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Use of GH_2 in Airport Terminal Operations

Feasibility study

Preface

This feasibility study has been conducted as part of the BSR HyAirport programme by Granlund Oy in the summer and autumn of 2024.

Established in 1960, Granlund is a prominent expert in the real estate and construction sector, focused on making buildings smarter, and more functional, and improving the well-being of occupants. With over 1,400 experts primarily in Finland, and expanding into Sweden and the United Kingdom, Granlund addresses the complex challenges of the built environment through innovative solutions.

As the Finnish market leader in MEP (Mechanical, Electrical, and Plumbing) design, Granlund ensures technical building systems' functionality, safety, and energy efficiency. Services span engineering, consultancy, and construction management, including architectural and structural design, property management, and energy efficiency, supporting both new construction and existing properties through the green transition.

Granlund also offers advanced construction management, supervision, and project management services, with expertise in cost control, 4D planning, and operational verification. Granlund Manager, Finland's leading property management software, consolidates essential data, while Granlund Designer brings transparency to construction projects.

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1. Introduction and Background of the Feasibility Work

Feasibility Study Objective and Scope

This feasibility study within the BSR HyAirport programme focuses on identifying and evaluating potential applications of hydrogen in airport terminal operations. The study primarily explores how fixed installations at airports, such as emergency power generators, combustion engines, and fuel cell-based systems (including CHP generation), can be adapted to use hydrogen as a fuel. Additionally, opportunities for electricity storage linked to these applications will be assessed.

Feasibility study contents

- *The work is divided into two key phases*:

  - Literature Review – This stage will map potential hydrogen applications for airport terminal operations, particularly for fixed installations. The review will analyze current hydrogen use in airports or similar facilities and identify emerging technologies that, while not yet commercialized, show potential for future airport applications. Input from partner organizations will further enrich the research.

  - Feasibility Calculations – Based on the findings from the literature review, the study will conduct calculations for a number of case examples. These will assess the viability of hydrogen-powered solutions, such as hydrogen-based emergency power generation in various airport sizes, using actual data from partner airports of the programme. These calculations will estimate hydrogen demand and the potential CO_2 emissions reductions for large, medium, and small-sized airports.

Study Objective and Audience

This report, prepared by Granlund's experts, serves as a comprehensive feasibility study aimed at a diverse audience, from professionals with limited knowledge of hydrogen technology to experts in the field. It bridges a critical gap in current research by offering a consolidated, practical exploration of hydrogen's potential application in airport operations. The study aims to provide evidence on the potential of hydrogen in fixer installations in an airport environment to complement other studies conducted during the BSR HyAirport programme.

The theoretical review, presented in Sections 3 to 7, covers key topics such as hydrogen production technologies (including its various color classifications) and insights from relevant research projects. These sections lay the groundwork for understanding the broader context of hydrogen technologies.

The practical analysis presented in Sections 8 through 11 provides a comprehensive assessment of energy demand through two case study examples, focusing on a large Baltic Sea Region airport. These case studies examine facilities with an average annual electricity demand of approximately 30,000 MWh and a heat demand of around 20,000 MWh. The framework of this analysis is designed to be scalable, making it applicable to a smaller airport with energy consumption below 24,000 MWh (including electricity demands exceeding 16,000 MWh and heat demands above 7,000 MWh), as well as to a larger airport, with energy needs approaching 40,000 MWh for electricity and 25,000 MWh for heat. While the calculations presented are general, they offer valuable insights into the feasibility and potential benefits of integrating hydrogen-based energy solutions within airport infrastructure.

2. Summary of the Conducted Work

This feasibility study, conducted by Granlund Oy as part of the BSR HyAirport project, evaluates the integration of hydrogen-based technologies into airport terminal operations for Airports in the Baltic Sea Region. The study focuses on exploring the feasibility of using hydrogen for fixed installations, such as backup power generation, fuel cell (FC) systems, and combined heat and power (CHP) solutions. Additionally, opportunities for electricity storage linked to these hydrogen applications were examined.

➢ The work is divided into two main phases:

- A literature review on existing hydrogen applications in airports, identifying emerging technologies and relevant global use cases.
- Case-specific calculations for potential hydrogen applications, providing insights into hydrogen consumption, CO_2 emissions abatement, and storage requirements. These calculations were supported by data provided by the project's partner airports.

The study also addresses a gap in available research by providing a clear, consolidated overview of hydrogen's potential role in airport terminal operations. This report is designed for a broad audience, catering to both individuals unfamiliar with hydrogen technology and experts in the field.

2.1. Summary of Key Calculations

The case studies in this report offer detailed evaluations of hydrogen-powered FC applications at a large Baltic Sea Region Airport. Both case studies, which focus on backup power generation and combined heat and power (CHP) systems, include comprehensive calculations aligned with the project's objectives.

For Case 1, which analyzes hydrogen-powered FCs for backup power generation, the report meticulously outlines the hydrogen production potential, consumption, and storage requirements. The calculations for a large Baltic Sea Region Airport reveal hydrogen consumption at circa 600 MWh/a with a corresponding hydrogen storage requirement of 500 m³. Integration with electricity markets is also examined, supporting the overall feasibility of the system. However, when considering a practical application, it is clear that smaller-scale storage—designed e.g. once-a-month refills—is more practical. In real-world scenarios, only 10-15% of the total hydrogen capacity is likely to be utilized each month, making a smaller, more flexible storage investment (50 to 75 m³) more realistic.

In Case 2, which focuses on CHP systems utilizing hydrogen FCs, the analysis delves into both power and heat generation. For a 14 MW system (hydrogen input), the proposed hydrogen FC CHP plant can theoretically meet the annual power demand of 59 GWh and heat demand of 36 GWh. Additionally, surplus heat utilization and energy storage integration are explored, aligning with the objectives set out in the case study. A practical alternative scenario was also proposed, suggesting a 3 MW CHP system to theoretically meet an annual power demand of 10 GWh and heat demand of 7 GWh. This adjustment provides a more scalable and economically feasible option for a range of different-sized airports.

Both cases were subjected to detailed sensitivity analyses, which examined the effects of fluctuating hydrogen prices and varying system efficiencies. These analyses provided critical insights into the economic feasibility of hydrogen-powered systems under different market conditions.

Furthermore, the hydrogen potential for a large Baltic Sea Region Airport was compared to that of mid-sized and small airports in Baltic Sea Region, allowing for a broader understanding of scalability across different airport sizes.

Overall, the findings demonstrate that hydrogen-powered systems offer significant potential for decarbonizing airport operations and represent a sustainable energy solution for the future.

This feasibility study is based on data collected from 2021 to 2024, reflecting the current state of hydrogen technology and its nascent deployment within the energy sector. As this technology remains relatively undeveloped and expensive, with limited historical use in many regions, it is important to approach future predictions with caution. While we can draw parallels from the historical evolution of power batteries—observing their gradual adoption and integration across various sectors, including consumer electronics and electric vehicles—the long-term trajectory of hydrogen technology remains uncertain.

Predictive analyses must be grounded in historical trends while acknowledging the unique challenges and opportunities that hydrogen presents. The success of hydrogen technologies will ultimately depend on a confluence of factors, including technological advancements, market dynamics, and the evolution of regulatory landscapes. As we look to the future, the strategic alignment of investment, research, and collaborative efforts will be crucial to unlocking the full potential of hydrogen as a sustainable energy source within the aviation industry and beyond.

3. Introduction to Topic

3.1. The Current State of Global Greenhouse Gas Emissions and the Potential of Hydrogen

Recent research highlights the alarming increase in global greenhouse gas (GHG) emissions, which have reached unprecedented levels, posing a severe threat to humanity as global warming accelerates. The primary driver of this increase is the burning of fossil fuels for energy, which significantly raises the concentration of carbon dioxide in the atmosphere, trapping heat and elevating global temperatures. The 2015 Paris Agreement aims to limit this temperature rise to 1.5°C, striving to keep the increase this century below 2°C above pre-industrial levels, necessitating a robust global effort to combat climate change.

Hydrogen emerges as a crucial element in addressing these energy challenges. It offers significant potential to reduce emissions, particularly in industries such as iron and steel, chemicals, and long-distance transportation. Moreover, hydrogen has a wide range of applications, including the production of fertilizers and oil refining [Zainal et al., 2024]. It is non-toxic, non-corrosive, non-self-igniting, and burns to produce water vapor without emitting CO_2 [Energy.gov, 2024].

However, the clean and widespread adoption of hydrogen in global energy transitions faces substantial challenges. The development of hydrogen infrastructure is slow, hindering its broader adoption. Additionally, producing hydrogen from low-carbon energy sources remains prohibitively expensive, with current hydrogen supplies primarily derived from natural gas and coal. Existing regulations also impede the growth of a clean hydrogen industry. Addressing these challenges is crucial for hydrogen to play a significant role in achieving a sustainable and low-carbon future. [Zainal et al., 2024].

In Europe, captive hydrogen production is the most common option, comprising around two-thirds of all hydrogen production [FCHO, 2020]. Hydrogen is currently used in oil refineries to remove impurities and upgrade heavy oil fractions, as a feedstock for chemical production (such as ammonia and methanol), and as a reducing agent in iron making.

3.2. Hydrogen as a Renewable Energy Resource

Hydrogen is the most abundant element in the universe, comprising 70% of its matter, including elements such as oxygen and nitrogen. It is found in water, plants, and the sun. Due to its lightweight nature, hydrogen evaporates from the Earth’s atmosphere under solar radiation.

As the simplest element, hydrogen consists of one proton and one electron. It is usually found combined with other elements, such as in water (H_2O), where it bonds with oxygen. Hydrogen can be extracted from water, natural gas, or biomass and serves as a clean energy source for powering and heating homes. It can be produced in various forms: CO_2-intensive ‘grey’ hydrogen, CO_2-neutral ‘blue’ hydrogen, and CO_2-free ‘green’ hydrogen from renewable energy sources [Energy.gov, 2024].

Hydrogen is known for its efficiency and renewability. It is non-toxic and holds the potential to create numerous employment opportunities. Given its versatility and abundance, hydrogen is a promising solution for future energy needs and environmental sustainability [Zainal et al., 2024].

3.3. The Color Spectrum of Hydrogen

Hydrogen is a colorless gas that can be categorized by thirteen color codes (Figure 1) based on its production method or CO_2 balance. These codes include green, blue, grey, brown, black, turquoise, purple, pink, red, and white [Zainal et al., 2024]. In the energy industry, colors like green, blue, brown, yellow, turquoise, and pink distinguish different types of hydrogen production. Since no global naming convention exists, meanings can vary over time and between countries [Arcos and Santos, 2023].

Hydrogen Production Methods and CO_2 Balance:

- Brown, Grey, and Black Hydrogen: These types contribute significantly to GHG emissions as they are derived from fossil fuels like coal and natural gas. Gray hydrogen, often produced via steam methane reforming (SMR), releases CO_2 and is commonly used in the petrochemical industry and for ammonia production. Black or brown hydrogen comes from coal gasification, releasing CO_2 and carbon monoxide.
- Green Hydrogen: A clean alternative, green hydrogen aims for zero emissions by using renewable energy sources like solar and wind power for water electrolysis. Despite being more expensive than blue hydrogen due to electrolyser material costs, recent advancements show promise. Green hydrogen production is carbon-emission-free, converting water into hydrogen and oxygen using electricity.
- Blue Hydrogen: Produced from fossil fuels with carbon capture and storage (CCS), blue hydrogen is more sustainable than traditional methods but still falls short of international GHG reduction targets.
- **Turquoise** Hydrogen: This type is produced via methane pyrolysis, consuming significantly less energy than water electrolysis and converting carbon into a solid form.
- **Aqua** Hydrogen: This technology involves placing oxygen into a sealed fuel deposit between grains of rock, using unswept petroleum as the fuel and the ground as the reactor vessel.
- Purple, Pink, and Red Hydrogen: These types are produced using nuclear power through different methods.
- White Hydrogen: Occurs naturally as a free gas in the continental crust, deep oceanic crust, volcanic gases, geysers, and hydrothermal systems.

- **Yellow** Hydrogen: Produced via electrolysis using electricity from the energy grid, with carbon emissions varying significantly depending on the grid's energy sources [Arcos and Santos, 2023].
- **Orange** Hydrogen: Refers to emerging processes that produce hydrogen using plastic waste as a feedstock. This low-cost, easily instrumented chemical process breaks down traditional hydrocarbon and biofuels into hydrogen without a carbon dioxide byproduct. Orange hydrogen is also produced using biomass and is present in organic forms such as accumulating municipal waste [Ind LLC, 2024]

Types of hydrogen colours	Definition by technologies used	Advantages	Drawbacks
	It is naturally occurring hydrogen molecules formed through fracking and found in underground deposits. Hydrogen is a byproduct of the industrial process.	Naturally occurring hydrogen	–
	Hydrogen is produced by water electrolysis using renewable energy sources such as solar, wind, and hydro.	1. Increase recycling 2. Promote bioenergy 3. Does not emit GHGs 4. Produce from clean electricity 5. Emits no carbon dioxide 6. Expected to have a lower price as it becomes more common.	1. High production costs 2. Energy losses 3. Lack of dedicated infrastructure 4. Need to ensure sustainability 5. Lack of value recognition
	Hydrogen is produced by SMR from fossil fuels (other than coal).	The most common form of hydrogen production.	1. Emits carbon dioxide 2. Emits other GHG 3. Continued use of some fossil fuels.
	Hydrogen from natural gas is produced through the SMR process to capture and bury GHGs.	1. Could capture and remove GHGs using carbon capture and storage (CCS) technology 2. Also known as low-carbon hydrogen.	1. Produce carbon dioxide as a byproduct
	Steam methanation of renewable natural gas with CCS.	1. Could capture and store carbon.	1. The process emits a large amount of carbon dioxide.
	Hydrogen is derived from the pyrolysis of methane (thermal splitting).	1. Produce hydrogen and solid carbon. 2. In the future, it may be valued as low-emission hydrogen, depending on several factors.	1. Generate a small number of GHGs
	Hydrogen is produced by coal gasification.	1. Produce liquefied hydrogen for low-emission usage.	1. This process emits large amounts of carbon dioxide, carbon monoxide, and other GHGs. (Opposite of green hydrogen)
	Hydrogen is produced using nuclear power plants. This chemo-thermal electrolysis process uses nuclear power and heat to split water.	1. Low carbon emissions	1. Use very high temperatures from a nuclear reactor. 2. Generate a small number of GHGs
	Hydrogen is produced using nuclear energy to power water electrolysis.	1. The steam generated from the nuclear reactors could be used for other hydrogen productions for more efficient electrolysis	1. Use very high temperatures from nuclear reactors. 2. Generate a small amount of GHGs.
	Hydrogen is produced from the energy grid via water electrolysis.	1. Hydrogen is produced through electrolysis using solar power.	1. Carbon emissions vary greatly depending on the sources used to power the grid.
	Thermal energy generated by nuclear power is used to power high-temperature catalytic water splitting. More minor, modular nuclear power plants are being implemented to augment wind, solar, and battery technology in the power sector.	1. No carbon dioxide emissions	1. Uses very high temperatures. 2. Generate a small amount of GHGs.
	Produced from waste plastics through gasification or pyrolysis with CCS.	1. Low raw material costs 2. Requires less energy.	1. At an early stage, more research is needed.

