure for the entire supply chain required to develop the hydrogen market. The plan is to create a hydrogen backbone in Groningen to supply hydrogen to some industrial clusters. Industries farther away can build their network or be provided with tube trailers. The switch between trailers and pipelines becomes economically viable with high demand and quantities (organization F).

Currently, there are only a few refueling stations, which means that transport companies can refuel in a few places. Moreover, those stations often have a breakdown due to malfunctions. In such a situation, hydrogen vehicles cannot drive. Therefore, the risk of having many hydrogen vehicles in the fleet is too high (organization L, M). Also, most refueling stations need larger supply capacities. To refuel buses and trucks, a sufficient buffer of hydrogen is required. Interviewee D: ''*You must increase the buffer capacity. Now you can barely refuel one truck or bus*'' (organization D, M).

The refueling station needs its filling infrastructure. The airport system has different supply possibilities: a pipeline from the electrolyzer, transport with tube trailers from the electrolyzer, and transportation with tube trailers from other suppliers. Large-scale production is cost-wise more interesting. If there is a 1 MW electrolyzer, the capacity could be too small. Therefore, a hybrid structure could be needed. Different supply methods require different designs to consider. Pipelines need a continuous flow of low-pressure and tube trailers, and tanks need a high-pressure flow. Interviewee J: ''*When using a pipeline of 3 bar and you must fill a car at 700 bar, you can calculate how much extra pressure you need. Filling a truck of 350 bar with a tube trailer of 300 bar requires less additional pressure*'' (organization J).

The hydrogen supply chain still needs to be fully developed. There is a lack of certain parties, such as manufacturers. Specific applications are scarce. For example, there are few suppliers of electrolyzers. Therefore, obtaining an average electrolyzer is hard. If the few suppliers focus on big companies, they cannot supply the rest of the market (organization H). Also, the availability of hydrogen vehicles is limited. Only two types of hydrogen passenger cars are being produced. Larger vehicles are not available (organization L). Interviewee M: *''There should be more bus builders. Currently, busses are not produced''*. Lastly, hydrogen maintenance can be more difficult. Interviewee L: *''We would like to do in-house maintenance, but this is impossible with hydrogen. Fortunately, we have a dealer, but we are open 24/7, and the dealer is not''*.

Furthermore, the workforce should be trained in electronics and electrical engineering. Interviewee B2: *''Our mechanics must be retrained from diesel motors to other technology. Also, we are actively looking for knowledge institutes, collaborative projects, and subsidy programs. In that way, we can build knowledge''*. Technically skilled employees are needed. There is a lack of skills in the sector. It is not possible to recruit and train people as fast as necessary. Projects are developing quickly now. Therefore, it is essential to collaborate with education institutes and universities. More people must choose to learn about fuel cell technology and electrolysis. Skills and training are crucial (organization D, I).

4.2.3 Political and regulatory barriers

The results reveal that hydrogen regulation is immature or does not exist. This corresponds with the expectation because the sector is still immature, especially for hydrogen energy applications on a bigger scale. Often regulation is not there and has to be developed within a project. Also, there are challenges on local level politics and planning permissions. Local authorities and teams are not familiar with hydrogen implementation and technologies. They tend to be on the conscious side. Therefore, getting approval and building installations takes longer (organization I).

Interviewee L: *''It is waiting for the municipality to issue the permit for a refueling station while the money is already on the shelf''*. Interviewee A: *''The policy is inconsistent, and it takes a long time before it is clear what the government wants with hydrogen. It will help if the frameworks are put down more clearly''*. It can take three years of research and preparation to start building something. Commercial parties do not have the money to do this. Permits, agreements, and contracts make it complex, which can be frustrating in the beginning (organization E).

For local governments, everything is new. The municipality is the competent authority to test if a plan is feasible and, from an environmental point of view, whether other aspects need to be considered. A permit application should be completed. External safety is an important aspect here. Therefore, risk distances should be considered. However, the municipality is not an expert on hydrogen. It often needs to be clarified whether requests are legal and which laws and regulations are involved. If that is all right, they can cooperate. It would be more interesting if you could ensure that companies in the area can further economically develop hydrogen applications. Interviewee G: *''It is a kind of step-by-step plan how I see it. First, we must check if it is allowed and possible. Then we can realize it and ensure that the environment benefits. The intention is to make it economically interesting''* (organization G).

The province realizes that it has a role in market development. Therefore, a vision for hydrogen development is made. Furthermore, the province can support municipalities with knowledge. First, however, they must find out what role they will play and how far they will go as a government (organization H). It is noticeable that businesses feel that government organizations are struggling. Interviewee L: *''The local government and province have no knowledge. HEAVENN chases developments, but for the municipality, it is a far from my bed show''*.

Companies are wondering about environmental permits regarding hydrogen. For example, how can it be transported to their company? Opinions regarding hydrogen are divided. Interviewee K: *''I speak to different parties and people from local politics. I notice that people are against hydrogen because they trust electricity more. The transition is going fast, and you do not want to miss the boat''*. Local politics should not determine whether hydrogen comes here. Local politics is intended to shape a good climate for inhabitants. If hydrogen fits here to supply the energy, it should not be blocked through parties' opinions (Organization K). Organizations state that they are missing laws and regulations to stimulate hydrogen. Interviewee A: *''Germany and America have a slightly more detailed plan to support hydrogen long-term. In the Netherlands and the rest of Europe, this has not yet fully landed''*.

At airports, there are strict safety regulations that hinder hydrogen applications. Workable regulation is essential for ground handlers. The fire department should say what is allowed and what is not. Moreover, it is challenging for manufacturers to develop h-GSE. There are significant safety risks. Therefore, h-GSE is not allowed at the airport without a safety certificate. Testing equipment and obtaining safety certificates is a significant obstacle for manufacturers. Governments should lead this and consider possible problems and how to solve that with regulation (organization B).

