



YAŞAR UNIVERSITY

GRADUATE SCHOOL

DOCTOR OF PHILOSOPHY THESIS

**TRANSITION TOWARDS NET-ZERO EMISSIONS**  
**HYDROGEN SOLUTIONS IN AIRPORT OPERATIONS**  
**MANAGEMENT: AIRPORT CASE**

MÜRÜVVET DENİZ SEZER

THESIS ADVISOR: PROF. (PHD) ERHAN ADA

CO-ADVISOR: PROF. (PHD) YİĞİT KAZANÇOĞLU

PHD IN BUSINESS ADMINISTRATION

BORNOVA / İZMİR  
JULY 2025



## JURY APPROVAL PAGE

We certify that, as the jury, we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of the Doctor of Philosophy.

### Jury Members:

### Signature:

Prof. (PhD) Erhan ADA

Yaşar University

.....

Prof. (PhD) Yiğit KAZANÇOĞLU

Yaşar University

.....

Prof. (PhD) Hasan SELİM

Dokuz Eylül University

.....

Prof. (PhD) Evrim URSAVAŞ

Groningen University

.....

Assoc. Prof. (PhD) Gökem ATAMAN

Yaşar University

.....

Assoc. Prof. (PhD) Muhittin SAĞNAK

İzmir Katip Çelebi University

.....

-----  
Prof. (PhD) Yücel Öztürkoğlu  
Director of the Graduate School



## ABSTRACT

### TRANSITION TOWARDS NET-ZERO EMISSIONS HYDROGEN SOLUTIONS IN AIRPORT OPERATIONS MANAGEMENT: AIRPORT CASE

Sezer, Mürüvvet Deniz

PhD, Business Administration

Advisor: Prof. (PhD) Erhan Ada

Co-Advisor: Prof. (PhD) Yiğit Kazançoğlu

July 2025

The transition to hydrogen aims to develop a more sustainable, low-carbon, and energy-secure system by reducing fossil fuel dependency. Hydrogen produced from renewable energy sources, such as solar energy, is directly related to the Sustainable Development Goals. Green hydrogen, especially produced from renewable sources, has zero carbon emissions and is critical in dealing with climate change. Hydrogen is an effective solution in carbon-intensive sectors such as the transportation sector. It contributes to green development with hydrogen production, storage, transportation, and infrastructure investments. However, one of the most important challenges to the establishment of the hydrogen system is high initial investment costs. Green hydrogen production, transportation, storage, and infrastructure investments are very expensive, and clear policies, targets, and incentive mechanisms for hydrogen are missing or nascent, especially in developing countries in the first phase of transition. In this context, this study aims to conduct a cost-benefit analysis of the transition to hydrogen in airport ground services. In addition, this study aims to ensure that the three pillars of sustainability are achieved in the transition to hydrogen. The economic, social, and environmental impacts of the transition to green hydrogen have been analysed. Although the most important impact of this transformation is thought to be in the environmental dimension, it has been observed that it will provide both social and economic benefits. According to the results, the transition to hydrogen requires significant investment costs; it is seen that the transition to hydrogen will provide a competitive advantage in the long term and is a profitable



investment, especially when carbon emission taxes are considered. Based on the results, the role of industry partners, policy makers, local and global authorities, and research institutions, who are important stakeholders of the hydrogen ecosystem, in achieving these goals has been discussed, and various suggestions have been developed.

**Keywords:** energy transition, hydrogen, energy supply chain, net zero emission, airport ground services, simulation





## ÖZ

### HAVAALANI OPERASYON YÖNETİMİNDE NET SIFIR EMİSYON- HİDROJEN ÇÖZÜMLERİNE GEÇİŞ: AIRPORT ÖRNEĞİ

Sezer, Mürüvvet Deniz

Doktora Tezi, İşletme Doktora Programı (İngilizce)

Danışman: Prof. Dr. Erhan ADA

Eş Danışman: Prof. Dr. Yiğit KAZANÇOĞLU

Temmuz 2025

Hidrojene geçişin amacı, fosil yakıt bağımlılığını azaltarak daha sürdürülebilir, düşük karbonlu ve enerji güvenliği yüksek bir sistem geliştirmektir. Güneş enerjisi gibi yenilenebilir enerji kaynakları ile üretilen hidrojen, sürdürülebilir kalkınma hedefleri ile de doğrudan ilintilidir. Özellikle yenilenebilir kaynaklardan üretilen yeşil hidrojen sıfır karbon emisyonludur ve iklim değişikliğiyle mücadelede kritik öneme sahiptir. Ulaştırma sektörü gibi karbon yoğun sektörlerde hidrojen etkili bir çözümdür. Hidrojen üretimi, depolama, taşıma ve altyapı yatırımlarıyla yeşil kalkınmaya katkı sağlamaktadır. Ancak hidrojen sisteminin oluşturulmasındaki en önemli engellerinden biri yüksek yatırım maliyetleridir. Özellikle gelişmekte olan ülkelerde, yani geçişin daha ilk aşamasında olan ülkelere, yeşil hidrojen üretimi, taşıma, depolama ve altyapı yatırımları oldukça pahalıdır ve hidrojen konusunda net politikalar, hedefler ve teşvik mekanizmaları eksik ya da yeni gelişmektedir. Bu kapsamda bu çalışmanın amacı havaalanı yer hizmetlerinde hidrojene geçiş için fayda maliyet analizini yapmaktır. Ayrıca bu çalışma hidrojene geçişte, sürdürülebilirliğin üç sac ayağının başarılmasını sağlamayı hedeflemektedir. Yeşil hidrojene geçişin ekonomik, sosyal ve çevresel etkileri analiz edilmiştir. Bu dönüşümün en önemli etkisinin çevresel boyut üzerinde olacağı düşünülse de uzun dönemde hem sosyal hem de ekonomik fayda sağlayacağı görülmüştür. Sonuçlara göre hidrojene geçişin önemli ölçüde yatırım maliyeti gerektirdiği yadsınamaz, fakat hidrojene geçişin uzun dönemde rekabet avantajı sağlayacağı ve özellikle karbon emisyon vergileri de dikkate alındığında karlı bir yatırım olduğu görülmüştür. Sonuçlar baz alınarak, hidrojen ekosisteminin önemli paydaşlarından olan endüstri



ortakları, politika yapıcılar, yerel ve küresel otoriteler ve araştırma kurumlarının bu hedeflerinin başarılmasındaki rolü tartışılarak çeşitli öneriler geliştirilmiştir.

**Anahtar Kelimeler:** enerji dönüşümü, hidrojen, enerji tedarik zinciri, net sıfır emisyon, havaalanı yer hizmetleri, benzetim





## ACKNOWLEDGEMENTS

This achievement is a dream my late mother entrusted to me. Even though I cannot say it to her in person, I felt her presence with me at every step. My deepest gratitude goes to her for her unconditional love, strength, patience, and endless support throughout my life. This thesis is dedicated to her dream, her love, and the strength she instilled in me.

I would like to express my sincere thanks to my advisors, Prof. (PhD) Erhan Ada and Prof. (PhD) Yiğit Kazançoğlu, for their guidance, trust, and patience throughout this journey. Your contributions made this process both meaningful and possible.

I am also grateful to my thesis monitoring committee members, Prof. (PhD) Evrim Ursavaş and Assoc. Prof. (PhD) Muhittin Sağnak, for their valuable insights and encouragement during the critical phases of this research.

Special thanks to Assoc. Prof. (PhD) Gökem Ataman, my department head and jury member, for his continuous support, and to Prof. (PhD) Hasan Selim, who has always been a source of guidance and encouragement since my master's studies.

I owe heartfelt thanks to my father, İbrahim Sezer who did more than I could ever ask for during this process, and to my sister, Ece Gümüş whose unwavering support means the world to me. I am also thankful to my brother Erdem Gümüş and his family, especially little nephew, Kerem Gümüş, for the joy and motivation they brought into my life.

To my lifelong friend, colleague, and soul sister Neslim - your support has been one of the pillars of this journey. To Pelin Çıbık, my friend since childhood, and to my dear friends Merve Keser and Burak Çetiner - thank you for being there in every moment.

This work would not have been possible without the presence and support of all these incredible people.

Mürüvvet Deniz Sezer  
İzmir, 2025



## TEXT OF OATH

I declare and honestly confirm that my study, titled “Transition Towards Net-Zero Emissions-Hydrogen Solutions in Airport Operations Management: Airport Case” and presented as a PhD Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Mürüvvet Deniz Sezer

17.07.2025





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## **SYMBOLS AND ABBREVIATIONS**

### **ABBREVIATIONS:**

|                 |                             |
|-----------------|-----------------------------|
| CO <sub>2</sub> | Carbon dioxide              |
| GHG             | Greenhouse gas              |
| GSE             | Ground support equipment    |
| HGPUs           | Hydrogen ground power units |
| GPUs            | Ground power units          |
| FCEVs           | Fuel cell electric vehicles |
| HST             | Hydrogen storage tank       |
| PV              | Photovoltaic System         |
| NPV             | Net present value           |



## **1. CHAPTER: INTRODUCTION**

Considering the increasing importance of environmental issues, particularly with climate change, there is a growing awareness of achieving a low-carbon economy (Gu et al., 2023). To address climate change, the energy system needs to transition to decarbonization. According to the Paris Agreement, the limit for the rise in the worldwide average temperature needs to be below 2 °C (Chaichaloempreecha et al., 2022). Thus, emission reduction policies are inevitable to achieve net-zero goals by 2050 (United Nations, 2015). For these purposes, the European Union is actively working on achieving climate neutrality by 2050 as a solution by decreasing the negative impact of greenhouse gas (GHG) emissions (European Commission, 2021). Considering these targets, the adoption of electrification, effects of energy policies, and the transition to renewable energy are expected to be responsible for approximately 70% of the required reductions in GHG (IRENA, 2022).

In line with these targets, achieving the net-zero carbon emissions target, using hydrogen can be considered as an essential energy carrier (Rawat et al., 2024) and is known as a promising energy carrier for decarbonization of the energy-intensive sectors. The generation of hydrogen using water electrolysis has received considerable attention as an approach for decreasing greenhouse gas emissions through the usage of low-carbon energy sources like nuclear power and renewable energy sources such as solar, wind, and hydropower (Anwar et al., 2021). However, location can be thought key driver for the cost-effectiveness of renewable energy sources due to the variation of effects (IRENA, 2022). In addition, hydrogen has diverse applications in this context, including transportation (aircraft, ships, vehicles, trains), energy storage, industry, medicine, energy-to-gas conversion, etc. It is an environmentally friendly alternative to the currently used fuels such as unleaded gasoline, gasoline, and kerosene (Yue et al., 2021). Thus, hydrogen possesses certain attributes that make it a viable energy carrier for nations heavily dependent on fossil fuel imports (Lie et al., 2024).

The IEA (International Energy Agency) estimates global hydrogen demand will increase from 97 million tons (Mt) in 2023 to 200 Mt in 2030 and 450-500 Mt in 2050 under the net-zero emissions target (IEA, 2024). In this context, to decrease net-zero emission targets, countries are adopting a hydrogen policy into their energy strategies to meet sustainability goals (Hassan et al., 2024). For instance, Germany's "National Hydrogen Strategy" plays a critical role in the green hydrogen transition in the industrial sectors for reducing emissions in the transportation industry. This strategy highlights developing a hydrogen infrastructure that includes storage and refueling stations. In addition, research and innovation regarding hydrogen technologies should be improved to decrease hydrogen production costs. To accomplish this aim, international collaboration is a fundamental requirement to create a global hydrogen economy (Nunez & Quitzow, 2024). Another important hydrogen project is Japan's "Basic Hydrogen Strategy," which mainly focuses on developing a hydrogen-centered energy transition through hydrogen-powered transport. Japan's strategies aim to develop a robust hydrogen infrastructure for the progress of the regional production of hydrogen and increased global collaboration (Lida & Sakata, 2019). Besides, South Korea's "Hydrogen Economy Roadmap" aims to be a leader in hydrogen transition by targeting the scaling up of hydrogen production via electrolysis and enhanced technology (Shin, 2022). The deployment of hydrogen-powered vehicles and the developing network of refueling stations in this country is an important step in building a sustainable strategy for developing a hydrogen ecosystem.

Hydrogen demand in the transportation sector is expected to be sufficient to trigger economies of scale, making the transportation sector critically important for hydrogen adoption. The transportation industry is one of the crucial sectors in achieving a net-zero emissions due to the carbon border adjustment (Perdana & Vielle, 2023). In addition, this industry has played a critical role in addressing the decrease in its significant carbon emissions since the aviation industry primarily depends on fossil fuels (European Commission, 2017). Moreover, its expected growth and reliance on fossil fuels exceed the average growth of other sectors (Gonzalez-Garay et al., 2022). This sector accounts for approximately 5% of global GHG emissions (Lai et al., 2022). Green hydrogen is important for the energy-intensive sectors such as steel, chemical, transportation, and refining sectors since

hydrogen deployment is inevitable for decreasing greenhouse gas emissions. Hydrogen could have a competitive advantage in transportation compared to the other sectors since the cost of diesel and gasoline is generally higher than that of natural gas. The demand for clean hydrogen in the transportation sector is expected to increase rapidly. The growth rate is expected to surpass that of all other sectors, with an annual rate of 12% between 2020 and 2050, ultimately reaching a volume of approximately 100 Mt by 2050, including applications such as sustainable aviation fuel and methanol for ships. Specifically, the forecast suggests that the aviation industry will experience a higher rate of growth compared to the average growth rate of other sectors. However, reducing CO<sub>2</sub> (carbon dioxide) emissions in the aviation sector presents unique challenges. Thus, there is increasing pressure on the industry to develop clean technology and renewable energy sources (Baroutaji et al., 2019). To reduce carbon dioxide emissions, the aviation sector will have to shift to hydrogen and biofuel (IPCC, 2021). Emissions primarily come from the airport's ground services, which include operations, cargo, and passenger services. According to Testa et al. (2014), ground services are a significant contributor to the carbon emissions of the airport industry. However, environmental concern and sustainability are currently challenging the aviation industry, just like other industries, to explore emission-free solutions (Ranasinghe et al., 2019). Moreover, as air travel is expected to increase in the coming years, the adoption of environmentally friendly technologies is anticipated to grow even more rapidly (Hasan et al., 2021). This makes the adoption of renewable resources in place of diesel-based ground handling operations imperative in the effort to mitigate GHG emissions. Thus, the aim of this thesis is to provide insights into the pros and cons of transitioning ground services to hydrogen over conventional powered ground logistics operations and to analyse the economic feasibility of this transition. Airport energy systems can integrate electrification and hydrogen resources to mitigate carbon emissions (Zhao et al., 2022). Besides, meeting decarbonization targets requires a power source for aircraft that is carbon-neutral. Ground handling services have to transition to hydrogen-based technology to reach net-zero emissions by 2030 (Aditya et al., 2025). Such systems or procedures will require some investments on the part of the airports to make the transition in order to achieve their carbon-neutral targets (Mahesh & Calvert, 2025). Therefore, this thesis aims to analyze economic feasibility to encourage the transition

to hydrogen in airport ground services. To address this aim, a cost/benefit analysis was performed concerning the hydrogen substitution of the airport ground handling services. Economic feasibility of the hydrogen transition in ground handling operations was assessed by comparing the net present value (NPV) of existing technology, which is based on diesel and hydrogen-based technologies. The developed simulation model aims to estimate the energy production and consumption of the ground handling services, considering the hydrogen demand of aircraft.

The simulation is predicated on the energy requirements of a hydrogen-powered ground logistics operation and the provision offered by the solar park, hydrogen storage tank (HST), and grid. Scenario analyses are added to the baseline to enhance the comprehension of the suggested results. Additionally, a sensitivity analysis is carried out on the price of diesel fuel and the cost associated with carbon emissions to validate the simulation results. Through the output of a simulation model, components like capital expenditures, operating expenses, and energy consumption costs are calculated in order to conduct a cost-benefit analysis. This study aims to provide an analysis economic feasibility of the green hydrogen transition in airport applications.

In this context, the purpose, scope, and method of the study are explained in the first section of the study. In the second and third sections, sustainability in airport logistics and the technologies for the analysis of environmental impacts in airport services, the theoretical framework on the subject is presented, and the relevant literature is reviewed. In the fourth section, the method of the research is detailed; the stages of development of the simulation model, the data collection process, and the analysis are explained. In the fifth section, the findings are discussed, and in the sixth section, the importance of the study is revealed with discussions on previous studies. In the seventh section, implications and policy recommendations are presented in light of the findings, and this thesis is concluded by discussing the results in the eighth chapter.

## **2. CHAPTER: SUSTAINABILITY IN AIRPORT LOGISTICS**

This section discusses sustainability in airport logistics, starting with the theoretical underpinning of this research. In addition, the following section presents air transport services and the environmental, social, and economic impacts of the airport operations.

### **2.1. Sustainability**

Recently, the concept of sustainability has become a significant issue in dealing with economic growth, environmental concerns, and social welfare in society (Rajesh, 2020). Sustainability is based on the triple bottom line approach and reveals that economic, social, and environmental issues should be addressed holistically as a triple structure (Yip et al., 2023). Rapid population growth and the increase in energy demand worldwide have revealed the necessity of a sustainable and renewable energy transition (Dincer & Acar, 2015). According to Andrés and Padilla (2018), the transportation sector's share of GHG emissions has grown by 20.8% since 2014. The amount of GHG emissions from the aviation sector will increase by 3% (Terrenoire et al., 2019; Bahman, 2023). GHG emission is the most significant type of emission source for the airport sector, and have multiple negative effects on the surrounding habitat while trying to reach net-zero carbon emission goals (Pamucar et al., 2021). In alignment with these concerns, sustainability applications in the transportation industry have also increased because of overcoming challenges such as environmental degradation, greenhouse gas emissions, climate change, and exhaustion of natural resources (Sheldon & Park, 2011; Kılıç et al., 2019). Thus, these significant concerns on the environmental and social impacts of airport logistics need to be reduced to reach net-zero emissions (Logan et al., 2022).

In order to achieve net-zero carbon emissions, the aviation sector is determined to significantly decrease (or decarbonise) its carbon emission intensity and achieve renewable energy targets by way of technology advancements & optimising operational processes and infrastructure, etc. Technologies that reduce carbon

emissions in transportation and minimize the environmental impact of airports should be adopted (Hu et al., 2022). In this context, the International Civil Aviation Organization develops several policies and plans depending on net-zero carbon emission goals by means of new technologies, operational improvements, and sustainable aviation fuels. To reduce dependence on traditional energy sources, the energy needs of airports can be compensated through renewable energy sources. Consequently, the transition to sustainable energy sources in airport logistics will be more important in the next ten years. Therefore, strategies and critical steps must be taken to ensure sustainability in the aviation industry.

Three significant theories, stakeholder theory, resource-based view, and system theory, that can be used as a basis to achieve this sustainable and green transformation, are presented as a theoretical background in the following section.

#### **2.1.1. Stakeholders Theory**

Various theories have been put forward to make businesses more sustainable. One of the most widely used of these theories is the stakeholder theory, which is closely interrelated with sustainability (Attanasio et al., 2022). In this theory, stakeholders must act with unity and ingenuity to develop long-term strategies and policies that achieve sustainable development goals (Freudenreich et al., 2020). Within the stakeholder theory, organizations have a variety of stakeholders who can significantly influence their processes and success. According to this theory, organizations and businesses should consider the requirements of their stakeholders and integrate them into their critical decision-making processes (Tapaninaho & Heikkinen, 2022). Accelerating the race toward sustainable transition, today's companies, local and global authorities, and institutions should collaborate to disseminate knowledge, support capital deployment, manage unexpected issues, and act rapidly. Stakeholders of this transition can be considered as employees, customers, suppliers, communities, local authorities, and governments.

In addition, stakeholders play a critical role in this transition to encourage sustainability concepts in airport logistics. Since airports have a complex structure with various stakeholders, when considering networks, entities, and operations and the interactions between these stakeholders have a significant influence on the three aspects of sustainability. Moreover, airports have significant impacts on the

environment, such as noise pollution, carbon emissions, and waste generation. To address these removals of negative impacts on the environment, it is imperative that stakeholders of airports (local authorities, regulatory authorities, research institutes) should support collaboration and provide long-term strategies to achieve the net-zero emissions goal.

Through the adoption of the stakeholder theory, airports can address the above-mentioned stakeholders, which are presented in Figure 2.1., as they make considerations of their concerns and insights into developing sustainable practices (Al Sarrah et al., 2021). One of the main stakeholders of the net-zero emission target in airports is governments and their regulations. Governments are key in the formulation of airport safety, social, and environmental policies (Değirmenci et al., 2023a). Employment opportunities, noise reduction laws, and many other strategies can be considered as means to achieve this green transition. Stakeholder theory aims to ensure accessibility by collaborating with stakeholders, complying with laws and policies established by governments to achieve sustainability in airport operations, and increasing process traceability for all parties concerned. Airports contribute to the regional economy and provide jobs; hence, it is a very essential component to make the economy viable. Stakeholder theory provides a perspective on the role of economic stakeholders, such as airlines, companies, and investors, in achieving the economic sustainability of airports. Collective actions involving green procurement and investment in energy-efficient infrastructure are encouraged to promote economic sustainability at the airport. The significance of these issues cannot be underestimated, and a proper balance between economic growth and social/economic sustainability must be ensured in a sustainable airport environment (Raimundo et al., 2023).

Collaboration with various stakeholders is key for airports to become sustainable. Thus, stakeholder theory even advocates stakeholder cooperation, as airports are a central part of the supply chain to ensure high standards of social and environmental management with their stakeholders (Raimundo et al., 2023). Moreover, airport logistics are linked to many stakeholders: fuel suppliers, ground handling services, national and/or international authorities, R&D organizations, as shown in Figure 1 (Eid et al., 2022).

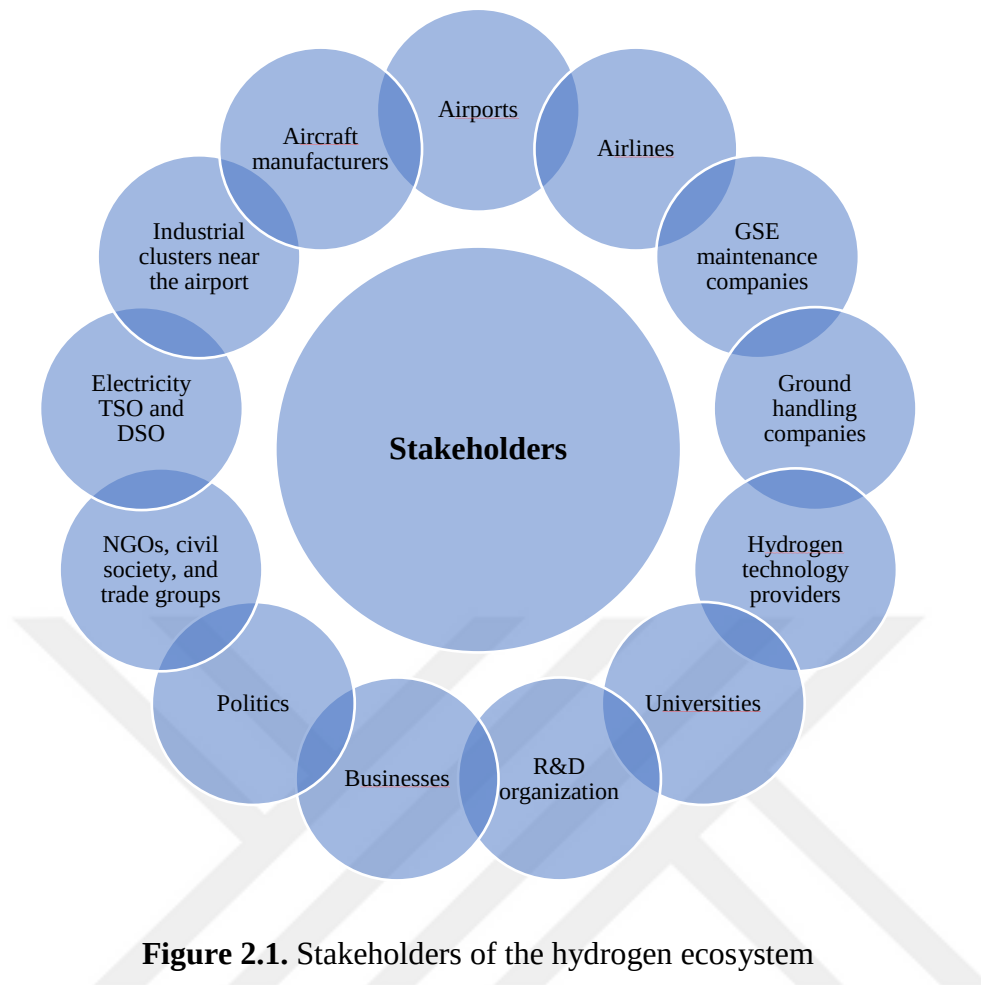


**Figure 2.1.** Stakeholders of the hydrogen ecosystem

Source: Author

To sum up, in the aim of implementing sustainable airport operations, stakeholder theory provides a framework of how to behave with various stakeholders. Understanding stakeholder relations and establishing a collaborative framework will help airports enhance operations, mitigate negative environmental impacts, and develop long-term sustainability strategies. By identifying stakeholder relations and developing a cooperative framework, airports can enhance operations, mitigate negative environmental impacts, and develop long-term, sustainable plans. This section comprehensively analyses the stakeholder theory and its importance for the realization of the green transition.