Figure 1. Explanation of the Hydrogen´s colors and technologies used [Zainal et al., 2024]

3.4. Production of Hydrogen and Technologies

Hydrogen is produced from fossil fuels and renewable sources. Hydrogen can be produced through various processes, utilizing different materials and methods. These include thermochemical, electrolytic, direct solar, and biological processes and they mean the following [Zainal et al., 2024]:

- *Thermochemical processes* release hydrogen from organic materials such as fossil fuels, biomass, or water through heat and chemical reactions. The main methods include :
  - *Natural Gas Reforming (Steam Methane Reforming or SMR):* This process involves reacting hydrocarbons with steam to produce a hydrogen and carbon monoxide mixture, known as syngas. It operates at high temperatures (700°C to 1000°C) and pressures (5–20 bar), depending on the desired yield, reactors, and catalysts [Di Nardo et al., 2024].
  - *Biomass Gasification:* This method converts biomass into hydrogen through decarbonization and separation processes. Hydrogen-rich compounds like methane, methanol, or ethanol are also produced through enzymatic hydrolysis and fermentation, which can be reformed to produce pure hydrogen via catalytic reactions [Energy.gov, 2024].
  - *Biomass-Derived Liquid Reforming: Liquid* fuel reacts with steam at high temperatures in the presence of a catalyst to produce reformate gas, mainly composed of hydrogen, carbon monoxide, and carbon dioxide. The carbon monoxide reacts with high-temperature steam in a water-gas shift reaction to produce additional hydrogen and carbon dioxide, after which the hydrogen is separated and purified [Energy.gov, 2024].
  - *Solar Thermochemical Hydrogen (STCH):* This method uses concentrated solar energy to thermally split water into hydrogen and oxygen at high temperatures through successive chemical reactions. STCH cycles are categorized into two-step and multi-step processes. Two-step cycles are easier to scale but require very high temperatures (1300–1800°C), while multi-step cycles perform better at lower temperatures (<1000°C) but increase system complexity [Song, 2022].
- *Electrolytic Processes*

Electrolysers use electricity to split water into hydrogen and oxygen, a mature technology that is evolving to efficiently use renewable energy. This method is commercially available and continuously improving.

- *Direct Solar Water Splitting Processes*

These processes use light energy to split water into hydrogen and oxygen. Though still in the research phase, they hold long-term potential for sustainable hydrogen production. Key methods include:

  - *Photoelectrochemical (PEC):* Hydrogen is generated from water using sunlight and specialized semiconductors known as photoelectrochemical materials, which harness light energy to directly split water molecules into hydrogen and oxygen. This long-term technological pathway holds the potential for producing hydrogen with minimal or zero greenhouse gas emissions.

- *Photobiological:* This process employs microorganisms and sunlight to convert water, and sometimes organic matter, into hydrogen. Currently in the early stages of research, this long-term technological pathway offers significant potential for sustainable hydrogen production with minimal environmental impact [Energy.gov, Hydrogen Production Processes, 2024].

➢ *Biological Processes*

Microorganisms like bacteria and algae produce hydrogen through biological reactions using sunlight or organic matter. These methods are in the development stage with pilot demonstrations, offering the potential for sustainable, low-carbon hydrogen production [Zainal et al., 2024]. Key processes include:

- *Microbial Biomass Conversion:* In fermentation-based systems, microorganisms like bacteria decompose organic matter to generate hydrogen. The organic matter can include refined sugars, raw biomass sources like corn stover, and even wastewater.
- *Photobiological:* In photolytic biological systems, microorganisms such as green microalgae or cyanobacteria harness sunlight to split water into oxygen and hydrogen ions. These hydrogen ions can then be combined directly or indirectly to release hydrogen gas.

Each of these hydrogen production methods presents unique advantages and challenges, contributing to a diverse portfolio of solutions for sustainable energy [Energy.gov, Hydrogen Production Processes, 2024].

3.4.1. Hydrogen Produced from Fossil Fuels

Hydrogen derived from fossil fuels is classified as blue hydrogen, with production methods primarily falling into *hydrocarbon reforming* and *pyrolysis* [Zainal et al., 2024]. The hydrocarbon reforming methods include:

➢ *Steam Reforming (SR):* This method produces grey hydrogen with high efficiency and low cost, but it has a significant carbon footprint. In contrast, electrolysis generates green hydrogen from renewable sources but loses nearly 70% of the energy input during the process.

➢ *Partial Oxidation (POX):* This process involves combustion with limited oxygen, resulting in the partial oxidation of carbon and the production of carbon monoxide (CO) instead of carbon dioxide (CO_2).

➢ *Autothermal Reforming (ATR):* ATR combines oxygen and carbon dioxide or steam in a reaction with methane to form syngas. The reaction occurs in a single chamber where methane is partially oxidized, making the process exothermic due to the oxidation.

3.4.2. Hydrogen Produced from Renewable Sources

Hydrogen produced from renewable sources is called green hydrogen, and the production methods include:

- *Biomass processes (*biological or thermochemical), and
- *Water splitting* (electrolysis, thermolysis, and photolysis).

The biological biomass pathway includes bio-photolysis, dark fermentation (DF), and photo fermentation (PF). The thermochemical biomass pathway includes pyrolysis, gasification, combustion, and liquefaction [Energy.gov, Hydrogen Production Processes, 2024].

A study commissioned by FlyZero has provided a comparison of the energy (in MJ) required to produce 1 MJ of stored energy via various pathways. These ratios help illustrate the energy efficiency of different fuel and energy storage technologies, with lower ratios indicating higher efficiency. The following table outlines the comparative figures (Table 1):

Table 1. Energy Efficiency of Different Pathways for Storing Energy

Energy Pathway	Energy Required to Produce 1 MJ of Stored Energy (Ratio)	Explanation
Kerosene	0.19	Energy used is mainly for oil extraction and refinement, as kerosene itself does not need "creation."
Battery Storage	1.09	Battery storage of electricity is relatively efficient from an energy perspective. However, poor gravimetric and volumetric densities limit its use in aviation.
Liquid Green Hydrogen (Electrolysis)	1.63	Producing 1 MJ of stored energy as green hydrogen requires 1.63 MJ, reflecting losses during electrolysis and compression.
Power-to-Liquid (PtL) SAF	2.55	The most energy-intensive pathway due to the complexity of producing synthetic aviation fuels via power-to-liquid technologies.

3.4.3. Hydrogen Costs

The table outlines the key hydrogen production costs and electrolyzer capital costs based on 2022 data. Grey hydrogen, produced from fossil fuels, remains the cheapest option, especially in regions like the Middle East and the US, where costs can be as low as €0.8 per kg. Blue hydrogen, incorporating carbon capture, is more expensive, ranging from €1.2 to €2 per kg. Green hydrogen, produced using renewable energy, has the highest costs, varying from €2.2 to €8.2 per kg. Capital costs for electrolyzers also differ, with alkaline electrolyzers being more affordable (€462 to €923 per kW), while PEM electrolyzers cost more (€646 to €1,569 per kW). The price of electricity, which makes up 90% of green hydrogen operating costs, is a significant factor in overall cost calculations.

This data (Table 2) highlights the significant cost variation between hydrogen production methods and technologies, as well as the importance of regional factors and electricity prices in determining total costs.

Table 2. Hydrogen Production and Capital Costs (2022 Data)

Category	Description	Cost Range	Reference
Hydrogen Production Costs			
Grey Hydrogen	Lowest-cost hydrogen, typically produced from fossil fuels (SMR)	€0.8 to €2.1 per kg	[Ajanovic et al., 2022]
Blue Hydrogen	Includes carbon capture and storage (CCS) costs	€1.2 to €2 per kg	[Ajanovic et al., 2022]
Green Hydrogen	Produced using renewable energy (RES)	€2.2 to €8.2 per kg	[Ajanovic et al., 2022]
Capital Costs of Electrolyzers			
Alkaline Electrolyzers	Traditional technology	€462 to €923 per kW	[Ajanovic et al., 2022]
PEM Electrolyzers	Advanced technology	€646 to €1,569 per kW	[Ajanovic et al., 2022]
Regional Hydrogen Cost Variations			
Grey Hydrogen	Lowest in the Middle East and US	Below €1 per kg	[Ajanovic et al., 2022]
Blue Hydrogen	Moderate production costs	€1.2 to €2 per kg	[Ajanovic et al., 2022]
Coal Gasification	Higher investment, but cheaper fuel input	Varies	[Ajanovic et al., 2022]
Biomass Gasification	Higher renewable potential	€1.6 to €3 per kg	[Ajanovic et al., 2022]
Cost Components for Green Hydrogen			
Investment Costs (Electrolyzers)	Main contributor to green hydrogen production	Significant	[Ajanovic et al., 2022]
Electricity Price	Represents 90% of total operating costs	Varies	[Ajanovic et al., 2022]

IRENA Cost Forecast for Green Hydrogen

According to the International Renewable Energy Agency (IRENA), green hydrogen costs are projected to decrease significantly in the coming years. Key factors contributing to this reduction include technological advancements, efficiency gains, and reductions in renewable electricity costs. IRENA anticipates that by 2030, green hydrogen will become cheaper than blue hydrogen.

Key drivers of the cost reduction forecast by IRENA:

- ✓ Up to 80% reduction in green hydrogen costs due to:
  - Lower electricity generation costs from renewable sources.
  - Improved efficiency in electrolysis technologies.
  - Increased operational hours (full-load hours) for electrolyzers.
  - Green hydrogen is expected to be cheaper than blue hydrogen by 2030.

3.4.4. Hydrogen Generation Efficiency and Methods

Hydrogen generation efficiency ranges from 65% to 75% using steam reforming (SR) of methane, while the partial oxidation (POX) process for methane yields around 50% efficiency. Water electrolysis, responsible for approximately 95% of total hydrogen production, is another significant method. Major car manufacturers, including Toyota, Honda, and BMW, remain committed to addressing hydrogen production costs and advancing this technology.

Hydrogen synthesis from hydrocarbons requires precise energy and temperature conditions. Industrial hydrogen production involves endothermic reactions, necessitating heat from external or internal sources. Although hydrogen generation at atmospheric pressure is thermodynamically favorable above 800°C, temperatures exceeding 1000°C are essential for substantial conversion rates in non-catalytic systems [Zainal et al., 2024].

Hydrogen production methods from fossil fuels include hydrocarbon reforming, steam reforming, partial oxidation, autothermal oxidation, and pyrolysis. Current technological advancements highlight the importance of catalysts in enhancing hydrogen production and managing critical parameters such as temperature and pressure. Key conclusions from these advancements are as follows:

- Catalysts can significantly increase hydrogen production.
- Different catalysts and temperatures impact hydrogen yield.
- The use of oxidants and high temperatures enhances hydrogen concentration.
- Hydrogen concentration improves in processes like pyrolysis and steam reforming during methane partial oxidation when performed without oxygen [Younas et al., 2022].

- These insights underscore the potential of catalytic processes and temperature management in optimizing hydrogen production for various industrial applications.

3.4.5. Hydrogen Supply Pathways and Compressor Optimization

Hydrogen possesses a significantly lower molar weight than natural gas, impacting the performance of conventional centrifugal compressors. As a result, existing compressors are typically not fully optimized for hydrogen blends, although the response varies among different compressor models. For instance, SIEMENS indicates that a hydrogen concentration below 10% results in only minor adjustments to existing compressors, while a concentration exceeding 40% necessitates their replacement.

According to the International Renewable Energy Agency [Irena, 2022], hydrogen supply for industrial applications can be categorized into three distinct pathways: captive, merchant, and by-product hydrogen:

- Captive Hydrogen: Produced internally by the consumer for exclusive use, this method is the most prevalent among large hydrogen consumers.
- Merchant Hydrogen: Generated at an external production facility and supplied to large-scale and retail hydrogen consumers.
- By-Product Hydrogen: Created incidentally during other processes where it is not the primary output; this hydrogen can be utilized as captive hydrogen or sold as merchant hydrogen.

Understanding these pathways is crucial for optimizing hydrogen utilization and infrastructure development in the energy sector.

3.5. Transmission Concepts of Hydrogen

Producing, transporting, and storing hydrogen fuel presents considerable challenges. Achieving the required large-scale hydrogen production will necessitate an unprecedented expansion of renewable energy capacity. Transporting hydrogen to airports will involve either gaseous pipelines or liquid hydrogen tanker deliveries. Additionally, refueling and servicing aircraft must be conducted safely and efficiently alongside traditional aircraft operations [Aerospace Technology Institute, 2022].

3.5.1. Hydrogen Transport and Infrastructure

Regardless of the production method, hydrogen must be transported if not produced on-site. Various technical processes facilitate this, such as transporting hydrogen as a gas in high-pressure containers, as liquefied gas in thermally-insulated containers, methanol or ammonia in liquid form, or chemically dissolved in a carrier medium using 'Liquid Organic Hydrogen Carrier' (LOHC) [Energy.gov, Hydrogen Production Processes, 2024].