4.2.4. Social and environmental barriers

The results reveal that social acceptance of hydrogen applications is relatively high. The expectation before was that there would be resistance against hydrogen, for example, due to safety concerns. In practice, these concerns are barely noticeable in society. However, there is resistance against the airport because of noise and pollution. Social acceptance of the airport and social acceptance of hydrogen are different things. Interviewee G: *''I see social acceptance for hydrogen, but you are dealing with Groningen Airport Eelde, which is another story''.*

Most organizations state that there is social support for hydrogen projects. Hydrogen production itself mainly has a positive impact on the environment. Also, the nuisance will decrease because there will no longer be diesel buses and trucks. Hydrogen vehicles make less noise and are cleaner. Customers even prefer hydrogen over diesel (organization A, M, L). Interviewee G: *''The city council recently organized an information meeting about hydrogen. There is much interest in the subject, and people see it not as scary or exciting. I expect there will be support here''*. On the other side, there is little social knowledge. People do not think anything of it and do not understand what it is. Interviewee K: *''People like it until it goes wrong for the first time. Nevertheless, pioneering means making mistakes, and the intention must be good''.*

Social acceptance is an essential aspect of hydrogen deployment. Some people see hydrogen as something new, strange, or dangerous. However, civilians have little knowledge, and these safety concerns could be wrong. Therefore, it is essential to inform society to change public perception and acceptance (organization G, I). Interviewee O: *''I notice not many safety concerns''*. Of course, new developments are always associated with certain risks, but you must accept that. Social acceptance for the airport project could grow if civilians directly benefit. This will be possible if neighbors participate in the project and are part owners of the solar park. This can be interesting in creating support. Furthermore, it helps if the refueling station is open for private individuals (organization G). The business itself can also help to support social acceptance. Interviewee L: *''We selected several motivated drivers for hydrogen taxis. They are also hydrogen ambassadors. The reactions are positive and mainly business customers like hydrogen''*.

It is also crucial that hydrogen projects should be deployed at a safe distance from people. If the distance is sufficient, residents do not hear of feel anything. If something goes wrong, you must prove that the effects have no consequences for neighbors (organization A, H). Interviewee A: *''Of course, you must watch out for large quantities. A mega electrolyzer with huge storage and trucks driving around will impact the environment''*. Laws and regulations ensure safety. This is a spatial issue, and businesses need permits to build something. For example, around a refueling station, there is a safety circle (organization H, M).

Compared with hydrogen social acceptance, social acceptance for Groningen Airport Eelde is much more difficult. Society is very divided about the airport. On the one hand, people strongly support it, and on the other hand, people are strong opponents. Interviewee G: *''I think for and against is 50/50. On the one hand, you have nature and the environment, but the Airport is almost 100 years old and part of the city''*. Supporters of the airport state that its role in society is essential for different reasons. The airport positively influences the economy and employment in the region, although this is difficult to measure. Currently, a new business area will be developed next to the airport. Industries related to aviation are interested in settling there, such as companies dismantling aircraft (organization G, O).

The airport has an extended sustainability vision and is working on different projects. This is positive because the aviation industry is immensely polluting now. Regional airports have an essential role in driving innovation. They are small and can pioneer. For example, in the field of electric flying and hydrogen flying, the airport could be a frontrunner in Europe. Also, the airport can play a role in developing a hydrogen hub in the Northern Netherlands. Interviewee G: *''The KLM flight academy purchased new electric aircraft, and the plan is to use them within 2 or 3 years. This will be a noise reduction of 70 percent*''. Electric flying significantly reduces nuisance, particularly for the flight academy because they fly a lot. Also, there are experiments with drone flights. Usually, this is not allowed on an airfield, but it is possible in collaboration with air traffic control. Interviewee O: *''Small packages and medicines can quickly be transported to the Wadden Islands. Those are good things too''* (organization G, H, O).

Furthermore, the airport has a medical function for the region. The trauma helicopter is housed there, and organ flights can be carried out for nearby hospitals. The trauma helicopter flies out five times a day, and organs can arrive 24 hours a day. Interviewee G: *''No one can be against the trauma helicopter; that is a smart point of sale*'' (organization G, O). Organisation O: *''Our members are positive about the airport, but we want to represent society. Therefore, we did a large survey in the Northern Netherlands. The survey showed that 78 percent of respondents have a positive attitude towards Groningen Airport Eelde*''.

Opponents point out several arguments against the airport. This makes it more difficult to gain support for hydrogen projects. These arguments are mainly about noise, pollution, and lack of profitability. Society of opponents (VOLE): *''Sustainability at airport Eelde is a distraction and greenwashing. There is no significant contribution to new technologies. Four million euros from taxpayers is needed to cover the losses. Furthermore, noise and pollution are very detrimental to our villages''*. Different airplanes give different noise nuisance. Organization G: *''I live close to the airport, and complaints are mainly about the KLM flight academy. Those small planes keep circling and making noise is more annoying than a Boeing 5 times a day. Those little planes fly low, and you hear it for a long time*''.

Electric flying would lower noise and emissions significantly, but opponents see sustainability as a reason to retain the airport and are also against it (organization G).

Shareholders invest money in it for a long time. Every time the airport comes with new plans, it needs to be more profitable. This is controversial in local politics because investments are necessary for the hydrogen project to get off the ground. Interviewee G: ‘’*Sustainability is the last resort for Groningen Airport Eelde*’’. The municipality council is mainly left-wing and is critical of where the money goes. It is a problematic political discussion if airports deserve more investments and extensions. Investments must be made now, while the effects are visible in several years, this makes it more difficult. Furthermore, the local business community attaches too little value to the airport (organization G). It will be a financial solution if the Schiphol Group takes over the airport. Then the finances come from there, not local governments (organization O).

4.2.5. Ranking barriers

Interviewees are asked whether they can rank barriers by importance. Most interviewees think that economic barriers are the most critical. Economic barriers are why there are few hydrogen applications (organization A, L, M). Nevertheless, all barriers are essential and interdependent. Interviewee I: ‘’*I cannot rank them, to be honest. They are all top of the list, especially those four*’’.

5. Discussion

In this part, outstanding results are discussed and compared with the literature. Also, learning points and recommendations will be given. Furthermore, results are validated by an airport manager. Finally, the chapter will conclude with implications, limitations, and recommendations for future research.

5.1. Interpretation of results

In this section, noticeable results are discussed and compared with the literature.

5.1.1 Hydrogen application

Stakeholders realize that the shift from diesel to renewable sources should be made to reach zero-emission goals, but there are more options than hydrogen. For example, GSE and other transport applications could be battery electric. The literature states that the electrification of energy demand is needed for a successful transition toward a low-carbon economy in 2050 (Fragkos et al., 2017). Hydrogen and fuel cell technology have great potential for various applications in the aviation industry, such as GSE (Baroutaji et al., 2019; Staffell et al., 2019). For example, hydrogen-powered forklifts have no emissions and require less maintenance. Moreover, they have a quick refueling time (McConnell, 2010).

The results of this paper confirm and reject the potential for hydrogen applications. Hydrogen is promising for specific applications that are too heavy for batteries or direct electrification. For example, vehicles that do not have time to charge. Literature approves various advantages of hydrogen applications. Such as fast refuel time (Offer et al., 2010), high operating time (Niaz et al., 2015; Yue et al., 2021), and longer lifetime than batteries (Sagaria et al., 2021). However, battery electric vehicles have a lower fuel cost per kilometer, fewer energy transition losses, and greater access to fuelling capability (Thomas, 2009). Both hydrogen applications and battery electric applications are promising. Businesses should look carefully at the role of hydrogen in the energy mix. Hydrogen should not be used for applications better suited for direct electricity.