### **2.1.2. Resource-Based View**

This section will continue with another important theory, “resource-based theory,” which forms the foundation for achieving sustainable and green transformation. For firms, it is crucial to support sustainability from a resource-based perspective through firm-specific resources and capabilities. The integration, optimization, and creation of resources serve strategic advantages that help overcome challenges posed by the sustainability paradoxes of environmental, social, and economic sustainability. An organization should adopt a resource-based approach to gain a competitive advantage (Jafari & Rezaee, 2014). The goal of resource-based theory in sustainable supply chain management is to show how focusing on sustainable supply chains and factors can provide a competitive edge. The resource-based view considers resources as key to obtaining a competitive advantage (Shibin et al., 2020). This perspective analyzes assets and competencies involved in creating value and/or securing a competitive edge. It always emphasizes value-added activities throughout the supply chain—such as risk assessment of faced situations, risk planning, and risk strategy development (Ngo et al., 2024). This approach helps develop sustainable supply chain strategies that benefit long-term success. According to the resource-based view, an organization’s strategic competitiveness primarily stems from its unique resources and capabilities (Alkaraan et al., 2024). To leverage these special talents, it is necessary to identify and highlight the company’s resources. Resource-based theory encourages organizations to explore their tangible and intangible resources to sustain and enhance sustainable practices. These special resources include knowledge, human capital, relationships, and technology. Implementing sustainable practices like waste management, eco-technologies, and energy-efficient infrastructure can reduce resource consumption. To achieve sustained competitive advantage, the efficient use of available resources is essential (Arda et al., 2023). Meeting sustainability goals requires the right combination of resources and capabilities. From this perspective, it is crucial that competitors' resources and capabilities are difficult to copy or imitate to sustain a competitive edge (Alkaraan et al., 2024). To gain a competitive advantage, companies must adopt unique, sustainability-related resources and capabilities. Knowledge in sustainable design and construction enables long-term, strategic decisions. Based on this theory, valuable resources should be durable and hard to replicate to maintain a competitive advantage over time. Implementing

environmental management systems and forming long-term partnerships with stakeholders and local communities are excellent examples of control measures and strategies to sustain strategic advantages (Mishra and Yadav, 2021).

Resource-based theory recognizes the potential for collaborative partnerships with other enterprises, organizations, and stakeholder actors, allowing companies to access a broader range of resources and capabilities (Ozdemir et al., 2023). It may also involve working together with suppliers, trade associations, universities, and government institutions on sustainable airport logistics. Collaboration is seen as essential to making the best use of resources. In this context, it is regarded as an important theory for ensuring sustainability, along with stakeholder theory.

### **2.1.3. Systems Theory**

Another important theory for achieving sustainability is systems theory, proposed by Bertalanffy, which dates back to the 1900s and gained popularity in the 20th century. It emerged from the need to study systems as a whole. The systems approach, which began as systems theory, was later applied across many fields, forming the foundation for numerous disciplines (Zelbst et al., 2019). The systems approach is used to manage and analyze complex and dynamic systems.

The systems thinking approach is one of the best frameworks for developing solutions to sustainability-related challenges. Because this method is based on providing a holistic understanding of the way things work, it facilitates long-lasting and creative thinking skills. Systems thinking that aims for actions to be resilient to shocks or changes in both social and ecological systems is needed to build a sustainable community without jeopardizing ecosystem health and social opportunities for future generations (Williams et al., 2017).

Fundamental ideas of systems theory can be summarized as follows.

This is the approach of systems theory; systems can achieve more as a whole than as individual parts. That is why a holistic view is required to process and control all systems of things.

Interconnectedness is another important element of systems theory. A system itself is a network of interrelated components, and changes to one part of the system can have a significant impact on others (Hossain et al., 2020).

Feedback is an additional noteworthy part of this theory. Feedback loops are crucial for monitoring and improving sustainability performance in the context of airport logistics. For instance, data on waste generation and energy consumption can help inform more resource-efficient and sustainability-oriented operational practices. Therefore, to address the social, environmental, and economic consequences of airport logistics and formulate mitigation strategies to limit their negative effects, it is important to understand the relationship between the system components, as well as the feedback mechanism that allows outputs to also influence inputs in the next system cycle.

The role of the systems approach to the net-zero transition is applied to the systems of energy, transportation, and the built environment to improve them, before finally exploring how to bring this understanding together to shape the net-zero transition. Airports are complex in their structure, and therefore, systems theory and sustainability in airport logistics are related to the systems theory. A holistic approach to solve the interoperability question is to use systems theory as a conceptual framework to explain the fundamental mechanisms that govern the interaction of systems, such as the prediction of airport logistics (Schiffling et al., 2022). Sustainable airport logistics measurements refer to understanding the environmental, social, and economic impacts of airport area operation (Couto & Baltazar, 2025) and dealing with them in a synchronised, systematic, and holistic way. Airport logistics consists of multiple sub-systems such as transportation, infrastructure, and supply chain, which interrelate with one another and need to be viewed holistically. To this end, sustainability requires various stakeholders, processes, and environmental aspects to be interconnected within logistics and airport logistics (Dimitriou & Karagkouni, 2022). Hence, it is essential to understand the estimated environmental, social, and economic impact of the net-zero emissions transition and to devise an action plan utilizing the feedback and footprints of elements to mitigate the detrimental impacts of activities.

According to (Razak et al., 2023), resilience and adaptability are being discussed as separate parts of system theory. Systems should be able to respond to internal and external influencing factors quickly, while swift problem-solving becomes a crucial objective of systems. Thus, airport logistics requirements lead to efficient and rapid solutions for the majority of challenges faced (Cavusoglu & Macario, 2022).

Improvement of climate change impacts or regulatory changes, dealing with sources of energy diversification, and promoting continuous innovation and improvement are some of the important issues that need to be timely and effectively solved in creating a sustainable airport (Lindbergh et al., 2022). Therefore, it is necessary to systematically address all system components holistically.

To summarize, by integrating systems theory into airport logistics processes, a systematic and holistic approach can be provided to achieve sustainability goals. By considering the relationships and dynamics of the elements within the system, it offers a holistic perspective for sustainability and contributes to the improvement of systems through feedback mechanisms. It enables the development of flexible, adaptable, and necessary policies for the challenges that will arise. When it comes to sustainability in airport logistics, system-level sustainability outcomes are the collective efforts of different stakeholders and processes. By integrating sustainable practices across the airport logistics system, emerging features such as reduced carbon emissions can be improved with the aforementioned theories discussed in this chapter.

## **2.2. Air Transportation Services**

In order to understand the structure of air transportation and analyse the impact of green transformation, air transportation services are investigated in this section. Air transportation is the movement of passengers, goods, and cargo using aircraft (Wensveen, 2023). It connects people and businesses around the world, facilitating international trade and contributing to economic growth. It has become one of the fastest transportation modes that connects international boundaries (Ekici et al., 2022). There are many stakeholders in air transportation, such as airlines, airports, regulators, local and global authorities, market dynamics, and industries. These stakeholders play a critical role in managing the economic, social, and environmental impacts of sustainability. The key stakeholders, such as airlines, airports, and regulatory bodies, market dynamics involve in the transition to net-zero aims in air transportation. Besides, airports play a vital role in the smooth functioning of air travel by providing the required infrastructure and services for airplane, including runways, terminals, control towers, and baggage systems (Dua & Guzman, 2024). To ensure the safety, security, and environmental compliance of the aviation industry,

regulatory bodies create and enforce strict regulations and standards (Sipos, 2024). Air transportation plays a pivotal role in developing a sustainable environment as an environmental, economic, and social aspects to achieve the net-zero emission target. As a social dimension, the aviation industry prioritizes safety above all else and takes extensive measures to prevent accidents and incidents. Airlines and regulatory bodies rigorously enforce safety protocols and procedures (Henderson, 2022). Moreover, the economic effects of air transportation are substantial and far-reaching. The sector contributes to the creation of jobs, generates revenue, and drives trade on both local and global levels. Various factors, such as supply and demand, pricing tactics, competition, and the financial success of airlines, must be carefully considered when examining air transportation (Wensveen, 2023).

When it comes to the environmental sustainability aspect, the aviation sector plays a important role in the release of greenhouse gases and the contamination of the environment. However, the industry is taking proactive steps to mitigate its carbon footprint, such as implementing efficient fuel practices, integrating alternative fuels, and investing in sustainable technologies.

The dynamic field of air transportation encompasses various facets of research, policy development, and industry practices, all aimed at addressing the diverse challenges and exciting opportunities within the aviation sector (Couto & Baltazar, 2025). Since this study focuses on airport ground services, various air transportation services are presented in detail in the following section.

### **2.2.1. Cargo**

One of the significant ground services at the airport is cargo services. Specialized cargo handling facilities (cargo terminals or cargo warehouses) at airports receive, store, and prepare goods for conveyance to the next destination. It has other specialized infrastructure handling tools, cargo aprons, and storage areas. Handling of cargo at an airport includes a wide range of tasks such as receiving cargo, inspecting and documenting it, weighing, identification, and security screening (Schwieterman & Hague, 2022). These protocols ensure adherence to all statutory requirements to maintain security and safety standards. Airlines operate freighter planes or dedicated cargo divisions, which are crucial for transporting cargo. These air freight companies offer a range of services, including express delivery, scheduled

cargo flights, charter flights, and specialized services for perishable or hazardous goods (Huang et al., 2024). Cargo agents manage the transport and delivery of cargo and work directly with logistics companies, freight forwarders, and cargo movers. Overseeing this logistics, identifying vast zones of cargo, and the security surrounding these areas at the airport have emerged as critical issues (Jiang et al., 2023). Cargo monitoring systems are helping logistics firms, shippers, and customers keep tabs on the location and state of cargo during a shipment. Efficient intermodal connectivity is a common feature of airport cargo logistics (Fernández et al., 2022). By using intermodal connections, which also reduce transit times and enhance operational performance, a full and integrated supply chain can be enabled.

Transportation plays a critical role in trade, economic growth, and sustainable supply chain management (Mahmood et al., 2024). Airports, therefore, will invest in partnerships, technology, and infrastructure to increase their capacity to handle cargo, streamline processes, and ensure that the flow of goods through the airport logistics is safe and efficient. With these improvements, airport sustainability goals can be achieved.

### **2.2.2. Passenger**

Passenger flow is crucial throughout the entire process of airport operations (Lin et al., 2023). Therefore, it is considered essential ground services for many airports. Many airports assert transportation services that enable passengers to navigate between terminals, parking garages, and other airport facilities. There are many similarities in the transportation for the customers at an airport. Airport shuttle buses transport people between airport terminals, parking lots, rental car agencies, and other areas of airport property (Öner et al., 2021).

These buses are typically available to all riders and run on the same routes (Tsigdinos et al., 2024). Moving walkways and escalators are common in airport terminals to allow travellers to cover large distances quickly. These walkways and escalators help get passengers between gates, security checkpoints, and other airport facilities.

A lot of airports provide designated taxi stands or shuttle services that enable passengers to obtain transportation to various destinations outside of the airport (Öner et al., 2021).

### **2.2.3. Freight**

The term airport logistics describes a group of activities and services that assure the rapid and effective movement of cargo via an airport (Wandelt et al., 2024). It covers cargo or freight transported at an airport. Airports are used for cargo transportation as well as passenger transportation. It is a concept that covers the movement, storage, handling, and transportation of cargo at the airport. Therefore, airports function as a hub for both passenger flights and cargo transportation. Airports carry out cargo transportation through large-scale cargo aircraft or cargo compartments of passenger aircraft. Airports allow logistics processes to be managed effectively (Nath & Upadhyay, 2024). Air transportation allows large quantities of cargo to be moved more rapidly, which can reduce inventory costs and make business processes more efficient. Airports provide faster cargo transportation than land or sea transportation. Air transportation allows urgent cargo to be delivered quickly in case of natural disasters or other emergencies (Bartle et al., 2021). This is especially critical for urgent medical supplies, spare parts, or other time-sensitive products. Cargo transportation facilitates the movement of materials at every stage in the supply chain. From producers to consumers, cargo transportation increases efficiency and optimizes material flow. Cargo transportation offers flexibility by using various modes of transport. This allows a variety of materials to be transported and delivered to different geographical areas. Cargo transportation is an essential part of today's global economy and trade, bringing a wide range of benefits to businesses and consumers (Florido-Benítez, 2023). In airport logistics, freight includes completing security and customs procedures. Safety measures are in place to prevent criminal activities and the transit of banned goods, and customs procedures ensure that goods are handled legal requirements. Therefore, effective freight management at airports is essential for maintaining supply chains, global trade, and the timely delivery of goods. To ensure an efficient and reliable cargo flow via the airport logistics network, collaboration between multiple stakeholders, including airlines, cargo handlers, customs officials, and transportation providers, is essential (Adenigbo,

2023). Sustainability goals are achieved through effective management of airport logistics networks involving many stakeholders.

## **2.3. Airport Operations**

Airport operations can be referred to as tasks that need to be conducted in the airside, landside, and terminal zones of the airport. Airport operations can be classified into three different groups, such as services to be provided for passengers, airport facilities services, ground and technical services. These groups are discussed in detail as follows.

### **2.3.1. Services to be provided for passengers**

Services to be provided for passengers are needed to enable a safe and efficient way through the airport (Bakır et al., 2022). These services can be considered as airline visibility & branding, staffing of an airport, proper coordination between the operations, catering, and customer services. When the airplane is parked at a contact stand, passengers can access the aircraft via a boarding bridge (Zhao et al., 2021). However, if the airplane is parked at a remote stand, passengers should be transported to the aircraft using a bus (Xiang et al., 2021). Thus, passenger buses are also considered fundamental ground equipment.

### **2.3.2. Ground Services**

Ground handling services at airports are provided by ground support equipment (GSE). The primary purpose of ground power units (GPUs) is to deliver power to airplanes while they are on the ground (Padhra, 2018). Portable GPUs typically feature a generator that is powered by a diesel engine. A different way of providing power to an airplane during turnaround periods is via external power sources or electrical contact stands (Padhra, 2018). In the contact stand, the aircraft may acquire electricity from the airport, often via a connection located under the boarding bridge. However, this limitation prevents the utilization on a larger scale once airplanes are not situated close to the terminal. GPUs can provide power to airplanes at remote stands as they are mobile fuel cell vehicles and provide an alternative to contact stands (Rivera et al., 2018). Once the GPUs are shifted to depend on renewable energy sources, there will be a decrease in emissions. Thus, airports are increasingly using hydrogen as a source of energy for their ground-based systems and operations,

such as GSE (Testa et al., 2014). Diesel engines and other fossil fuels have historically been used to power GPUs. However, due to technological advancement, hydrogen ground power units (HGPUs) powered by fuel cell technology are more of a possibility (Testa et al., 2014). Based on the study results, turnarounds account for the biggest hoard of emissions from airports, where the plane is powered by an APU or a diesel GPU (Padhra 2018). They also power the airplane while it is being loaded and refuelled. GPUs are also critical for getting aircraft in and out of flight for free, and saving on fuel and emissions where possible, by reducing the time main engines or auxiliary power units (APUs) need to run. Fuelling the emissions at the airport is GSE, which is largely responsible for what is emitted at airports. GSE refers to the various types of such articles, such as GPUs and refuelling trucks (Baroutaji et al., 2019). Decarbonizing the power supply and electrifying final energy demand are necessary to meet zero-emission targets.

HGPUs or battery-powered e-GPUs are the most viable alternative to reduce carbon emissions in airports. Each option carries its strengths and weaknesses. The hydrogen infrastructure limitations are related to the limitations of the HGPU. The e-GPU brings with it a challenge of higher energy costs, as the airport is more dependent on the grid (Xiang et al., 2021). Similarly, e-GPU poses another challenge due to the need for enormous battery sizes and long recharge times to power an airplane. Similarly, a HGPUs is a more promising option for wide-body aircraft due to the increasing potential for hydrogen as a sustainable aviation fuel. The next chapter will continue with the environmental, social, and economic impact of the airport operations, which is the main study topic of the thesis.

## **2.4. Environmental, Social, And Economic Impact of Airport Operations**

The concerning impact of airport operations on the environment, society, and economy has been highlighted, considering waste, noise pollution, GHG emissions, fuel and energy consumption, and environmental effects.

### **2.4.1. Energy and Fuel Utilization**

Ground services at airports can be energy dependent, and the sources can vary between diesel generators, grid electricity, and alternative sources like solar and wind energy systems (El Zein et al., 2025). Adoption of alternative sources for

ground service, renewable energy sources, improves the equipment efficiency, at the same time lowering its adverse impact on nature (Rahman et al., 2022).

Diesel generators require diesel fuel to make electricity. Normally, the generator needs a fuel supply when it is running (Mobarra et al., 2022). As fuel consumption/resources and emissions aim to decrease, initiatives are critical to reduce them with the aid of technologies such as hybrid systems or variable speed diesel generators, to accomplish our sustainable development goals. This should be followed by energy efficiency measures to minimize energy losses and to improve the efficiency of energy use in ground services (Martyushev et al., 2023). These measures entail energy-saving components deployment, power distribution system optimization, the application of smart control systems, and a switch to supply with renewable energy sources (Iddio et al., 2020). Some airports have set up wind turbines or solar panels to generate power by electrifying ground services. Reducing carbon emissions through the use of renewable energy sources, less reliance on traditional fuel-based power generation, and overall sustainability are some examples of positive impacts of the green hydrogen transition (Karmaker et al., 2022). The aviation sector has witnessed several studies focusing on improving GPU efficiency and evaluating their environmental footprint (Bahman, 2023). Specific fuel and energy consumption of a GPU is influenced by the design technology and operational procedures used by the airport. A range of techniques and technologies has evolved to ensure increased use of renewable energy resources. In this context, the environmental impacts of the use of these renewable energy sources are discussed in the next section.

#### **2.4.2. Environmental Impacts**

Ground services at airports have many environmental impacts since they contribute substantially to the carbon footprint of the aviation industry by increasing its overall emissions and environmental impact (Bahman et al., 2023). In addition to CO<sub>2</sub>, ground services emit nitrogen oxides and particulate matter (PM), all of which damage the environment. These pollutants can lead to adverse impacts on the health of surrounding communities. Airport ground services emit greenhouse gases that can increase heat in the atmosphere and contribute to climate change. Thus, utilizing

cleaner fuel substitutes and developing emerging technologies can minimize these negative impacts (Singla et al., 2021).

Use of maintenance and environmental guidelines, as well as employee education and training on the significance of responsible maintenance practices and environmental management, contribute to reducing the environmental footprint of airport ground services.

Governments and airport authorities can also contribute to achieving net-zero emissions by implementing legislation and regulations that limit airport ground services emissions and encourage the deployment of low-carbon technologies. Emission scenarios, effective implementation of carbon pricing policies, or grants and incentives for sustainable land support technologies and equipment will be needed to curb adverse environmental impacts (Perdana & Vielle, 2023).

Airport ground services require energy, and burning fossil fuels to generate that energy, it is capable generate higher carbon emissions and a higher overall energy footprint. With fossil fuel-based power, airport GSE (e.g., diesel generator) emits detrimental gases and greenhouse gases. Reducing greenhouse gas emissions from airport ground service is a target-driven approach that includes technological developments such as using cleaner alternative fuels and renewable energy sources in procedures. The next section discusses the impact of greenhouse gas emissions, noise congestion, and waste, which are the principal environmental impacts of airport ground services.

#### **2.4.3. Greenhouse Gas Emissions**

Greenhouse gas emissions significantly influence the transition to net-zero emissions in airport ground service, and various measures are being explored to address this challenge. These alternative fuels, such as biodiesel, electricity, hydrogen, and hybrid technologies, reduce fuel consumption or carbon emissions; however, noise pollution is a by-product of these vehicles and ground station operations (Al-Mohannadi et al., 2024). This can negatively affect the health and quality of life of airport employees, travellers, and the local population. Additionally, the functioning of ground service requires significant amounts of fuel like gasoline or diesel (Bahman et al., 2023). High fuel production can create both negative economic and

environmental impacts, such as increased airport operating costs and higher carbon emissions. Airport vehicles and ground service emit greenhouse gases, such as carbon dioxide and nitrogen, during operations. Therefore, alternative solutions are required to reduce carbon emissions for airport ground services. In this context, hydrogen, an energy carrier obtained from renewable sources, has an important share in reducing carbon emissions.

#### **2.4.4. Noise Congestion**

Airport ground services are a huge source of noise pollution. GSE can contribute to noise pollution, especially those operated by diesel generators, which cause disturbance to surrounding communities, airport personnel, and wildlife in the vicinity (Sreenath et al., 2021). The influence can be lessened using noise-reducing measures, like the establishment of sound isolation systems or the distance of ground service from impact areas.

#### **2.4.5. Wastes**

In this section, wastes, which are important pollutants, are discussed. Waste generated by ground services at airports includes the types of waste produced by daily activities as a result of aircraft service (Sebastian & Louis, 2021). Some common sources of pollution in air-ground services are solid waste, hazardous waste, fuel and emissions, noise pollution, and water pollution. Waste affects to a range of operations, including baggage, fuelling, maintenance, and general services at the airport (Tjahjono et al., 2023).

Solid waste includes ground handling, packaging materials, food and passenger waste, and maintenance waste. Various disposal and special processing processes should be applied to hazardous waste. Vehicles such as luggage tow trucks, service vehicles, and GSE generally run on fossil fuels, causing emissions and environmental pollution, and ultimately negative effects on human health. Ground vehicles and aircraft engines cause noise during their use, which negatively affects airport staff, passengers, and residents of the airport's surroundings. When chemicals are not used properly in ground operations, wastes that cause water pollution cause environmental pollution.

Various strategies can be developed to reduce the waste generated at airports. Establishing and promoting effective waste management systems with circular economy practices, separation, recycling, and waste-to-energy programs, developing procedures for hazardous waste, reducing the negative effects on the environment by adopting noise-reducing technologies, fuel efficiency, and emission reduction strategies should be developed. Encouraging the use of electric or hybrid vehicles or adopting and using alternative fuels are considered to be very effective strategies in reducing carbon emissions (Zein et al., 2025).

Decision-makers and managers can develop various strategies to reduce the environmental impact of airport ground services. Increasing the energy efficiency of ground services and optimizing load management systems to reduce overall energy consumption, regular maintenance of GSE to reduce emissions, one of the important strategies is to consider renewable energy alternatives to power airport ground equipment, production it cleaner with lower carbon alternatives (Gómez Comendador et al., 2019). It is the adaptation of technologies that enables the transition to energy sources in the processes. Therefore, one of the important goals is to invest in research and development for more environmentally friendly hydrogen technologies by developing units that use recyclable energy sources to achieve the net-zero emission target in airport ground equipment. In achieving this goal, airports, local and global authorities, research and development institutes, and universities should collaborate to minimize carbon footprint and other negative impacts through sustainable practices and technological advances (Eid et al., 2022). In this context, the effects of hydrogen and traditional technologies on airport ground service were discussed in the following chapter.



### **3. CHAPTER: THE TECHNOLOGIES FOR ANALYSIS OF ENVIRONMENTAL AND ECONOMIC IMPACTS IN AIRPORT SERVICES**

In order to decrease environmental impacts in airport ground services, several technologies have been employed. The technologies that are used to mitigate environmental effects have been investigated to find different alternative renewable energy sources. Renewable energy integration is a critical issue to decrease the environmental impacts of airport services. Since they are increasingly adopting renewable energy sources, such as solar panels, to produce clean and green energy. This renewable energy can be used to power various operations to eliminate dependency on fossil fuels as well. Applying these technologies and adopting sustainable practices in airport ground services leads to a decrease of greenhouse gas emissions, energy consumption, and environmental impact in airports.

This section provides an overview of prior studies conducted on hydrogen. First, an overview of the hydrogen supply chain is presented in a holistic way, with the hydrogen infrastructure consisting of the stages of the hydrogen supply chain. Then, applications and studies related to hydrogen application at airports are presented. The next sub-section focuses on the sustainable energy supply chain and applications for airport GSE. The section concludes with a discussion of the importance of hydrogen applications at airports for sustainability, identifying the research gap and detailing the motivation and contribution of this thesis to the literature.

#### **3.1. Existing Technologies**

Various possible solutions can be produced to decrease carbon emissions in airport operations management. Transition to hydrogen by using renewable energy sources is one of the promising technologies to achieve net-zero carbon emissions. Diesel-powered airport ground services cause significant carbon emissions. Examining the literature, the carbon emission amounts resulting from the use of diesel GPUs and diesel buses are presented. The yearly CO<sub>2</sub> emission of a diesel GPU used for 1.5

hours daily is 36.4 kg ( $\times 10,000$ ), and the CO<sub>2</sub> emission of a diesel GPU based on hours is projected as 664.84 kg CO<sub>2</sub>/h (Nuhn, 2023). The CO<sub>2</sub> emission of a diesel bus is projected as 2.68 kg CO<sub>2</sub>/l diesel (Carbon Footprint Report, 2023). The use of hydrogen technology obtained from renewable energy sources plays an important role in reducing these emerging carbon emissions. Therefore, hydrogen-based technologies are discussed in the following section.