3.5.2. Efficient Transport Methods

Hydrogen, when transported through pipelines, offers an energy density nearly comparable to natural gas, making pipeline transport particularly economical [Energy.gov, 2024] and capable of providing the necessary capacities for climate-neutral energy. The highly integrated German and European natural gas transmission networks present an economically advantageous way to distribute large quantities of energy. These networks are already in place, socially accepted, and can be gradually converted to hydrogen operation at an estimated 10-15% of the cost of new construction [Reuß et al., 2017].

3.5.3. Energy Content and Transport Dynamics

The upper calorific value of natural gas is around 11 kWh/Nm³, approximately three times higher than that of hydrogen at 3.5 kWh/Nm³. Consequently, about three times the volume of hydrogen is required to maintain the same energy content. Factors such as density, flow velocity, and pressure are crucial when comparing the energy flow of hydrogen and natural gas through a pipeline. Hydrogen's density is nine times lower, and its flow rate is three times higher than that of natural gas. This allows almost three times the volume of hydrogen to be transported through a pipeline at the same pressure within the same timeframe [Siemens Energy, 2020].

Land transportation options include compressed gas (CG) trucks for short distances of up to 100 km, and liquid hydrogen (LH_2) trucks for medium distances exceeding 500 km. For long distances, up to 1,000 km, hydrogen can be transported via pipelines. For overseas transport, LH_2 ships are suitable for distances greater than 1,000 km.

3.6. Storage Concepts of Hydrogen

Hydrogen’s extremely low density (0.09 kg/m³), due to being the lightest element, poses a significant challenge to hydrogen mobility. Despite its high specific energy (33 kWh/kg), its energy density remains low at ambient conditions (0.003 kWh/l), compared to conventional fuels like gasoline (10 kWh/l). Higher energy densities are critical for reducing specific costs related to volume and weight in storage and transportation [Hurskainen, VTT, 2019].

Liquid organic hydrogen carriers (LOHCs) present a promising solution for hydrogen infrastructure, as both loaded and unloaded carriers naturally exist in a fluid state. The most common method to achieve higher hydrogen storage densities is compression in gaseous form (GH_2). Stationary tube systems typically operate at pressures between 200 and 350 bar, with GH_2 at 700 bar considered the most viable for automotive applications. However, even at 700 bar, hydrogen’s density remains low (40 g/l or 1.3 kWh/l), and high-pressure gas vessels incur significant investment costs and material requirements. Low-pressure applications also have capital costs of around €785[1] ($850) per kg of storable hydrogen [Reuß et al 2017].

3.6.1. Liquid Hydrogen (LH_2)

Liquid hydrogen (LH_2) offers a density increase to 71 kg/m³ (2.4 kWh/l) by cooling hydrogen below 21 K. While the theoretical energy demand for liquefaction is 3.9 kWh/kg, actual plants require 12-15 kWh/kg, representing 36-45% of hydrogen's energy content. LH_2 can be stored in cryogenic tanks at low pressure (<10 bar), allowing large bulk storage systems with high energy densities. However, hydrogen boil-off must be considered due to unavoidable heat ingress [Ustolin et al., 2022].

3.6.2. Liquid Organic Hydrogen Carrier

LOHC systems consist of hydrogen-lean and hydrogen-rich liquid organic compounds that store hydrogen through repeated catalytic hydrogenation and dehydrogenation cycles. Hydrogenation is exothermic, while dehydrogenation is endothermic. The main advantage of LOHC technology is hydrogen storage in chemically bound form under ambient conditions, eliminating the need for high-pressure or super-insulated tanks. LOHC technology can utilize existing fossil fuel infrastructure, such as tanker ships, rail trucks, and tank farms. The LOHC system based on dibenzyltoluene (H0-DBT)/perhydro dibenzyltoluene (H18-DBT) is promising due to its high storage density (up to 6.2 wt-% of hydrogen), ease of handling, thermal robustness, and high cycle stability. Additionally, H0-DBT is widely available as an industrial heat transfer fluid [Tsogt et al., 2024].

3.6.3. Seasonal Storage

Seasonal storage is crucial for balancing the seasonal fluctuations in renewable power generation, such as peak wind production in winter and solar power in summer. Seasonal storage systems require high storage capacities with a low number of charge cycles annually, making them economically viable due to lower capacity costs and minimal long-term losses [Elberry et al., 2021].

3.7. Fuels Cells

A fuel cell (FC) is a device that converts chemical energy from a fuel directly into electricity through electrochemical reactions. Unlike batteries, fuel cells can continuously generate electricity if supplied with fuel and air or oxygen from an external source. This allows fuel cells to provide power for much longer periods than batteries, which have a limited amount of fuel and oxidant that depletes over time. Due to this capability, fuel cells have been used for decades in space probes, satellites, and manned spacecraft [Shumm, 2024].

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[1] The price is converted based on currency data on 24.7.2024.

3.7.1. Hydrogen Fuel Cells: Efficiency and Versatility in Clean Energy

Hydrogen FCs utilize the chemical energy of hydrogen or other fuels to efficiently produce electricity with minimal environmental impact. When hydrogen is used, the only byproducts are electricity, water, and heat. Fuel cells can power systems ranging from large utility power stations to small electronic devices like laptops.

Hydrogen FCs, which produce energy without greenhouse gas emissions, hold great promise for transportation. Hydrogen is a highly efficient and environmentally friendly fuel, producing no greenhouse gases, ozone-depleting chemicals, or significant pollutants. When generated from renewable sources like solar and wind, hydrogen can support a sustainable energy system. It is already being used in various applications, including drone ambulance services [Zhang et al., 2024].

Fuel cells are classified based on the type of electrolyte they use, determining their electrochemical reactions, catalysts, operating temperatures, fuel requirements, and suitable applications.

There are several types of FC, each with unique advantages and limitations.

- Polymer Electrolyte Membrane (PEM) Fuel Cells

PEM fuel cells are known for high power density, low weight, and compact size. Operating at around 80°C, they start quickly and are durable. They are primarily used in transportation, including cars, buses, trucks, and some stationary applications.

- Direct Methanol Fuel Cells (DMFCs)

DMFCs use methanol mixed with water, directly fed to the fuel cell anode. They are often used in portable applications like cell phones and laptops.

- Alkaline Fuel Cells (AFCs)

One of the earliest FC technologies, AFCs was used in the U.S. space program. Challenges include carbon dioxide tolerance, membrane conductivity, temperature management, and durability.

- Phosphoric Acid Fuel Cells (PAFCs)

PAFCs use liquid phosphoric acid as an electrolyte, achieving over 85% efficiency in co-generating electricity and heat, though they are less efficient at generating electricity alone. They are large, heavy, and costly due to the need for high platinum catalyst loadings.

- Molten Carbonate Fuel Cells (MCFCs)

MCFCs are being developed for natural gas and coal-based power plants, offering cost reductions and improved efficiency. Operating at high temperatures, they internally reform methane and other hydrocarbons to hydrogen, reducing costs. Current research focuses on enhancing corrosion-resistant materials and fuel cell designs to extend operational life.

- Solid Oxide Fuel Cells (SOFCs)

SOFCs use a ceramic electrolyte and are about 60% efficient in converting fuel to electricity. When waste heat is captured, efficiency can exceed 85%. The primary challenge is developing low-cost, durable materials for high operating temperatures.

- Reversible Fuel Cells

These cells generate electricity from hydrogen and oxygen, producing heat and water, and can also perform electrolysis using electricity from renewable sources to split water into hydrogen and oxygen. This capability allows them to store excess energy as hydrogen, aiding the integration of intermittent renewable energy sources [Energy.gov, Fuel Cells, 2024].

3.8. Summary of Section 3

Global greenhouse gas (GHG) emissions have reached unprecedented levels, primarily driven by fossil fuel consumption, leading to accelerated global warming and posing severe risks to humanity. The 2015 Paris Agreement aims to limit global temperature rise to well below 2°C above pre-industrial levels, ideally capping it at 1.5°C. To meet these goals, substantial global efforts are needed. Hydrogen, with its potential to significantly reduce emissions, emerges as a crucial player. It is particularly promising in sectors like steel production, chemicals, and long-distance transportation due to its ability to burn cleanly, producing only water vapor. However, widespread adoption faces challenges, including slow infrastructure development, high production costs, and regulatory barriers.

Hydrogen, the universe's most abundant element, is found in water, plants, and the sun. It is versatile and can be produced from various sources, including water, natural gas, and biomass. The different types of hydrogen—grey, blue, and green—reflect the carbon intensity of their production processes. Green hydrogen, produced from renewable energy sources, offers the most sustainable option, though it is currently the most expensive. Hydrogen's efficiency and potential for creating jobs make it a promising candidate for future energy needs and environmental sustainability.

Hydrogen production is categorized using color codes that reflect its production method and CO_2 balance. These include green, blue, grey, brown, and other variations. Each color represents a different production process and associated environmental impact. However, the lack of a global naming convention means that these colors can have different meanings in different contexts.

Hydrogen production methods fall into several categories:

- Thermochemical Processes

These involve extracting hydrogen from fossil fuels or biomass through heat and chemical reactions. Methods include steam methane reforming, biomass gasification, and solar thermochemical hydrogen production.

- Electrolytic Processes

Using electricity to split water into hydrogen and oxygen, this method is maturing and increasingly efficient.

- Direct Solar Water Splitting

Research is ongoing into using sunlight to split water into hydrogen and oxygen.

- Biological Processes

Involving microorganisms to produce hydrogen from organic matter or sunlight, these methods are still in the developmental stage.

Hydrogen production from fossil fuels is known as blue hydrogen, with methods such as steam reforming and partial oxidation being common. Green hydrogen, produced from renewable sources, includes processes like electrolysis and biomass conversion. Current production methods and technologies face challenges related to efficiency, cost, and scale.

Hydrogen generation efficiency ranges widely depending on the method. Steam reforming and partial oxidation are efficient but have high carbon footprints. Electrolysis, a leading method, is more energy-intensive but is crucial for green hydrogen production.

Hydrogen's low density impacts transportation efficiency. Supply pathways include captive, merchant, and by-product hydrogen. Various transportation methods are used, including pipelines, compressed gas trucks, and liquefied hydrogen tankers. Existing compressor technologies are generally not optimized for hydrogen, and adjustments are required based on hydrogen concentration.

The production, transportation, and storage of hydrogen face significant challenges. Expanding renewable energy capacity is essential for large-scale production. Transport methods include pipelines and liquid hydrogen tankers, with infrastructure needing to adapt to hydrogen's unique properties. Hydrogen's low density poses storage challenges. Methods for increasing storage density include compression and using liquid organic hydrogen carriers (LOHCs). Each method has its own cost and technical considerations, impacting the feasibility of hydrogen as a widespread energy solution.

The demand for large-scale hydrogen liquefaction, particularly for aviation, will require advanced technologies and substantial investment. Hydrogen liquefaction facilities may need to be located near power sources or airports to manage logistics effectively. As demand grows, decentralized liquefaction plants may become more viable, providing a solution to the challenges of transporting hydrogen over long distances [Aerospace Technology Institute, 2022].

4. Hydrogen-Powered Aircraft at Airports

Recent research from various sources highlights the importance of planning and infrastructure development for hydrogen as a fuel at airports. Reports from 2022 to 2024 emphasize three main pathways for supplying hydrogen to airports: liquid hydrogen delivered by trucks, gaseous hydrogen supplied through pipelines, and on-site generation using electrolysis. These methods are seen as vital steps toward decarbonizing aviation, with large airports likely needing to adopt combinations of these solutions as hydrogen demand scales.

A report by Jacobs, for example, stresses the importance of early adoption of hydrogen infrastructure, citing the need for airport operators to start planning now to support hydrogen-powered aircraft, which could be in service as early as 2035. Hydrogen's potential for decarbonizing aviation is enormous, not only for fuelling aircraft but also for powering terminal buildings through hydrogen gas blending [Connected Places Catapult, Business Airport International, accessed 10.9.2024].

In the UK, the FlyZero project similarly outlines liquid hydrogen as the most feasible fuel for Zero Emission Flight (ZEF) by 2050, urging airports to prepare infrastructure for both liquid and gaseous hydrogen to meet decarbonization goals set in the government's Jet Zero Strategy. This strategy aims for net-zero aviation emissions by 2050, with the first hydrogen-powered aircraft projected to fly as early as 2024 [Connected Places Catapult, accessed 10.9.2024].

The transition will require significant investment and collaboration between airports, fuel suppliers, and local industries to ensure the supply chain and safety measures are in place, alongside rapid infrastructure adaptation [Business Airport International, accessed 10.9.2024].

Ideally, aviation would utilize green hydrogen generated from renewable electricity, providing a sustainable and low-carbon fuel alternative. However, the current technology for mass-producing green hydrogen is still in its infancy, making it more expensive in the short term. Supplying the necessary quantities of green liquid hydrogen for aviation will necessitate substantial infrastructure development and significant investment in clean energy production [Aerospace Technology Institute, 2022].

4.1. Current Situation in the Market

The coming years (5-10) are critical for the adoption of hydrogen and other sustainable fuels, as the first hydrogen-powered flights are expected to enter broader commercial service between 2030 and 2035 [Schiphol News, Airbus, 2024].

The Air Transport Action Group (ATAG) aims for the aviation industry to reduce CO_2 emissions by 50% by 2050, relative to 2005 levels. To meet this goal, the industry must develop alternatives to petroleum-based fuels, such as hydrogen, sustainable aviation fuels (SAFs), electric propulsion, and hybrid solutions, alongside improving aircraft and air traffic management efficiency.

Hydrogen (H_2) is a sustainable alternative fuel that can fully decarbonize aviation when produced using renewable energy (green hydrogen). Hybrid-electric propulsion systems, combining hydrogen fuel cells and batteries, produce zero emissions during flight. Hydrogen can also be burned in combustion engines, producing no CO_2 or soot and significantly reducing NO_x emissions [Gu et al., 2023].