5.1.2. Hydrogen airport ecosystem

The results reveal that parties think differently about a decentralized hydrogen system. It is also possible to choose a more centrally organized system. Both have their advantages and disadvantages. The advantage is that the airport and nearby business park are less dependent on external influences, such as international conflicts or grid congestion (organization H, K). The literature identified several advantages. Decentralized hydrogen production attracts innovative businesses that accelerate the hydrogen economy. Local clusters can stimulate innovation and develop technological breakthroughs (Coenen et al., 2010).

However, the disadvantage is that a particular scale and demand are needed to realize a feasible business model. Currently, the airport's demand is low, and nearby industries are required. However, nearby industries, such as transport companies, face many barriers to switching to hydrogen deployment. Subsidies are needed to produce price-competitive and create demand. Furthermore, it may be more lucrative to manufacture hydrogen centrally or import it from abroad. Lastly, the Netherlands is an electrified country with a stable network. Such a network would be better for remote areas without a stable network (organizations A, C, J).

Legally it is not possible to realize an off-grid hydrogen ecosystem. Literature states that it is economically also not feasible. A German case study found that producing hydrogen using grid-connected solar power is already market competitive with fossil fuels. Moreover, it has further potential for a price reduction due to economies of scale and the learning effects of electrolyzers and solar energy systems. Hydrogen production in an off-grid mode with battery backup is not economically feasible today. In the future, the economic parameters will become more competitive through learning curve effects and stimulating policies, which is promising (Bhandari & Shah, 2021).

5.1.3. Economic barriers

Different economic barriers are identified. These are high investment costs, high operational costs, realizing an economically viable business model, and gaining subsidies. The results reveal that hydrogen is expensive in both OPEX and CAPEX. Mainly through high investment costs and high hydrogen price levels. Currently, hydrogen cannot compete with fossil fuels, especially not without subsidies. This makes it hard to realize an economically viable business model. In particular for small airports and small businesses with limited budgets. However, organizations think that this is going to change in the future. More supply and demand will lower the price of hydrogen and the price of hydrogen applications. Moreover, increasing the renewable electricity supply will reduce the cost of green hydrogen.

Recent literature approves this. According to Panchenko et al. (2022), it is only a matter of time before the widespread production and use of hydrogen. Currently, the production of green hydrogen on an industrial scale is immature. The economics of green hydrogen projects cannot compete with fossil fuels. Over time, technology costs and the cost of producing green electricity will reduce, fostering the hydrogen economy (Panchenko et al., 2022). The decreasing cost of solar photovoltaics will lead to a significant reduction in hydrogen costs. The Levelized cost of hydrogen will decrease from the current 1.0–2.7 €/kg_{H2} to 0.7–1.8 €/kg_{H2} by 2030 and 0.3–0.9 €/kg_{H2} by 2050, depending on the location (Vartiainen et al., 2022). Moreover, the costs of battery electric vehicles (BEV) and FCEV will decrease. By 2040, FCEVs might be less expensive than BEVs per mile and have notable cost advantages for larger vehicle sizes and longer driving ranges (Morrison et al., 2018). The government has an important role here because subsidies are required foster development and decrease costs (van Benthem et al., 2006).

5.1.4. Technical barriers

Various technical barriers are identified. These are a lack of infrastructure, knowledge, skills, and the need for applications. Most of these things are strongly dependent on investments. The results reveal that it takes time before infrastructure is developed, especially on a large scale. Currently, there are few FCEVs and refueling stations. FCEVs are barely available because they are not produced on a large scale. This means that parties should invest in infrastructure and manufacturing facilities. For example, manufacturers of fuel cell buses, trucks, and cars. Furthermore, there is a lack of skills in the sector. More technically skilled employees are needed.

It is uncertain when large-scale deployment of hydrogen is going to take place. The fundamental hydrogen infrastructure includes production, storage, delivery, and end-use applications (DOE, 2002). Literature states that by 2050 many cars, trucks, and buses could be powered by hydrogen (Mostafaeipour et al., 2016). However, this will only be possible with infrastructure. Moreover, people are needed to develop hydrogen infrastructure and applications. The industry faces talent challenges. Currently, there are only demonstration projects. The lack of policies, markets, and platforms prevents the quantity and quality of skilled employees from matching market demands (Wu et al., 2022). Technologically, hydrogen technologies are there. However, it is a challenge to integrate them and apply them on a large scale. This is strongly dependent on economic barriers.

5.1.5. Political and regulatory barriers

Different political and regulatory barriers are identified. These include a lack of regulation and standards, government knowledge, and complicated regulatory procedures. The results reveal that regulation is often absent and should be developed in a project. Also, at airports are strict safety regulations that hinder hydrogen applications. Furthermore, receiving permission from municipalities to start developing and deploying is challenging. Especially at the municipality level, interviewees face challenges. There is little knowledge about hydrogen, and therefore the municipality is cautious. This results in long and complicated regulatory procedures.

These results are backed by recent literature. The immature regulations and standards result in issues regarding the popularization of hydrogen projects and withhold companies from investments. There are complicated and lengthy regulatory approval procedures leading companies to opt for a different solution (Wu et al., 2022). This is regrettable because government support is crucial for hydrogen development. Subsidies and incentive tax measures are required to foster growth and decrease costs (van Benthem et al., 2006). Businesses need consistent regulations to deploy hydrogen projects. Therefore, a more stable policy plan is required to reduce uncertainty. Especially municipalities need more knowledge and a better framework to assess permits concerning spatial integration and external safety.

5.1.6. Social and environmental barriers

Various social and environmental barriers are identified. These are lack of public knowledge, safety concerns, and airport resistance. The results reveal that the social support for hydrogen projects is relatively high. Hydrogen deployment can positively influence the environment, and it is possible to carry out projects at a safe distance from people. However, there are still safety concerns in society, for example, with neighbors of a hydrogen project. This could be because society needs to gain more knowledge about hydrogen. The social acceptance of Groningen Airport Eelde is controversial. Opponents complain about pollution, nuisance, and financial losses. Supporters point out the importance for society and the economy.