## **3.2. Hydrogen-Based Technologies**

This section covers literature related to hydrogen-based technologies, considering hydrogen infrastructure, hydrogen value chain, diesel vs hydrogen supply chain, and hydrogen applications for the transition to net-zero emissions at the airport.

### **3.2.1. Hydrogen Infrastructure**

Because of the significant negative environmental impacts of fossil fuels, there is a growing awareness of renewable energy sources and energy transition to tackle the climate change crisis (Yue et al., 2021). Hydrogen is considered an important energy carrier to achieve this goal. The conversion from a fossil fuel-based economy to a clean hydrogen economy can be achieved by adapting hydrogen technology to processes globally (Agarwal, 2022). In addition, hydrogen is a technology that produces almost zero carbon emissions at the point of use by eliminating emissions (Siddiqui & Dincer, 2021). Therefore, hydrogen has a very important share in the energy conversion by reduction of the emissions, since the only by-product obtained from hydrogen to electricity production is pure water when produced by fuel cells (Rasul et al., 2022).

Therefore, hydrogen is a promising energy carrier that has the potential to decrease airport emissions. It is viewed as an environmentally benign substitute for fossil fuels because of its carbon-free and high energy content (Sharma et al., 2021). Additionally, it has the potential to reduce yearly CO<sub>2</sub> emissions. In addition, hydrogen technology can provide 30 million new job opportunities by 2050 (Mathiesen et al., 2015). Hydrogen has the potential to fuel more than 400 million automobiles, 15-20 million trucks, and 5 million buses by the year 2050 (Vodovozov et al., 2022), and this accounts for 20-25% of the transportation sector (Mostafaeipour et al., 2016).

However, the development of hydrogen energy systems requires significant efforts, such as sustainable resources, manufacturing techniques, end-use possibilities, storage, and delivery. Developing a hydrogen ecosystem is very important for achieving net-zero emissions, increasing adoption of the Sustainable Development Goals, and mitigating the global warming effect. Many research studies emphasize hydrogen-based technology to minimize environmental effects in airport logistics. Hydrogen technologies might greatly reduce environmental effects in airport ground logistics (Martinez-Valencia, 2021).

There are multiple ways in which hydrogen-based technologies could assist in sustainability:

- Zero Emissions: Hydrogen-based technology, such as hydrogen fuel cell vehicles and equipment, generates no emissions. Substituting traditional fossil fuel-driven vehicles and equipment with hydrogen-based alternatives in airport ground logistics can eliminate CO<sub>2</sub>, nitrogen oxides, particulate matter, and other harmful pollutants, leading to enhanced air quality and decreased environmental impact (Perdana & Vielle, 2023).
- Hydrogen-based devices improve local air quality by emitting water vapor as a by-product. This is crucial in heavily populated regions close to airports, as ground logistics operations can add to air pollution. Airports can decrease the release of harmful pollutants that impact human health and the environment by implementing hydrogen fuel cell vehicles and equipment (Singla et al., 2021).
- Hydrogen-based vehicles and equipment, like hydrogen-powered GSE, operate quietly in comparison to traditional alternatives due to noise reduction (Sreenath et al., 2021).
- Hydrogen can be produced by electrolysis by renewable energy sources, such as solar or wind power, making it easier to incorporate into renewable energy systems. Hydrogen fuel cell technologies are renowned for their exceptional energy efficiency, outperforming conventional internal combustion engines in terms of energy conversion rates (Bergero et al., 2023). In addition to reducing dependence on fossil fuels, storing energy as hydrogen enables it to power hydrogen-based vehicles, equipment, and infrastructure during periods

of high demand. Improved efficiency can result in lower energy consumption and associated GHG emissions (Yue et al., 2021).

- Because of their long-range operation, hydrogen fuel cell vehicles have longer driving ranges than battery electric vehicles.
- Infrastructure Development: The building of hydrogen fuelling infrastructure is necessary for the integration of hydrogen-based technologies in airport ground services. It is possible to design this infrastructure to support future growth and serve as a catalyst for the use of hydrogen outside of airport operations (Lida & Sakata, 2019).
- Displaying leadership: Adopting hydrogen-based technologies in airport ground logistics demonstrates an airport's dedication to sustainability and environmental responsibility (Logan et al., 2022). It can demonstrate leadership and inspire players in the aviation industry and other sectors to develop and implement hydrogen-based solutions.

Hydrogen-based solutions display potential for decreasing environmental impacts in airport ground services and promoting sustainability in the aviation sector, although they face obstacles including hydrogen infrastructure development, cost factors, and technical progress.

### **3.2.2. Hydrogen Supply Chain**

The hydrogen value chain encompasses the interconnected activities of production, storage, transit, and utilization, which should be seen as an integrated system. Thus, developing a hydrogen network depends on the form of hydrogen, gaseous or liquid, since hydrogen is a versatile energy carrier. Besides, storage becomes increasingly important due to the seasonality of solar and wind energy (Kebede et al., 2022). Therefore, it is crucial to establish a buffer to mitigate the impact of demand and seasonal changes, as well as outages (Li et al., 2020). The transportation methods employed in the hydrogen supply chain vary for the different types of hydrogen (Reuß et al., 2017). Hydrogen in liquid form can be carried via trucks, ships, or trains, while hydrogen in its gaseous state can be delivered through high-pressure pipes, railway tube cars, or tube trailers (Xie et al., 2024).

Production, storage, delivery, and end-use applications make up the core hydrogen infrastructure (DOE, 2002). There are several methods and resources for producing

hydrogen, such as nuclear, renewable energy sources like biomass and water, and carbon sources like coal and gas (Megía et al., 2021). Biomass processing, water electrolysis, and thermochemical cycles are examples of renewable sources (Chelvam et al., 2024). The great majority of sustainable hydrogen production processes use electrolysis, a vital carbon-neutral technique. Compared to the other techniques discussed, electrolysis is a more costly and intricate procedure (Qyyum et al., 2021). Deployment of the hydrogen requires economical and effective ways to distribute and transport hydrogen because of the challenges of low density, high diffusivity, and safety concerns. The quantities and delivery distances determine the transportation and storage options' economic feasibility. Large capital expenditures are essential to improve distribution infrastructures (Parolin et al., 2024). Because they reduce demand fluctuations and seasonal variations, storage terminals are crucial to the network. The type of hydrogen and the degree of production centralization influence the mode of transportation. Liquid hydrogen can be transported by ship, truck, or railroad. Pipelines, tube trailers, or railroad tube trains can all be used to transport hydrogen gas (Böhm et al., 2022). Liquid hydrogen transportation costs less per unit volume compared to gaseous hydrogen.

Fuel cells have the potential to power autos, heavy, and public transportation, according to the IEA (2015). Fuel cells are required to chemically transform hydrogen energy for end-use. Fuel cell electricity generation is a promising technology due to its high efficiency, low emissions, durability, and less noise (Das et al., 2017). Several challenges need to be addressed before fuel cells can efficiently substitute for existing uses for cost reduction, improved efficiency and reliability, optimal system sizes, and material safety (Yue et al., 2021).

The overall structure of the hydrogen value chain is presented in Figure 3.1 and discussed in detail in the following sections.

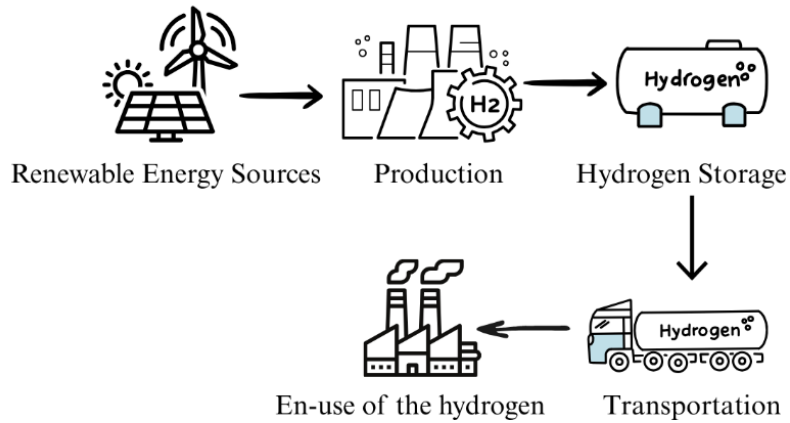


**Figure 3.1.** The general structure of the hydrogen supply chain

Source: Author

The detail of the stages of the hydrogen supply chain is discussed in the next section.

#### **3.2.2.1. Production**

Hydrogen as an energy carrier can be produced in different ways to be converted for use as a clean energy source (Hassan et al., 2023). Siddiqui & Dincer (2021) mentioned that hydrogen can be formed both through traditional production and a renewable energy-based pathway. To identify hydrogen as a clean energy carrier, it is necessary to examine all its environmental impacts throughout its entire life cycle (Acar & Dincer, 2020). Hydrogen types can be defined using different color-coding, which is based on their production methods (Schlund et al., 2022). According to the colour coding model, three basic types of hydrogen are distinguished: grey, blue, and green hydrogen. Besides, brown, pink, and turquoise hydrogen are also defined, which is shown in Figure 3.2. In general, grey hydrogen is produced using fossil fuels such as natural gas, steam reforming (Nakkeeran & Victor, 2025). Green hydrogen is formed from renewable energy sources such as wind and solar energy (Sarker et al., 2023). The term "blue hydrogen" describes hydrogen made from natural gas in which, with the aid of carbon capture and storage, roughly 90% of the carbon is captured (Yue et al., 2021). Green hydrogen supports environmental sustainability by indicating that the hydrogen is produced using renewable energy

sources, resulting in a low-carbon footprint. This approach aims to substantially reduce emissions compared to conventional airport ground services powered by fossil fuels. Additionally, the term 'green' aligns with broader green transition policies, sustainable aviation goals, and environmentally conscious airport operations. Thus, the use of 'green' emphasizes the technology's role in minimizing environmental impact and contributing to a low-carbon future.

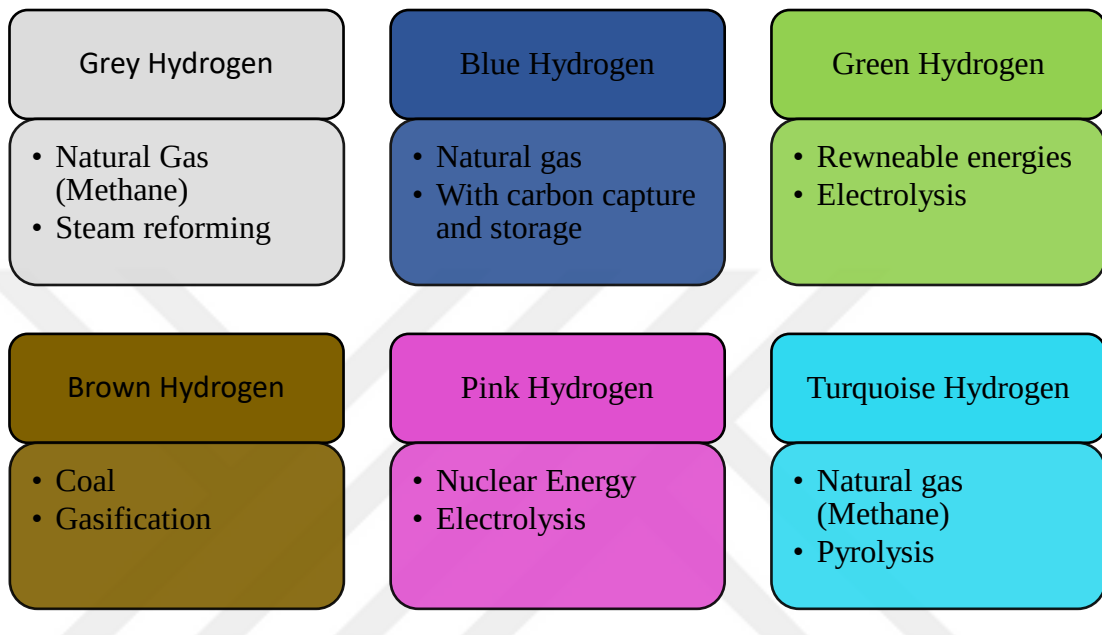


**Figure 3.2.** The type of hydrogen based on their production methods

Source: IEA, 2019

### 3.2.2.2. Storage and transportation of hydrogen

The hydrogen transportation and storage are also a significant step in the hydrogen value supply chain. Hydrogen energy storage provides a balance between energy supply and demand because time-scale fluctuations and seasonal changes alter energy supply and demand (Wang et al., 2024). Moreover, Zini & Dalla Rosa (2014) argued that surplus energy can be sold to the grid at high electricity prices because of the gain competitive advantages.

Similarly, Farahani et al. (2020) stated that the imbalances in electricity supply and demand can be addressed by fuel cell electric vehicles (FCEVs) through adopting much of flexible, reliable, and cheaper solutions. They were also able to show that

20% to 30% of the energy supply can be extracted from the storage. There is a classification of hydrogen storage as physical and chemical storage (Baroutaji et al., 2019). At present, hydrogen is generally stored in a pressurized gaseous state in metallic tanks, cylinders, containers, or underground (Rusman & Dahari, 2016). Cryogenic tanks are used to store liquid hydrogen, while hydrogen is stored in metal hydrides for solid hydrogen (Rusman & Dahari, 2016). End-use, security regulations, spatial constraints, volume, transportation, and expenses are all deciding aspects that can be utilized to characterize the sort of storage (Erdener et al., 2023). Transportation method also depends on similar considerations, including hydrogen availability, storage type, end use, distance, and degrees of scale. In this regard, transportation decisions for large-scale hydrogen applications (trucks, ship tanks, and pipelines) were reviewed by Klebanoff (2021). Nonetheless, important work continues to overcome the technical and economic hurdles of storing and shipping hydrogen.

#### **3.2.2.3. End-use of the hydrogen**

The last stage of the hydrogen supply chain is the utilization of hydrogen by numerous sources. Hydrogen is used in industry for a wide variety of purposes. Wulf et al. (2018) stated that the benefit of producing hydrogen from renewable energy is the advantages for FCEV in the transportation sector and the possibility to store surplus electricity. In addition to being used as a chemical substance in industry, it is also used to generate electricity. Acar & Dincer (2020) presented the feasibility and advantages of hydrogen fuel for transportation systems. Testa et al. (2014) conducted a study aiming to reduce airport air pollution by converting GSE vehicles to hydrogen fuel. Though hydrogen can be used for a variety of implementations, as mentioned, this paper is focused on the potential of hydrogen as a power source in the transport sector.

#### **3.2.3. Hydrogen Supply Chain vs Diesel Supply Chain**

This section includes a comparison of the hydrogen and diesel supply chain. Figures 3.3 and 3.4 illustrate the hydrogen and diesel supply chain, respectively.

The hydrogen value chain begins with the generation of hydrogen through the utilization of renewable energy sources. Hydrogen will be generated by electrolysis and stored in immense tanks. Hydrogen will be provided to the GPU and the

hydrogen bus from the storage tanks. The structure of the hydrogen supply chain is presented in figure 4.

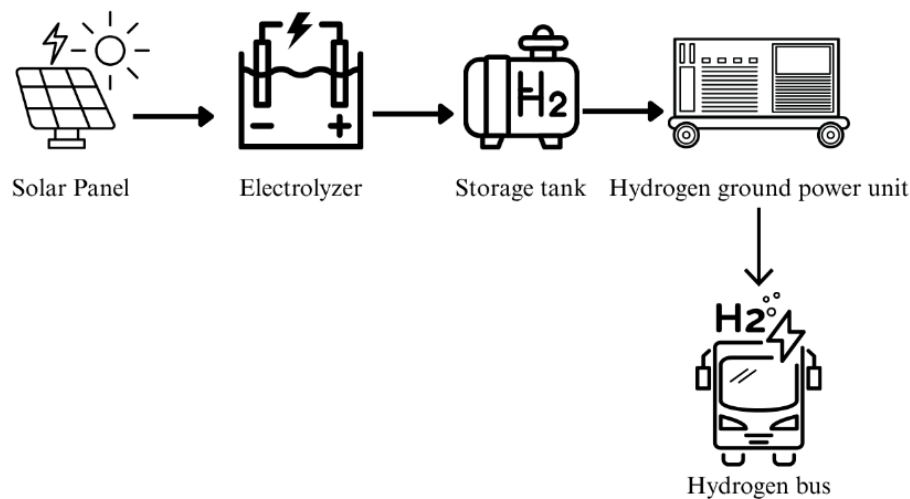


**Figure 3.3.** The structure of the hydrogen supply chain

Source: Author

The diesel supply chain begins with oil extraction. The diesel is transported via pipelines to the airport fuel station. This station will fuel diesel GPU and diesel buses. The structure of the diesel supply chain is indicated in Figure 3.4.

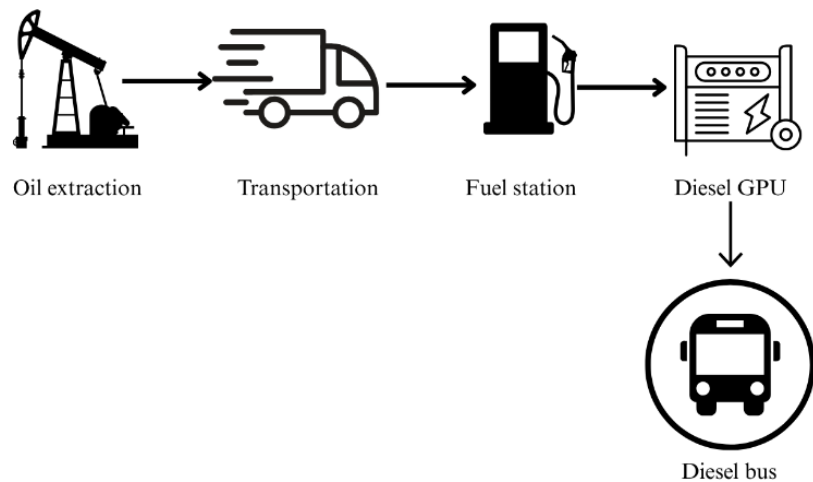


**Figure 3.4.** The structure of the diesel supply chain

Source: Author

After discussing the general structure of the hydrogen and diesel supply chain, the following subsection covers the airport practices of hydrogen.

#### **3.2.4. Airport Practices**

This section discusses the practices of hydrogen technology in airports. Hydrogen is recognized by the aviation sector as the energy of the coming years. Hydrogen and fuel cell technology may play many different roles in aviation (Baroutaji et al., 2019). Hydrogen has high performance in renewable energy storage, whereas fuel cells produce electricity to power the equipment (Zhang et al., 2016). Xiang et al. (2021) examined a hydrogen-solar-storage integration system for airport powering. Their case studies illustrated the advantage of hydrogen integration to the economy, technology, and environment. The results indicate a 67.29% reduction in emissions and a 41.6% reduction in total yearly costs. For the effective implementation of hydrogen use in airport ground handling services, it is necessary to establish an effective hydrogen value chain infrastructure for production, transportation and storage. In addition, the developed system allows the realization of not only short-term environmental and economic impacts but also brings long-term benefits. The potential of delivering electricity to both the airport vehicles and GSE through the use of fuel cell devices is currently being explored (Staffell et al., 2019). Diesel-powered ground services are a major contributor to pollution in and around airports.

In this context, hydrogen and fuel cells have the potential to significantly reduce carbon emissions from the aviation sector (Siddiqui & Dincer, 2021). Decarbonizing the aviation sector is receiving increasing attention given its current contribution of around 2.5% of global CO<sub>2</sub> emissions (Carlson et al., 2024). Thus, green hydrogen transition is required for the importance of airport decarbonization for curbing greenhouse gas emissions and reaching the targets set in the Paris Agreement of limiting global temperature rise to 1.5 degrees (Barke et al., 2020). Değirmenci et al. (2023b) discovered the potential application of hydrogen as a primary energy source in ground handling equipment.

In the next section, the environmental impacts of hydrogen fuel, which is considered a cleaner and more sustainable alternative to fossil fuels, are examined through airport ground services.

### **3.2.5. Environmental Aspects of Airport Hydrogen-powered Ground Services**

Hydrogen, which is formed from a renewable and low-carbon energy source such as wind, solar, or fossil fuels with carbon capture and storage, plays a critical role in reducing environmental effects such as noise pollution and greenhouse gas emissions (Martinez-Valencia, 2021). To address the impacts of the hydrogen transition, Değirmenci et al. (2023b) examine hydrogen replacement as an energy carrier in aviation and discuss several challenges of this transition, including the deficiency of supply chain studies that provide a comparative analysis with kerosene, which is currently the key fuel used in aviation. They emphasized the hydrogen supply chains for airports by creating various scenarios, such as environmental impact, cost, sustainability, and safety, in numerous supply chain scenarios have been examined to develop and recommend a broad approach to supply chain development. Besides, Undavalli et al. (2023) provided a comprehensive analysis of sustainable aviation fuels based on their operational performance and capability of the fuel system. They also analyzed hydrogen as a sustainable fuel in the aviation sector by considering future production capability to meet aviation requirements. In their systematic review of the literature, Bahman et al. (2023) reviewed previous studies that have measured the environmental impacts of airport operation and maintenance activities based on the Life Cycle Assessment (LCA) framework. In addition, Sharma et al. (2021) highlighted that environmental and economic aspects need to be considered for establishing hydrogen infrastructure. From the environmental point of view, there are several challenges related to the fossil fuel-based energy system, such as CO<sub>2</sub> emissions, air pollution, and depletion of energy sources. Thus, they analyzed the numerous aspects of hydrogen, including production, applications of the fuel cell, and storage. Furthermore, Hoelzen et al. (2022) aim to enable a holistic overview of efforts and evaluate the importance of an H<sub>2</sub> infrastructure for aviation. While the transition to hydrogen fuel for aircraft can be a long-term goal, in the short term, airport ground services, such as ground power units, buses, forklifts, and baggage tugs at airports can be powered by hydrogen technologies. Since ground airport services were responsible for ~6 Mt CO<sub>2</sub> emissions in 2020, and are growing rapidly. Real case examples of the transition to hydrogen have been achieved for the power forklift trucks through technologies developed by Amazon, Walmart, and Plug Power, and some European airports have also provided the transition to hydrogen in

their GSE (Bruce et al., 2020; Ling-Chin et al., 2024). In this context, the transition to hydrogen has many positive environmental effects, but this transformation requires significant investment. In this respect, in the following section, literature on the cost-benefit analysis of the transition to hydrogen, which is also the main purpose of this thesis, is presented.

### **3.2.6. Economic Aspects of the Hydrogen-powered Ground Services**

The economic features of hydrogen play a crucial role in facilitating the transition to hydrogen, as economic constraints are the primary obstacle to this change. The primary economic obstacle to the hydrogen transition is the initial investment cost, which includes expenses related to hydrogen production and infrastructure. Le et al. (2024) discussed that hydrogen technologies have various advantages, such as decreasing carbon emissions, increasing energy security, and accelerating a benign and sustainable energy transition. In this context, fuel cells powered by hydrogen technology are important for providing high efficiency and decreasing negative environmental impact. However, one of the significant vulnerabilities of this transition is the cost challenges, and it is still under consideration by researchers (Le et al., 2024).

According to Leaver & Gillingham (2010), a hydrogen-fuelled vehicle fleet provides economic advantages over a traditional fleet. However, even if 75% of the hydrogen is produced from fossil fuels rather than renewables, the change in savings will range from 65% to 25% when the price of oil rises to \$240 per barrel in 2030 and the carbon tax rises to \$90/tonne of CO<sub>2</sub>. Besides, Amoo & Fagbenle (2014) analyze the economic effect of hydrogen energy on the transportation and energy industries in Nigeria based on the effect of alternative and conventional fuels in these sectors. Jiao et al. (2023) examined the flexibility of integrated energy systems and hydrogen energy. They emphasized that integrated energy systems can provide potential solutions to improve efficiency and deal with current energy challenges. They implemented techno-economic analysis to enhance the performance of the energy system for transitioning to a low-carbon economy. Hydrogen can be an alternative energy carrier to fossil fuels by using it as clean energy in industrial processes. There is an increasing concern and studies on the hydrogen production approaches through solar, wind, and biomass gasification. Hauglustaine et al. (2022) analyzed

the differences between the environmental and economic effects of the hydrogen production methods of the various types of hydrogen. They highlighted sustainable policies both environmentally and economically by presenting benefits and challenges that vary by type of hydrogen. Testa et al. (2014) provide a comparative assessment, observing specifically at GSE vehicles equipped with proton exchange membrane (PEM) fuel cells, comparing emissions from diesel and hydrogen technologies. This study aims to introduce hydrogen technology at airports as a way to reduce harmful environmental impacts by educating airport stakeholders on sustainable environmental policy.