To grasp the scale of global demand, consider that meeting the aviation hydrogen needs with offshore wind-generated electricity would require around 175,000 km² of installed wind farms, roughly 30% of the North Sea area. Alternatively, using photovoltaic electricity in regions with high sunlight intensity would necessitate about 50,000 km² of solar panels, equating to approximately 0.6% of Australia's land area or 2.2% of Saudi Arabia's land area. Producing this amount of green hydrogen through electrolysis would also require around 1,400 million tons of water annually, which could be sourced from purified seawater, thus minimizing conflicts over limited freshwater resources [Aerospace Technology Institute, 2022].

The hydrogen aviation sector is evolving rapidly, though progress remains largely at the prototype stage, with few models in regular use. Development timelines have been extended, delaying broader market adoption. However, a significant milestone is anticipated with the first commercial hydrogen-electric passenger flight between London and Rotterdam, set to launch in 2024. Initially announced in 2021, this flight will feature a 19-seat aircraft developed by ZeroAvia, marking a breakthrough for zero-emission aviation and a pivotal step toward decarbonizing short-haul travel [Schiphol News in 2021, Accessed in 2024]. Further updates on this project remain limited as of 2024, underscoring the experimental nature of hydrogen-powered aviation at this stage.

In line with this, Airbus launched a liquid hydrogen handling project, GOLIAT, in 2024. This initiative aims to demonstrate small-scale liquid hydrogen ground operations at European airports, ensuring the necessary infrastructure is in place for hydrogen-powered aviation. The project will also explore how liquid hydrogen can be safely and efficiently integrated into airport refueling processes, positioning hydrogen as a key fuel for short- and medium-haul aviation [Airbus, 2024].

5. Review of Existing Applications of Hydrogen

Hydrogen has emerged as a key enabler in the global transition toward sustainable energy systems. Its applications have broadened significantly in recent years, driven by advancements in technology and growing policy support. Below is a review of key hydrogen applications from 2021 to 2024, highlighting the current state and potential for various sectors:

- Industrial Applications

Hydrogen's largest current use is in industries such as refining and chemical production. Traditionally, hydrogen is used to remove sulfur in oil refining and ammonia synthesis for fertilizers. However, the focus is increasingly shifting towards low-carbon hydrogen, often termed "green hydrogen," produced via electrolysis using renewable energy. By 2023, many industries had begun to explore replacing "grey" hydrogen (produced using natural gas) with greener alternatives to meet climate targets and reduce carbon emissions. The global refining sector is expected to become a significant consumer of low-carbon hydrogen by 2030 [Global Hydrogen Review 2023, IEA].

- Transportation

Hydrogen’s role in transportation has expanded beyond small experimental projects to larger-scale applications. Hydrogen-powered fuel cell electric vehicles (FCEVs) have been gaining traction, especially in heavy-duty transportation sectors like trucks, buses, and even aviation. By 2023, major automotive manufacturers, including Toyota and Hyundai, had expanded their hydrogen-powered vehicle lines, and various countries began investing in hydrogen refueling infrastructure [IEA, 2023]. Hydrogen's high energy density makes it particularly attractive for long-haul applications, where battery-electric solutions face limitations.

- Power Generation and Storage

Another growing application for hydrogen is energy storage. In times of surplus renewable electricity, hydrogen can be produced via electrolysis and stored, then converted back to electricity during periods of high demand or low renewable output. Hydrogen offers a long-term, large-scale storage solution that complements other energy storage technologies, such as batteries, and helps to balance grids with a high share of intermittent renewable sources. Research in 2021 highlighted the increasing role of hydrogen as a clean energy carrier, especially in regions focusing on the decarbonization of electricity grids [Frowijn & van Sark, 2021; SpringerLink].

- Heating

Hydrogen can also play a role in decarbonizing heat, which is a significant challenge given the current reliance on fossil fuels for heating residential, commercial, and industrial buildings. Blending hydrogen into natural gas pipelines or using pure hydrogen for heating purposes has been explored in various pilot projects globally. The UK, in particular, has been advancing hydrogen for domestic heating, with trials in different regions to assess its feasibility and impact on infrastructure [Eadson et al., 2022, SpringerLink].

- Maritime and Aviation

In maritime shipping and aviation, sectors that are hard to decarbonize using traditional batteries due to weight and range limitations, hydrogen is emerging as a potential solution. By 2024, hydrogen FCs and hydrogen-derived fuels like ammonia and synthetic kerosene were being tested in pilot projects for both aviation and large ships [IEA, 2023]. These applications are still in the early stages, but they hold significant promise for reducing emissions in long-distance travel.

Between 2021 and 2024, hydrogen applications have expanded considerably. Governments and industries worldwide are investing in hydrogen to decarbonize sectors like industry, transportation, and power generation. Despite challenges, such as high production costs and the need for extensive infrastructure, hydrogen’s versatility positions it as a cornerstone of future low-carbon economies.

5.1. Existing Applications in Airports

As hydrogen technology matures, airports are gradually incorporating hydrogen solutions, although primarily in ground support roles rather than in aviation itself. Several international airports have begun utilizing hydrogen FCs for ground support equipment (GSE), such as baggage tugs, tow tractors, and airport shuttles. A notable example is Hamburg Airport, which has integrated hydrogen-powered buses as part of its ground transportation fleet since 2015. The use of hydrogen for GSE is gaining traction because it offers a zero-emission alternative to diesel-powered equipment. Airports like Toulouse Blagnac and Kansai International are also exploring hydrogen refueling stations for GSE as part of broader efforts to decarbonize their operations [Hoelzen et al., 2021].

In terms of direct aviation applications, hydrogen remains in the conceptual and testing phases. Airbus, in collaboration with airports such as Singapore Changi, is actively studying the feasibility of accommodating hydrogen-fueled aircraft by 2035. These projects focus on infrastructure readiness, such as developing hydrogen storage, refueling systems, and safety protocols for handling cryogenic hydrogen [Airbus, 2023]. However, widespread application remains distant, with most airports unprepared for the rapid adoption of hydrogen aircraft [SpringerLink].

5.2. Existing Applications in Other Places

Beyond airports, hydrogen is being deployed in various transportation sectors globally. Hydrogen-powered vehicles, including buses, trucks, and trains, are already in operation in several cities. In particular, South Korea and Japan have been pioneers in deploying hydrogen buses for public transport, supported by the development of hydrogen refueling infrastructure. The HyNet project in South Korea aims to establish over 100 hydrogen refueling stations by 2025. Meanwhile, Japan's Toyota has spearheaded the use of hydrogen in the automotive sector through its Mirai hydrogen fuel cell vehicle [Toyota Mirai, 2021; SpringerLink].

The maritime industry is also exploring hydrogen as a fuel alternative, especially in Europe. Norway, for example, has begun testing hydrogen-powered ferries and is investing in hydrogen refueling infrastructure for its maritime industry. These initiatives highlight hydrogen’s versatility and its potential to decarbonize multiple transport sectors.

5.3. Funded Projects in Europe

Europe is at the forefront of hydrogen development, with numerous projects funded under programs like the European Green Deal and Horizon Europe. One of the most significant is the "Hydrogen Valleys" initiative, which aims to create hydrogen ecosystems across various regions by integrating production, storage, and utilization in industrial and transport sectors. This initiative covers 23 hydrogen valleys in Europe, including projects at airports like Madrid-Barajas, where hydrogen is being tested for both ground operations and potential aviation use [FCH 2 JU, 2022].

Another notable project is the Clean Hydrogen Partnership, which aims to accelerate hydrogen innovations across Europe. The initiative has secured over €1 billion in funding to develop hydrogen-powered solutions for transport, including aviation. Moreover, the Hydrogen Aviation Initiative, launched in 2022, focuses on hydrogen production and distribution at airports, aiming to make European airports hydrogen-ready by 2030 [European Commission, 2022].

5.4. Overview of Technologies Proposed for the Airport: Hydrogen-Powered Fuel Cell Engines for Backup Power Generation and Combined Heat and Power with Fuel Cell Components

➢ Hydrogen-powered Fuel Cell for backup power generation

Hydrogen-powered FC engines are emerging as a sustainable alternative for backup power generation, particularly in applications like data centers, hospitals, and other critical infrastructure. These FCs convert hydrogen into electricity through a chemical reaction, generating zero emissions – producing only heat and water as byproducts.

A notable feature of hydrogen FCs is their ability to provide uninterruptible power. Unlike traditional diesel generators, hydrogen FCs are faster to start. They are designed to be highly scalable, making them suitable for anything from small installations to megawatt-scale power generation. For example, Microsoft's 3 MW hydrogen FC system successfully replaced diesel generators in data centers, demonstrating its viability in high-power applications [PV magazine International, Hitachi Energy].

One of the key benefits is the emission-free operation, which significantly reduces carbon footprints. This is crucial for sectors aiming for decarbonization. The scalability of these systems also makes them adaptable for various needs, from temporary installations to permanent energy solutions [WHA International, Inc., Hydrogen Council, accessed 10.9.2024].

For more information, companies like Hitachi Energy have been at the forefront of deploying such systems, showcasing how hydrogen FCs can meet the increasing demand for cleaner and more reliable backup power [Hitachi Energy, accessed 10.9.2024].

- A Combined Heat and Power system utilizing Fuel Cells technology

A CHP system utilizing FC technology is a sophisticated energy solution that integrates multiple components to generate electricity and heat simultaneously. These systems are particularly known for their high efficiency, low emissions, and ability to operate on various fuels, including hydrogen and natural gas.

The main components of FC-CHP Technology are the following:

- Fuel Cell Stack

At the core of the FC-CHP system is the FC stack, where the electrochemical reactions take place, converting fuel into electricity and heat. The fuel cell stack is responsible for the primary function of the system—producing direct current (DC) electricity. The type of fuel cell (e.g., Proton Exchange Membrane Fuel Cell (PEMFC) or Solid Oxide Fuel Cell (SOFC)) dictates the operating temperature, fuel requirements, and overall system efficiency.

- Fuel Processor

The fuel processor is a crucial component that reforms the raw fuel (typically natural gas or hydrogen) into a usable form, often producing hydrogen through steam reforming. The fuel processor’s importance cannot be understated, as it significantly affects both the efficiency and cost of the entire system. Studies suggest that the fuel processor can contribute up to 80% of the Balance of Plant (BoP) costs in an FC-CHP system. This component is highly sensitive to the type of fuel being processed, and its design impacts both the system's capital and operational expenses.

- DC/AC Inverter

Since FCs generate DC electricity, the DC/AC inverter is required to convert this into alternating current (AC) electricity, which is the standard for most industrial and commercial applications. High-quality inverters are critical for ensuring the reliability and efficiency of the power supplied to the grid or directly to end-users.

- Heat Exchanger

The heat exchanger is another vital element in CHP systems. As fuel cells generate heat as a byproduct of electricity production, the heat exchanger captures this waste heat and repurposes it for domestic heating, hot water production, or other industrial processes. Efficient heat recovery maximizes the system's overall efficiency, often pushing it beyond 80%, by combining both electrical and thermal outputs.

- Control Systems

Control systems manage the various sub-systems within the CHP-FC, ensuring optimal performance. These include monitoring fuel input, regulating electricity generation, and maintaining heat recovery. Advanced control systems allow for real-time adjustments to maintain peak efficiency under varying loads and operational conditions, while also ensuring safe and reliable operation.

- The Role of Fuel in FC-CHP Efficiency and Costs

The choice of fuel plays a critical role in the overall performance of an FC-CHP system. Hydrogen is the most efficient fuel, offering high energy density and producing only water as a byproduct. However, its availability and storage costs can be limiting factors. Natural gas is a more widely available and cost-effective fuel but requires a fuel processor to reform it into hydrogen, increasing the system’s complexity and operational costs. The fuel processor, being one of the most expensive components of the system, is particularly sensitive to the type of fuel used. While hydrogen-fed systems are more straightforward and efficient, the widespread use of natural gas makes reformer-based systems more commercially viable in many markets. However, advancements in hydrogen production and storage technologies are expected to reduce these costs and drive more widespread adoption of hydrogen-based FC-CHP systems in the future.

5.5. Ground Applications Safety

Safety is paramount in the use of hydrogen, particularly in the context of airports and ground operations. Hydrogen is highly flammable, and handling it in large quantities—especially in liquid form—presents unique challenges. To mitigate these risks, various safety protocols and technologies are being developed. Airports implementing hydrogen must invest in advanced leak detection systems, explosion-proof equipment, and ventilation systems to handle potential gas leaks safely.

The International Air Transport Association (IATA) and other regulatory bodies are developing guidelines to standardize hydrogen safety measures at airports. These regulations cover the entire hydrogen supply chain, from production and transportation to storage and refueling [IATA, 2023]. Hydrogen's low density and cryogenic nature, when stored in liquid form, also require specialized infrastructure, including insulated tanks and pipelines.

Training airport personnel to handle hydrogen safely is also crucial. Currently, safety programs are being tested in pilot projects at major airports like Frankfurt and Amsterdam Schiphol, where hydrogen is being incorporated into ground operations.

5.6. Summary of Section 5

As hydrogen-powered flights become more prevalent, airport infrastructure will need to evolve to meet the specific requirements of hydrogen. The successful integration of hydrogen into airports will require advancements in hydrogen production, storage, and safety protocols. Ground applications of hydrogen, such as the use of hydrogen-powered GSE, are already underway at several international airports, laying the groundwork for more widespread use. However, significant challenges remain, particularly in terms of safety, regulatory frameworks, and infrastructure readiness.

With numerous funded projects across Europe and other parts of the world, hydrogen’s potential to decarbonize airport operations is substantial. The findings suggest that collaboration across the aviation sector is essential to address these challenges. Airports must modernize their infrastructure and collaborate with stakeholders to facilitate hydrogen's broader adoption. Research will continue to play a pivotal role, focusing on infrastructure development, safety standards, and technological advancements necessary to meet the demands of hydrogen-fueled aviation [Gu et al., 2023].