Literature approves that social acceptance can be controversial. Transformation to new technology and infrastructure often provokes protests from the population. To achieve social acceptance, it is crucial to understand societal positions and conflicts. Society can have controversial as well as consensual views. Controversial arguments refer to security, competitiveness, and environmental protection. There are concerns about flammable and explosive safety risks, especially when infrastructure is built around communities. Nevertheless, consensus can be reached on the common goal of addressing climate change and zero-emission targets (Glanz & Schönauer, 2021; Wu et al., 2022).

Achieving social acceptance for an airport hydrogen ecosystem is challenging since airports have opponents and supporters in society. However, sustainable aviation practices such as electric flying significantly reduce noise and pollution. This can help to reach more social acceptance. According to Glanz & Schönauer (2021), technology openness, information transparency, and citizen participation will result in broader acceptance. Social perception and acceptance appear contradictory, but it is essential not to rashly reduce these arguments to residents' irrational, selfish, and uninformed motivations. Instead, these should be taken seriously and included in implementation processes through transparency and participation.

5.2. Design recommendations

The research determined learning points and design recommendations for an airport hydrogen ecosystem. The recommendations include two pathways focused on net-zero emission targets. One until 2030 and one until 2050. Between these years, significant changes in circumstances are expected. For example, decreasing OPEX and CAPEX of hydrogen deployment (Panchenko et al., 2022). The recommendations build upon former case studies at Groningen Airport Eelde (Eefting, 2022; Kamphuis, 2022) and other literature. The advice might be relevant for policymakers and small airports with their stakeholders. Mainly for airports with similar characteristics.

5.2.1. Until 2030

The Paris Agreement requires a significant reduction of emissions in 2030 (United Nations, 2015). Therefore, airports should focus on making their GSE battery electric. Currently, h-GSE is not economically feasible and legally allowed. Moreover, a large share of GSE is more appropriate for battery electric applications.

The infrastructure for the hydrogen ecosystem should be operational. This includes a solar park to supply sufficient green electricity, a battery pack to reduce grid dependency, an electrolyzer, a storage facility, and a hydrogen refueling station. Since airport demand will be limited at this stage, demand from nearby industries is needed. Therefore, a feasible business model for the airport and their stakeholders should be completed. Subsidies and supporting government practices will be essential because hydrogen cannot compete with fossil fuels at this stage. Therefore, funding for involved stakeholders is necessary to take away barriers.

To serve transport customers, the refueling station should have enough capacity to supply the demand for trucks, cars, buses, and FCEV GSE. Furthermore, GSE that requires too much power for batteries should be converted to hydrogen. Also, heating installations should be replaced by electric heat pumps or hydrogen heating.

Governments should develop clear and consistent policies and regulations. If uncertainty reduces, businesses can realize a feasible business model for hydrogen projects. National governments and provinces should give proper support to municipalities. Municipalities need more knowledge and a better framework to assess permits concerning safety and spatial issues. Furthermore, this should make hydrogen accessible to smaller businesses. Finally, governments should subsidize and promote hydrogen technology development. This will foster the manufacturing of electrolyzers, trucks, and buses.

To achieve social acceptance, airports should apply technology openness, information transparency, and citizen participation. Arguments of civilians and opponents should be taken seriously and included in decision-making. Sustainability aircraft practices can help to achieve more social acceptance. For example, electric aircraft significantly reduce noise and pollution. Small aircraft, for example, used for flight schools, should be battery electric. This contributes to social acceptance and net-zero emission targets.

5.2.2. Until 2050

Net-zero practices should be reached by 2050 (United Nations, 2015). If demand increases, the airport can be connected with a pipeline to the hydrogen grid. Then both centralized and decentralized production facilities can supply the airport. This will ensure energy supply and increases hydrogen storing possibilities. Furthermore, more BEVs can be replaced by FCEVs. Especially GSE that must drive long distances and requires high amounts of energy. Airports should cooperate with FCEV providers to replace conventional GSE. At this time, FCEVs might be less expensive than BEVs per mile and have notable cost advantages for larger vehicle sizes and longer driving ranges (Morrison et al., 2018).

Moreover, if an airfield aims to achieve net-zero emissions targets by 2050, all aircraft must be battery electric or hydrogen-powered. Companies like Boeing and Airbus are developing hydrogen aircraft. Airports should be prepared to facilitate hydrogen-powered aircraft because facilitating these aircraft will require massive investments in storage and refueling infrastructure. Also, the airport should adjust its destination model to facilitate net-zero aircraft.

Likely, electric flying and hydrogen flying cause safety concerns among civilians. Here again, the airport must communicate appropriately to achieve social acceptance. Transparency, technology openness, and citizen participation will result in broader acceptance.

5.2.3. Replicability

The recommendations are mainly valid for airports with similar characteristics. Thus, small and regional airports. Large airports have different characteristics and the advantage of profiting from economies of scale. They can realize hydrogen demand with their own GSE fleet and are less dependent on external stakeholders. Furthermore, electricity grid constraints will make it more likely to switch to FCEVs instead of BEVs. Therefore, it will be more viable for larger airports to realize a hydrogen grid connection. However, large airports are less suitable for the pilot project due to high operational pressure.

Solar electricity is considered the primary green energy source for airport energy systems (Xiang et al., 2021). Therefore, airports should have solar parks that supply enough green electricity. For example, the solar park at Groningen Airport Eelde is twenty hectares and supplies 22MW. Therefore, airports should have space for this. Furthermore, Groningen Airport Eelde is nearby industrial clusters. If airports are in rural areas, creating a particular scale and demand for hydrogen is more challenging.

Moreover, circumstances differ across the world. Groningen Airport Eelde is in the middle of Europe’s first Hydrogen Valley, also called the HEAVENN project. This provides knowledge and research in the area. Lastly, regulations and subsidy mechanisms differ across the world. Groningen Airport Eelde is dependent on European Union subsidies. The EU released a large amount of funding for hydrogen development (Haghi et al., 2018). Therefore, the results are more valid for European Union countries.

5.3. Validation airport manager

Noticeable results are discussed with an airport manager. This form of validation gave interesting confirmations and contradictions.

The results reveal that stakeholders notice few conflicts. However, according to the manager, essential conflicts hinder progress. These are about the roles and responsibilities of stakeholders. Multiple companies developing infrastructure and applications are SMEs, meaning they are more vulnerable to risks. For example, a developer of h-GSE cannot provide safety certificates for the applications. Because of strict safety regulations, uncertificated GSE cannot be used at the airport. Also, infrastructure developers' uncertainty results in delays and project scaling down.

Furthermore, demand for the refueling station must be created, but it is unclear who takes the lead. Currently, demand is limited, which makes it challenging to realize a feasible business case. To take away barriers, more funding is needed for potential stakeholders. For example, subsidies for hydrogen trucks and cabs.