Besides, Van Dijk et al. (2024) investigate airport liquid hydrogen infrastructure potential, considering the Rotterdam-Hague Airport hydrogen-powered through-portage system. This paper suggests that trailer-based logistics is the most practical means of delivering liquid hydrogen to airports and storage and dispensing using these trailers. This method is critical for the development of hydrogen infrastructure and ensuring connectivity for the efficient operation of airport ground handling. However, storage and transportation can still pose significant challenges, according to Lu et al. (2025), cost-competitive hydrogen supply chains are required to accelerate hydrogen deployment and low-carbon economy. Consequently, this review shows that the main drivers of storage and transport costs are CAPEX and facility size.

Moreover, Asghari et al. (2025) analyzed market-based pricing and decision-making approaches and used the market equilibrium model to evaluate H<sub>2</sub> pricing and demand dynamics. This paper highlights the uncertainties and challenges of the transition to hydrogen as well as the actions that will guide both industry individuals and policymakers in establishing a competitive and sustainable energy market. It investigated how price-sensitive demand, environmental production methods, and the impacts of entering the market accord with competitive advantage. It aimed to increase the hydrogen ecosystem market share, profitability, and sustainability. This study shows that cooperative integration is the most successful strategy for growing sustainably. In addition, they emphasized that this technique could lead to green hydrogen production and achieve a market share of green hydrogen of 19.06%. The joint tariff agreements increase profitability in a complementary way, depending on the decision-making strategy, while at the same time, they help in reaching

environmental and financial feasibility objectives. They discussed strategic pricing mechanisms as a key to ensuring policies and sustainable growth of the hydrogen ecosystem. According to Qyyum et al. (2021), the current status of the hydrogen supply chain is still inefficient by leading to higher costs of green hydrogen production and higher capital costs of the system. The price of electrolyzer systems and the increased prices of the fuel cell and maintenance systems can be decreased by the establishment of an efficient hydrogen system (Qyyum et al., 2021). According to Testa et al. (2014), performing an accurate cost assessment is essential for the commercialization of hydrogen technology. Besides, Terlouw et al. (2022) also state that life cycle analysis and overall cost evaluations are commonly utilized to determine the economic and environmental benefits of hydrogen energy storage. They stated that airports must then assess the economic impact of transitioning to hydrogen technologies.

Although some studies review the costs of hydrogen production, little research focuses specifically on the financial costs of the green hydrogen transition in airport ground services. There is also an increasing realization of the need for the claim of cheap and sustainable alternative energy sources, such as electricity and hydrogen, to reduce the environmental impact of petrol and diesel-fueled GSE at airports. According to Glenk & Reichelstein (2019), gaseous green hydrogen becomes increasingly attractive for small and medium-sized applications, while within a decade, it will be competitive in cost for large-scale supply. Hoelzen et al. (2022) identified that hydrogen aviation fuel needs an ecosystem of economically supplying green liquid hydrogen infrastructure. Besides, Jiang et al. (2024) present a framework to evaluate the economic and environmental performance of four components of disparate fuel pathways, entire fuel lifecycles, and financial policies. According to the findings of the study, electricity and hydrogen may be the most viable options for cost reduction, technological development, and the clean transition. The study also examines whether financially-viable solar energy and hydrogen fuel cell-based structures will become feasible. Green hydrogen, which is a zero-carbon alternative to fossil fuels, is generated from renewable energy through electrolysis (Saqlain, 2023; Zaghdoud, 2025). This is achieved using a life cycle cost analysis proposed by Xie et al. (2021) or a net present cost analysis in a simulation model conducted by Singh et al. (2021). Farahani et al. (2020) developed a

simulation model estimating the costs of the various components required to utilize hydrogen FCEVs alongside the electrical grid to supply power to an office building. Oldenbroek et al. (2017) stated that renewable energy sources and FCEVs are considered reliable and cost-efficient energy systems in urban areas. They presented that the TCO of FCEVs is based on a passenger car, is substantially higher than that of all other vehicles (Cox et al., 2020). Gulotta et al. (2023) performed a bibliometric analysis to assess the impact of technologies on the life cycle sustainability of fuel cells from green hydrogen. To identify the environmental and economic impacts of hydrogen deployment, the study has conducted an overview of LCA and LCC studies.

Moreover, the socioeconomic impacts arising from this transformation were studied by Sharma et al. (2023), and critical areas such as storage, mixing, and risk assessments that need to be addressed in the future were highlighted.

In addition, Testa et al. (2014) conducted a comparison of the expenses associated with a diesel GPU and HG. Their research suggests that HGPUs are more expensive than GPUs, even if there have been improvements in PEM fuel cell technology and the generation of gaseous hydrogen using electrolyzers at airports. Although their study offers a cost analysis of GPUs and HGPUs, the utilization of steam methane reforming for hydrogen production restricts its ability to reduce carbon emissions in airport operations. Bergero et al. (2023) examine the strategies to attain net-zero emissions goals and analyze the difficulties and possible remedies for decreasing carbon emissions in the aviation industry. This study found that up to 61% and 27% of aviation emissions could be avoided by reducing demand for air travel and improving the energy efficiency of aircraft, respectively. This reduction is in line with the airport's 2050 emissions targets. Bergero et al. (2023) mention that a transition to sustainable fuels, reduction of demand, and implementation of energy efficiency measures will be critical to achieve net-zero emissions.

Additionally, Dray et al. (2022) explore multiple pathways for achieving net climate neutrality for aviation. They also analyze the costs and emissions associated with achieving this goal. Focusing on the possible decrease in carbon dioxide emissions and the link to the savings impact at the airport, this analysis investigates productivity improvements and the economic implications. Zhou et al. (2022) discuss

the importance of sustainable airport energy systems and flexibility for hydrogen-based renewable grid energy storage. They studied energy structures, power supply networks, energy migration models, and decision-making techniques. Electric power is used in aviation energy systems to reduce carbon emissions. Transitioning to renewable energy systems is critical to achieving this goal. Their findings suggest that using renewable energy effectively is an important precondition for installing carbon-neutral energy systems at airports. This emphasizes the necessity of establishing sustainable energy practices and efficiently using resources (Zhou, 2022). To increase the efficiency of hydrogen production, Anser et al. (2025) stated that developed an innovative optimization approach considering the entire hydrogen supply chain, i.e., production up to efficient storage and distribution, especially with renewable sources. This model aims to improve the hydrogen distribution infrastructure and lower costs, and reduce the environmental impact.

According to Sun et al. (2025), the inefficiency of electrolysis technologies used so far is among the barriers to widespread use. According to the study, the efficiency of current technology is between 60% and 80% with production costs of around \$5 per kilogram. Under this condition, hydrogen can be assumed to be a viable energy carrier by improving the efficiency up to 80% and reducing the price below \$2/kg (per H<sub>2</sub>). Incentive programs are of great importance for this transformation. The study and development of new hydrogen storage technologies will also require incentives so that they can act as a globally applicable and widely used technology. On the other hand, supportive regulatory frameworks that improve energy security, cost-effectiveness, and scalability should also be promoted. Hydrogen innovation and deployment depend on regulations, standards, policies, and state-of-the-art technologies. Securing economic viability, successful storage and transportation strategies, energy security, and reliability are the main challenges for hydrogen deployment (Kamran & Turzyński, 2024). Kaheel et al. (2025) analyzed the impacts of green transformation in developing countries using a new decision support system that combines multi-criteria decision making and decision tree analyses to best respond to hydrogen production decisions.

The developed decision support system aims to evaluate different scenarios regarding demand and supply, cost and profit margins, and the policies and environmental effects to balance economic viability and ecological responsibility. A

comparative carbon footprint for conventional production methods is presented by Sabbani et al. (2025). They evaluated the requirement of investigating the fuel cell's operational, technical, environmental, and economic concerns. The review research discovered the technical aspects, based on the fuel cell performance, and applications. The environmental impact of hydrogen production via electrolyzer is quantitatively evaluated. The economic impacts of fuel cell technology deployment are analyzed considering market growth, forecasts, and investments into fuel cell systems. Dissanayaka et al. (2025) present a transition management approach to scrutinize key sustainable strategies for developing a low-carbon economy in Australian airports. According to the result of the study, five key strategies for this green transition can be described as collaboration with stakeholders, assessing emissions from aircraft ground equipment, adopting the Airport Carbon Accreditation program, evaluating air pollutant emissions directly released from airport sources, and sustaining air pollutant emissions. Besides, they highlighted that carbon emissions related to air transportation are caused by infrastructure, vehicle traffic sources, ground handling sources, and aircraft. To reach the net-zero emission target by 2050, airports should adopt these strategies into their environmental strategies. Roucham et al. (2025) conducted bibliometric research in 2018–2022 for green hydrogen and renewable energy fields. They presented emerging trends and key drivers of this green transition. The findings show significant progress regarding the hydrogen and renewable energy domain, averaging 93.56 %. The focus of the research has evolved from technical studies to the investigation of social and economic conditions. The study also stressed the importance of applying existing storage efficiency methods, integrating research with current energy infrastructures, managing risk, and developing policies to enhance efficiency in the hydrogen transition, and to emphasize the importance of energy security for the future. Creative research, global partnerships, and supportive legislative frameworks play a major role in achieving green hydrogen as a clean energy solution through sustainable transition progress. Hybrid systems that incorporate hydrogen infrastructure into existing energy infrastructures, optimize resource use, and increase system resilience can help to bridge the gap between these technologies (Li et al., 2023).

Based on the literature, it can be said that the transition to hydrogen is still in its early stages for developing countries in particular. Different studies have examined the green hydrogen transition from the three main dimensions of sustainability: environmental, social, and economic. Although several studies, especially the ones mentioned above, have examined the costs of hydrogen production for the green hydrogen transition, which is considered a significant investment, very few studies focus on the financial costs of the green hydrogen transition, especially in airport ground handling services. However, there is a growing realization of the need for affordable and sustainable alternative energy sources such as hydrogen to reduce the environmental impact of diesel-fuelled ground services at airports. Therefore, this study contributes to the literature by performing a cost-benefit analysis of the green hydrogen transition in emerging countries.

After the comprehensive economic aspects of the hydrogen-powered ground services analysis, the current status, role, strategies, and future position of hydrogen in Türkiye are presented in detail in the next section.

### **3.2.7. Hydrogen Transition: Türkiye's Current Status, Strategies, and Future Perspectives**

Green hydrogen, which is produced from renewable energy like solar, wind, hydropower, and bioenergy, is seen as a main energy source to achieve the global net-zero target stated by the Paris Agreement, aiming to achieve the current range of target net-zero by 2050 and reducing carbon emissions by 45% before 2030. New geopolitical realities, increased price, decreased production cost, and the energy crisis influenced by the COP27 net-zero targets would lead to steady demand growth globally for hydrogen post-2030. The adoption and development of hydrogen in Türkiye are increasing due to the augmented level of awareness of the low-carbon economy strategies and clean energy transition. The historical development of hydrogen in Türkiye has accelerated in recent years, and important steps have been taken by regulators and policymakers. Türkiye's perspective on hydrogen technologies has improved with energy policies, green transition strategies, and international collaborations. The steps taken by Türkiye regarding hydrogen technologies are summarized.

In the 2000s, limited researches were focused on renewable energy sources and the potential of hydrogen. Fundamental studies on hydrogen production and usage increased during this period. Different universities and research institutes in Türkiye have conducted studies on hydrogen production technologies. Besides, various theoretical studies have been carried out on the usability of hydrogen as an energy carrier. In the 2010s, with the growing potential of hydrogen as a green energy source in the world, Türkiye has also started to proceed towards hydrogen technologies. The growing use of renewable resources such as solar and wind energy has also been seen as a significant potential in the production of hydrogen. Figure 3.5 presents solar energy capacity in Türkiye from 2008 to 2023 (in megawatts). During this period, Türkiye has set national goals that include the production and use of hydrogen to increase the use of renewable energy resources. Since hydrogen can be produced through electrolysis, especially with electricity obtained from wind and solar energy, the potential application areas related to hydrogen began to be discussed in 2010.

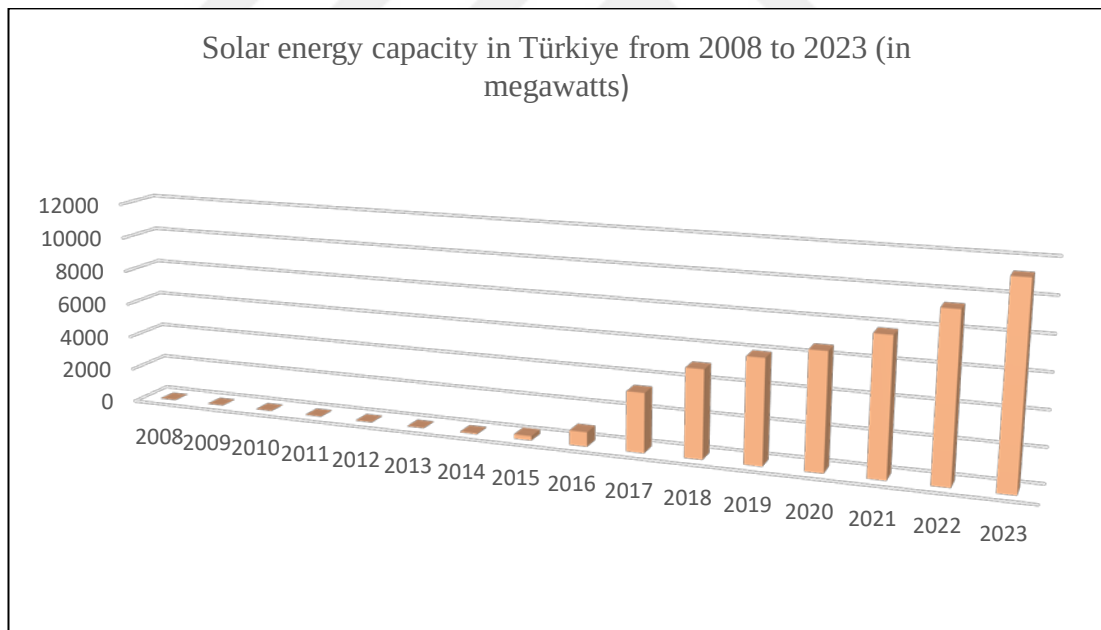


**Figure 3.5.** Solar energy capacity in Türkiye from 2008 to 2023 (in megawatts)

Source: Statista, 2025

Various pilot projects were launched in Türkiye, including hydrogen-powered vehicles and small-scale energy storage systems. Besides, international collaborations and strategies began to be developed in 2020. The National Hydrogen Strategy was launched in 2021, and the role of hydrogen in the energy sector was revealed within the framework of this strategy. Türkiye's green hydrogen production is considered to have great potential, especially in regions where renewable energy capacity is increasing. Türkiye has increased its cooperation with the European Union on hydrogen projects on hydrogen production and infrastructure in line with Europe's hydrogen strategies (SHURA, 2021b). Green energy projects in Europe are expected to progress Türkiye's hydrogen market and its applications of it. In the early 2020s, industrial establishments and universities in Türkiye started to invest more in hydrogen technologies, and the public sector has also started to encourage projects in this area. In particular, the Hydrogen Energy Platform has been established, and knowledge sharing and cooperation between stakeholders of this transition have been increased. When it comes to the future of Türkiye's hydrogen sector, studies and research regarding hydrogen technologies will increase rapidly in parallel with technological developments worldwide after 2025 (SHURA, 2021a). Towards the end of the 2020s, Türkiye is expected to focus more on new technologies, especially renewable energy, in hydrogen production. For this aim, policies and incentives regarding the production and use of green hydrogen will further strengthen the role of hydrogen in Türkiye's energy strategy. Priority areas such as air and maritime transportation, cement, and the ceramics industry for the use of hydrogen are determined, and strategies should be developed in these areas (SHURA, 2021b). Türkiye is focusing on developing the necessary infrastructure for hydrogen to be used in these energy-intensive sectors.

Within the scope of the Green Deal in Europe, numerous regulations and strategies have been put forward, such as the European Climate Law, the EU Industrial Strategy, the European Hydrogen Strategy, and the EU Energy System Integration Strategy. These strategies aim to achieve the Green Deal goals by subsidizing the infrastructure for clean energy technologies, including hydrogen, and developing alternative structures for fossil fuels. Thus, the preparation of the regulatory agenda and the development of the hydrogen infrastructure have been carried out effectively. In addition, it addresses strategies that will encourage investments by regulating

bureaucratic procedures (Vivanco-Martín & Iranzo, 2023). In this context, current and future strategies in Türkiye have been discussed. Türkiye is expected to become a leading green hydrogen economy in this context, according to the National Hydrogen Technologies Strategy and Roadmap published in January 2023. Demand for green hydrogen in Türkiye is expected to surpass 1-1.5 Mt (million tons) by 2030 and 2-2.5 Mt by 2050 (PwC, 2023). Energy stakeholders should develop strategic market entry plans for the country's emerging hydrogen economy, supported by comprehensive analyses of market potential, feasibility studies, and in-depth assessments of competition to identify and implement innovative business models effectively (The Republic of Türkiye Ministry of Energy and Natural Resources, 2023). Thanks to technological developments, hydrogen production costs are expected to fall to competitive levels in many countries by 2030 and beyond. Green hydrogen demand is expected to increase rapidly, especially after 2030 (The Republic of Türkiye Ministry of Energy and Natural Resources, 2023). Green hydrogen studies, projects, and investments have increased with various policies and regulations to achieve a zero-carbon emission target in Türkiye. In this context, pilot projects were aimed to be introduced in Türkiye. According to the protocol signed on February 15, 2022, work was initiated at the Enerjisa Production Bandırma Power Plant for the first green hydrogen production and use in Turkish industry. In addition, Eti Maden, Tübitak-MAM, and Aspilsan Energy are involved in the project as important stakeholders in green hydrogen deployment. Within the scope of Green Hydrogen Strategies, TÜPRAŞ aims to produce green hydrogen with solar energy in Batman and Kırıkkale (in the planning phase) in 2025, while planning to sell hydrogen to the logistics and transportation sectors. In August 2022, TÜPRAŞ acquired Entek Energy, which currently with a capacity of approximately 450 MW, and applied for a preliminary license for an additional 1 GW of capacity by 2030. Another initiated project is the GAZBİR-GAZMER Hydrogen Project. Within the scope of this project, an R&D laboratory was established in 2021 for the testing and management of the process of mixing hydrogen into the natural gas pipeline. According to recent studies, up to 20% of hydrogen can be incorporated in pipelines. The Turkish Ministry of Energy and Natural Resources launched the National Hydrogen Technologies Strategy and Roadmap in January 2023, placing Türkiye among the foremost green hydrogen economies on a global scale (The Republic of

Türkiye Ministry of Energy and Natural Resources, 2023). The published strategy outlines significant strategic priorities such as electrolyser capacity targets until 2053, reducing costs in green hydrogen production, R&D support for local resources, partnerships, green hydrogen and ammonia exports, priority green hydrogen sectors, and hydrogen transportation and distribution. Türkiye's national hydrogen strategy sets goals to achieve 2 GW of hydrogen production capacity by 2030, expand to 5 GW by 2035, and reach an impressive 70 GW by 2053.

In summary, while hydrogen was considered only in narrow areas such as energy production and transportation, currently, Türkiye has started to determine strategies for the development of hydrogen as an important energy source. Thanks to advancing technology, increasing environmental awareness, and global cooperation, hydrogen is becoming an economically and environmentally critical energy source for Turkey. Türkiye's Roadmap of the green hydrogen transition, which is presented in Figure 3.6, includes short-term, medium-term, and long-term targets, considering different hydrogen production methods, market potential, technological developments, infrastructure investments, and policy supports.

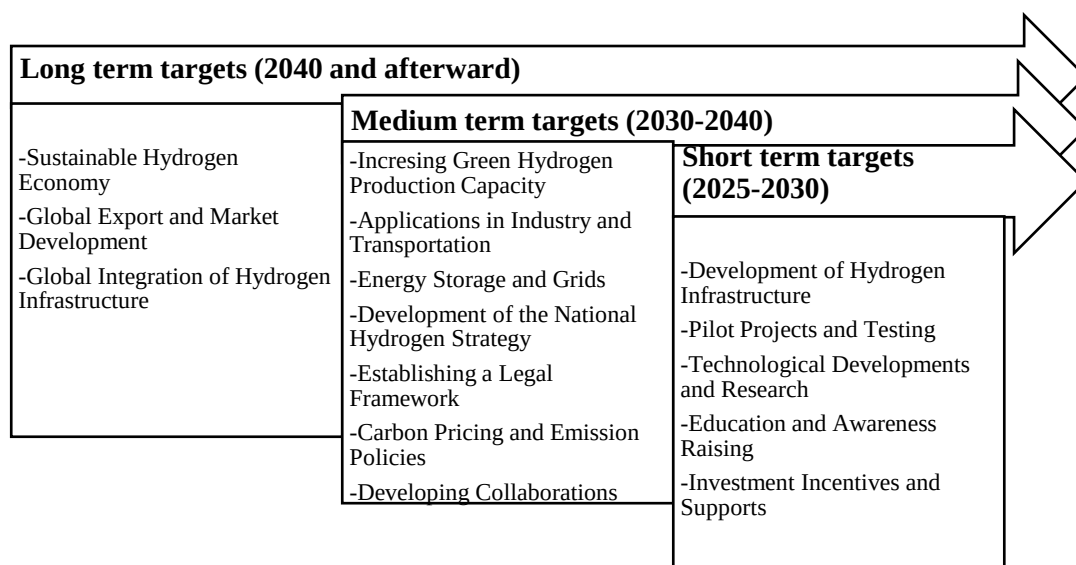


**Figure 3.6.** Roadmap of the green hydrogen transition in Türkiye

Source: Author

In the next section, short-term, medium-term, and long-term targets for the transition to green hydrogen are presented in detail.

### **1. Short-Term Targets (2025-2030):**

The short-term target is summarized as follows.

- **Infrastructure Development** is the development of the necessary infrastructure for hydrogen production by producing domestic electrolyser technology, initiating pilot projects for hydrogen production with renewable energy, and establishing the first hydrogen storage and transportation infrastructures.
- **Pilot Projects and Trials:** initiating hydrogen-powered vehicles, industrial applications, and small-scale energy storage projects.
- **Technological Developments and Research:** Accelerating research and development studies, investigating new technologies that reduce hydrogen production costs.
- **Education and Awareness:** Organizing education and awareness campaigns on hydrogen at the public and industrial levels, initiating research programs on hydrogen and green energy at universities.
- **Investment Incentives and Supports:** Encouraging public and private sector collaborations for hydrogen production, providing financial incentives, including tax, subsidies, and research funds.

### **2. Medium-Term Targets (2030-2040):**

The medium-term target is discussed as follows.

- **Increasing Green Hydrogen Production Capacity:** Developing renewable energy (wind, solar) infrastructure and using it in hydrogen production, establishing hydrogen production facilities nationwide.
- **Application in Industry and Transportation:** Creating infrastructure for hydrogen to have a wider application area in the industry and transportation sectors, especially the use of hydrogen in heavy transport vehicles and industrial processes. The integration of hydrogen into the industry and transportation sectors will be an important step. Investments can be made for hydrogen-powered vehicles, machines, and facilities in these sectors.

- **Energy Storage and Networks:** Hydrogen has the potential to solve the energy storage problem of renewable energy systems. Infrastructure investments are critical for this transition.
- **Implementation Stages of the National Hydrogen Strategy:** Full implementation of the national hydrogen strategy. Creating incentives, regulations, and investment plans in line with this strategy.
- **Legal Framework:** Creating new regulations, permits, and safety standards for hydrogen production, use, and transportation, developing national and international standards that will ensure the safety of the hydrogen infrastructure.
- **Carbon Pricing and Emission Policies:** Emphasizing the potential of hydrogen to reduce carbon emissions; encouraging the use of hydrogen in line with carbon emission targets through mechanisms such as the carbon trading system and carbon tax.
- **International Collaborations:** Increasing collaborations with hydrogen markets in Europe and worldwide, strengthening Türkiye's role in the hydrogen market in the international arena, and establishing partnerships with Europe and other countries for hydrogen projects.

### **3. Long-Term Goals (2040 and afterward)**

The long-term objectives for the transition to hydrogen are presented below.

- **Sustainable Hydrogen Economy:** Türkiye is becoming a major player in hydrogen production and use worldwide, with large-scale production of hydrogen to achieve carbon neutrality targets and widespread use in energy, industry, and transportation.
- **Global Export:** Increasing Türkiye's hydrogen exports, especially by exporting green hydrogen, Türkiye is assuming a leadership role in the hydrogen economy.
- **Infrastructure Integration:** Integrating Türkiye's hydrogen network with global energy networks, providing both energy production and storage capacity for hydrogen.