6. Review of Research in the Field on Future Hydrogen Solutions for Airports

The global shift toward decarbonization has intensified research into alternative energy solutions for aviation. Hydrogen, due to its potential for zero-emission combustion, is a front-runner in the future fuel mix for airports and aviation. Transitioning from kerosene to hydrogen-powered aircraft will inevitably increase demand for renewable energy, especially if hydrogen is generated via electrolysis. This demand applies not only to hydrogen but also to battery-electric and sustainable aviation fuels (SAF), particularly those produced through the power-to-liquid (PtL) pathway.

This section presents an overview of three major research studies that explore hydrogen solutions for airports. These studies outline various hydrogen supply and delivery models, address investment requirements, and evaluate the technical and economic feasibility of hydrogen infrastructure at airports. Additionally, these reports examine hydrogen's integration into airport operations, focusing on transport, storage, and refueling methods. The following sections offer insights into the proposed models for hydrogen delivery, storage, and usage at airports, along with economic analyses to determine the viability of such transitions.

6.1. Hydrogen Delivery Methods to Airports Presented by Aerospace Technology Institute in 2022

Aerospace Technology Institute has proposed in 2022 various scenarios for the UK for hydrogen delivery to the airports.

The method of hydrogen delivery to airports will vary based on the airport's size, location, geography, and hydrogen demand. Some airports might transition between different supply options as demand increases. The potential hydrogen delivery methods are summarized in the three scenarios below:

- Scenario 1: Off-Site Hydrogen Generation and Liquefaction, Road Tanker Delivery
  - *Overview:* Hydrogen is produced and liquefied off-site and delivered to the airport via road tankers.
  - *Storage:* The liquid hydrogen is offloaded into highly insulated storage tanks at the airport, designed to maintain cryogenic temperatures to prevent vaporization. All cryogenic liquids, including liquid hydrogen, must be stored in highly insulated tanks to prevent vaporization due to rising temperatures. The storage of liquid hydrogen is a well-established industry, with manufacturers capable of supplying the necessary infrastructure. Maintaining cryogenic temperatures, specifically cooling down to -253˚C, is energy-intensive and challenging.
  - *Infrastructure:* An established industry already exists for cryogenic liquid storage, ensuring tanks are efficient and safe. The airport should maintain a buffer stock, typically two days' worth, to handle supply disruptions.
  - *Challenges:* Maintaining consistent cryogenic temperatures is crucial for operational efficiency and to prevent material fatigue in storage tanks due to thermal cycling.
- Scenario 2: Off-Site Hydrogen Generation, Pipeline Delivery, On-Site Liquefaction
  - *Overview*: Hydrogen is produced off-site and transported to the airport via a gas pipeline, where it is then liquefied on-site.
  - *Pipeline Details:* The diameter and specifications of the pipeline depend on various factors, including airport size, hydrogen demand, and pipeline length. Distribution of hydrogen gas by pipeline over long distances is a feasible technology with potential for wide adoption. This can be achieved through constructing purpose-built hydrogen pipelines or repurposing natural gas pipelines. Pipeline transport is the most effective method for moving large volumes of gaseous hydrogen, either as pure hydrogen at various pressures or blended into natural gas systems at different percentages and pressures.
  - *Advantages:* Pipelines are an efficient method for transporting large volumes of hydrogen over long distances and can be integrated into existing or new pipeline systems.
  - *Challenges:* Significant capital investment is required for pipeline construction and associated facilities. The reuse of natural gas pipelines is complicated by hydrogen embrittlement, particularly in high-pressure steel pipelines.
- Scenario 3: On-Site Hydrogen Production and Liquefaction at the Airport

- *Overview:* Hydrogen is produced and liquefied locally at the airport using electricity from the power grid and water from the local network.
- *Requirements:* This scenario requires substantial electrical power, likely necessitating multiple high-voltage power lines.
- *Feasibility:* Due to high power demands, this method may not be suitable for most airports. However, it allows for direct control over hydrogen production and reduces dependency on external supply chains.
- *Environmental Impact:* The carbon footprint of this green hydrogen depends on the source of the electricity and the efficiency of the electrolysis process.

Each scenario presents unique infrastructure requirements and challenges, particularly concerning hydrogen storage and delivery to refueling stands. The complexity and cost of installing vacuum jacket pipes and other infrastructure to minimize hydrogen boil-off are key factors in determining the best hydrogen delivery option for each airport.

Two types of pipe technology can be used to distribute liquid hydrogen from the storage tanks to the refueling stands: vacuum jackets or solid insulation pipes. The most common solution, a vacuum jacket pipe, would require a culvert below the surface of the airport's taxiways and aprons. It is anticipated that the culvert would need to be large enough for a person to walk along, enabling the pipe to be visually inspected and the vacuum maintained. In addition, the top of the culvert would need to be open to prevent the possibility of gas accumulating in the event of hydrogen leakage. The downsides of this type of installation are the potential disruption to the airport's operations that may be caused during the installation of the culvert and the likelihood that the hydrant route would clash with already installed utilities. This clash may require the diversion of existing utilities, adding significantly to the construction costs. The system includes a liquid hydrogen vacuum jacket pipe, with a secondary return pipe for hydrogen gas boil-off. It may also be possible to integrate the boil-off within an outer layer of the pipe, helping to minimize heat loss from the liquid hydrogen central core. The gaseous hydrogen can be re-liquefied for aircraft use or utilized for other applications, such as direct combustion for airport boilers or to refill FCs for gaseous hydrogen ground support equipment.

Potential alternative systems may also be considered for further investigation:

- A looped hydrant system would keep liquid hydrogen flowing to reduce boil-off, however, this would increase costs and may create challenges with pressure differentials.
- A cryogenic hydrogen gas pipeline would be easier to install and operate, however it would require multiple liquefaction systems at stands.

Table 3 below presents potential costs from 2030 to 2050. The estimates include upper and lower-bound capital cost forecasts, with median figures also provided. Due to the complexities and risks of building new airport infrastructure, actual costs are likely closer to the upper bound. In the presented study, all financial figures were initially listed in millions of British Pounds (GBP)[2]. However, as the parties involved in the project (BSR HyAirport) primarily operate in euros (EUR), all investment values in the report are now converted and presented in euros for clarity and consistency. This approach ensures that stakeholders working in EUR can easily interpret and compare the financial data without needing to perform currency conversions themselves. All values in this table (Table 3) are rounded to the nearest whole number.

Table 3. Potential costs from 2030 to 2050 with upper and lower-bound capital cost forecasts (in millions of euros)

Airport Size	Scenario 1: Liquid hydrogen delivered to the airport		Scenario 2: Gaseous hydrogen pipeline supply to the airport		Scenario 3: Hydrogen generated on-airport	
	Median cost	+/-	Median cost	+/-	Median cost	+/-
Large	386	267	743	594	2,970	1,545
Medium	119	71	238	178	1,010	475
Small	24	12	30	30	119	59
Airport Size	Scenario 1: Liquid hydrogen delivered to the airport		Scenario 2: Gaseous hydrogen pipeline supply to the airport		Scenario 3: Hydrogen generated on-airport	
	Median cost	+/-	Median cost	+/-	Median cost	+/-
Large	624	297	1,010	624	2,267	1,545
Medium	208	89	327	208	1,099	505
Small	48	18	59	18	137	59

The cost forecasts were calculated by the Aerospace Technology Institute by using the highest and lowest benchmarks to establish an upper and lower bound. A median value was then determined, although actual costs are expected to be closer to the upper bound due to the uncertainties of new airport infrastructure. To offset some of these costs, surplus hydrogen during off-peak times could be sold or repurposed. Additionally, sizing facilities to meet peak demand allows for potential revenue from selling excess hydrogen for uses like ground vehicles, backup power, and even heating.

6.2. A Flexible Hydrogen Supply Chain Model in Germany

Already in 2017, German researchers [Reuß et al., 2017] proposed a flexible hydrogen supply chain model that encompasses the entire supply chain, highlighting the advantages and drawbacks of various technologies. The model includes four fundamental stages: hydrogen production, storage, transport, and fueling at the station. Integrating these stages requires additional interconnections to facilitate state changes such as liquefaction, compression, or hydrogenation and dehydrogenation. Consequently, the

[2] Currency rate on 25.9.2024 1 pound = 1.19 EUR

fueling station stage incorporates the reconversion to gaseous hydrogen as well as the fueling process. Each link in this process chain was analyzed within the framework of a corresponding module and evaluated using static calculations. The model setup is presented in Figure 2.

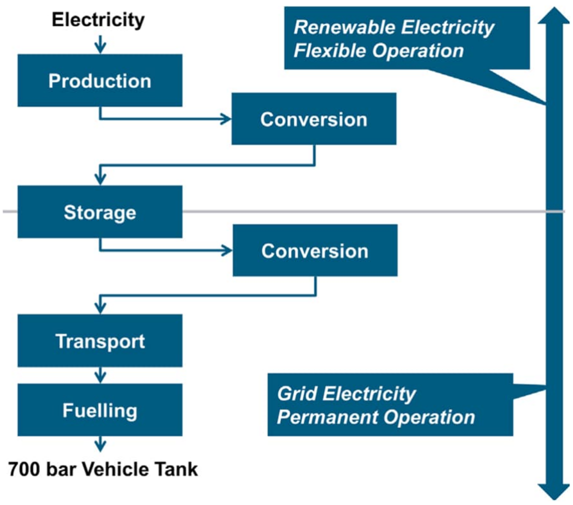

Figure 2. A Flexible Hydrogen Supply Chain Model in Germany, 2017

Table 4. General Assumptions for All Modules

Assumption	Value	Unit
Weighted Average Cost of Capital (WACC)	8	%
Electricity cost (RES)	0.06	€/kWh
Operational Hours (RES)	5,300	hours/year
Storage Days	60	days
Storage Part	30	%
Utilization of Fueling Station	70	%
Diesel Cost	1.2	€/l
Driver Wage	35	€/h
Natural Gas Cost	0.04	€/kWh
Water Cost	4	€/m³

As summarized in Table 4, the electrolyzer and the conversion system for hydrogen storage are designed to operate efficiently at 5,300 full load hours per year. This system is powered by wind energy, with a levelized cost of electricity (LCOE) set at 0.06 €/kWh. The model assumes access to renewable energy sources, allowing the system to capitalize on periods of lower electricity prices.

To address the fluctuations between hydrogen production and demand, the storage system is designed with a buffer of 60 days of production. This includes 18 days for seasonal storage and 42 days for strategic reserve. A portion of the hydrogen—30% of annual production—is stored before it is transported, which results in 1.85 charging cycles per year and an average storage duration of 200 days.

After storage, it is assumed that demand remains constant, with the plants and grid operating continuously to meet consumption. For the fueling stations, the utilization rate is assumed to reach 70% of daily capacity during the system's depreciation period. This utilization level is factored in to ensure steady operation and energy supply across all modules.

The study concludes that liquid hydrogen is cost-efficient only for long-distance transportation over 500 km.

6.3. Economics: Investment and Production Costs researched in three European Airports

The German researchers examined three airport archetypes from 2019-2022 to understand potential liquid hydrogen (LH_2) demands for different aircraft segments. The study focused on small airports (less than 20,000 departing commercial flights per year), large airports (more than 100,000 departing commercial flights per year), and medium airports. Bremen Airport (BRE) represented small airports, Hamburg Airport (HAM) represented medium airports, and Frankfurt-Main Airport (FRA) represented large airports.

For example, Frankfurt-Main Airport (FRA), an international hub with a high concentration of widebody aircraft, had a kerosene demand of 4,661 kt in 2019. Smaller regional airports, such as Bremen Airport (BRE), had significantly lower demand (38 kt), driven largely by smaller aircraft for short-haul flights [Hoelzen et al 2022]. The study provides a detailed breakdown of the infrastructure requirements and costs associated with transitioning to liquid hydrogen, as well as comparisons between different hydrogen transportation methods (Table 5).

This research offers valuable insights into the capital expenditure (CAPEX) and operational expenditure (OPEX) required for hydrogen infrastructure in airports of varying sizes, emphasizing the complexities of scaling up hydrogen solutions for the aviation sector.

Table 5. Comparison of Hydrogen Transportation Methods

Features	CGH_2 Trailer	LH_2 Trailer	CGH_2 Pipeline	LH_2 Ship	NH_3 Ship	LOHC Ship
Pressure (MPa)	20–50	0.1–0.4 (-253°C)	2–3	~0.1	~0.1	~0.1
Depreciation Period (Year)	12	12	40 (30–55)	N/A	N/A	N/A
Capacity (kg H_2)	500 (20–25 MPa) / 1000 (50 MPa)	4000–4300	N/A	75,000 (SUISO FRONTIER), ~113,360 (160,000 m³ LH_2 ship)	~190,000 (estimated for 160,000 m³ NH_3 ship)	~8,265,600 (estimated for 160,000 m³ LOHC ship carrying H18-DBT)
Transportation Cost (€/kg H_2)	2.69	0.74	0.64 / 500 km / 0.11–0.21 / 1000 km	0.7–1.5 (with liquefaction 2–2.5)	0.8–0.9 (with dehydrogenation 1.8–2.9)	1.6–2.7
CAPEX (€)	660,000 / trailer (50 MPa) (2019)	860,000 / trailer (2019)	Invest (€) = $0.0022D^2 + 0.86D + 247.5$ (pipeline diameter D in mm)	179,944,000 / ship	134,924,800 / ship	99,600,000 / ship
OPEX (€/year)	2%	2%	2–4.7%	9,900,000 + 4% CAPEX	9,047,000 + 4% CAPEX	15,604,000 + 4% CAPEX

7. Future Hydrogen Energy Development Directions

Future research should focus on scaling up green hydrogen production while advancing methods for its transportation, storage, and distribution. A key component of this effort is expanding hydrogen fueling infrastructure, particularly in rural and remote regions, which remain underserved. For hydrogen to become a core element in the global energy system, governments must adopt policies that position green hydrogen as a cost-effective, resilient, and sustainable energy source. Significant cost reductions are anticipated through improvements in electrolysis efficiency, economies of scale, and lower renewable energy costs, which are projected to decline by up to 80% by 2030.