Stakeholders have different expectations about a decentralized ecosystem. The regulation does not allow the realization of an off-grid network with nearby industries, but it could also not be beneficial. Manager: *''Where ends our role as an airport? We are a facilitator of aircraft and not an energy company''*. The airport wants to stick to its role, and other companies are needed to build energy infrastructure.

Furthermore, importing hydrogen instead of producing it is possibly more viable. The airport took this into account. In the beginning stages, hydrogen will be imported. Both importation and production could be possible, but this highly depends on the hydrogen price.

Society is divided about the airport because of nuisance and financial situation. According to the manager, sustainability policy helps to gain community support. The airport involves neighbors and notices positive effects. If society and government support the airport, the number of flights can grow, resulting in a more financially healthy situation. Therefore, sustainability indirectly contributes to the future-proof and lucrative business model. Moreover, the airport can purchase green energy from nearby villages to produce hydrogen. In this way, residents directly profit.

5.4 Study implications

The study gives both theoretical and practical implications.

5.4.1 Theoretical implications

This paper has several implications for theory. First, the study further explored and identified various barriers that hinder organizations in hydrogen development. Second, the role of an airport in the system is further investigated, and cooperation between landside stakeholders is analyzed. Third, the study shows that conflicts and challenges are controversial. Aligning different objectives and take new roles can be a challenge for successful cooperation. Fourth, the study made clear that social support is controversial. A distinction should be made between the social acceptance of hydrogen and the social acceptance of an airport. This implies challenges for airports regarding communication and citizen participation.

5.4.2 Practical implications

This paper also has practical implications for decision-makers. First, it shows airport managers what potential roles stakeholders could have in a hydrogen airport ecosystem. This can help estimate demand and determine the capacity of the refueling station. Second, it shows the parties' challenges in overcoming barriers that hinder them. For example, due to uncertainty, parties will not make investments. This gives a better understanding of the challenges of setting up a hydrogen ecosystem. Decision-makers should be aware of the uncertainty that different parties feel. Third, the study shows that appropriate communication and information provision helps to gain social support. Also, design advice is given in chapter 5.2.

5.5. Limitations and future research

There are still some limitations in the study. First, the collected interviews could be more comprehensive. This kind of research is dependent on external parties. Favorably more stakeholders from different categories could be interviewed. For example, more transport and industrial companies. More parties were contacted, but these were not open for an interview or did not respond. Secondly, the study is performed in the Northern Netherlands. Since laws and circumstances differ elsewhere, the results may be more valid for European Union countries. Third, the study is qualitative. This increases the possibility of subjectivity from the researcher and respondents.

The study brings several possibilities for further research. Such as the investigation of the business model feasibility of a hydrogen airport ecosystem. Including demand and production volumes of the system. Also, a quantitative comparison between a centrally organized and a decentralized system is needed. Furthermore, since the development of such systems is immature, more research on further development stages is needed. Such as the development of h-GSE and transport applications. Moreover, future research can focus on different worldwide regions to comprehensively understand regional contexts. For example, a multiple case study including various airports in the world. Lastly, further research could include a survey for civilians to understand social acceptance better.

6. Conclusions

Transformation of the transport sector is required to achieve zero-emission targets. Hydrogen has a high power density and is suitable for storing renewable energy. Therefore, hydrogen is highly appropriate for landside airport applications. However, there are significant challenges that impede the adoption of hydrogen. This paper investigated the role of an airport in developing a local hydrogen ecosystem. Collaboration and stakeholder involvement is essential to implement such a system.

Hydrogen will play a significant role in the future energy mix. However, it should not be used for applications better suited for direct electricity. It is challenging to realize a feasible business model. Therefore, subsidies and demand from nearby industries are needed. Stakeholders are willing to participate, but they face various barriers. Moreover, barriers are interdependent.

Economic barriers include high investment costs, high operational costs, business model feasibility, and gaining subsidies. Hydrogen cannot compete with fossil fuels, but this is expected to change by 2040. Technical barriers are a lack of infrastructure, knowledge skills, and the need for applications. The hydrogen supply chain is immature and significant investments are needed. Political and regulatory barriers include a lack of regulation and standards, government knowledge, and complicated regulatory procedures. The government is crucial in market development and reducing uncertainty. Social and environmental barriers are lack of public knowledge, safety concerns, and airport resistance. Social acceptance is controversial, for example, due to airport nuisance.

The paper provides learning points and design recommendations for policymakers and small airports with their stakeholders. These include two pathways focused on net-zero emission targets. One until 2030 and one until 2050. Airports should realize the required infrastructure for a hydrogen ecosystem. The government has a crucial role since subsidies, and stable policy plans are required. Municipalities need proper support regarding permits and spatial decisions. Appropriate communication is required to gain social acceptance. Moreover, sustainable aviation practices help to realize social acceptance. The advice is beneficial for small airports. Although significant challenges exist, hydrogen is promising for realizing net-zero targets.

References

Adams, W. C. (2015). Conducting Semi-Structured Interviews. In Handbook of Practical Program Evaluation (4th ed., pp. 492–505).

Ahmad, S., Ouenniche, J., Kolosz, B. W., Greening, P., Andresen, J. M., Maroto-Valer, M. M., & Xu, B. (2021). A stakeholders' participatory approach to multi-criteria assessment of sustainable aviation fuels production pathways. International Journal of Production Economics, 238(February 2020), 108156. https://doi.org/10.1016/j.ijpe.2021.108156

Barke, A., Thies, C., Melo, S. P., Cerdas, F., Herrmann, C., & Spengler, T. S. (2020). Socio-economic life cycle assessment of future aircraft systems. Procedia CIRP, 90, 262–267. https://doi.org/10.1016/j.procir.2020.01.096

Baroutaji, A., Wilberforce, T., Ramadan, M., & Olabi, A. G. (2019). Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. Renewable and Sustainable Energy Reviews, 106(September 2018), 31–40. https://doi.org/10.1016/j.rser.2019.02.022

Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. Renewable Energy, 177, 915–931. https://doi.org/10.1016/j.renene.2021.05.149

Coenen, L., Raven, R., & Verbong, G. (2010). Local niche experimentation in energy transitions: A theoretical and empirical exploration of proximity advantages and disadvantages. Technology in Society, 32(4), 295–302. https://doi.org/10.1016/j.techsoc.2010.10.006

Das, V., Padmanaban, S., Venkitusamy, K., Selvamuthukumaran, R., Blaabjerg, F., & Siano, P. (2017). Recent advances and challenges of fuel cell based power system architectures and control – A review. Renewable and Sustainable Energy Reviews, 73(March 2016), 10–18. https://doi.org/10.1016/j.rser.2017.01.148

DeLuchi, M. A. (1989). Hydrogen vehicles: an evaluation of fuel storage, performance, safety, environmental impacts, and cost. International Journal of Hydrogen Energy, 14(2), 81–130. https://doi.org/10.1016/0360-3199(89)90001-3

Detz, R., Lenzmann, F., Sijm, J., & Weda, M. (2019). Future Role of Hydrogen in the Netherlands. A Meta-Analysis Based on a Review of Recent Scenario Studies.