#### **3.2.8. Research Motivation and Contributions**

The International Air Transportation Association (IATA) aims to decrease CO<sub>2</sub> emissions in the aviation industry by 50 % by 2050 (IATA 2017). In addition, IATA

has concluded that the most effective approach to decrease the industry's environmental impact can be achieved with the transition to sustainable liquid fuel since conventional fuel efficiency improvements alone are not enough to achieve this industry's goals of reducing carbon emissions, and alternative options such as transitioning to hydrogen-powered systems require extensive changes to the industry's infrastructure (IATA 2017). Ground operations in airports need to address environmental challenges to create sustainable solutions; nevertheless, environmentally friendly infrastructure necessitates substantial investments, considering the economic aspects of this transition. According to Frieden and Leker (2024), a structured legal framework should be developed towards a green hydrogen ecosystem and improved production of green hydrogen support, required infrastructure, and cost reduction. In align with this, green hydrogen strategy is a key consideration in developing low-carbon emissions.

The IRENA (2020) report stated that well-structured procedures and guidelines should promote investment in these technologies to enable lower production costs and the required infrastructure. Even though the cost of production for renewable technologies has declined meaningfully lately, green hydrogen is still expensive compared with the price of hydrogen from fossil fuels. To gain a competitive advantage, the partnership and collaborative research projects between policy-makers, industries, universities, and research institutions should be developed to provide a common solution for increasing innovation and investment in renewable energy, and develop policies and strategies.

Kumar et al. (2024) underline hydrogen's potential as a cleaner aviation fuel. They discuss using hydrogen to achieve low carbon emissions and higher efficiency compared to conventional fuels. This review emphasizes hydrogen's application in aircraft, identifying trends and obstacles to this transition. In this context, production cost is the core constraint in the deployment of green hydrogen. The deployment of hydrogen as a viable alternative in ground operations at airports presents a promising path for mitigating noise and emissions, while concurrently enhancing operational efficiency (IATA, 2022). Kovač et al. (2021) and Osman et al. (2022) argued that hydrogen is an environmentally friendly method that uses only renewable energy for a sustainable energy transition. Still, it requires sustainable policies and a significant amount of capital. They stated that the costs of renewable energy infrastructure and

electrolyzer systems cause high production costs, thus studies should be increased to choose between hydrogen production methods, find appropriate economic solutions, and make them advantageous. Therefore, in this replacement, market regulations are also crucial to deal with the entry barriers, significant investment, and encouraging the usage of novel hydrogen technologies. In this context, governments' incentives, subsidies, taxes, grants, and public procurement policies have a direct impact on balancing the higher costs of hydrogen adoption and the struggle with market demand and the price of hydrogen products (Shan & Kittner, 2025). Moreover, ground services account for a significant portion of carbon emissions from non-flight operations. Since they operate within a limited area and along defined routes, they provide a controlled and practical testing environment for the transition to hydrogen. Hydrogen-powered buses and GPUs offer multifaceted advantages in terms of technological feasibility, operational efficiency, infrastructure integration, and alignment with sustainability goals. Therefore, they represent key application areas for green hydrogen transition at airports. Focusing on these vehicles enables a more manageable technological shift while delivering impactful outcomes. Thus, there is a need for various studies that discuss the optimization of the environmental and financial balance of hydrogen deployment, and research continues to investigate ways to balance environmental sustainability and economic performance (Pastore et al., 2022). Thus, it is significant to emphasize the importance of this transition as economically feasible. In this thesis, the aim is to explain the following research objectives:

Research objectives:

1. To build a simulation model to provide a cost-benefit analysis of the deployment of hydrogen at the airport ground services
2. To provide implications to industry, local, and global authorities in creating hydrogen solutions in airport ground operations.

Consequently, this thesis proposes the following research questions:

RQ1. How to model the economic impacts of the hydrogen transition in the airport ground services to reach the net emissions target?

RQ2. What are the learning points and barriers to adaptation to hydrogen at the airports?

Towards a decarbonized system is required to achieve sustainable development goals, especially SDG-7 Affordable and Clean Energy, SDG-12 Responsible Consumption and Production, SDG-13 Climate Action, and SDG-17 Partnerships for the Goals, according to the Paris Agreement (United Nations, 2015). Figure 3.7. illustrates the research motivation and the relationship between the Sustainable Development Goals. Especially, Research Motivation and the Relationship Between SD7, which is presented in Figure 3.8, has a significant importance for this transition.

The aviation sector is currently accountable for 3% of the total CO<sub>2</sub> emissions, increasing by 6% annually. Transition to electricity as the primary power source using hydrogen-powered ground operations in airports (Brelje & Martins, 2019).

Ground services in the airport are considered critical, energy-demanding equipment. Thus, hydrogen is a significant energy carrier for the transition to the net-zero emission target in the airport, and therefore, it is becoming increasingly prominent in the ground handling operations in the airport. Since there are several significant reasons for hydrogen, they are presented as follows.

- ✓ Clean energy pathway for powering the ground services
- ✓ Eliminating CO<sub>2</sub> and NO<sub>x</sub> and generating noise pollution (Testa et al., 2014).
- ✓ Charging hydrogen fuel cells is much faster than normal batteries, which reduces equipment downtime.
- ✓ Hydrogen-powered ground handling equipment is expected to become cheaper than diesel-powered ones, due to longer lifespans and lower maintenance costs (Testa et al., 2014).
- ✓ Paves the way for new employment opportunities



**Figure 3.7.** Research Motivation and the Relationship Between Sustainable Development Goals

Source: IEA, 2019



**Figure 3.8.** Research Motivation and the Relationship Between SD7

Source: IEA, 2019

Therefore, this study aims to contribute to the 2030 and 2050 decarbonization targets of airports. This study makes a unique contribution to the literature on the environmental, economic, and social assessment and analysis of hydrogen solutions for achieving net-zero carbon targets in airport ground equipment. Furthermore, it paves the way for further analysis of the adaptability, repeatability, scalability, cost, and learning pathways and barriers to hydrogen deployment.

Based on the literature review discussed in section 3, it can be concluded that there is a need for research to analyze the economic impacts of the deployment of hydrogen in the airport support equipment, considering the economic advantages. This study aims to fill this research gap by exploring the economic feasibility of substituting

hydrogen in the ground services. This analysis enables valuable insights for decision-makers and stakeholders by presenting the potential consequences and benefits of the hydrogen transition.

The main contribution of this thesis can be summarized as:

- Conducting a comprehensive economic analysis to investigate the cost-benefit analysis of the hydrogen deployment in the ground services
- Providing deep insight, the impact of several factors on the costs-benefits of hydrogen transition using a simulation model
- Presenting transition pathways for the regional airport and proposing practical recommendations for decision-makers and stakeholders in this transition





## 4. CHAPTER: METHODOLOGY

After conducting an extensive literature review, an analysis of the processes within the hydrogen transition is undertaken. Thereafter, an investigation of the technical characteristics and applicability of transition to hydrogen solutions for ground services. Based on the analysis of the processes within the hydrogen transition and system analysis, data gathering for the hydrogen deployment in the airport ground services is conducted. After obtaining data, a simulation model is developed by Python. The model is tested, and the simulation is run. Different scenarios are developed, and performance analyses are conducted for alternative scenarios. Based on the output of the simulation model, a cost-benefit analysis is conducted. Finally, the best scenario is selected. The methodology section examines simulation analysis for the green hydrogen transition in the ground services. The framework of the methodology is presented in Figure 4.1.

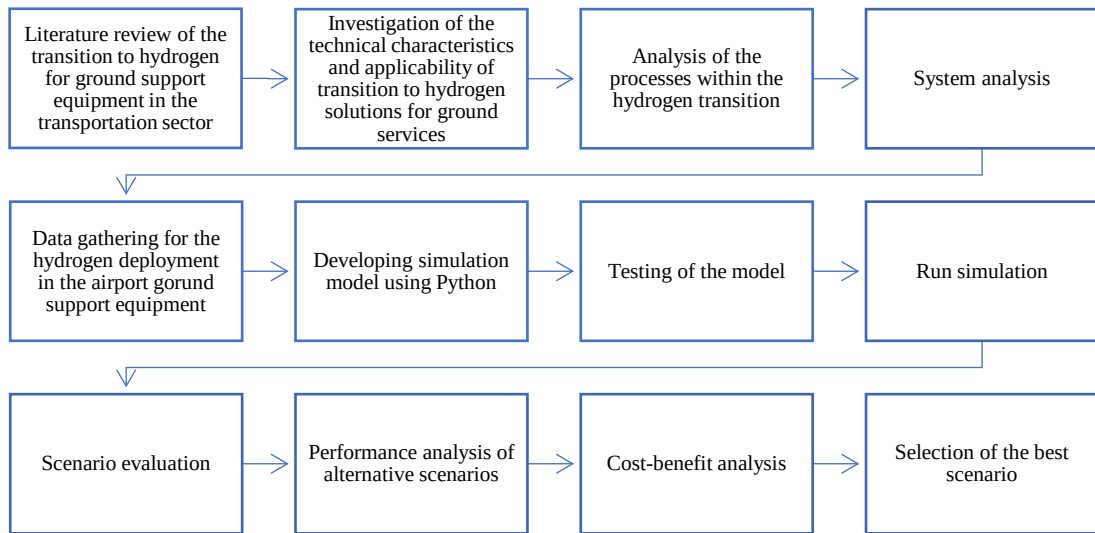


**Figure 4.1.** Framework of the methodology

Source: Author

The methodology section consists of two parts: simulation and cost-benefit analysis. A simulation model is developed by using Python to determine and implement the demand and supply of the energy system at the airport setting. A cost-benefit analysis was performed using the simulation outputs, including energy production and consumption for the energy devices. According to the results of the study, both the increase in the number of hydrogen ground services and the impact of the different scenarios were evaluated with what-if scenario analyses. Next, the model development process is discussed in detail, considering research design, model development, data collection, and implementation.

#### **4.1. Study Design and Simulation Model Analysis**

In the development stage of the model, the assumptions for the developed simulation model are first summarized, and then the model parameters are presented.

The subsequent assumptions are proposed in the model:

- Due to the life cycle of the energy equipment in the model being 25 years, and thus the life cycle of the project is determined as 25 years.
- The model considers the installed solar park to be connected to the grid and the electrolyzer as a system without potential conversion losses. It is expected that losses will be eliminated with the development of these systems, with technological developments and regulations in the coming years. The efficiency of converting alternating current (AC) grid electricity to direct current (DC) varieties is between 95% and 98%, but the losses associated with this conversion process are not included in the model.
- Hydrogen produced over the system's needs is sold directly to local consumers at market price. Excess solar energy is sold back to the grid.
- Demand estimation was based on the analysis of the current distribution of flight schedules.

The general structure of the system in the simulation model and the data collection phase are discussed in the following section. The data collection phase was conducted using various sources, such as literature, national and international reports, and interviews. Detailed information is detailed in the subheadings.

The general supply and demand structure of the airport is presented in Figure 4.2. According to the Figure 4.2, energy is provided from the grid or PV and used in the daily regular operations of ground services at the airport. The amount of energy produced from PV is calculated by solar irradiance and temperature. The energy demand of ground services is determined by the frequency of flights. The energy obtained from the grid causes financial costs and carbon tax imposition due to carbon emissions released. PV is connected to the electrolyzer to avoid energy losses. The microgrid transfers the electricity acquired from the national grid to the electrolyzer to produce hydrogen.

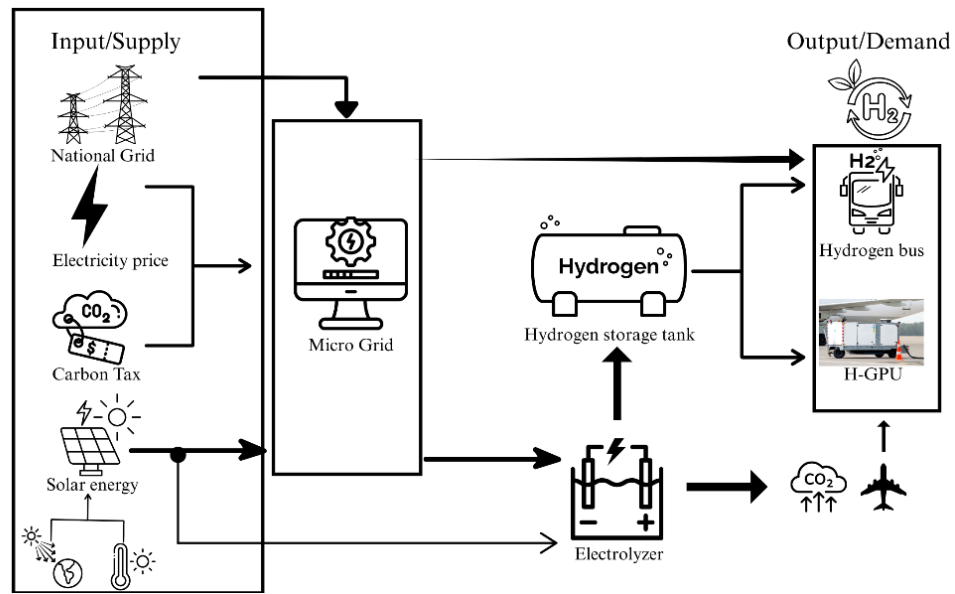


**Figure 4.2.** Airport Energy supply and demand

Source: Author

The energy system capacities, efficiency rate of the equipment, and the economic data of the energy system and equipment are presented in Table 4.1. When the literature was examined, it was found that a 7% discount rate was taken as the basis for hydrogen systems (Terlouw et al., 2022).

**Table 4.1.** Data for the energy system and devices

| ENERGY EQUIPMENT    | CAPACITY                       | RATE OF EFFICIENCY        | CAPITAL EXPENDITURE (CAPEX)            | OPERATING EXPENDITURE (OPEX)                                  | LIFETIME (YEARS)                         |
|---------------------|--------------------------------|---------------------------|----------------------------------------|---------------------------------------------------------------|------------------------------------------|
| <b>PV</b>           | 20,000 kW                      | -                         | -                                      | €10 / kW (Ceylan et al., 2023; Caponi et al., 2022)           | 25 (Tebibel, 2024; Kalinci et al., 2015) |
| <b>ELECTROLYZER</b> | 1000 kW (Ciancio et al., 2024) | 0,80 (Sin et al., 2024)   | 900 €/kw (Ciancio et al., 2024)        | 4 % of CAPEX (Pettinau et al., 2024; Ulleberg & Hancke, 2020) | 25 (Xiang et al., 2022)                  |
| <b>HST</b>          | 35 kg (Zhu et al., 2024)       | 0,72 (Şenol et al., 2024) | € 500/kg (Papadias, & Ahluwalia, 2021) | 2 % of CAPEX (Caponi et al., 2022; Jin et al., 2023)          | 25 (Xiang et al., 2022)                  |
| <b>HGPU</b>         | 120 kW (GAE,2023)              | 0,6 (Yue et al., 2021)    | € 200,000 (GAE,2023)                   | €10.64 / kW (Xiang et al., 2022)                              | 25 (Tebibel, 2024)                       |
| <b>GPU</b>          | 290 l (GAE,2023)               | -                         | € 85,000 (GAE,2023)                    | €2,000 (GAE,2023)                                             | 25 (Tebibel, 2024)                       |
| <b>DIESEL BUS</b>   | 480 l (Topal & Nakir, 2018)    | -                         | € 250,000/unit (Alcantara, 2025)       | €0,26/km (Topal & Nakir, 2018)                                | 25 (Xiang et al., 2022)                  |
| <b>HYDROGEN BUS</b> | 35 kg (Kasperek et al., 2022)  | 0,6 (Yue et al., 2021)    | € 400,000/unit (Rout et al., 2022)     | €0,11/km (Kim et al., 2021)                                   | 25 (Xiang et al., 2022)                  |

Source: Author

In most of the economic studies on hydrogen applications, yearly OPEX is expressed as a fraction of the initial investment. These cost components contain operation and maintenance (O&M) costs, and all the other operational costs. Table 4.1 summarises, for each energy equipment and energy system, the specific operation cost and the corresponding annual OPEX, CAPEX, capacity, and efficiency. Specifically, most of the studies available in the literature indicate that OPEX for PEM electrolyzers ranges between 3.5 and 4.0 % of CAPEX. Besides, among them, PEM electrolysis is prominent for its high efficiency (80–90 %) and high hydrogen purity (99.99 %), and oxygen as a by-product.

Important inputs of the model, such as energy demand for ground services, commodity prices, and carbon emission tax, are discussed in the next section.

Firstly, the PV system model, which is the main input of the simulation model, is presented.

#### 4.1.1. Photovoltaic System Modelling

The model was developed based on an established solar park with solar panels producing a maximum of 20.0 MW of electricity under airport standard test conditions (STC). The estimation was made by considering the solar radiation and temperature data projected for the next 25 years with a moving average. The solar radiation and temperature data were taken as the basis for Izmir province (European Commission, 2024).

Considering the 20 MW capacity PV solar panel, solar irradiance and temperature are forecasted for a forthcoming 25-year period. It is estimated based on the data of the past years using a moving average (European Commission, 2024). An example of the hourly solar radiation data based on the 5 days (European Commission, 2024) is presented in Appendix 1. In addition, an Example of the hourly solar temperature data based on the 5 days (European Commission, 2024) is indicated in Appendix 2.

The obtained data were used to forecast the projected electricity output from the PV system. The hourly electricity produced from the PV system was modeled by adopting the PV system model developed by Xiang et al. (2021).

$$PV_{out} = N_{pv} T_{SD} \frac{I_D}{I_S} [1 + \alpha(T_{PV\_C} - P_{PV})] \quad (5)$$

where the cell temperature is calculated through Equation 6 (Zouine *et al.*, 2019):

$$T_{PV\_C} = T_A + \frac{I_P}{800} (T_N - 20) \quad (6)$$

Symbol and expression of parameters are presented in Table 4.2. Moreover, under the STC, while the cell temperature is 25°C, the irradiance is 1000 W/m<sup>2</sup> (Xiang et al., 2021). A panel's average operating cell temperature is 46°C (Zouine et al., 2019). Besides, the rated power of a PV panel can be designed by dividing the maximum capacity of the solar park by the number of PV panels.

**Table 4.2.** Parameters for PV system sub-model

| <i>Parameters</i>                              | <i>Expression of Parameters</i>                                   |
|------------------------------------------------|-------------------------------------------------------------------|
| <b>PV_OUTPUT_POWER</b> ( $P_{out}$ )           | PV Power Output in Kw at Time T                                   |
| <b>PV_NUMBER_PANELS</b> ( $N_{pv}$ )           | Number of PV Panels                                               |
| <b>PV_POWER_PER_PANEL</b> ( $P_{pv}$ )         | Rated Power of PV Panel at Standard Test Conditions in Kw         |
| <b>IRRADIATION_DATA</b> ( $I_D$ )              | Solar Radiation Intensity In $W/M^2$ At Time T                    |
| <b>PV_STANDARD_IRRADIATION</b> ( $I_s$ )       | Solar Irradiance Intensity at Standard Test Conditions in $W/M^2$ |
| <b>PV_TEMPERATURE_COEFFICIENT</b> ( $\alpha$ ) | Temperature Coefficient of Power                                  |
| <b>CELL_TEMPERATURE</b> ( $T_{PV\_C}$ )        | PV Cell Temperature in $^{\circ}C$ at Time T                      |
| <b>PV_STANDARD_CELL_TEMP</b> ( $T_{SD}$ )      | PV Cell Temperature Under Standard Test Conditions in $^{\circ}C$ |
| <b>TEMPERATURE_DATA</b> ( $T_A$ )              | Ambient Temperature                                               |
| <b>IRRADIATION_PANEL</b> ( $I_p$ )             | Plane Module Irradiance                                           |
| <b>PV_NOCT_TEMP</b> ( $T_N$ )                  | Normal Operating Cell Temperature                                 |

Source: Author

Another important component of the system, the determination of energy demand and collection of data, is detailed in the next section.

#### 4.1.2. Energy Demand of the System

Hydrogen demands are calculated based on the flight distributions of flights at a large-scale airport. Accordingly, hourly flight frequencies are shown in Table 4.3 and Figure 4.3. When the distributions of flights are considered, the mean = 5.863, the standard deviation = 3.204.

Probability Plot (Normal) graph was created to evaluate the conformity of the data to the normal distribution. In the graph, it was observed that the data were largely aligned around the theoretical normal distribution line. This shows that the data set meets the assumption of normal distribution. In addition, the p-value obtained in the normal distribution test was found to be 0.06, and since this value was greater than 5% significance level, the hypothesis  $H_0$  could not be rejected. Therefore, it is concluded that the analysed data are statistically suitable for normal distribution ( $X \sim N(\mu=5.863, \sigma^2= 3.204)$ ). The hourly demands for 25 years were obtained by generating random numbers following the normal distribution with a Monte Carlo simulation.

While the use of hydrogen buses is determined based on the number of flights, 30% of flights are operated by hydrogen buses, while 70% of flights are executed using a passenger boarding bridge (IATA, 2022).

**Table 4.3.** Demands flights based on the week

| <b><i>t</i></b><br><b>(hours)</b> | <b>Demand_Flights</b> |               |                 |               |               |                |                  |
|-----------------------------------|-----------------------|---------------|-----------------|---------------|---------------|----------------|------------------|
|                                   | <b>Thursday</b>       | <b>Friday</b> | <b>Saturday</b> | <b>Sunday</b> | <b>Monday</b> | <b>Tuesday</b> | <b>Wednesday</b> |
| 0                                 | 0                     | 1             | 1               | 0             | 1             | 2              | 3                |
| 1                                 | 1                     | 2             | 2               | 1             | 0             | 3              | 4                |
| 2                                 | 3                     | 3             | 2               | 5             | 3             | 7              | 2                |
| 3                                 | 4                     | 5             | 5               | 1             | 1             | 6              | 2                |
| 4                                 | 3                     | 7             | 6               | 10            | 9             | 4              | 9                |
| 5                                 | 5                     | 3             | 3               | 2             | 3             | 4              | 5                |
| 6                                 | 7                     | 7             | 7               | 6             | 8             | 7              | 6                |
| 7                                 | 7                     | 9             | 8               | 9             | 7             | 6              | 9                |
| 8                                 | 8                     | 6             | 11              | 10            | 8             | 9              | 6                |
| 9                                 | 4                     | 1             | 3               | 4             | 2             | 3              | 2                |
| 10                                | 9                     | 12            | 8               | 11            | 10            | 11             | 12               |
| 11                                | 13                    | 7             | 11              | 10            | 14            | 14             | 10               |
| 12                                | 4                     | 13            | 10              | 6             | 3             | 8              | 7                |
| 13                                | 6                     | 4             | 2               | 6             | 6             | 7              | 2                |
| 14                                | 6                     | 2             | 6               | 3             | 4             | 4              | 5                |
| 15                                | 5                     | 9             | 6               | 5             | 9             | 6              | 5                |
| 16                                | 4                     | 6             | 11              | 12            | 6             | 9              | 10               |
| 17                                | 2                     | 3             | 2               | 4             | 1             | 0              | 1                |
| 18                                | 5                     | 5             | 3               | 7             | 4             | 8              | 5                |
| 19                                | 9                     | 5             | 8               | 9             | 8             | 7              | 10               |
| 20                                | 3                     | 12            | 8               | 10            | 11            | 7              | 9                |
| 21                                | 10                    | 6             | 8               | 4             | 5             | 8              | 6                |
| 22                                | 5                     | 7             | 5               | 6             | 5             | 6              | 4                |
| 23                                | 6                     | 7             | 8               | 4             | 5             | 8              | 4                |

Source: Author

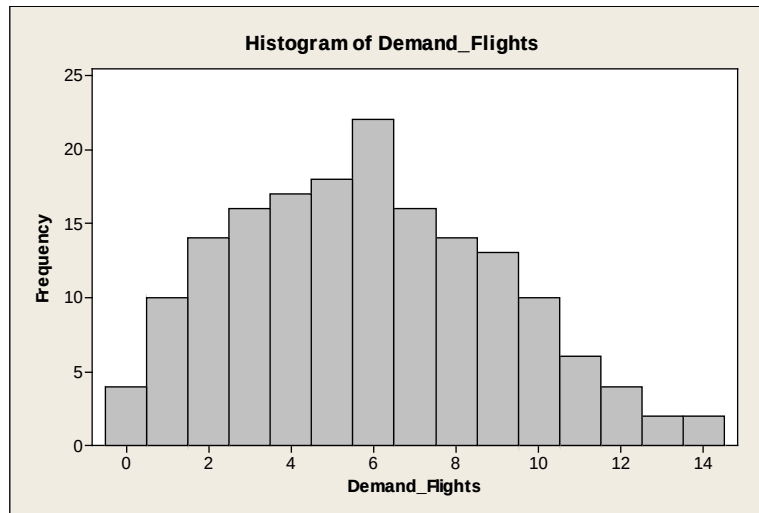


**Figure 4.3.** Histogram of Demand Flights

Source: Author

Detailed information about commodity prices is present in the next section.