A major challenge lies in the lack of infrastructure for the large-scale storage, transportation, and distribution of liquefied hydrogen. This gap has led many countries, including Japan and South Korea, to rely on imports to meet their hydrogen demand. The successful adoption of a hydrogen-based energy system will hinge on market dynamics and competitive pricing, with hydrogen-powered technologies needing to contend with alternatives such as batteries and biofuels. Moreover, governments and industry stakeholders are investing in hydrogen corridors and dedicated pipeline networks to overcome infrastructure limitations.

In particular, the development of FC vehicles (FCVs) faces challenges due to the limited refueling infrastructure and high associated costs. Toyota, Hyundai, and Nikola have all made substantial investments in FCVs, yet widespread adoption remains slow. Increased demand, however, could reduce costs through economies of scale, with forecasts suggesting that FC trucks and buses will dominate the heavy-duty vehicle market by 2040.

Hydrogen also holds great promise for hard-to-decarbonize sectors, such as heavy-duty transport, aviation, shipping, and industry. It is especially suitable for industries like mining, steel, and cement production, where high energy density and carbon reduction are paramount. Airbus and Rolls-Royce are actively exploring hydrogen propulsion for commercial aviation, with trials expected to begin by 2035.

Traditional applications of hydrogen, such as in methanol production and oil refining, are expected to grow modestly by 2050. However, the demand for hydrogen as a clean fuel is projected to skyrocket from 2030 onward, potentially accounting for 35% of global hydrogen demand by 2050. The International Renewable Energy Agency (IRENA) expects green hydrogen to represent up to 12% of global energy use by 2050, contributing significantly to decarbonization targets.

Transitioning the global energy infrastructure to accommodate hydrogen will be a decades-long process, complicated by the legacy of existing infrastructure built over the last century. The development of hydrogen-compatible pipelines and storage facilities will require substantial investment, estimated at around €184–€276 billion by 2030. Economic disruptions, such as those seen during the COVID-19 pandemic or supply chain issues, could delay these efforts, though the global energy crisis has heightened the urgency of hydrogen deployment.

To ensure a successful transition, policymakers must focus on identifying cost-effective pathways for integrating hydrogen into the global energy mix. The exploration of synergies between hydrogen and natural gas sectors is particularly promising, with blending hydrogen into existing natural gas networks being explored in several countries, including Germany and Australia. Additionally, green ammonia is emerging as a key vector for hydrogen storage and transportation, particularly for global shipping.

8. Case Example Calculations

This section presents two viable case studies tailored for a large Baltic Sea Region Airport, showcasing the potential applications of hydrogen-powered technologies in enhancing the airport's energy infrastructure.

Case 1: Hydrogen-Powered Fuel Cell Engines for Backup Power Generation

The first case (Case 1) outlines a comprehensive evaluation process for assessing the feasibility and effectiveness of deploying hydrogen-powered FC engines for backup power generation at the airport. This analysis covers critical aspects such as hydrogen production, consumption, and storage potential. It also explores integrating these systems into the airport's broader energy infrastructure, including opportunities for participating in electricity markets and strategies for storing surplus energy.

- *Assumption:* A fully developed hydrogen infrastructure is in place, with hydrogen readily available at the airport.
- *Phases:*
    - *Hydrogen Production Potential Assessment:*
        - ✓ Identify the airport's backup power generation requirements, including production cycles and fuel consumption.
        - ✓ Evaluate the maximum output capacity of the fuel cell engines and estimate the hydrogen consumption necessary for electricity generation.
        - ✓ Calculate the potential electricity output from hydrogen (kWh per kg of hydrogen).
    - *Hydrogen Consumption and Storage Requirements:*
        - ✓ Determine the hourly hydrogen consumption during backup power operation.
        - ✓ Estimate the required hydrogen storage capacity based on the airport's operational periods.
        - ✓ Calculate the storage needs (kg of hydrogen) concerning the backup power capacity.
    - *Participation in Electricity Markets:*
        - ✓ Analyse the feasibility of selling surplus electricity generated from hydrogen in electricity markets or demand response programs.
        - ✓ Assess the potential for using FC engines to support base load power generation.
        - ✓ Calculate the necessary hydrogen quantity and storage capacity for base load operation.

- *Electricity Storage Integration:*
  - ✓ Evaluate the efficiency of storing electricity generated from hydrogen as part of the overall energy solution.
  - ✓ Explore the integration of an energy storage system (e.g., batteries) to enhance system efficiency and flexibility.

Case 2: Combined Heat and Power Generation Using Hydrogen Fuel Cell Technology

The second case delves into the feasibility of implementing an FC-based CHP system at the large Baltic Sea Region Airport. This example includes a detailed assessment of the airport's current energy consumption patterns and examines how the CHP system can be seamlessly integrated into the existing infrastructure. Additionally, the case explores surplus energy management, including electricity storage solutions and the potential for utilizing excess heat in other airport operations. The study evaluates the overall efficiency, environmental impact, and economic benefits of adopting such an advanced energy system.

➢ *Assumption*

A fully developed hydrogen infrastructure is in place, with hydrogen readily available at the airport.

➢ *Phases:*

- *Initial Data Collection:*
  - ✓ Assess the airport's current heat and electricity consumption, as well as the fuels currently in use.
  - ✓ Determine the electrical output of the fuel cells and the efficiency of the heat recovery system.
- *On-Site Electricity and Heat Utilization:*
  - ✓ Calculate the potential of the fuel cell CHP system to meet the airport's electricity and heat demand.
  - ✓ Estimate the necessary hydrogen consumption and storage capacity required for the fuel cell CHP system's operation.
- *Electricity Storage Integration:*
  - ✓ Analyse the feasibility of storing electricity produced by the CHP system for future use.
  - ✓ Investigate various storage options (e.g., batteries) and conduct a high-level cost-benefit analysis.

- *Utilization of Surplus Heat:*
  - ✓ Explore opportunities to utilize excess heat generated by the CHP system in other airport operations, such as tarmac heating or selling heat to the district heating network.

8.1. Data/Statistics Summary

The power and heat data used in this report were provided by representatives from various European airports. To maintain confidentiality regarding backup technology details, the airports are categorized as large, medium, and small Baltic Sea Region Airports. This classification ensures that sensitive information is protected while allowing for a comprehensive analysis of energy performance across different airport sizes.

➢ Local Historical Electricity Prices

To estimate the potential financial savings from the CHP system, historical electricity prices of the local electricity market from August 2023 to July 2024 need to be included. Electricity prices vary, but for simplicity, we can use the average market prices for 2023. Based on past trends, the average electricity price has ranged from €0.10/kWh to €0.20/kWh.

➢ Currency

For the rough investment calculation of the 14 MW CHP system, the consultant used the provided cost ranges in USD and converted them into euros. We'll use the exchange rate provided in the additional data of 1 USD = 0.92 EUR for this calculation (rate based on week 37, 2024).

8.2. Calculation of the Technical Potential of the Application

This study focuses on integrating hydrogen technologies into airport terminal operations, specifically targeting emergency power generation and CHP systems at the large Baltic Sea Region Airport. The study covers both the technical and economic viability of using hydrogen FCs for backup power and CHP generation.

8.2.1. Case 1: Hydrogen-Powered Fuel Cell Engines for Backup Power Generation

This case example evaluates the potential of replacing existing backup power generation with fuel cell-based engines through simple calculations. Actual backup power generation data for the large Baltic Sea

Region Airport over several years, including typical backup power utilization cycles, has been used in the assessment.

The backup power generation system for this Airport comprises of 15 generator units of various sizes ranging from 136 kVA to 1,600 kVA. In this Airport, backup power generators are tested every few weeks for a continued 2–3-hour period each time. Additionally, backup power generators may sometimes be used as baseload power sources for the Airport during times of extremely high grid electricity market prices. Overall, the backup power generation system in the Airport sees significantly more use compared to other partner Airports of the project team based on data received.

Key Elements of the calculation are the following:

- The Potential Hydrogen Consumption Calculation for Backup Power
    - *Assumptions*
        - ✓ Efficiency of Hydrogen FC: Typically, hydrogen FCs have an electrical efficiency between 40-60% [U.S. Department of Energy (DOE) - Fuel Cell Technologies Office; Ballard Power Systems - Fuel Cell Efficiency Overview, 2024]. Here it is assumed a 50% electrical efficiency for hydrogen FC engines for this calculation.
        - ✓ Energy Content of Hydrogen: Hydrogen contains approximately 33.33 kWh/kg (lower heating value, LHV) [IEA - Hydrogen as a Fuel, The Hydrogen Council - Hydrogen Insights, 2024].

- Hydrogen Storage Requirements

The total hydrogen consumption per year and the storage capacity requirements were considered to determine how much hydrogen storage is needed.

- *Assumption for Storage:* Hydrogen stored as a liquid: Liquid hydrogen has an approximate density of 70.85 kg/m³ [IEA - Hydrogen Storage, Air Products - Liquid Hydrogen Properties, 2024].

For backup power generation of 592 MWh/year, the hydrogen-powered FC system will require 35.5 tones (precisely 35,520 kg) of hydrogen per year. Given the energy density of liquid hydrogen, approximately 500 m³ of liquid hydrogen storage will be needed annually (summary in Table 6). The feasibility analysis shows that the FC system can provide the necessary power output for a large Airport's backup power needs, assuming the availability of hydrogen storage infrastructure.

When considering the practical application, it is clear that smaller-scale storage—designed e.g. once-a-month refills—is more practical. In real-world scenarios, only 10-15% of the proposed storage capacity is likely to be utilized each month, making a smaller, more flexible storage investment more realistic.

Table 6. Summary Table of Potential Hydrogen Consumption Calculation for Backup Power

Description	Unit	Value
Annual Backup Power Production	MWh/year	592
Annual Backup Power Generator Fuel Consumption	litres	177,600
FC Electrical Efficiency	%	50%
Hydrogen Energy Input	MWh/year	1,184
Hydrogen Consumption	tons/year	35.5
Liquid Hydrogen Storage Required	m^3/year	500
Practical Storage Capacity Application	m^3/year	50-75

8.2.1.1. CO_2 Emissions Calculation for Case 1

Hydrogen-powered FCs generate zero direct CO_2 emissions during their operation because the only byproducts are water and heat. However, the overall emissions savings depend on how the hydrogen used in the FC is produced. Here are the three primary methods of hydrogen production and their impact on CO_2 emissions:

- **Grey Hydrogen**

This is hydrogen produced via steam methane reforming (SMR) using natural gas, without capturing any CO_2 emissions. While hydrogen FCs emit no direct CO_2, grey hydrogen production results in significant indirect CO_2 emissions due to the burning of fossil fuels.

- **Blue Hydrogen**

Blue hydrogen is also produced via SMR, but with carbon capture and storage (CCS) technology that traps and stores a portion of the CO_2 emissions. Blue hydrogen significantly reduces the indirect CO_2 emissions compared to grey hydrogen, but it does not eliminate them entirely.

- **Green Hydrogen**

This is produced using renewable energy sources (e.g., solar, wind) to split water into hydrogen and oxygen via electrolysis. Since the process relies on renewables, green hydrogen results in zero associated CO_2 emissions—both direct and indirect.

Table 7 provides a summary of emissions and emission savings based on the hydrogen production method. Column "CO_2 Emissions" shows emissions of the hydrogen backup power generation and column "CO_2 Savings" shows the avoided emissions of the replaced fossil fuel-based backup power generation. For the CO_2 savings calculation, it has been assumed that current backup power generation is 100% fueled by fossil fuel (carbon intensity 2.473 kgCO_2/litres) to provide a reasonable view on the carbon savings potential of GH_2, as opposed to marginal carbon savings when comparing against biofuels. Total emission reduction with GH_2 as fuel is thus 439 tCO_2/year minus emissions from the GH_2 depending on type of hydrogen that is used.

Table 7. Table: CO_2 Emissions Savings Based on Hydrogen Production Method

Hydrogen Type	Hydrogen Consumption (tons/year)	CO_2 Emissions (tons/year)	CO_2 Savings (tons/year)
Grey Hydrogen	35.5	355	84
Blue Hydrogen	35.5	124	315
Green Hydrogen	35.5	0	439

Using fossil fuels for backup power results in 439 tons of CO_2 emissions annually. Switching to alternative fuels saves CO_2 as follows:

- Grey Hydrogen: Emits 355 tCO_2 annually, saving 84 tCO_2.
- Blue Hydrogen: Emits 124 tCO_2 annually, saving 315 tCO_2.
- Green Hydrogen: Emits 0 tCO_2, saving the full 439 tCO_2.

Each step from grey to green hydrogen increases CO_2 savings compared to fossil fuels.

8.2.2. Case 2: Combined Heat and Power Generation Using Hydrogen Fuel Cell Technology

Case 2 presents the system's capacity to meet the airport's combined power and heat demands, including surplus heat utilization and integration with energy storage systems. This section outlines the theoretical potential of an FC-based CHP, i.e. the CHP in this example aims to provide most or all the heat and power needs of the airport.

8.2.2.1. Case 2 Calculation: Combined Heat and Power Generation Using Hydrogen Fuel Cell Technology

To determine the required capacity of a CHP system using hydrogen FC technology, we need to calculate the system size that will meet both the annual power and heat consumption demands, given the overall efficiency of 85% and assumed typical splits for electrical efficiency (η_e=50%) and heat efficiency (η_h=35%) for the hydrogen fuel cell system. Table 8 presents information on the annual electricity and heat consumption, along with calculations of the required CHP-FC capacity to meet the consumption load.

These values (presented in Table 8) seem reasonable for a system that can meet the power, and heat demands over a full year.

A 14 MW CHP system using hydrogen FC technology with 85% efficiency should be capable of meeting the annual power consumption of circa 59 GWh and heat consumption of circa 36 GWh under operation of 8,016 hours.

The installed cost for a 14 MW system ranges from €3,700–€9,200 per kW.