DOE. (2002). National Hydrogen Energy Roadmap. (US Department of Energy (DOE), 2002.

National Hydrogen Energy Roadmap. Washington, DC.), November. http://www1.fe.doe.gov/programs/fuels/publications/programplans/2002/national_h2_roadmap.pdf

DOE. (2012). DOE funds to deploy fuel cells for baggage vehicles at airports. Fuel Cells Bull, 5, 3–4.

Eefting, J. (2022). Hydrogen ecosystem design at a small regional airport: Groningen Airport Eelde's road to net-zero emissions.

El-Emam, R. S., & Khamis, I. (2019). Advances in nuclear hydrogen production: Results from an IAEA international collaborative research project. International Journal of Hydrogen Energy, 44(35), 19080–19088. https://doi.org/10.1016/j.ijhydene.2018.04.012

Elam, C. C., Padró, C. E. G., Sandrock, G., Luzzi, A., Lindblad, P., & Hagen, E. F. (2003). Realizing the hydrogen future: The International Energy Agency's efforts to advance hydrogen energy technologies. International Journal of Hydrogen Energy, 28(6), 601–607. https://doi.org/10.1016/S0360-3199(02)00147-7

Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews, 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

Enevoldsen, P., Sovacool, B. K., & Tambo, T. (2014). Collaborate, involve, or defend? A critical stakeholder assessment and strategy for the Danish hydrogen electrolysis industry. International Journal of Hydrogen Energy, 39(36), 20879–20887. https://doi.org/10.1016/j.ijhydene.2014.10.035

European Commission. (2017). Reducing emissions from aviation climate action.

Fragkos, P., Tasios, N., Paroussos, L., Capros, P., & Tsani, S. (2017). Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Policy, 100(March 2016), 216–226. https://doi.org/10.1016/j.enpol.2016.10.023

Ful Cells Bull. (2015). Plug Power, FedEx project rolls out fuel cell airport tractors. 5, 2–3.

Glanz, S., & Schönauer, A. L. (2021). Towards a low-carbon society via hydrogen and carbon capture and storage: Social acceptance from a stakeholder perspective. Journal of Sustainable Development of Energy, Water and Environment Systems, 9(1), 1–18.

https://doi.org/10.13044/j.sdewes.d8.0322

Greer, F., Rakas, J., & Horvath, A. (2020). Airports and environmental sustainability: A comprehensive review. Environmental Research Letters, 15(10). https://doi.org/10.1088/1748-9326/abb42a

Groningen Airport Eelde. (2022). No Title. Project WAviatER. https://www.groningenairport.nl/over-groningen-airport-eelde/de-organisatie/duurzaamheid/project-waviater

Haghi, E., Raahemifar, K., & Fowler, M. (2018). Investigating the effect of renewable energy incentives and hydrogen storage on advantages of stakeholders in a microgrid. Energy Policy, 113(September 2017), 206–222. https://doi.org/10.1016/j.enpol.2017.10.045

HEAVENN. (2022). No Title. About HEAVENN. https://heavenn.org/about/

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., & Hanke-Rauschenbach, R. (2022). 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 Production Processes. (n.d.). 2021. https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php

IEA. (2015). Hydrogen production & distribution. International Energy Agency.

Kamphuis, J. (2022). Challenges and prospects of renewable hydrogen-based strategies for the decarbonization of ground support equipment. University of Groningen, Faculty of Economics and Business MSc Thesis Supply Chain Management & Technology and Operations Management.

Karlsson, C. (2016). Research Methods for Operations.

Li, L., Manier, H., & Manier, M. A. (2020). Integrated optimization model for hydrogen supply chain network design and hydrogen fueling station planning. Computers and Chemical Engineering, 134, 106683. https://doi.org/10.1016/j.compchemeng.2019.106683

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Ostergaard, P. A., Möller, B., Nielsen, S., Ridjan, I., KarnOe, P., Sperling, K., & Hvelplund, F. K. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy, 145, 139–154.

https://doi.org/10.1016/j.apenergy.2015.01.075

McConnell, V. P. (2010). Rapid refill, high uptime: Running forklifts with fuel cells. Fuel Cells Bulletin, 2010(10), 12–19. https://doi.org/10.1016/S1464-2859(10)70327-8

Momirlan, M., & Veziroglu, T. N. (2005). The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. International Journal of Hydrogen Energy, 30(7), 795–802. https://doi.org/10.1016/j.ijhydene.2004.10.011

Morrison, G., Stevens, J., & Joseck, F. (2018). Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. Transportation Research Part C: Emerging Technologies, 87(June 2017), 183–196. https://doi.org/10.1016/j.trc.2018.01.005

Mostafaeipour, A., Khayyami, M., Sedaghat, A., Mohammadi, K., Shamshirband, S., Sehati, M. A., & Gorakifard, E. (2016). Evaluating the wind energy potential for hydrogen production: A case study. International Journal of Hydrogen Energy, 41(15), 6200–6210. https://doi.org/10.1016/j.ijhydene.2016.03.038

Nambisan, S. S., Kajkowski, J., & Menon, R. (2000). A Preliminary Survey of Ground Service Equipment Running Times and Its Implications for Air Quality Estimates at Airports. The 2020 Vision of Air Transportation, 303, 144–152.