#### **4.1.3. Commodity Prices**

The fluctuation of electricity and diesel prices depends on various factors, including crises, wars, and oil prices. The system needs grid electricity when the electricity produced from PV is insufficient. In this case, it will purchase electricity at the current electricity price. The electricity price, based on the average data published by EMRA (Energy Market Regulatory Authority) over the past year is the average electricity price is approximately 0,11 €/kWh. When there is surplus electricity, it is planned to sell it to the grid. Based on the solar energy production model, when there is abundant sunshine, electricity prices will be lower, so the model assumes a selling price of 0.01 €/kWh for electricity. Electricity and diesel prices remain constant during the project time because of the dependency on a variety of factors. The average diesel price over the past year is 0,84 €/l, which remains constant during the project lifetime. The electricity price over time and diesel price over time are presented in Tables 4.4 and 4.5, respectively.

The hydrogen market price is determined as 17 €/kg in 2023, and it will linearly decrease to 2.7 €/kg in 2040, and it will remain constant after 2040 (Terlouw et al. 2022).

**Table 4.4.** Electricity price over time

| Month     | Year | €/kwh  |
|-----------|------|--------|
| June      | 2023 | 0,09 € |
| July      | 2023 | 0,09 € |
| August    | 2023 | 0,09 € |
| September | 2023 | 0,09 € |
| October   | 2023 | 0,11 € |
| November  | 2023 | 0,11 € |
| December  | 2023 | 0,11 € |
| January   | 2024 | 0,11 € |
| February  | 2024 | 0,11 € |
| March     | 2024 | 0,11 € |
| April     | 2024 | 0,11 € |
| May       | 2024 | 0,11 € |
| June      | 2024 | 0,13 € |

Source: Author

**Table 4.5.** Diesel price over time

| Month     | Year | €/l    |
|-----------|------|--------|
| June      | 2023 | 0,51 € |
| July      | 2023 | 0,60 € |
| August    | 2023 | 0,88 € |
| September | 2023 | 0,87 € |
| October   | 2023 | 0,85 € |
| November  | 2023 | 0,87 € |
| December  | 2023 | 0,81 € |
| January   | 2024 | 0,89 € |
| February  | 2024 | 0,95 € |
| March     | 2024 | 0,93 € |
| April     | 2024 | 0,96 € |
| May       | 2024 | 0,92 € |
| June      | 2024 | 0,90 € |

Source: Author

#### **4.1.4. Carbon Emissions and Tax**

The yearly CO<sub>2</sub> emission of a diesel GPU employed for 1.5 hours daily is 36.4 kg (x10,000), and the CO<sub>2</sub> emission of a diesel GPU based on hour is anticipated as 664.84 kg CO<sub>2</sub>/h (Nuhn, 2023). The annual carbon emission amount from GPU diesel consumption was calculated by multiplying the hourly carbon emission rate by the total operating hours per year. The CO<sub>2</sub> emission of a diesel bus is estimated as 2.68 kg CO<sub>2</sub>/l diesel (Carbon Footprint Report, 2023). According to the Republic of Türkiye Ministry of Environment, Urbanization and Climate Change (2023), the CO<sub>2</sub> tax is determined as a €75/ton CO<sub>2</sub> in 2026 and assumed to increase linearly by 4% starting from this year.

#### **4.2. Developing Simulation Model**

A flowchart of the simulation model is presented in Figure 4.4. The flow chart was developed in Python to determine the energy production and consumption of the system in the green hydrogen transition in airport ground services.

The simulation model starts by checking whether there is a demand for hydrogen at time  $t$ . In case of demand, it is evaluated whether there is stock in the current HGPU. In case the supply of HGPU meets the demand and there is also production in solar energy, the system converts this energy into hydrogen. The remaining excess hydrogen in the system is sold at the market price. In case the HGPU inventory is not enough to meet the hydrogen demand, the system provides additional power from the PV system, HST, or the grid to meet the demand. If the solar energy and HST are not enough to meet the demand, the system purchases electricity from the grid to produce the required hydrogen. When the demand is met, the system checks whether there is excess hydrogen. Then, the excess hydrogen is used to refill the HST, and the excess hydrogen can be sold. The simulation was run for 25 years, which is the lifespan of the energy equipment. In addition, in case there is no demand for hydrogen but solar radiation is available, the system converts solar energy into hydrogen and sells it at the market price. The excess solar energy should not exceed the capacity of the electrolyzer, in which case the system sells the excess electricity to the national grid. The simulation is developed assuming that HGPU and HST are at full capacity and the inventory of these devices is updated at the end of each hour.



Simulation model parameters are shown in Table 4.6.

**Table 4. 6.** Simulation model parameters

| PARAMETERS              | DESCRIPTION                             |
|-------------------------|-----------------------------------------|
| EFFICIENCY_ELECTROLYZER | The efficiency rate of the electrolyser |
| EFFICIENCY_HGPU         | The efficiency rate of the HGPU         |
| EFFICIENCY_HST          | The efficiency rate of the HST          |
| EFFICIENCY_BUS          | The efficiency rate of the bus          |
| ENERGY_DENSITY_HYDROGEN | Energy density of the hydrogen          |
| CAPACITY_HST            | HST capacity                            |
| CAPACITY_HGPU           | HGPU capacity                           |
| CAPACITY_ELECTROLYZER   | Electrolyser capacity                   |
| CAPACITY_BUS            | Bus capacity                            |

Source: Author

The simulation model variable is presented in Table 4.7.

**Table 4.7.** Simulation model variables

| VARIABLES             | DESCRIPTION                                                         |
|-----------------------|---------------------------------------------------------------------|
| DELTA_HST             | Margin for the HST capacity and HST inventory level in kg at time t |
| DEMAND_HGPU           | The hydrogen demand of HGPU in kg at time t                         |
| DEMAND_BUS            | The hydrogen demand of BUS in kg at time t                          |
| DEMAND_TOTAL_HYDROGEN | Total hydrogen demand in kg at time t                               |
| EXCESS_HYDROGEN       | Excess hydrogen volume in kg at time t                              |
| INVENTORY_HGPU        | Hydrogen inventory level of HGPU in kg at time t                    |
| INVENTORY_HST         | HST inventory level in kg at time t                                 |
| HYDROGEN_GRID         | Hydrogen power from the grid in kg at time t                        |
| POWER_GRID            | Electricity power imported from the grid in kW at time t            |
| HYDROGEN_TOTAL        | Production of hydrogen by PV, HST, and grid in kg at time t         |
| POWER_HST             | Hydrogen power from HST in kg at time t                             |
| HYDROGEN_PV           | Hydrogen power by PV in kg at time t                                |
| POWER_PV              | Generated power by PV in kg at time t                               |
| SUPPLY_NEEDED         | Hydrogen supply for energy equipment in kg at time t                |
| SURPLUS_POWER         | Surplus of hydrogen after fulfilling demand in kg at time t         |

Source: Author

The scenarios developed are discussed in the following section.

#### **4.2.1. Scenarios**

Scenario analysis was performed to see the impact of different parameters on the model, and the results were evaluated. By adding to the baseline scenario, 3 different scenarios were examined. In the first scenario, the number of hydrogen buses and GPUs was increased in order to scrutinize the demand coverage rate and the efficiency of the hydrogen stock in the system. In the second scenario, based on the baseline scenario, a carbon tax cost is added for carbon emissions from diesel consumption. The third scenario considers the case where both scenarios 1 and 3 are implemented.

##### **Baseline**

The baseline scenario is based on the current distribution of annual flights. It aims to examine the potential economic advantages of the hydrogen conversion of ground services. It generates revenue through the sale of excess energy generated through the use of hydrogen and solar energy. It can only become economically advantageous if it has the potential to generate revenue to cover its costs through the sale of excess energy. This approach can serve as a guiding role for decision-makers to transition to this transformation and play a motivating role in their investment decisions.

##### **4.2.1.1. Scenario 1: Increased hydrogen-powered ground services**

The scenario was developed to analyse the impact of increasing the number of hydrogen ground services, i.e., increasing the capacity, on the results. This scenario was developed to examine the compatibility of the HST and the demand in the system.

##### **4.2.1.2. Scenario 2: imposition of the carbon emission tax**

The second scenario includes the imposition of a CO<sub>2</sub> tax on diesel-powered ground services to take carbon emission costs into account. In achieving zero carbon targets, one of the important policies of governments is to adopt emission mitigation measures such as carbon taxes. Accounting for the cost of the carbon emission tax is critical to emphasize the importance of the transition to green hydrogen. With carbon regulations at the border, government regulations, incentives, as well as taxation are expected to increase, especially in energy-intensive sectors such as transportation and the cement sector.

#### **4.2.1.3. Scenario 3: increased hydrogen-powered ground services and imposition of the carbon emission tax**

In this scenario, where both the number of hydrogen ground services is increased and carbon emissions are incorporated, the implementation of a CO<sub>2</sub> tax offers a sustainable way to reduce carbon emissions. Understanding all these impacts has important implications for taking steps towards sustainable policy development at airports.

In the next section, the research design, parameters, model variables, and data related to the cost-benefit model are discussed. First, we will present the research design and model structure.

### **4.3. Research Design of the Cost-Benefit Analysis**

A cost-benefit analysis is implemented considering the NPV of energy devices such as PV (Photovoltaic System) and electrolyzers (Gudlaugsson et al., 2023). To ensure adoption of all related costs for the green hydrogen transition in the airport case, different cost components are integrated into the model, such as Capital expenditure (CapEx) and operating and maintenance (OpEx) costs for energy devices such as HGPU, Hydrogen bus, HST, and electrolyzer, and the energy costs (COE) that vary depending on the demand for hydrogen, electricity, and diesel.

A simulation model is developed by using Python to analyse the green hydrogen transition in the ground services, such as the GPUs and hydrogen bus, in an airport setting. Hydrogen is produced from solar energy or obtained by purchasing electricity from the grid and using an electrolyzer. A cost-benefit analysis was performed using the simulation outputs, including energy production and consumption. In the baseline scenario, forecasts were made by considering the current flight demands. The base scenario is extended by three scenarios presented in Table 4.8.

- In the first scenario, the amount of the hydrogen-powered airport ground services is increased (HGPUs increased to 3, hydrogen bus number increased to 3).
- In the second scenario, a carbon tax is executed based on the amount of carbon released.

- In the third scenario, the first two scenarios were implemented simultaneously.

**Table 4.8.** Summary of the scenarios

| <b>Scenarios</b>                                                                                                      | <b>The structure of the scenarios</b>                                                          | <b>Impact of the scenarios</b>                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Baseline Scenario</b>                                                                                              | Based on the current distribution of annual flights hours                                      | It aims to examine the potential economic advantages of the hydrogen conversion of ground services. It generates revenue through the sale of excess energy generated through the use of hydrogen and solar energy. It can only become economically advantageous if it has the potential to generate revenue to cover its costs through the sale of excess energy. |
| <b>Scenario 1</b><br><br>Increased hydrogen-powered airport ground services                                           | Increasing the number of hydrogen ground services                                              | The scenario was developed to analyse the impact of increasing the number of hydrogen ground services, i.e., increasing the capacity, on the results. This scenario was developed to examine the compatibility of the HST and the demand in the system.                                                                                                           |
| <b>Scenario 2</b><br><br>Imposition of the Carbon Emission Tax                                                        | Imposition of the carbon emission costs                                                        | The second scenario includes the imposition of a CO <sub>2</sub> tax on diesel-powered ground services to take carbon emission costs into account. In achieving zero carbon targets, one of the important policies of governments is to adopt emission mitigation measures such as carbon taxes.                                                                  |
| <b>Scenario 3</b><br><br>Increased hydrogen-powered airport ground services and Imposition of the Carbon Emission Tax | Both the number of hydrogen ground services is increased and carbon emissions are incorporated | In this scenario, where both the number of hydrogen ground services is increased and carbon emissions are incorporated, the implementation of a CO <sub>2</sub> tax offers a sustainable way to reduce carbon emissions.                                                                                                                                          |

Source: Author

#### 4.2.1. Development of the Cost-Benefit Model

This study investigates the feasibility of investment in ground services for green hydrogen conversion in the transition to zero-carbon energy. It is intended to calculate the feasibility NPV of the hydrogen investment and present it by comparing it with the current situation. Capital expenditure (CapEx) and operating and maintenance (OpEx) costs for energy devices such as HGPU, Hydrogen bus, HST, and electrolyzer are included in the model. The energy costs that vary depending on the demand for hydrogen, electricity, and diesel are considered. The capital cost of the solar park installation is not included in the model, but the installation costs of other equipment are included. However, the operating and maintenance costs for all vehicles are included.

The parameters used are presented in Table 4.9.

**Table 4.9.** Key parameters of the model

| <i>Symbol of parameters</i> | <i>Expression of parameters</i>                                                                  |
|-----------------------------|--------------------------------------------------------------------------------------------------|
| $N$                         | Project duration                                                                                 |
| $t$                         | Year in the project life cycle                                                                   |
| $r$                         | Discount rate                                                                                    |
| $i$                         | Energy equipment of the system (GPU, HGPU, Hydrogen Bus, Diesel Bus, HST, Electrolyser, and PV)  |
| $CapEx_{t,i}$               | The yearly capital expenses of the energy vehicle and system $i$ , in year $t$ .                 |
| $O\&M_{t,i}$                | The yearly O&M cost of the energy vehicle and system $i$ , in year $t$ .                         |
| $OpEx_{t,i}$                | The yearly operational expenses of the energy vehicle and system $i$ , in year $t$ .             |
| $COE_t$                     | The yearly cost of energy in year $t$ (hydrogen, electricity, and diesel).                       |
| $R_{electricity}$           | The yearly revenue from selling excess electricity produced from excess solar energy in year $t$ |
| $R_{hydrogen}$              | The yearly revenue that is obtained from selling a surplus of hydrogen in year $t$ .             |

Source: Author

The yearly total cost ( $TC_t$ ) is the summation of the energy-related cost, such as CapEx, OpEx, and COE (Zhao et al., 2022). The ( $TC_t$ ) is calculated using equation 1.

$$TC_t = \sum_{t=0}^N \frac{CapEx_{t,i}}{(1+r)^t} + OpEx_{t,i} + COE_t$$

$$OpEx_{t,i} = COE_{t,i} + O\&M_{t,i} \quad (1)$$

The yearly cost of energy in year COE, noted as  $COE_t$  for HGPU, is calculated by multiplying the yearly hydrogen consumption by the current hydrogen market price. Additionally, the cost of electricity is calculated by multiplying yearly electricity consumption from the grid and the electricity market price. Additionally, the COE for the GPU is calculated by multiplying the annual diesel consumption by the diesel price. The energy consumption of hydrogen and electricity is acquired from the developed simulation model.

Revenue generation is considered by selling excess electricity and hydrogen in the system. Equation 2 is used for the calculation of the yearly generated revenue ( $REV_t$ ) (Jovan & Dolanc, 2020).

$$REV_t = R_t^{electricity} + R_t^{hydrogen} \quad (2)$$

where  $R_y^{electricity}$  indicates revenue from electricity. It is calculated by multiplying the annual PV excess energy by the electricity selling price. Revenue from selling hydrogen shows  $R_y^{hydrogen}$  and the hydrogen surplus is multiplied by the market price of hydrogen minus the unit cost of hydrogen (Jovan & Dolanc, 2020).

Equation 3 is used for the calculation of the NPV of the green hydrogen transition (Jang et al., 2022).

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

where  $CapEx_{t,i}$  indicates the yearly capital expenses of the energy vehicle and system,  $OpEx_{t,i}$  shows the yearly operational expenses of the energy vehicle and system,  $Rev_y$  indicates revenue generation is considered by selling excess electricity and hydrogen in the system.

The cost for the hydrogen production per kg is designed via Equation [4] (Jovan & Dolanc, 2020).

$$H_{2\_cost} = \frac{CapEx}{total\ H2\ production(kg)} + \frac{OpEx_{PV,EL,HST}}{total\ H2\ production(kg)} +$$

$$electric\ energy\ price \left( \frac{\text{€}}{kWh} \right) *$$

$$electricity\ consumption\ for\ hydrogen\ production \left( \frac{kWh}{kg} \right) \quad (4)$$

After the model design and data collection phase, considering the simulation model and cost-benefit analysis, the results in light of the developed model are discussed in the next chapter.



## 5. CHAPTER: RESULTS

This section includes the cost-benefit analysis results for the deployment of hydrogen in the ground services at the airport. Firstly, the baseline scenario is discussed. Thereafter, the results of the scenarios are investigated. This section presents a sensitivity analysis to understand the effect of the system parameters (diesel prices and carbon emission tax).

### 5.1. Baseline Scenario:

In the base scenario, the system's green hydrogen deployment is performed. According to the results, while the hydrogen-based system CapEx is € 1.517,500, the O&M (Operation & Maintenance) cost € 6.068,561, COE (Cost of Energy) € 1.576,151. CapEx cost includes capital expenses of the electrolyzer, the HST, the hydrogen-powered GPU, and the hydrogen-powered bus; the diesel-based system CAPEX is € 335,000, the O&M cost is € 352,285, and the COE is € 1.837,760. This projected cost difference has been a contributing factor to the long delay in the transition to hydrogen technology.

The cost of a hydrogen-powered GPU and a hydrogen-powered bus is presented in Figures 5.1 and 5.2.

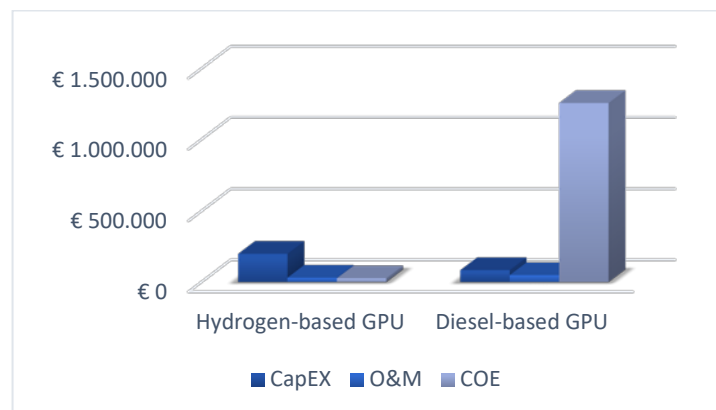


**Figure 5.1.** Cost Assessment of the hydrogen-powered GPU

Source: Author

The cost of a hydrogen-powered GPU and a hydrogen-powered bus is presented in Figures 5.1 and 5.2. The analysis indicates that the total capital investment required for the HGPU project is €200,000, which is higher than the €85,000 required for the diesel GPUs project. In addition, including the hydrogen infrastructure equipment, the total capital investment amounts to approximately €1.5 million. The cost of maintenance for HGPU and diesel GPU is €31,920 and €50,000, respectively. In align with the Eefting (2022), the cost of the maintenance of the HGPU is lower than that of the diesel GPU. Additionally, the cost of energy for the HGPU is €27,797, which is lower than the €1.258,000 required for the GPU. The lower maintenance costs of hydrogen compared to diesel maintenance costs provide a significant advantage for the hydrogen transition. Cost Assessment of the hydrogen-based bus is presented in the Figure 14.

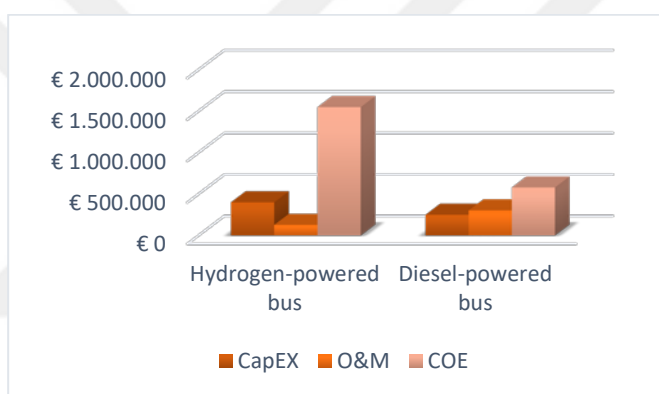


**Figure 5.2.** Cost Assessment of the hydrogen-based bus

Source: Author

The analysis indicated that the total capital investment required for the hydrogen bus project is €400,000, which is higher than the €250,000 required for the diesel bus project. Additionally, including the hydrogen infrastructure equipment, the total capital investment amounts to €1.5 million. The maintenance cost for a hydrogen bus and a diesel bus is €127,891 and €302,275, respectively. Furthermore, the cost of energy for the hydrogen bus is € 1.548,000, which is also higher than the €579,474 required for the diesel bus. When analyzing the operating expenses of the hydrogen supply chain, it accounts for € 6.068,000.

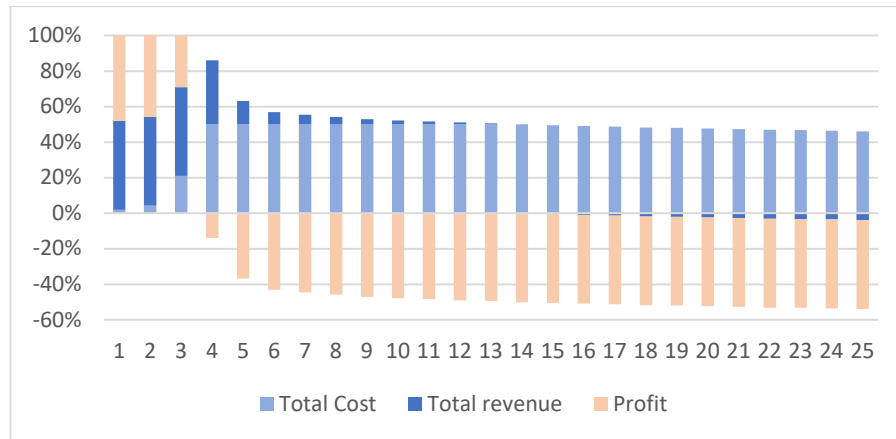


**Figure 5.3.** Annual changes in the cost components of the hydrogen transition (%)

Source: Author

When the hydrogen system and diesel system are compared in the baseline scenario, it is seen that the diesel system has a lower cost and more economic advantages. However, the hydrogen system generates revenue by selling the excess electricity and excess hydrogen produced by the system. Considering the total cost, the transition to hydrogen requires a significant investment. In addition, operation and maintenance costs and the energy costs required for the conversion are also included in the system. In the cumulative analysis, the total costs are approximately € 9.162,000, and the revenue is € 12.886,000. In this case, the cumulative profit in the system is € 3.724,000. Figure 5.3 presents annual changes in the cost components of the hydrogen transition (%). Total NPV of the baseline scenario is approximately € 8.770,000.

The annual cost, revenue and profit trends presented in the graph show that the investment generated positive profitability in the early years, but systematically incurred losses in the medium and long term. Especially from the 4th year onwards, the negative profitability has become permanent as the total revenue has been below the total cost. This poses a risk to the long-term economic sustainability of the investment. However, the fact that the loss levels are quite limited and the revenue-cost differential stabilizes over time indicates that the system offers a moderate loss-generating but controllable structure. This structure reveals that even limited

increases in energy costs can disrupt the economic balance, demonstrating the vulnerability of highly energy-dependent systems to exogenous price shocks.

The annual cost, revenue, and profit ratios presented in the graph show that the investment generated positive returns in the first few years, but systematically shifted to negative returns from year 4 onwards. In contrast, the positive Net Present Value (NPV) of the investment shows that the strong revenues and profits in the early years offset the moderate losses in the later years at present value. This suggests that the investment is operating efficiently in the short term and that losses are limited and predictable, albeit unsustainable, in the long term. A positive NPV indicates that the investment is financially acceptable under today's conditions and that long-term losses have limited impact on the financial assessment due to the discounting effect. Moreover, these findings suggest that in infrastructure investments that are sensitive to energy costs, dependence on highly volatile fuels such as diesel may pose long-term risks, and therefore, it is important to consider alternative energy options. In conclusion, although the graph presents a negative trend on an annual basis, a positive NPV value provides an important assurance for decision makers in the holistic financial evaluation of the investment.

Besides, the model indicates an average hydrogen product cost of €7.59 per kg and decreases over time. This amount is consistent with Turkey's target of reducing production costs to 4.85-5.17 USD/kg H<sub>2</sub> by 2030 and 1.38-2.46 USD/kg H<sub>2</sub> by 2050 (SHURA, 2021a). Though the current market price for selling hydrogen is about €17 per kg, declining at a higher rate in the specified period.

The scenarios are discussed in the following section.

## **5.2. Scenario 1**

According to the simulation results; in scenario 1, airport ground service demands increased. Grid generation increased as PV generation remained the same with the baseline scenario. The system started using electricity from the grid to meet demand. In this case, HST inventory decreased by 50.98%. Overproduction decreased by 47.28% and hydrogen loss decreased by 3.02%. Capacity increase significantly increased grid generation to meet demand HST inventory decreased while HGPU inventory increased and therefore, system efficiency increased (overproduction and

lost H<sub>2</sub> decreased). When the hydrogen system and diesel system are compared in the baseline scenario, it is seen that the diesel system has a lower cost and more economic advantages.