Table 8. Summary for CHP using Hydrogen Fuel Cell Technology (maximum potential)

Description	Unit	Data Provided	Calculation
Annual Power Consumption	MWh/year	58,539	Provided by the Airport (data on 08.2023-07.2024)
Annual Heat Consumption	MWh/year	36,120	Provided by the Airport (data on 08.2023-07.2024)
Annual Energy Production	MWh/year	94,659	58,539 + 36,120
Total CHP Efficiency	%	85	U.S. EPA - CHP Efficiency, European Commission - Energy Efficiency in CHP
Electrical Efficiency (η_e)	%	50	U.S. EPA - CHP Efficiency, European Commission - Energy Efficiency in CHP
Heat Efficiency (η_h)	%	35	U.S. EPA - CHP Efficiency, European Commission - Energy Efficiency in CHP
Total Energy Input	MWh/year	111,364	94,659 ÷ 0.85
Hydrogen consumption	Tons/year	3,341	111,364 ÷ 33.33
Annual Working Load	Hours/year	8,016	U.S. DOE - CHP Working Hours, The Carbon Trust - CHP: Saving Energy Across Industry
Hydrogen Input Capacity (potential)	MW	~14	111,364 ÷ 8,016
Electricity Capacity (potential)	MW	7.0	14 × 0.5
Heat Capacity (potential)	MW	5.0	14 × 0.35
CO_2 Emissions Avoided	Tons CO_2/year	Electricity 38 kg CO_2 /MWh and District heating 161.5 kgCO_2/MWh	In total 8,087 tons of CO_2 avoided
Minimum total investment cost	EUR (€), million	-	59
Maximum total investment cost	EUR (€), million	-	129

8.2.2.2. CO_2 Emissions Calculation for Case 2

Since hydrogen FCs don't produce CO_2 emissions during operation (they produce only water and heat as byproducts), this calculation indicates avoided CO_2 emissions of hydrogen replacing existing heat and power use.

- **Assumptions**
  - The local electricity grid has an average carbon intensity of 38 kgCO_2/MWh [data from the local electricity grid operator] for electricity consumption.
  - The local district heat provider has an average district heat carbon intensity of 161.5 kgCO_2/MWh (in 2023) [data from the representatives of the airport].

Table 9 summarizes the CO_2 emissions avoided through the potential energy production of the system.

Table 9. CO_2 Emissions Possibly Avoided Through the Potential Energy Production of the System, Capacity of 14 MW

Description	Unit	Calculation	Results
Total Energy Produced (Potential)	MWh/year	-	94,659
Electricity Consumption Avoided CO_2	Tons of CO_2/year	58,539 MWh × 38.5 kgCO_2/MWh	2,254
Heat Consumption Avoided CO_2	Tons of CO_2/year	36,120 MWh × 161.5 kgCO_2/MWh	5,833
Total CO_2 Emissions Avoided	Tons of CO_2/year	2,254 tons + 5,833 tons	8,087

8.2.2.3. Power Storage Calculation Using Li-ion Batteries

To calculate the energy storage capacity required, the consultant assumed that the hydrogen-based CHP system could have surplus energy at times. A standard practice is to size the battery storage system to cover peak demand or store 10-20% of total energy production for flexibility.

➢ Assumptions

- The battery will store 10% of the annual electricity produced.
- Lithium-ion battery efficiency is typically around 90%.
- For cost purposes, Li-ion batteries are approximately €300-€400 / kWh [Bloomberg NEF Energy Storage, IEA - Global EV Outlook, McKinsey - Battery 2030].

Table 10 organizes the battery storage size and cost estimate based on 10% of the electricity production.

Table 10. Potential battery size if the CHP system´s capacity is 14 MW

Description	Unit	Calculation	Result
Total Electricity Production	MWh/year	-	58,539
Required Energy Storage (10%)	MWh/year	0.10 × 58,539 MWh	5,854
Energy Storage (Equivalent)	kWh	5,853.9 MWh × 1,000	5,853,900
Li-ion Battery Storage Cost	€ billion	2.05 billion	Based on average €350/kWh

A larger battery would be impractical for this application. In practice, the power storage capacity will be limited to 1–1.5 MW, which significantly reduces the investment cost compared to initial theoretical estimates.

8.3. Sensitivity Analysis

The sensitivity analysis is crucial because it helps evaluate how variations in key factors, such as hydrogen efficiency, prices, or system costs, can impact the overall feasibility and performance of a project. By testing different scenarios, it provides insights into potential risks and uncertainties, allowing decision-makers to understand the robustness of the system under changing conditions. This analysis ensures that the system can remain viable even when external factors, such as fuel costs or market conditions, fluctuate.

The sensitivity analysis assesses how variations in hydrogen efficiency and hydrogen prices impact the system.

Here are two key parameters (summary in Table 11):

- *Variation in Hydrogen Efficiency*:
  - ✓ Base case assumes 50% efficiency.
  - ✓ Sensitivity analysis: ±10% efficiency, resulting in 45% and 55% efficiency scenarios.
- Variation in Hydrogen Price:
  - ✓ Current hydrogen prices Green hydrogen price ranges from €2,200 to €8,200 per ton, while grey hydrogen costs range from €800 to €2,100 per ton, depending on production methods.

Table 11. Summary of Two Key Parameters in Three Cases

Scenario	Efficiency (%)	Hydrogen Consumption (tons/year)	Green Hydrogen Cost (Low) (€)	Green Hydrogen Cost (High) (€)	Grey Hydrogen Cost (Low) (€)	Grey Hydrogen Cost (High) (€)
Base Case	50	36	78,000	291,000	28,000	75,000
Lower Efficiency	45	32	70,000	262,000	26,000	67,000
Higher Efficiency	55	39	86,000	320,000	31,000	82,000

8.3.1. Case 2: Sensitivity Analysis for the CHP System Installation Costs

This sensitivity analysis evaluates how variations in two key parameters impact the installation costs of a 14 MW combined heat and power (CHP) system:

- Installation Cost per kW: A ±20% variation was applied to the initial cost range of €3,700–€9,200 per kW, resulting in an adjusted range of €3,400 – €12,000 per kW.

The analysis provides insights into how these factors can influence overall costs, aiding in more accurate budgeting and financial planning for the CHP system.

8.3.1.1. Storage Risks

- Risk 1: Hydrogen storage risks

Hydrogen storage presents significant risks due to its highly flammable nature, especially under high-pressure or low-temperature storage conditions. Additionally, the storage infrastructure needs to meet stringent safety standards. Costs could rise due to necessary precautions, specialized equipment, or future regulatory changes.

- Risk 2: Battery degradation risk for Li-ion batteries

Storage risks include degradation over time, which reduces the efficiency of the system. Battery lifecycles depend on usage patterns and environmental factors, and replacements may be required within 8-12 years, potentially increasing long-term costs.

- Risk 3: Capacity fade & Energy loss

Li-ion batteries experience a capacity fade, where the usable capacity diminishes over time. Additionally, energy losses during charging and discharging cycles (around 10%) must be factored into energy storage effectiveness.

8.3.1.2. Cost Calculations with Sensitivity Ranges

Here are considered four possible scenarios:

- Scenario 1: Base Case – Original installation cost.
- Scenario 2: -20% Cost – Installation costs decrease by 20%.
- Scenario 3: +20% Cost – Installation costs increase by 20%.
- Scenario 4: Exchange Rate Fluctuations – The impact of a stronger or weaker euro on the overall cost.

The sensitivity analysis Table 12 highlights how installation costs for the CHP system fluctuate based on changes in both installation costs and exchange rates. The results show that installation costs could range from €39 million to €156 million, with exchange rate fluctuations and a ±20% variation in installation costs driving the majority of the differences. These variations underscore the importance of considering financial and operational risks when planning the CHP system installation.

Table 12. Sensitivity Analysis of CHP System Installation Costs and Exchange Rate Fluctuations

Scenario	Minimum Cost (EUR, million)	Maximum Cost (EUR, million)
Base Case	59	129
Installation Cost –20%	39	85
Installation Cost –20%	48	104
Installation Cost +20%	59	128
Installation Cost +20%	72	156

Additionally, potential storage risks like hydrogen flammability and battery degradation should be carefully considered, as they can introduce long-term maintenance costs and safety concerns.

8.4. Summary of Case Studies

➢ Case 1: Hydrogen-Powered Fuel Cell Engines for Backup Power Generation

Section 8 outlines various steps like hydrogen production potential, consumption, and storage requirements. These were described in detail, including calculations for hydrogen consumption, storage needs, and integration with electricity markets. The assumptions, such as the efficiency of hydrogen fuel cells and storage capacity, are presented.

- *Calculations match*

There are detailed calculations on hydrogen consumption (592 MWh) and storage requirements, as well as assumptions about FC efficiency and hydrogen energy content.

- *All promised elements are included*

Hydrogen consumption, storage, electricity market participation, and integration with energy storage systems are covered as described in the case objectives.

➢ Case 2: Combined Heat and Power (CHP) Generation Using Hydrogen Fuel Cell Technology

This case study also provides a detailed assessment, including power and heat consumption at the large Baltic Sea Region Airport. It covers efficiency, hydrogen consumption, and potential for electricity and heat storage. There are specific calculations for CHP system sizing, capacity, and heat/electricity production.

- *Calculations match*

The document provides detailed calculations for CHP capacity (14 MW system), power and heat consumption, and potential CO_2 emissions avoided.

- *All promised elements are included*

The assessment for surplus heat usage, CHP integration, and storage options are fully described, meeting the case study description.

8.5. Case 2: Potential Calculation vs. Realistic Feasibility

Table 13 organizes the key data for a 3 MW CHP system with FC components with several European funding programs that provide substantial support. A smaller, for example, a 3 MW CHP system depicts a more realistic application sizing at least at the outset. Such a system could provide a stable baseload heating with other forms of heat production providing supplementary heat for the airport. All values in this table (Table 13) are rounded to the nearest whole number.

Table 13. Key Data for the 3 MW CHP-FC technology

Description	Unit	Value
Hydrogen Input Capacity	MW	3
Annual Working Hours	Hours/year	8,016
Technology Efficiency	%	85
Total Energy Output	MWh/year	20,351
Electrical Efficiency (η_e)	%	50
Heat Efficiency (η_h)	%	35
Electrical Energy Output	MWh/year	10,971
Heat Energy Output	MWh/year	8,380
Total Energy Input	MWh/year	23,943
Hydrogen Consumption	Tons/year	718
CO_2 Emissions Avoided (Electricity)	Tons/year	455
CO_2 Emissions Avoided (Heat)	Tons/year	1,353
Total CO_2 Emissions Avoided	Tons/year	1,808
Minimum Investment Cost	€ million	12.7
Maximum Investment Cost	€ million	27.7
Funding Source	**Potential Grant Share**	**Notes**
Clean Hydrogen Partnership	40–60%	Focuses on the hydrogen value chain; up to €113.5M available in 2024
EU Innovation Fund	50–60%	Supports large-scale clean energy projects with significant CO_2 reductions

For funding support on hydrogen-powered projects like the 3 MW CHP system, several European funding programs provide substantial support:

- Clean Hydrogen Partnership (under Horizon Europe)

This partnership offers funding for hydrogen-related projects across the entire value chain. For 2024, €113.5 million is available, with additional funding from the RePowerEU plan. Up to €60 million is allocated for strategic projects like Hydrogen Valleys, which focus on large-scale hydrogen infrastructure and technology adoption. This is ideal for innovative projects that integrate hydrogen into infrastructure, such as your proposed CHP system [Clean Hydrogen Partnership, ManagEnergy, 2024].

  - *Potential Funding Share:* Grants can cover a significant portion, typically ranging from 40-60% of eligible project costs, depending on the innovation level and EU-specific rules.

- Innovation Fund (EU)

The Innovation Fund supports large-scale clean energy projects aimed at decarbonizing industries, including hydrogen fuel cell technology. It is particularly suited for projects that significantly reduce CO_2 emissions, making your CHP system, which avoids 3,307 tons of CO_2 annually, a potential candidate. The first round awarded €1.25 billion to hydrogen-related projects across Europe [Hydrogen Europe, Clean Hydrogen Partnership, 2024].

  - *Potential Funding Share:* Projects can receive up to 50-60% of the eligible project costs, depending on project size and impact.

8.6. Comparison with Medium-size and Small-size Airports

This analysis framework is designed with scalability in mind, allowing it to be applied across a range of airport sizes. The analysis framework can be readily adapted to both medium and small Airports. Although the calculations are generalized, they provide valuable insights into the feasibility and potential advantages of incorporating hydrogen-based energy solutions into airport infrastructure.

8.6.1. Case 1: H_2-Powered FC Engines for Backup Power Generation

Case 1 focuses on providing backup power for a small-sized and a large-sized airport using H_2-powered FCs.

- Potential for a Small-sized Airport (Case 1)

The small-sized airport case example considers an Airport with an existing backup power generation system comprising three generators and utilizing fossil diesel as fuel. Based on data received from the Airport, the annual diesel fuel consumption is only circa 170 litres.

Table 14 presents the energy calculation data and potential annual emission savings.

Table 14. Summary Table of Potential Hydrogen Consumption Calculation for Backup Power – Small-sized Airport

Description	Unit	Value
Annual Backup Power Generator Fuel Consumption	litres	168
Annual Backup Power Generator Fuel Consumption	kWh/year	1,680
Generator Efficiency (assumption)	%	40
Annual Backup Power Generation	kWh/year	672
FC Electrical Efficiency	%	50
Hydrogen Energy Input	kWh/year	1,344
Hydrogen Consumption	kg/year	40
Liquid Hydrogen Storage Required	m³/year	0.6
CO_2 Emission Savings	Tons CO_2/year	0.45

Switching the backup power generation to H_2 FC-based systems would result in 0.5 tons of CO_2 savings per year for the small-sized airport based on provided data in 2023. Hydrogen consumption of this system is very limited, only 40 kg of hydrogen annually, and would require a 0.6 m³ storage capacity if stored as liquid hydrogen.

- Potential for a Medium-sized Airport (Case 1)

The medium-sized airport case example considers an Airport with an existing backup power generation system comprising of four generators and utilizing fossil diesel or light fuel oil as fuel. Based on data received from the Airport, the annual diesel fuel consumption for the backup power generation system at this airport is circa 10,000 litres.

Table 15 presents the energy data and potential annual emission savings.