Navas-Anguita, Z., García-Gusano, D., Dufour, J., & Iribarren, D. (2020). Prospective techno-economic and environmental assessment of a national hydrogen production mix for road transport. Applied Energy, 259(November 2019), 114121. https://doi.org/10.1016/j.apenergy.2019.114121

Nazir, H., Muthuswamy, N., Louis, C., Jose, S., Prakash, J., Buan, M. E. M., Flox, C., Chavan, S., Shi, X., Kauranen, P., Kallio, T., Maia, G., Tammeveski, K., Lymperopoulos, N., Carcadea, E., Veziroglu, E., Iranzo, A., & M. Kannan, A. (2020). Is the H2 economy realizable in the foreseeable future? Part III: H2 usage technologies, applications, and challenges and opportunities. International Journal of Hydrogen Energy, 45(53), 28217–28239. https://doi.org/10.1016/j.ijhydene.2020.07.256

Niaz, S., Manzoor, T., & Pandith, A. H. (2015). Hydrogen storage: Materials, methods and perspectives. Renewable and Sustainable Energy Reviews, 50, 457–469. https://doi.org/10.1016/j.rser.2015.05.011

Offer, G. J., Howey, D., Contestabile, M., Clague, R., & Brandon, N. P. (2010). Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy, 38(1), 24–29. https://doi.org/10.1016/j.enpol.2009.08.040

Panchenko, V. A., Daus, Y. V., Kovalev, A. A., Yudaev, I. V., & Litti, Y. V. (2022). Prospects for the production of green hydrogen: Review of countries with high potential. International Journal of Hydrogen Energy, 48(12), 4551–4571. https://doi.org/10.1016/j.ijhydene.2022.10.084

Qyyum, M. A., Dickson, R., Ali Shah, S. F., Niaz, H., Khan, A., Liu, J. J., & Lee, M. (2021). Availability, versatility, and viability of feedstocks for hydrogen production: Product space perspective. Renewable and Sustainable Energy Reviews, 145(September 2020), 110843. https://doi.org/10.1016/j.rser.2021.110843

Rosso, M., Bottero, M., Pomarico, S., La Ferlita, S., & Comino, E. (2014). Integrating multicriteria evaluation and stakeholders analysis for assessing hydropower projects. Energy Policy, 67, 870–881. https://doi.org/10.1016/j.enpol.2013.12.007

Sagaria, S., Costa Neto, R., & Baptista, P. (2021). Assessing the performance of vehicles powered by battery, fuel cell and ultra-capacitor: Application to light-duty vehicles and buses. Energy Conversion and Management, 229(December 2020), 113767. https://doi.org/10.1016/j.enconman.2020.113767

Schlund, D., Schulte, S., & Sprenger, T. (2022). The who's who of a hydrogen market ramp-up: A stakeholder analysis for Germany. Renewable and Sustainable Energy Reviews, 154(September 2021). https://doi.org/10.1016/j.rser.2021.111810

Schürmann, G., Schäfer, K., Jahn, C., Hoffmann, H., Bauerfeind, M., Fleuti, E., & Rappenglück, B. (2007). The impact of NOx, CO and VOC emissions on the air quality of Zurich airport. Atmospheric Environment, 41(1), 103–118. https://doi.org/10.1016/j.atmosenv.2006.07.030

Shakeel, S. R., Takala, J., & Zhu, L. D. (2017). Commercialization of renewable energy technologies: A ladder building approach. Renewable and Sustainable Energy Reviews, 78(December 2015), 855–867. https://doi.org/10.1016/j.rser.2017.05.005

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. Energy and Environmental Science, 12(2), 463–491. https://doi.org/10.1039/c8ee01157e

Testa, E., Giammusso, C., Bruno, M., & Maggiore, P. (2014). Analysis of environmental benefits resulting from use of hydrogen technology in handling operations at airports. Clean

Technologies and Environmental Policy, 16(5), 875–890. https://doi.org/10.1007/s10098-013-0678-3

Thomas, C. E. (2009). Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy, 34(15), 6005–6020. https://doi.org/10.1016/j.ijhydene.2009.06.003

Toyota, Hino deliver fuel cell bus for Haneda airport route in Tokyo. (2011). Fuel Cells Bulletin, 2011(1), 3. https://doi.org/10.1016/s1464-2859(11)70005-0

United Nations. (2015). Paris Agreement.

van Benthem, A. A., Kramer, G. J., & Ramer, R. (2006). An options approach to investment in a hydrogen infrastructure. Energy Policy, 34(17), 2949–2963. https://doi.org/10.1016/j.enpol.2005.05.006

Vartiainen, E., Breyer, C., Moser, D., Román Medina, E., Busto, C., Masson, G., Bosch, E., & Jäger-Waldau, A. (2022). True Cost of Solar Hydrogen. Solar RRL, 6(5). https://doi.org/10.1002/solr.202100487

Wu, M., Wu, Y., He, J., Xu, M., & Zhang, T. (2022). ScienceDirect Barrier identification , analysis and solutions of hydrogen energy storage application in multiple power scenarios based on improved DEMATAL- ISM approach. International Journal of Hydrogen Energy, 47(71), 30329–30346. https://doi.org/10.1016/j.ijhydene.2022.07.009

Xiang, Y., Cai, H., Liu, J., & Zhang, X. (2021). Techno-economic design of energy systems for airport electrification: A hydrogen-solar-storage integrated microgrid solution. Applied Energy, 283(November 2020), 116374. https://doi.org/10.1016/j.apenergy.2020.116374

Yang, C., Nicholas, M., & Ogden, J. (2006). COMPARISON OF IDEALIZED AND REAL-WORLD CITY STATION SITING MODELS FOR HYDROGEN DISTRIBUTION.

Yin, R. K. (2018). Case study research and applications: Design and methods. In SAGE Publications, Inc. (Vol. 53, Issue 5). https://doi.org/10.1177/109634809702100108

Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. Renewable and Sustainable Energy Reviews, 146(May), 111180. https://doi.org/10.1016/j.rser.2021.111180

Zhang, F., Zhao, P., Niu, M., & Maddy, J. (2016). The survey of key technologies in hydrogen energy storage. International Journal of Hydrogen Energy, 41(33), 14535–14552.