Considering the total cost of the hydrogen deployment, the transition to hydrogen requires a substantial investment, such as HST, electrolyser capital expenditure. Besides, the capital investment cost of hydrogen vehicles, such as GPUs and hydrogen-powered buses, is also quite high. In addition, operation and maintenance costs and the energy costs required for the deployment are also included in the system. In the cumulative analysis, the total costs are approximately € 14 million, and the revenue is € 8 million 400 thousand. Based on this scenario, the NPV obtained as a € 3 million 493 thousand. Figure 17 indicates annual changes in the cost components of the hydrogen transition (%).

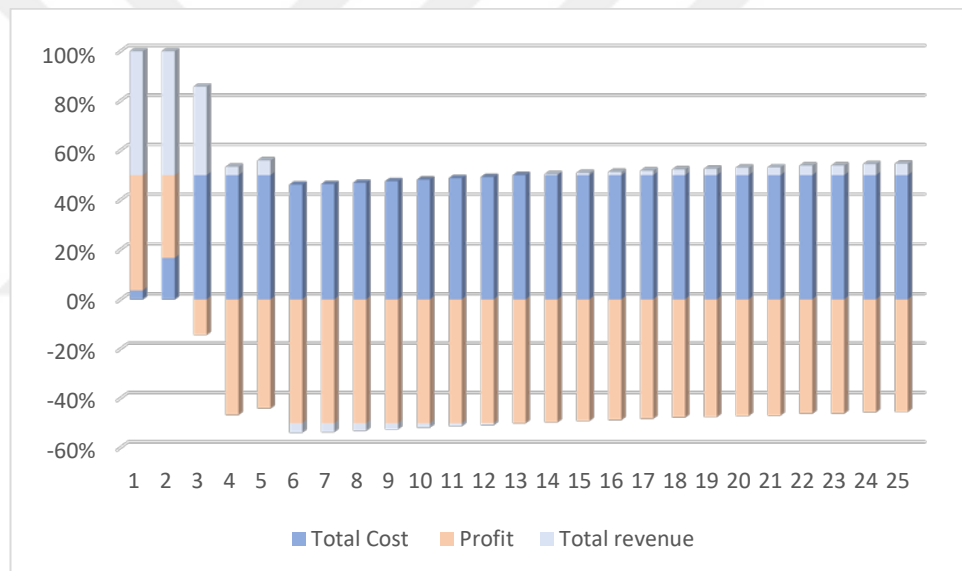


**Figure 5.4.** Annual changes in the cost components of the hydrogen transition (%)

Source: Author

Figure 5.4 presents the percentage distribution of three key financial indicators (Total Revenue, Total Cost, Profit/Loss) over 25 years. The light blue column (Total Revenue) remains at an approximately constant level from year 6 onwards. It indicates that revenue is not increasing and the system has a limited revenue potential. The blue column (Total Cost) shows a constant level from year 6 onwards.

This means that costs remain high, but they are under control. According to the result of Figure 5.4, the total cost needs to be reduced, or revenue-enhancing measures should be taken. According to the 25-year perspective NPV (Net Present Value) analysis, a positive NPV indicates that the investment is profitable at present value.

When the annual total cost, revenue, and profit ratios presented in the graph are analysed, positive profitability is observed in the first years of the investment, but from the 4th year onwards, the system continuously generates negative profit. Although at first all, this indicates that the investment is not sustainable, the positive Net Present Value (NPV) indicates that the investment is economically rational in the long term. In the NPV calculation, high profits in the early years offset or even exceed the present value of losses incurred in later years. Especially when evaluated within the framework of discounted cash flows, the investment generates a positive return in total since late-period losses are considered with a low present value. This emphasizes that the annual profitability trend alone is not a sufficient indicator for investment projects and that financial assessments should be based on present value. In conclusion, although the graph provides important information on annual performance, it can be said that holistic and time-valued indicators such as NPV are more significant indicators for decision makers.

### **5.3. Scenario 2**

This scenario purposes to investigate the effect of the imposition of the carbon emission tax. Carbon emission in this scenario is caused by the diesel consumption of the ground services. While the GPU emits 664.84 kg CO<sub>2</sub> per hour, a diesel bus, 1 litre of diesel fuel emits approximately 2.68 kg of CO<sub>2</sub> per litre. In this regard, approximately 0.94 kg of CO<sub>2</sub> is released per kilometre.

The border carbon adjustment mechanism is planned to be implemented in Türkiye as of January 1, 2026. In this context, according to the EU's Border Carbon Adjustment Mechanism, as of January 1, 2026, it is expected that the carbon footprint of the products to be imported to the EU in the six carbon-intensive sectors, namely iron and steel, aluminium, cement, fertilizer, electricity and hydrogen sectors, will be measured. A carbon tax will be imposed for each ton released into the atmosphere during production. Accordingly, the cost of the carbon emission tax on

diesel ground services is included in this scenario. The carbon emission tax, which is planned to start at €75 / ton CO<sub>2</sub> in Türkiye, is expected to increase gradually.

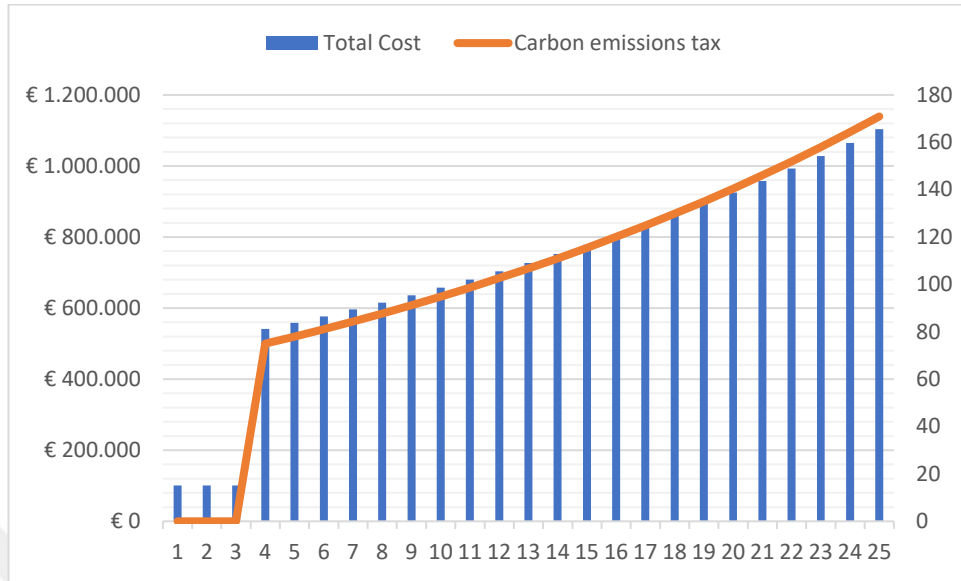


**Figure 5.5.** Impacts of the Carbon Emission Tax on Total Costs

Source: Author

In Figure 5.5, the carbon emission costs increased by applying a carbon emission tax; in parallel, the total cost of carbon increases. According to the result, a 4% increase in the carbon emission tax results in a 3% increase in total costs.

Figure 5.5 shows the impact of the carbon emission tax on the total cost of investment. The figure shows that there is a sharp increase in the total cost starting from the 4th year after the imposition of the carbon tax, and the cost increases steadily with the carbon tax in the following years. This reveals that fossil fuel-based systems are highly sensitive to carbon pricing. The increasing carbon tax has become one of the main determinants of total cost, increasing the economic burden of investment over time. This result shows that environmental policy instruments have important implications not only for environmental protection but also for economic decision-making processes. Reducing the carbon footprint and switching to low-emission alternative technologies to ensure the long-term sustainability of investment is considered not only an environmental responsibility but also an economic

imperative. As a result, it stands out as a strategic energy and decisive factor for the current investment model in the face of the increase in carbon tax.

#### 5.4. Scenario 3

In this scenario, both the number of hydrogen ground equipment units is increased, and a carbon emission tax is applied. In this scenario, with the addition of carbon emissions, the cost of diesel ground equipment increases to approximately €18.265.035 million. Thus, it is about the same as the cost of hydrogen, which is presented in Table 5.1. However, when the revenue from hydrogen sales is considered, it can be said that the advantages of transition to hydrogen in this scenario can be seen in both terms of reducing environmental impacts and cost.

**Table 5.1.** Comparison of the hydrogen and diesel-powered systems

|                                                           | <b>Total Cost</b> | <b>Revenue</b> | <b>Profit</b>  |
|-----------------------------------------------------------|-------------------|----------------|----------------|
| <b>Hydrogen-powered System</b>                            | € 14.391.457      | € 8.403.081    | € -5.988.376   |
| <b>Diesel Powered System</b>                              | € 3.195.035       | -              | € - 3.195.035  |
| <b>A carbon tax is applied to diesel ground equipment</b> | € 18.265.035      |                | € - 18.265.035 |

Source: Author

The use of hydrogen increases investment costs. However, with the introduction of the carbon emission tax in Scenarios 2 and Scenario 3, hydrogen reaches a cost level competitive with diesel.

#### 5.5. Sensitivity Analysis

Sensitivity analysis has been carried out considering critical parameters such as the diesel price and carbon emission tax to analyse the effect of these parameters. on changes the total cost.

##### 5.5.1. Sensitivity Analysis of the Diesel Price

The sensitivity analysis conducted in this study reveals that the economic performance of the investment is moderately sensitive to changes in diesel prices. The results of the analysis show that in scenarios where the diesel price tends to

increase, total costs increase and annual profitability ratios decrease slightly. In contrast, a limited improvement in profitability is observed in scenarios where diesel prices fall. However, these changes do not radically alter long-term trends, and the profitability profile in particular remains broadly similar. This suggests that the investment is not completely independent of diesel price fluctuations, but that these changes do not radically affect economic feasibility. Hence, it can be said that the system has some flexibility against volatility in energy costs. However, the vulnerability of fossil fuels such as diesel to price volatility may create economic uncertainties in the long run, and therefore, the consideration of alternative energy sources (e.g. hydrogen) is important for risk mitigation strategies. In conclusion, sensitivity analysis once again emphasizes the need to test investment decisions not only under fixed assumptions but also under changing market conditions. The analyses of the diesel price are carried out, and the results are presented in Table 5.2.

**Table 5.2.** Sensitivity analyses of the diesel price

| Diesel price | Difference | Total Cost    | Increase (%) |
|--------------|------------|---------------|--------------|
| 0,672        | -20        | ₺2.157.483,32 |              |
| 0,756        | -10        | ₺2.341.259,36 | +8.52%       |
| 0,84         | 0          | ₺2.525.035,40 | +7.85%       |
| 0,924        | 10         | ₺2.708.811,44 | +7.28%       |
| 1,008        | 20         | ₺2.892.587,48 | +6.78%       |

Source: Author

According to Table 5.2, every 10% change in diesel price caused a change of approximately 7-8% in total cost. 10% change changes output by 7-8%. This causes a fairly stable and linear change. In this case, the variable can be considered as a moderately sensitive parameter. When the sensitivity coefficient is less than 1, it is said to indicate low sensitivity. It is appropriate to trace it in management and decision processes, but not to consider it as a critical, risky parameter on its own in this system.

As a result of the sensitivity analysis, the total cost and profitability indicators of the investment were found to be moderately sensitive to changes in diesel price. This indicates that changes in diesel prices in the range of  $\pm 10$ -20% affect the economic

performance of the system, but this effect does not radically change the overall feasibility of the investment. In other words, while diesel price fluctuations have an impact on profitability, they do not create a decisive change in long-term evaluation criteria such as Net Present Value (NPV). This finding suggests that the project is relatively resilient to current market conditions, but that diesel price increases should be carefully monitored. Investors are recommended to develop risk management strategies that consider such moderate sensitivities, especially in economic environments where energy costs are volatile. Moreover, this result also proposes that the investment may have a reasonable basis for transitioning to alternative energy sources.

### 5.5.2. Sensitivity Analysis of the Carbon Emission Tax

Based on Table 5.3, every 10% change in carbon tax price caused a change of approximately 8-9% in total cost. 10% change changes output by 8-9%. This causes a fairly stable and linear change. In this case, the variable can be considered as a moderately sensitive parameter in the system.

**Table 5.3.** Sensitivity analyses of the carbon emission tax

| Carbon Emission Tax | Difference | Total Cost | Increase (%) |
|---------------------|------------|------------|--------------|
| 76,0                | -20        | € 546.911  |              |
| 85,5                | -10        | € 602.649  | +10,19       |
| 95,0                | 0          | € 657.795  | +9,15        |
| 104,5               | 10         | € 714.127  | +8,56        |
| 114,0               | 20         | € 769.866  | +7,81        |

Source: Author

The sensitivity analysis conducted in this study aims to assess the potential impact of carbon emission tax on the economic performance of the investment. The results of the analysis revealed that in scenarios where the carbon tax is increased, total costs increase significantly and annual profitability levels decrease rapidly. Especially in systems with a fossil fuel-based operating model, the carbon tax was observed to be a direct and highly influential parameter on the economic feasibility of the investment.

This shows that internalization of carbon costs can significantly affect the sustainability of the investment, and decision makers should not ignore such environmental costs. On the other hand, the analysis also revealed that the system remains relatively resilient, and profitability does not completely disappear when the carbon tax is below certain thresholds. This result suggests that investment is moderately sensitive to the carbon tax and that changes in environmental regulations should be carefully monitored. Moreover, the findings of the analysis emphasize that the transition to low-carbon technologies is a strategic necessity not only in terms of mitigating environmental risks but also economic risks.

As a summary of the results, to summarize, the second scenario, which involves the imposition of a carbon emission tax, is considered the most favourable. Border carbon adjustments appear to be highly effective in driving the green transition. However, the first scenario, which includes an increase in ground services capacity, entails higher costs compared to the second scenario due to the significant investment required. Nevertheless, technological advancements and a gradual transition are crucial strategies in this context. Although the third scenario—which includes carbon emissions—does not currently appear profitable, it can be expected to become economically competitive in the future through infrastructure support, technological improvements that enhance efficiency, and incentivizing mechanisms introduced by governments.

In light of the results obtained, the discussions and the implications are presented in Chapters 6 and 7, respectively.



## 6. CHAPTER: DISCUSSIONS

Green hydrogen is the most suitable for the sustainable energy transition with zero carbon emissions. The production of green hydrogen by electrolysis is consistent with the net-zero carbon emission targets and enables cooperation between sectors, thus reducing technological costs and providing flexibility to the electricity system. Another factor in reducing the costs of green hydrogen is technological developments. It is primarily considered an energy carrier for sectors requiring high energy density. Green hydrogen has other socio-economic benefits like reducing air pollution, promoting economic development, and creating and enhancing strategic competitiveness. For green hydrogen to be fully accepted, it must overcome certain obstacles. The most important of these obstacles is its high cost. To expand the practice of green hydrogen, it is essential to develop special policies for each stage of technology preparation and market entry.

Considering the literature review discussed in section 3, it can be stated that there is a need for research to provide a cost-benefit analysis of the green hydrogen transition in the airport ground services in Türkiye, considering the economic advantages. Therefore, this study aims to fill this research gap by exploring the economic feasibility of substituting hydrogen in the ground services. According to the results, the transition to hydrogen necessitates substantial investment costs; it is realized that the transition to hydrogen will provide a competitive advantage in the long term and is a profitable investment, especially when carbon emission taxes are imposed.

The Paris Climate Agreement obliges the world to target global warming to an ideal limit of 1.5 °C. To achieve this goal, CO<sub>2</sub> and other greenhouse gases essential to reach near zero by 2050 and achieve a reduction of around 40% by 2030. In line with these goals, the ETC stated that all high-income countries should achieve net-zero emissions by 2050, and all middle- and low-income countries by 2060 (ETC, 2023). Rapid and large-scale deployment of clean energy technology is required, most notably the expansion of electricity supply to achieve full decarbonization, the deep

electrification of most energy end-uses, and a major expansion of the role of low-carbon green hydrogen, primarily produced through electrolysis. Pipelines from southern Europe or North Africa appear as competitive alternative by 2030, because hydrogen produced in Spain is 1.62 \$/kg by using electricity from tracking solar PV, and hydrogen imported with pipeline transport to Germany is 0.15 \$/kg and 0.26 \$/kg; Hydrogen delivered to Germany is 2.03 \$/kg; domestic production hydrogen produced in Germany through onshore wind (2.05 \$/kg + 0.15 \$/kg) is 2.20 \$/kg (BloombergNEF, 2022). In this regard, hydrogen produced in southern Europe is seen as having a more competitive advantage compared to northern European countries. According to import versus domestic hydrogen production based on the countries; the landed cost of hydrogen delivered from Spain to Germany in 2030 can be summarized as follows: importing Australia 3.25 \$/kg, importing Canada 3.05 \$/kg, importing UAE 3.02 \$/kg, importing Chile 2.95 \$/kg; while domestic production in Germany is 3.08 \$/kg. Under these conditions, the import option is more advantageous for certain countries.

For the 20 countries studied, both Malaysia and Türkiye experienced a mitigation in the weighted average of new public-scale solar PV capacity additions in 2022, falling below the weighted average fossil-levelized cost of electricity estimate for newly added capacity. Similarly, Türkiye surpassed 1 GW of net additions for the second consecutive year, with total installed costs rising by 20% and a 40% annual growth in new solar PV capacity between 2021 and 2022. In the long term, technological advancements, along with abundant supplies of raw materials, are expected to support the energy transition. Reducing future increasing demand for energy transition materials through innovation is significant, and it can be achieved with the support of public policies (IRENA, 2024).

Hydrogen is anticipated to play a key role in the conversion to a low-emission carbon economy; however, achieving this green transformation will inevitably require substantial investment in infrastructure and the progress of the necessary technologies. Based on the Energy Futures Initiative report, the hydrogen market will expand to \$250 billion by 2030 and \$1 trillion by 2050 (EFI, 2023). Chiroasca et al. (2024) stated that green hydrogen can substitute fossil fuels to decrease emissions in numerous sectors, as the priority sector industry and transport. However, cost reduction is critical for the embracing of green hydrogen across the world, and thus,

diminishing the usage of rare materials and improving system efficiency is a fundamental requirement of this transition. To accelerate the common usage of hydrogen, infrastructure must be established, production enhanced, and demand for green hydrogen needs to be increased to make hydrogen as affordable and competitively priced (McKinsey & Company, 2021). Patonia & Poudineh (2022) discussed that green hydrogen needs to struggle with the high costs and technology dependence in the next years. Providing sustainable and renewable solutions, such as larger production volume, technological improvements, support, and initiatives for green hydrogen, has positive impacts on cost reduction.

Xiang et al. (2021) assert that an airport may produce electricity autonomously via a hydrogen-solar-storage integrated energy system, instead of depending on the grid. Guilbert & Vitale (2021) present an overview of the main hydrogen applications considering present and future situations while examining funding and barriers to building a prosperous future by discussing all the critical challenges in the energy sectors.

While aircraft-powering technologies such as hydrogen and electricity are considered key points for reducing carbon emissions, as they use clean energy sources (Martinez-Valencia et al., 2021). Sun et al. (2025) stated that society's acceptability is a significant driver for the replacement of hydrogen. However, concerns about the technology's affordability, environmental benefits, and energy safety are influencing public acceptability. The most important challenge is the lack of infrastructure, especially the shortage of vehicle hydrogen refueling facilities, which hinders the broad acceptance and applicability of this transition. Uncertainties about the efficiency of current production techniques and the high cost of production also hinder the adoption of this technology. In terms of production costs, green hydrogen, at \$5 per kilogram, requires to decrease below \$2 per kilogram to compete with conventional fuels, meaning its production cost disadvantages are still being investigated. In addition, increased awareness and educational activities are fundamental requirements for adopting hydrogen technologies in different industries, and government support and policies would also directly impact consumer assurance and market growth. Carbon prices will also have an important impact on this green transition. A carbon price of \$50 per tonne would be a value that could significantly increase the economic attractiveness of hydrogen. In summary, hydrogen has an

important role in reducing global energy-related carbon emissions by 30%. However, providing sustainable advantages of this transition can only be achieved by solving the problems of infrastructure progress, production prices, and storage technologies (Sun et al., 2025).

Taha et al. (2024) provide a comparative study of hydrogen production between small-sized airports and larger-sized airports. On-site hydrogen production from renewables can be an appropriate solution for small-sized airports, however, larger-sized airports can be supplied with hydrogen via transportation from dedicated green hydrogen production plants or other sources of hydrogen. Thus, their paper evaluated two different hydrogen supply scenarios. They assessed in-house hydrogen production in the small airport of Stockholm Skavsta as a case study, while offshore green hydrogen supply in the larger airport of Arlanda. The optimum size of the production and storage facility is determined by considering the levelized cost and carbon emissions. For the large-sized airport, the research estimates the hydrogen supply from offshore production facilities transported by different types of transportation. According to the results, the levelized cost is changing between 2.93 and 2.44 Euro/kg H<sub>2</sub> in the case of in-house production. The least cost for larger airports is obtained from the compressed hydrogen offshore and onshore pipeline. This paper is significant for establishing a pathway for airports' in-house hydrogen production and outsourced hydrogen supply for decarbonization aims.

In the project realized at Groningen Airport Eelde, a small-scale airport, the demand is quite low. Therefore, PV generation is sufficient for this system. Even more income is obtained by selling the excess hydrogen produced from PV. However, in the project we have realized for large-scale airports, the demand is quite high and therefore, when the demand is not able to obtain electricity from PV generation, it has to supply electricity from the national grid.

According to Feng et al. (2024), a carbon tax can be considered a critical incentive to reach the net-zero emissions target and encourage an energy revolution. However, a carbon tax can create negative socio-economic impacts. The study results predict that when the carbon emission decrease target is below 15%, the inclusion of a carbon tax strategy can meaningfully reduce carbon emissions and fossil fuel energy

consumption. In addition, this change can only slightly reduce the economic growth rate, and is evaluated from the perspective of the environment and the economy.

Bhuiyan & Siddique (2025) stated that hydrogen can be seen as a pioneer and clean energy carrier in the shift to low-carbon emissions, as a technology that can be integrated with renewable energy systems. However, there are some basic difficulties in the progress of hydrogen technology. The most important of these are the lack of infrastructure, missing links in the value chain, and its high cost. More work and innovation are needed, especially in the transportation and storage stages of the supply chain. The low density of hydrogen creates problems in the storage stage, transportation-related risks, and insufficient infrastructure in the transportation stage. The absence of global standards and investment also plays a role in the progress of the hydrogen ecosystem. In this direction, Bhuiyan & Siddique (2025) evaluated the potential of hydrogen as a sustainable energy carrier and presented views and suggestions on developments and current challenges in production, storage, and transportation.

All stakeholders playing a key role in this transformation should collaborate to overcome the challenges of this green transition.

Barriers to the hydrogen transition are discussed in the next section.

### **6.1. Barriers to Hydrogen Transition**

Companies that prioritize hydrogen conversion appreciate several benefits, including their commitment to innovation and their role as pioneers in attaining sustainability and reducing emissions. Hydrogen has several benefits, as mentioned before in the energy sector, but several barriers need to be overcome before it can be widely used globally. This transition necessitates the cooperation and trustworthiness of other participants in the sector (Network for Business Sustainability, 2012). One of the primary obstacles associated with hydrogen is the financial constraints resulting from the substantial initial capital expenditure. Furthermore, the expenses related to operations are also significantly higher since hydrogen storage systems have higher costs compared with battery storage systems. However, ongoing research and advancements indicate that the potential for hydrogen systems will have increased by 2030 (Hassan et al., 2021). The production costs of hydrogen are influenced by the

methods used to produce it (Papadis & Tsatsaronis, 2020), resulting in higher expenses compared to fossil fuels (Acar & Dincer, 2020). The challenges facing the transportation sector include the economic viability of FCEV and the availability of sufficient hydrogen infrastructure (Nazir et al., 2020b). For instance, timing the alteration of gas pipeline infrastructure is a key challenge (BloombergNEF, 2022). One additional limitation of the hydrogen deployment is the society's acceptance of hydrogen (Schmidt and Donsbach, 2016), which adversely impacts the trust of different stakeholders in hydrogen systems.

The high initial investment prices of the necessary technologies, such as electrolyzers and HST, are one barrier to producing hydrogen from renewable energy sources (RES) (Zhou & Searle, 2022). Compressed hydrogen tanks pose safety risks due to their potential to rupture or explode. Similarly, liquefied hydrogen presents challenges, as some of the stored hydrogen may evaporate, leading to both resource loss and additional safety concerns. Several barriers remain at several stages of the hydrogen supply chain, particularly in storage methods, which come with significant drawbacks. These methods are highly energy-intensive, reducing hydrogen's effective energy content. Mobility and energy storage applications require support from technological advancements, and the adoption of innovative methods is essential to address the substantial reduction in overall energy efficiency. In addition, regulatory barriers are one of the expansions of the clean hydrogen industry (IEA, 2019). Despite these barriers, the International Energy Agency (IEA, 2019) predicts that by 2030, the cost of producing hydrogen from renewable energy sources could reduce by 30% as a result of increasing hydrogen production and decreasing costs for renewable energy technology.