Table 15. Summary Table of Potential Hydrogen Consumption Calculation for Backup Power – Medium-sized Airport

Description	Unit	Value
Annual Backup Power Generator Fuel Consumption	litres	10,030
Annual Backup Power Generator Fuel Consumption	kWh/year	100,300
Generator Efficiency (assumption)	%	40
Annual Backup Power Generation	kWh/year	40,120
FC Electrical Efficiency	%	50
Hydrogen Energy Input	kWh/year	80,240
Hydrogen Consumption	kg/year	2,407
Liquid Hydrogen Storage Required	m³/year	34
Practical Storage Capacity Application	m³	3-5
CO_2 Emission Savings	Tons CO_2/year	27

Switching the backup power generation to H_2 FC-based systems would result in 27 tons of CO_2 savings per year for the medium-sized airport based on provided data in 2023.

8.6.2. Case 2: CHP Generation Using Hydrogen FC Technology

In Case 2, hydrogen FC technology is used for both power and heat generation. If airports were to replace their current heating and power systems with hydrogen-based CHP systems, the total CO_2 emissions could be drastically reduced. The calculations have been made similarly to the large-scale airport but using received data from small or medium-sized Airports in the Baltic Sea Region.

➢ Potential for a Small-sized Airport (Case 2)

The small-scale airport data is presented in Table 16. Based on the calculation, a circa 200 kW fuel cell CHP could provide most heat and power needs of the small-sized Airport, with resulting carbon emission savings at 339 tons of CO_2 annually.

Table 16. Summary for CHP using Hydrogen Fuel Cell Technology (maximum potential) – Small-sized Airport

Category (Small-sized Airport, Case 2)	Unit	Value
Electricity Consumption	MWh/year	893
Natural Gas Consumption (for heating)	m^3/year	43,094
Heat Consumption	MWh/year	465
Total Energy Consumption	MWh/year	1,358
Total CHP Efficiency	%	85
Electrical Efficiency (η_e)	%	50
Heat Efficiency (η_h)	%	35
Total Energy Input	MWh/year	1,598
Hydrogen Consumption	kg/year	47,941
Annual Working Load	Hours/year	8,016
Hydrogen Input Capacity (potential)	MW	0.2
Grid Electricity Carbon Factor	kgCO_2/kWh	0.274
Natural Gas Carbon Factor	kgCO_2/kWh	0.202
CO_2 Savings (Electricity)	Tons CO_2/year	245
CO_2 Savings (Heat)	Tons CO_2/year	94
Total CO_2 Savings	Tons CO_2/year	339

The results show that for the small-sized airport, theoretically, a small FC CHP would suffice for baseload heat and power generation with potential for significant carbon emission savings. It should be noted that actual CHP unit sizing should be conducted using hourly demand data and in addition to the rating, the system's power-to-heat ratio should be determined based on that data.

➢ Potential for a Medium-sized Airport (Case 2)

The Medium-scale Airport data is presented in Table 17. For this example, a replacement of the Airport's existing Gas CHP system with an FC-based CHP has been reviewed. The current CHP plant of the Airport consists of six modules with 2 MW rated output each (for a total of 12 MW), all utilizing natural gas as fuel. Potential hydrogen input capacity has been calculated with the same average annual working load as the current CHP system.

Table 17. Summary for CHP using Hydrogen Fuel Cell Technology (maximum potential) – Medium-sized Airport

Category (Medium-sized Airport, Case 2)	Unit	Value
CHP Thermal Output Rating	MW	12
CHP Gas Consumption	MWh/year	33,915
CHP Electricity Generation	MWh/year	9,602
Total CHP Efficiency (estimated)	%	85
Electrical Efficiency (η_e)	%	33
Heat Efficiency (η_h) (estimated)	%	52
CHP Heat Production	MWh/year	14,902
Total CHP Energy Production	MWh/year	28,828
Annual Working Load	Hours/year	2,400
Hydrogen Input Capacity (potential)	MW	14
Hydrogen Consumption	Tons/year	865
Natural Gas Carbon Factor	$kgCO_2/kWh$	0.202
Total CO_2 Savings	Tons CO_2/year	6,850

The results in Table 18 indicate significant carbon emission savings potential when if the existing gas-fired CHP system should be replaced with an FC-based CHP system. The calculation presents the full potential but especially in this example, it would be extremely important to conduct detailed design and sizing to minimize the cost-effectiveness of the FC CHP system.

9. Summary of Total Potential Demand for Hydrogen in Large Airport Terminal Operations

The total potential demand for hydrogen in the large Baltic Sea Region Airport's terminal operations can be derived from the case studies discussed earlier. The two primary applications assessed in the study are backup power generation using hydrogen-powered Fuell Cells and the integration of hydrogen-based Combined Heat and Power systems.

- Backup Power Generation (Case 1):

The hydrogen-powered FC engines are estimated to consume approximately 36 tons of hydrogen annually to meet the airport's circa 600 MWh backup power generation requirement. This assumes a 50% FC efficiency and an energy content of 33.33 kWh per kg of hydrogen. The total hydrogen storage needed annually for backup power is approximately 500 m³ of liquid hydrogen. In practical situations, it's expected that only 10-15% of the suggested storage capacity will be used, considering periodic storage refills, which makes investing in a smaller, more adaptable storage solution a more feasible choice.

- Combined Heat and Power (CHP) System (Case 2):

For the CHP system, designed to meet both electricity and heat demand at the large Airport, the total energy requirement is estimated at 59 GWh of electricity and 36 GWh of heat annually. Based on these energy needs and the proposed 14 MW hydrogen FC system, the hydrogen consumption would significantly exceed that of the backup power application. Calculations show that the CHP system would require 36 tons of hydrogen annually, considering both electricity and heat outputs. The hydrogen storage needs for this system are expected to scale accordingly, depending on the infrastructure for either gaseous or liquid hydrogen. In total, this potential system capacity would reduce annually circa 8,100 tons of CO_2.

A more moderate proposal for a 3 MW CHP-FC system that operates for 8,016 hours per year, can produce theoretically circa 20 GWh of energy annually (for example 12 GWh electricity and 8 GWh heat). This system would require 718 tons of hydrogen annually and avoids a total of 1,800 tons of CO_2 emissions per year from heat and electricity. The estimated investment cost ranges from €13 million to €28 million. Grants can cover a significant portion, typically ranging from 40-60% of eligible project costs, depending on the innovation level and EU-specific rules.

10. Recommendations and Suggestions for Future Work

➢ Scaling up Green Hydrogen Production

The next step should focus on expanding green hydrogen production capabilities. Investing in renewable energy infrastructure to support large-scale hydrogen generation, especially through electrolysis, is essential. Partnerships with renewable energy providers could help drive down costs and improve production efficiency.

➢ Enhancing Hydrogen Storage and Transportation

Future research should explore advancements in hydrogen storage solutions, such as liquid hydrogen or solid-state storage technologies, and improving transportation methods. Developing scalable storage systems, especially for airports, will be crucial in enabling consistent hydrogen supply. Exploring innovative hydrogen carriers like LOHC (Liquid Organic Hydrogen Carriers) could further enhance the storage and transport efficiency of hydrogen.

➢ Hydrogen Infrastructure Development

Expanding hydrogen refueling and production infrastructure is critical. Future work should focus on creating a robust network for hydrogen supply, particularly at airports and other strategic locations. Investment in pipelines and liquid hydrogen tankers could help overcome current logistical barriers. Pilot projects at airports should be expanded to validate the technologies on a larger scale.

➢ Integration with Renewable Energy Sources

A more integrated approach between hydrogen generation and renewable energy sources like solar and wind power is recommended. Coupling these systems will not only increase efficiency but also stabilize energy supplies at airports. Collaboration with renewable energy developers can help establish a seamless transition toward greener airport energy systems.

➢ Economic Feasibility and Incentives

Further economic analysis is needed to understand the long-term feasibility of hydrogen applications in airport environments. Policymakers should introduce financial incentives, subsidies, or carbon credits to accelerate hydrogen adoption. Continued studies on cost reduction opportunities, particularly in hydrogen production and storage, will be important for encouraging investment.

- Pilot Projects and Case Studies

Conducting more pilot projects at both large and small airports could provide concrete data and practical insights into hydrogen applications. These pilot projects would help identify technical, economic, and operational challenges in real-world conditions, further enhancing the credibility of hydrogen solutions for aviation.

- Policy and Regulatory Framework Development

Collaboration with national governments and international bodies should focus on creating favorable policies for hydrogen adoption in aviation. Developing regulations that standardize safety, infrastructure, and operational procedures will ensure a smoother transition to hydrogen-based energy solutions.

- Technological Innovation and Safety Research

Ongoing research into improving the efficiency of hydrogen fuel cells, electrolyzers, and safety technologies is recommended. Addressing hydrogen safety concerns in storage and transportation through advanced detection systems and materials research will help build industry confidence in adopting hydrogen.

- Cross-Sector Collaboration

Developing partnerships with automotive, maritime, and industrial sectors to leverage advancements in hydrogen technology is important. Sharing knowledge and infrastructure among sectors could accelerate the development of hydrogen solutions and lead to synergies across industries.

- Educational and Training Programs

To ensure the successful implementation of hydrogen technologies, it is important to provide specialized training for airport personnel and other stakeholders. Educational programs focusing on the safe handling of hydrogen, system maintenance, and integration with existing infrastructure will be critical for ensuring long-term success.

These recommendations are designed to support the continued development and implementation of hydrogen use in the Airport environment and specifically to supplement other upcoming hydrogen solutions at Airports.

11. Conclusions on the Conducted Research

This feasibility study underscores the substantial potential of hydrogen in transforming energy systems within airports, highlighting its capacity to decarbonize critical infrastructure, such as backup power generation and CHP applications. As the aviation industry seeks to mitigate its environmental impact, hydrogen-powered technologies emerge as a promising solution, offering significant environmental and operational benefits.

Research conducted by Granlund Oy, complemented by various case studies, indicates that hydrogen FC systems could provide a technically viable solution to meet the burgeoning energy demands of airports. However, the successful implementation of such systems hinges on the establishment of a robust hydrogen infrastructure capable of supporting the unique operational requirements of airports as well as technological and market improvement to be able to compete in the future against other low-carbon energy supply solutions. Furthermore, the integration of liquid hydrogen storage systems can be effectively designed to accommodate the diverse energy requirements of airports across different scales, from smaller regional facilities to major international hubs. This flexibility is critical in addressing the varying energy demands associated with airports, which can fluctuate significantly based on e.g. location and airport operations.

➢ Case 1: Hydrogen-Powered Fuel Cell Engines for Backup Power Generation

The study assesses hydrogen FC engines for backup power at airports, with calculations showing a hydrogen consumption of 600 MWh annually. This aligns with assumptions on FC efficiency and energy content, confirming objectives for hydrogen consumption, storage needs, and grid integration.

➢ Case 2: Combined Heat and Power Generation Using Hydrogen Fuel Cell Technology

This analysis examines hydrogen FC technology for CHP at a large Baltic Sea airport, documenting a 14 MW CHP capacity, power and heat metrics, and CO_2 reduction potential. Key aspects, like heat utilization and CHP integration, validate the study's objectives.

➢ Potential Calculation vs. Realistic Feasibility

Table 14 details a 3 MW CHP system, providing stable airport heating with additional sources. Key data on hydrogen input, energy output, and CO_2 savings support the feasibility of this project, with potential funding from EU programs.

- Comparative Analysis Across Airport Sizes

Hydrogen-powered FC systems are scalable across airport sizes, enhancing both backup power and CHP applications effectively. This case study presents an in-depth assessment of hydrogen FC technology for CHP systems at a large Baltic Sea Region airport. The analysis covers power and heat consumption, alongside detailed calculations for CHP system sizing and capacity. The documented calculations demonstrate a 14 MW CHP capacity, power and heat consumption metrics, and significant potential for CO_2 emissions reduction. The full spectrum of required elements, including surplus heat utilization and CHP integration, has been thoroughly explored, validating the case study's scope and objectives.

The outputs are following:

- Backup Power Generation for Airports:
  - ✓ *Small-Sized Airport:* Transitioning from fossil fuels to hydrogen fuel cells in this small airport example could result in CO_2 emissions savings of 0.5 tons annually, with a minimal hydrogen consumption of 40 kg.
  - ✓ Medium-Sized Airport: The potential savings increase significantly, with CO_2 emissions reductions of 27 tons per year due to the larger backup power requirement.
- CHP Generation Using Hydrogen FC Technology:
  - ✓ *Small-sized Airport*: FC CHP system could meet most power and heat demands, leading to annual carbon savings of circa 340 tons.
  - ✓ Medium-Sized Airport: Replacing existing gas CHP systems with hydrogen fuel cells could yield significant emissions reductions, with potential savings of 6,850 tons annually.

Summary of Total Potential Demand for Hydrogen

The total potential demand for hydrogen in the large Baltic Sea Region Airport's operations is assessed through two primary applications: backup power generation and CHP systems.

- Backup Power Generation

Approximately 36 tons of hydrogen is needed annually to meet a backup power requirement of

600 MWh. This system requires around 500 m³ of liquid hydrogen storage, emphasizing the need for efficient storage solutions that align with operational demands.

- Combined Heat and Power System

The CHP system is projected to require about 3,300 tons of hydrogen annually, meeting both electricity and heat demands of 59 GWh/a and 36 GWh/a, respectively. The transition to this system could achieve a substantial reduction of circa 8,900 tons of CO_2 emissions per year.

While this study presents encouraging findings, it also emphasizes the necessity of overcoming several existing barriers to fully realize the potential of hydrogen as a mainstream energy source in the aviation sector. Key challenges include the need for substantial investment in hydrogen infrastructure, the high initial costs associated with the technology, and the safety concerns that must be addressed to ensure public confidence in hydrogen-powered systems. Therefore, ongoing investment in hydrogen infrastructure and continued research into advanced storage and fuel cell technologies are imperative for facilitating a successful transition to hydrogen.

Moreover, collaboration among stakeholders—airports, energy providers, and policymakers—will be essential to create a conducive environment for hydrogen-powered operations. By fostering partnerships and engaging in dialogue, these entities can work together to develop the regulatory frameworks and market incentives necessary to support the adoption of hydrogen technologies in aviation.

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