https://doi.org/10.1016/j.ijhydene.2016.05.293

Appendix 1 Extended coding tree

Example Quote	Quantity	First order code	Second order code	Dimension
We are pioneering with hydrogen. In 2018, we won a major tender. We would like to invest in sustainability. Electric is not always feasible and profitable for us.	14	Current hydrogen role	Current hydrogen economy	Stakeholder collaboration and expectations
We first established the sustainability program two years ago. Also called sustainability vision. We have formulated objectives that are in line with the climate agreement.	3	Current renewable energy		
An integrated energy supplier. In other words, generation, production, transport and sale of energy. Pretty big player	2	Energy supplier role		
We are part of HEAVENN, the hydrogen valley of the Northern Netherlands, where we are realizing an ecosystem with hydrogen applications in the provinces of Groningen, Friesland and Drenthe	14	Hydrogen Northern Netherlands		
I think that's the biggest problem right now. That we have too little. If that supply increases, you will also see that the hydrogen price will fall	4	Little renewable energy		
That is why we want to start research projects. My project is one of them. To see what the future potential of green hydrogen is.	17	Figure out hydrogen future	Future hydrogen economy	
Hydrogen is an indispensable element in the mix that we want to supply.	9	Future energy mix		
Where the hydrogen is made is a second point. We are thinking about windmills, but you can also make it in Australia or the Sahara. Solar cells can generate more energy there	5	Import hydrogen from abroad		
But I think there's a certain lower limit where the bulk is just electrification. like electric cars is better than hydrogen. Most homes will be fine with a heat pump	4	Mainly direct electrification		
I think hydrogen will play a key role in the northern Netherlands particularly. You have very specific elements and challenges that will be difficult so solve with any other solution or technology.	9	Promising hydrogen future		
The heavy transport I think. I don't see many hydrogen-powered cars anytime soon, but that's a personal assessment.	21	Specific applications		
That is the nice thing about hydrogen. No one knows exactly what will happen in the future. You have many forms and everyone is looking what form works best for different applications	6	Uncertain future		
Yeah absolutely. It is essential. Particularly between research and industry. We are part of that ass well and work closely with the RUG.	11	Collaboration with partners	Stakeholder collaboration	
Because it is a new sector that we are developing. If you have to develop a sector, we also see in Emmen that you have to include the entire chain from production, maintenance, supporting and contractors.	6	New parnerships		
Need collaboration of industry large and small. It is important to highlight that. When we talk about industry everybody tends to talk about large industry. But the innovation is not with those companies.	8	Different organisations needed		
Yes there are different interests. I think conflict is a strong word. I think you just have competition. That is not conflict but healthy competition that is just beginning	3	Competition parties	Stakeholder conflicts	
It is more like different parties have different motivations and objectives. So the challenge is to align those. There are some challenges there.	4	Different objectives stakeholders		
No actually not. Everyone understands that it has to be done together. That's funny that they are looking for that cooperation and don't see each other as a competitor.	3	No conflicts		
Airport Eelde has released the playing field for parties to do their thing there. There is a solar park. Furthermore, Everyone is pioneering. I don't know the good thing about that either.	18	Airport role	Hydrogen airport ecosystem	
Yes, of course. If we can refuel in more places, our employability will increase. So that's just more convenient. If possible, we will join.	7	Business opportunity		
No actually not. Everyone understands that it has to be done together. There are actually movements to make a business park completely autonomous.	10	Decentralized system		
If you set up companies there, it will become more interesting for employment from our municipality.	4	Economic benefits		
But you notice now more and more, especially in the Dutch situation, but you see that also already in Germany, that of course the electric grid is not provided to supply so much electricity.	7	Grid capacity		
Good point, you would expect it to work that way, but it requires a lot of paperwork. As a private party, you are not allowed to install your electricity grid yourself.	9	Grid connection		
If a bus were to be refueled in Eelde, there would actually have to be a circulation close by that would be suitable for this. So a regional bus that covers long distances.	18	Hydrogen demand		
That depends on whether they can build up enough buffer and produce hydrogen cheaply enough and whether they have enough demand.	4	Succes depending on scale		
They want all transport to be zero emissions by 2028. Then you are forced to look for alternatives. But that can also be electric, but that does not fully have our future.	16	Zero emmission target		
That is of course not very efficient. This is because you are very worried about the loading time. So the time to charge the GPUs	12	Electric GSE	Ground support equipment	
So as ground support equipment platforms become more and more fully electric powered. Can you then make your choice of do we do it indeed lead battery, litium battery, fuel cell.	10	Ground support equipment		
Ground power units and large aircraft tractors	16	Hydrogen GSE		

Example Quote	Quantity	First order code	Second order code	Dimension
As an entrepreneur you have to invest and the question is whether you will get it back. That is difficult now because it is so new and unclear and because it is not really there yet.	5	Business model hydrogen	Economic barriers	Barriers inhibiting hydrogen deployment and recommendations
Diesel is by far the cheapest, first of all because you have a very large diesel tank at the bottom.	5	Diesel cheaper		
That hydrogen can become cheaper. And the volume of equipment is also still quite small. Comparable to solar panels 10 years ago	12	High hydrogen price		
So I mean if you buy diesel for €80,000 electric for €140,000 and hydrogen for €300,000	9	High investment costs		
I currently think that the vast majority of hydrogen projects are not economically viable.	8	No viable business model		
That should free up the government a lot more, to make those subsidy streams true. Now it's very half-hearted about the old subsidy system.	11	Subsidies		
They are not yet available from the factory. We've been working on this. It also comes with a hefty price tag. That gap cannot be closed yet.	3	Availability	Technological barriers	
In the Netherlands you can only fill up with hydrogen in a few places. If that doesn't happen anymore, nobody will buy a hydrogen car.	25	Hydrogen infrastructure		
They are mature individually. Hydrogen is produced and used for many decades.	4	Technology excists		
We are actively looking for knowledge institutes. Collaborative projects, subsidy programs so that we can build that knowledge.	18	Research and knowledge		
This is wider than the sector a lack of skills. We cannot recruit and train people as fast as we need.	8	Technical staff and skills		
Technology development is simply needed to enable the use of hydrogen. I expect this is more a matter of time.	8	Technology development		
Mainly laws and regulations to stimulate hydrogen. Name a mandatory emission reduction for companies or other applications.	10	Missing stimulating policy	Political and regulatory barriers	
The fact that the local government and province actually have no knowledge of hydrogen is concerned. HEAVVENN chases it, but in the municipality it's a far from my bed show.	11	Policy not consistant and slow		
Anyway, a workable regulation, of course, that is not unimportant.	25	Regulation		
If a filling station has to be installed with a pipeline, it must comply with laws and regulations. External safety is therefore an important aspect.	5	Permits		
They don't want the noise nuisance from overflying planes. That's what you mainly run into.	10	Hinder environment	Social and environmental barriers	
That is a very important key issue. More work on that is needed. Public acceptance and informing the public	5	Inform public		
Then the nuisance will decrease because you will no longer have diesel buses and trucks. Those things make a lot less noise and smell less.	2	Positive for environment		
It must be safe but you can't rule out everything.	3	Safe and responsible		
They keep circling and making noise. That Boeing will be gone soon. Those little things go low and you hear them for a long time.	12	Resistance airport		
But you don't build a factory in a residential area	5	Safe distance people		
There are questions about safety and of course references are made to explosions.	12	Safety concerns		
So there is a lot of work that we have to do. we need to do more on public perception and public acceptance. It is a normal perception that people have about hydrogen.	12	Social acceptance		
You clearly have social acceptance for hydrogen.	9	Social support hydrogen		
I think that GAE is doing very well in Europe by being a forerunner in this field. I applaud that very much.	10	Support airport		
No they are all important. All of them. They are all equally important. I cannot really rank them to be honest. They are all on the top of the list.	5	Ranking barriers	Ranking barriers	