## **7. CHAPTER: IMPLICATIONS**

New clean energy systems will play a critical role in significantly reducing emissions, achieving net-zero targets, and decreasing the future influences of climate change (ETC, 2023). Due to the growing demand for green energy in energy-intensive sectors, it is estimated that Türkiye's green hydrogen demand may reach 1-1.5 Mt by 2030 and 2-2.5 Mt by 2050. Research and development initiatives aiming at advancing the adoption of green hydrogen production technologies are currently underway. For airport ground equipment, energy efficiency and the source of electricity used (e.g., grid power, renewable sources) play an important role in determining its environmental impact.

Hydrogen is a capable energy carrier that has the potential to decrease airport emissions. Various challenges prevent the commercialization and acceptance of the hydrogen transition. Stakeholder engagement is crucial for the development of a local hydrogen ecosystem, as stakeholders are essential for supplying technology and creating demand. Airports should handle simultaneous goals for stakeholders.

Hydrogen is currently not a feasible rival to fossil fuels, although it is anticipated to become more competitive by 2040. Additionally, hydrogen offers significant benefits for airports and their stakeholders. It is important to provide guidelines to practitioners on how to construct an airport hydrogen ecosystem and the implications to be implemented to cope with the hydrogen transition. Furthermore, the analysis can aid in the advancement of infrastructure and policy strategies. Developing a suitable business model is difficult, and consequently, policymakers support is crucial for promoting market growth and reducing uncertainty.

Transitioning to hydrogen as an aviation fuel requires a broad range of technical and security, and safety challenges. There are several obstacles to the transition to domestic hydrogen, including high production costs, infrastructure requirements, uncertainty in renewable energy supply, lack of policy support, and financing constraints (BloombergNEF, 2022). In terms of sales, while regional centres are

increasingly moving towards Türkiye, development efforts in this field are currently dominant. However, space, cost, and grid limitations for imports may become bottlenecks. Efforts should be accelerated to find solutions to overcome these restrictions, particularly for Europe.

One of the technical challenges is hydrogen storage capability. Hydrogen can be stored in liquid or gaseous form. However, because there is space available, liquefied HST can be an appropriate type for airports (IEA, 2019). As an alternative, some places could be able to store hydrogen more underground. This might only be practical, though, depending on particular geological conditions. The characteristics are often inappropriate and coincide with the airport's location. However, to maintain appropriate operations, airports require a certain buffer for supply interruptions of hydrogen. To meet the increasing demand for hydrogen, the most effective approach to meet the hydrogen supply needs will be the production of hydrogen through electrolysis, preferably at an airport or a nearby airport. Although a 10% improvement in efficiency has been projected by the year 2030, it has been suggested that further improvements can be achieved through technological advancements (Gu et al., 2023). Hydrogen can be transported to airports via many modes of transportation, such as trucks, trains, and pipelines, or it can be generated directly at airports. If hydrogen is transported to airports in its gaseous state or produced on-site, it must undergo a liquefaction procedure before it can be stored or replenished.

For the first implication of this transition for security and safety challenges, ***airport rescue, and firefighting***, the physical characteristics of hydrogen vary significantly from conventional fuel. As a result, rescue and firefighting procedures in the airport should be revised and adapted to meet the additional challenges hydrogen poses. New specialized equipment, training, and expertise are necessary to acquire for this transition.

***The second attempt for the deployment of hydrogen is developing appropriate regulations, policies, and standards.*** Currently, attempts are underway to provide technical standards and regulatory frameworks for the safety and certification of hydrogen fuel systems. Policymakers should take a proactive approach to alleviate the burden on businesses during this transformation by developing a range of action plans. These measures should include fuel and electricity subsidies, decreases in fuel

taxes and excise duties, value-added tax discounts, and support for public transport, all aimed at facilitating the green transformation (OECD, 2023). Additionally, leading hydrogen applications should receive targeted support from local and global authorities.

Another implication is ***fleet optimization for ground support equipment***, and right-sizing the fleet can reduce fuel consumption and emissions. Regular maintenance and tuning of GSE engines can ensure optimal performance, reduce emissions, and improve fuel efficiency. Retrofitting older equipment with emission-reducing technologies can also help decrease the carbon footprint. Energy consumption for GSEs can be optimized with operational practices. Implementing operational practices such as reducing idle time, optimizing routes, and using power units on the ground instead of running engines can significantly reduce fuel consumption and emissions.

***Training and education of employees is another implication to deal with the challenges of the hydrogen transition.*** When airports start using hydrogen, employees must have the proper safety training to operate the newly acquired equipment and adapt to the new working environments. Employees engaged in hydrogen operations need to be knowledgeable about the recent regulations and capable of identifying potential risks related to the new fuel. To scale up hydrogen, a coordinated and comprehensive approach across the value chain is essential to develop the necessary skills to support hydrogen expansion.

***Increased collaboration and building trust in to hydrogen transition*** are crucial. Thus, sharing hydrogen-related information and theoretical knowledge enables the safe sharing of information and builds trust pathways and outcomes across stakeholders. In this context, Türkiye aims to collaborate with both public and private sectors to advance the industry by enhancing technology, standards, and strategies, while supporting commercial demand and investments across the supply chain. Governments establish objectives and foster partnerships to enhance transparency, participation, and collaboration, facilitating risk-sharing among stakeholders during this transition. To increase the incentives for hydrogen production and usage in Türkiye, the government should establish funding for R&D activities and increase incentives based on the hydrogen transition. Türkiye plans to

develop an incentive mechanism to promote the practice of green hydrogen in carbon-intensive industries, with the transportation sector identified as a priority customer.

***Advancing technological developments within existing systems*** is essential to establishing sustainable production and storage approaches. These advancements are critical to reducing the dominant role of fossil fuels in energy systems, particularly in applications like deploying hydrogen in GSE. A key step toward ushering in the 'hydrogen age' is the seamless integration of these technologies while promoting sustainable approaches (Sharma et al., 2021). Digital platforms serve as systems that cultivate trust and facilitate progress. Developing standardized and modular designs that facilitate collaboration among all stakeholders, efficiently managing potential hydrogen demands across the supply chain, and ensuring effective project management will be crucial steps in this transformation.

#### ***Increasing demand for hydrogen***

According to the national hydrogen technology strategy and roadmap, Türkiye aims to expand its hydrogen electrolyser capacity significantly. The target is to achieve 2 GW, 5 GW, and 70 GW by 2030, 2035, and 2053. Additionally, the strategy seeks to lower hydrogen production costs to competitive levels, with projections of 2.4 USD/kg by 2035 and 1.2 USD/kg by 2053.

#### ***Creating market opportunities for companies looking to enter the hydrogen market***

Companies seeking to enter the hydrogen market should assess its potential carefully, evaluating growth opportunities and key hydrogen application areas. Conducting a thorough competitive analysis will help identify unique competencies that can provide a competitive advantage. For Türkiye to thrive in the hydrogen market, it must develop and implement a distinctive market entry strategy. Türkiye has the potential to be a green hydrogen supplier for European and neighbouring countries due to several advantages, including its expanding renewable energy capacity, geographic proximity to key markets, extensive natural gas pipeline infrastructure, robust logistics capabilities, abundant natural resources, and relatively low green hydrogen production costs. As a result, energy producers, distributors, pipeline operators, logistics providers, and technology companies leading this transformation will play pivotal roles in capitalizing on these emerging business opportunities.

### ***Development of infrastructure***

To achieve decarbonization, energy-efficient infrastructure, eco-friendly technologies, and waste management systems should be developed by accelerating sustainable initiatives. A crucial part of the overall planning process is land use. To develop hydrogen airports, additional infrastructure could be needed, such as liquefaction plants, hydrogen manufacturing plants, and storage tanks (Gu et al., 2023).

### ***Effect of economies of scale***

Cost reductions for hydrogen can be achieved in many areas of the value chain through economies of scale. For example, hydrogen production and transportation costs can be decreased by applying economies of scale. In addition, costs can be reduced by providing an institutional framework, technological advances, availability of skilled labour, and appropriate geographical conditions.

### ***Development of the hydrogen hub***

Hydrogen hubs are critical to the global energy ecosystem in line with the goal of decarbonization. Hydrogen hubs support the efforts of many countries to reduce global greenhouse gas emissions. These mechanisms, which encourage further innovation in clean energy, create economies of scale at the local level that streamline the costs of hydrogen production. As hydrogen becomes more affordable, its applicability will increase, and it will become an important energy carrier across the world.

### ***Formulating strategies for risk mitigation***

Developing a commitment system to mitigate potential risks is essential for ensuring that government regulations are effectively managed in collaboration with stakeholders. This approach will support supply chain expansion and establish a competitive market mechanism to minimize risks associated with H<sub>2</sub> procurement.

***Cost-related regulations*** are a fundamental requirement for the successful transition to hydrogen. Initial investments, operational costs, and capital costs are critical factors that must be addressed for an effective hydrogen transition. At this point, digital technologies empowered by data analytics and enhanced O&M practices should also contribute to lower O&M costs.

***The environmental advantages of the hydrogen transition are among the most significant outcomes of this shift.*** The development of zero-carbon emission strategies and hydrogen conversion is crucial in shifting the focus from an 'economic' to a 'socio-economic-environmental' perspective. From both environmental and social standpoints, it has become a cornerstone of sustainability, representing a shared value among a broad range of stakeholders.

The transition to hydrogen provides significant opportunities in terms of social, environmental, and economic aspects in line with the Sustainable Development Goals. Thus, it simultaneously provides the triple bottom line of sustainability. In terms of the environment, especially green hydrogen production reduces greenhouse gas emissions by reducing dependence on fossil fuels and provides positive effects on the environment. In terms of social aspects, the reduction of air pollution directly positively affects public health. In addition, the hydrogen sector can create new business opportunities in many areas such as production, distribution, infrastructure, and R&D, and thus, it provides local employment and income generation opportunities. Understanding the energy transformation process facilitates society's adaptation to technological change. In terms of the economy, it contributes to the transformation of industrial policies by encouraging the formation of new value chains; at the same time, it increases energy supply security by reducing dependence on imported energy sources. However, for this transformation to be realized inclusively and fairly, infrastructure investments, regulations, and social acceptance processes need to be managed effectively.

## **8. CHAPTER: CONCLUSIONS**

This study investigates the economic feasibility of switching to hydrogen in airport ground equipment to achieve zero carbon. Within the scope of the study, a simulation model was developed in Python to determine and implement the demand and supply of the energy system. According to the results of the study, both the increase in the number of hydrogen vehicles and the impact of the carbon emission tax were evaluated with what-if scenario analyses. According to the results, the transition to hydrogen requires significant investment costs, but it is seen that the transition to hydrogen will provide a competitive advantage in the long term and is a profitable investment, especially when carbon emission taxes are considered in the system.

Hydrogen production and use in Türkiye are still in their early stages. However, due to its high renewable energy potential (solar and wind, etc.), Turkey may have an advantageous position for green hydrogen and may be in a position to progress in parallel with international markets. However, energy costs, technological developments, policies, and incentives are directly effective in making this transition economically advantageous. Decreases in the cost of renewable energy sources have an important share in reducing green hydrogen production costs in this transition. Increasing the efficiency of the electrolyzer and developments in production technologies reduce hydrogen production costs. Especially in developing countries like Turkey, incentives provided by governments and carbon pricing mechanisms are effective in making countries competitive in the transition to green hydrogen. It is necessary to increase the infrastructure investments required for the storage, transportation, and distribution of hydrogen, which is one of the important challenges of hydrogen. It is expected that the costs of green hydrogen will decrease through economies of scale and technological improvements.

Türkiye's planned YEKA (Renewable Energy Resource Area) projects for the post-2030 period, hydrogen valley projects such as the Southern Marmara Hydrogen Coast Project, domestic electrolyzer investment and production, and EU-supported

funds are expected to reduce the price. With the carbon pricing mechanisms to be implemented in some important sectors; the target of the IEA (2024), to reduce the cost of green hydrogen to below 1 USD/kg by 2050, the target of the gradual transition and price reduction between 2035-2053 in the Hydrogen Roadmap plan of the Ministry of Energy and Natural Resources of Turkey, and the target of the green hydrogen price in developing countries to fall to 1-1.5 USD/kg around 2050, as set forth by the Hydrogen Council, can be achieved.

The major limitations of this transition are that the production infrastructure is still developing. Hydrogen production is in its early stages, and large-scale green hydrogen projects are still in the feasibility or pilot stages. The pipelines, filling stations, and logistics systems required for storage, transportation, and distribution, which are the most important stages of the hydrogen value chain, are still in the development stage. Since all equipment is imported at this stage, exchange rate fluctuations significantly affect prices. Although renewable energy investments have recently increased in Turkey, system costs are still seen as higher than in Europe.

As a limitation of the study, as the model is developed based on a large-scale airport with particular operational characteristics, extrapolating the results to other airports requires careful consideration of their specific infrastructural and logistical differences. As hydrogen adoption remains in the early stages of commercialization, several technical performance parameters rely on theoretical estimations or data derived from pilot-scale implementations. Given the evolving nature of national and international regulations, the model may have limitations in accurately capturing the potential impacts of future regulatory frameworks.

As a future work of the study, the integration of simulation outputs into decision support systems to assist airport operators in evaluating the feasibility, operational planning, and environmental impact of hydrogen-based airport ground services. The model can be expanded to incorporate various types of ground support equipment to enhance its comprehensiveness and applicability with technological development. Future studies can include comparative scenario analyses across airports of varying sizes and geographic locations to assess the scalability and adaptability of hydrogen-based airport ground services implementation. Incorporating real-time data from IoT-

based ground service can improve the model's reliability and responsiveness to operational variations.





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## APPENDICES

### APPENDIX 1

| 8      | 7     | 6    | 5    | 4    | 3    | 2    | 1    |      |
|--------|-------|------|------|------|------|------|------|------|
| 130,35 | 23,42 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2021 |
| 118,08 | 33,83 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2022 |
| 115,22 | 31,22 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2023 |
| 121,22 | 29,49 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2024 |
| 118,17 | 31,51 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2025 |
| 118,20 | 30,74 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2026 |
| 119,20 | 30,58 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2027 |
| 118,52 | 30,95 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 202  |
| 118,64 | 30,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2029 |
| 118,79 | 30,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2030 |
| 118,65 | 30,82 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2031 |
| 118,69 | 30,78 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2032 |
| 118,71 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2033 |
| 118,69 | 30,80 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2034 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2035 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2036 |
| 118,69 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2037 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2038 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2039 |
| 118,69 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2040 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2041 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2042 |
| 118,69 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2043 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2044 |
| 118,69 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2045 |
| 118,69 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2046 |
| 118,70 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2047 |
| 118,69 | 30,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2048 |



| 32     | 31    | 30   | 29   | 28   | 27   | 26   | 25   | 24   | 23   | 22   | 21   |
|--------|-------|------|------|------|------|------|------|------|------|------|------|
| 119,25 | 29,49 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 111,95 | 32,09 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 112,00 | 29,49 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 114,40 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 112,78 | 30,65 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,06 | 30,16 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,41 | 30,39 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,09 | 30,40 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,32 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,23 | 30,37 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,17 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,35 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,20 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 113,19 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |



|        |       |      |      |      |      |      |      |      |      |      |      |
|--------|-------|------|------|------|------|------|------|------|------|------|------|
| 56     | 55    | 54   | 53   | 52   | 51   | 50   | 49   | 48   | 47   | 46   | 45   |
| 83,64  | 33,83 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 110,94 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 110,53 | 28,62 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 101,70 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 107,72 | 29,97 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,65 | 29,84 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 105,36 | 30,25 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,58 | 30,02 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,20 | 30,04 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,05 | 30,10 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,27 | 30,05 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,17 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,16 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,20 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,19 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,19 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,19 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,19 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,18 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 106,19 | 30,07 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |



|        |       |      |      |      |      |      |      |      |      |      |      |
|--------|-------|------|------|------|------|------|------|------|------|------|------|
| 80     | 79    | 78   | 77   | 76   | 75   | 74   | 73   | 72   | 71   | 70   | 69   |
| 110,24 | 27,75 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 131,94 | 29,49 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 109,94 | 28,62 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,37 | 28,62 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 119,75 | 28,91 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 115,69 | 28,72 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,60 | 28,75 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,68 | 28,79 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 116,99 | 28,75 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,43 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,37 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,26 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,35 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,33 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,31 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,33 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,76 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 117,32 | 28,77 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |



| 104    | 103   | 102  | 101  | 100  | 99   | 98   | 97   | 96   | 95   | 94   | 93   |
|--------|-------|------|------|------|------|------|------|------|------|------|------|
| 127,51 | 28,62 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 127,62 | 32,96 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 112,76 | 30,36 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 122,63 | 30,65 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 121,00 | 31,32 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 118,80 | 30,78 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,81 | 30,92 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,20 | 31,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 119,94 | 30,90 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,32 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,15 | 30,95 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,14 | 30,93 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,20 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,16 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,18 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 120,17 | 30,94 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |

|      |      |      |      |      |       |        |        |        |        |        |        |
|------|------|------|------|------|-------|--------|--------|--------|--------|--------|--------|
| 116  | 115  | 114  | 113  | 112  | 111   | 110    | 109    | 108    | 107    | 106    | 105    |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 67,82 | 147,57 | 191,64 | 192,64 | 168,83 | 160,64 | 157,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,11 | 141,13 | 198,71 | 210,25 | 242,08 | 213,65 | 149,24 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 70,69 | 147,53 | 180,17 | 146,54 | 155,06 | 147,73 | 137,40 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,21 | 145,41 | 190,17 | 183,14 | 188,66 | 174,01 | 148,13 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,67 | 144,69 | 189,68 | 179,98 | 195,27 | 178,46 | 144,92 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,86 | 145,88 | 186,68 | 169,89 | 179,66 | 166,73 | 143,48 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,58 | 145,33 | 188,84 | 177,67 | 187,86 | 173,07 | 145,51 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,70 | 145,30 | 188,40 | 175,84 | 187,60 | 172,75 | 144,64 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,71 | 145,50 | 187,97 | 174,47 | 185,04 | 170,85 | 144,54 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,66 | 145,37 | 188,41 | 175,99 | 186,83 | 172,22 | 144,90 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,39 | 188,26 | 175,44 | 186,49 | 171,94 | 144,69 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,42 | 188,21 | 175,30 | 186,12 | 171,67 | 144,71 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,29 | 175,58 | 186,48 | 171,95 | 144,77 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,44 | 186,36 | 171,85 | 144,72 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,41 | 188,25 | 175,44 | 186,32 | 171,82 | 144,73 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,27 | 175,48 | 186,39 | 171,88 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,45 | 186,36 | 171,85 | 144,73 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,37 | 171,86 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,86 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,86 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,86 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,86 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,68 | 145,40 | 188,26 | 175,46 | 186,36 | 171,85 | 144,74 |
| 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 69,69 | 145,40 | 188,26 | 175,46 | 186,36 | 171,86 | 144,74 |





## APPENDIX 2

| 10    | 9     | 8    | 7    | 6    | 5    | 4    | 3    | 2    | 1    |      |
|-------|-------|------|------|------|------|------|------|------|------|------|
| 12,16 | 11,48 | 8,97 | 7,17 | 7,16 | 7,04 | 7,41 | 7,87 | 7,85 | 8,15 | 2021 |
| 11,35 | 9,33  | 6,14 | 4,01 | 4,08 | 4,24 | 4,25 | 4,31 | 4,35 | 4,51 | 2022 |
| 10,49 | 8,36  | 5,27 | 3,34 | 3,36 | 3,64 | 3,89 | 4,24 | 4,69 | 5,38 | 2023 |
| 11,33 | 9,72  | 6,79 | 4,84 | 4,87 | 4,97 | 5,18 | 5,47 | 5,63 | 6,01 | 2024 |
| 11,06 | 9,14  | 6,07 | 4,06 | 4,10 | 4,28 | 4,44 | 4,67 | 4,89 | 5,30 | 2025 |
| 10,96 | 9,07  | 6,04 | 4,08 | 4,11 | 4,30 | 4,50 | 4,80 | 5,07 | 5,56 | 2026 |
| 11,12 | 9,31  | 6,30 | 4,33 | 4,36 | 4,52 | 4,71 | 4,98 | 5,20 | 5,63 | 2027 |
| 11,05 | 9,17  | 6,14 | 4,16 | 4,19 | 4,37 | 4,55 | 4,82 | 5,05 | 5,50 | 2028 |
| 11,04 | 9,19  | 6,16 | 4,19 | 4,22 | 4,40 | 4,59 | 4,86 | 5,11 | 5,56 | 2029 |
| 11,07 | 9,22  | 6,20 | 4,22 | 4,26 | 4,43 | 4,62 | 4,89 | 5,12 | 5,56 | 2030 |
| 11,05 | 9,20  | 6,17 | 4,19 | 4,22 | 4,40 | 4,59 | 4,86 | 5,09 | 5,54 | 2031 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,11 | 5,56 | 2032 |
| 11,06 | 9,21  | 6,18 | 4,21 | 4,24 | 4,41 | 4,60 | 4,87 | 5,11 | 5,55 | 2033 |
| 11,05 | 9,20  | 6,17 | 4,20 | 4,23 | 4,40 | 4,59 | 4,87 | 5,10 | 5,55 | 2034 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2035 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2036 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2037 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2038 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2039 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2040 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2041 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2042 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2043 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2044 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2045 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2046 |
| 11,06 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2047 |
| 11,05 | 9,20  | 6,18 | 4,20 | 4,23 | 4,41 | 4,60 | 4,87 | 5,10 | 5,55 | 2048 |















|       |       |       |       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 106   | 105   | 104   | 103   | 102   | 101   | 100   | 99    | 98    | 97    | 96    | 95    |
| 14,25 | 13,30 | 10,26 | 8,04  | 8,88  | 10,34 | 11,37 | 11,88 | 12,05 | 12,23 | 12,35 | 12,33 |
| 15,07 | 14,11 | 13,08 | 11,74 | 11,61 | 11,40 | 11,44 | 11,55 | 11,60 | 11,78 | 11,61 | 11,08 |
| 8,89  | 6,97  | 4,53  | 2,97  | 2,96  | 3,12  | 3,15  | 3,10  | 3,27  | 3,25  | 3,40  | 3,54  |
| 12,74 | 11,46 | 9,29  | 7,58  | 7,82  | 8,29  | 8,65  | 8,84  | 8,97  | 9,09  | 9,12  | 8,98  |
| 12,23 | 10,85 | 8,97  | 7,43  | 7,46  | 7,60  | 7,75  | 7,83  | 7,95  | 8,04  | 8,04  | 7,87  |
| 11,29 | 9,76  | 7,60  | 5,99  | 6,08  | 6,34  | 6,52  | 6,59  | 6,73  | 6,79  | 6,85  | 6,80  |
| 12,09 | 10,69 | 8,62  | 7,00  | 7,12  | 7,41  | 7,64  | 7,76  | 7,88  | 7,97  | 8,01  | 7,88  |
| 11,87 | 10,43 | 8,39  | 6,81  | 6,89  | 7,12  | 7,30  | 7,39  | 7,52  | 7,60  | 7,63  | 7,52  |
| 11,75 | 10,29 | 8,20  | 6,60  | 6,70  | 6,95  | 7,15  | 7,25  | 7,38  | 7,46  | 7,50  | 7,40  |
| 11,90 | 10,47 | 8,40  | 6,81  | 6,90  | 7,16  | 7,36  | 7,46  | 7,59  | 7,68  | 7,71  | 7,60  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,27  | 7,37  | 7,50  | 7,58  | 7,62  | 7,50  |
| 11,83 | 10,39 | 8,31  | 6,72  | 6,81  | 7,06  | 7,26  | 7,36  | 7,49  | 7,57  | 7,61  | 7,50  |
| 11,86 | 10,42 | 8,35  | 6,75  | 6,85  | 7,10  | 7,30  | 7,40  | 7,53  | 7,61  | 7,65  | 7,53  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,58  | 7,62  | 7,51  |
| 11,84 | 10,40 | 8,33  | 6,73  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,85 | 10,41 | 8,34  | 6,74  | 6,83  | 7,09  | 7,29  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,40 | 8,33  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |
| 11,84 | 10,41 | 8,34  | 6,74  | 6,83  | 7,08  | 7,28  | 7,38  | 7,51  | 7,59  | 7,63  | 7,52  |



|       |       |
|-------|-------|
| 120   | 119   |
| 7,76  | 8,02  |
| 12,81 | 12,85 |
| 4,28  | 5,45  |
| 8,28  | 8,77  |
| 8,46  | 9,02  |
| 7,01  | 7,75  |
| 7,92  | 8,52  |
| 7,79  | 8,43  |
| 7,57  | 8,23  |
| 7,76  | 8,39  |
| 7,71  | 8,35  |
| 7,68  | 8,33  |
| 7,72  | 8,36  |
| 7,70  | 8,34  |
| 7,70  | 8,34  |
| 7,71  | 8,35  |
| 7,70  | 8,34  |
| 7,70  | 8,34  |
| 7,70  | 8,35  |
| 7,70  | 8,34  |
| 7,70  | 8,34  |
| 7,70  | 8,35  |
| 7,70  | 8,34  |
| 7,70  | 8,35  |
| 7,70  | 8,34  |
| 7,70  | 8,35  |
| 7,70  | 8,35  |

