Bachelor of Aeronautical Engineering Thesis

Hydrogen Hybrid Electric Propulsion Systems

Sustainable Aviation Through Cross-Sectoral Technology Transfer

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Hydrogen Hybrid Electric Propulsion Systems

Towards Sustainable Aviation: Adapting Hydrogen Hybrid Electric Propulsion Systems Through Technology Transfer from Maritime and Truck Sectors

Abstract

This thesis explores the potential for adapting hydrogen hybrid-electric propulsion systems (HHEPS) from the maritime and truck sectors to meet sustainability challenges in aviation. Given the significant greenhouse gas emissions in the transportation sector, particularly from aviation and maritime, hydrogen-based propulsion offers a promising alternative to traditional fossil fuels. Utilizing a systems engineering approach, this study presents a comprehensive breakdown of HHEPS, including power requirements, infrastructure needs, and operational dynamics specific to aviation. A feasibility framework assesses the scalability and compatibility of these technologies, identifying areas where maritime and truck advancements provide a solid foundation for aviation, such as hydrogen storage and refueling infrastructure. However, adaptations are essential to address aviation's unique demands, including high-altitude operations and stringent safety standards. This research contributes to sustainable aviation by proposing pathways for technology transfer, offering insights for industry stakeholders committed to achieving environmental goals. Future research is recommended to explore advanced hydrogen storage materials, optimized refueling logistics, and certification standards tailored for aviation

Thesis report

By

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To obtain the degree of Bachelor of science in Aeronautical Engineering
At Inholland University of Applied Sciences

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Preface

This thesis, *Hydrogen Hybrid Electric Propulsion Systems: Sustainable Aviation Through Cross-Sectoral Technology Transfer*, was completed as part of my Bachelor program at Inholland University of Applied Sciences. The research investigates how hydrogen-based propulsion technologies, developed and proven in the maritime and truck sectors, can be adapted to meet the sustainability goals within aviation, in alignment with Dutch initiatives for a greener aerospace sector. This project was supported by the Netherlands aerospace group (NAG) and supervised by Mr. Peter Kortbeek.

This thesis is primarily intended for an academic audience, including my university advisors, thesis committee. Additionally, this work may be of interest to industry professionals and policymakers in the fields of sustainable aviation, hydrogen propulsion, and cross-sectoral technology adaptation, especially those engaged in the Dutch aerospace and environmental sectors.

This thesis is organized to accommodate readers with varied interests and engagement levels:

- The Summary provides a concise overview of the research findings and conclusions for those seeking a high-level understanding.
- The Introduction section lays the groundwork for the research, covering the background, problem description, objectives, research questions, and study scope.
- The Research Methodology and Literature Review offer a detailed explanation of the research approach and an exploration of the foundational knowledge on hydrogen-based propulsion.
- Chapters 4 through 10 cover data collection, HHEPS technology for aircraft, power requirements, technical analyses, and case studies from maritime and truck sectors.
- Chapters 11 through 18 detail solutions, infrastructure, operational aspects, recent innovations, technology translation, and challenges, leading to the Conclusion and Recommendations.
- References and Appendices provide supporting documentation, such as survey questions, case study specifications, and industry standards, for further exploration.

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Finally, I would like to extend my heartfelt thanks to my family and friends for their constant support, patience, and encouragement. Their belief in me has been a source of strength and motivation throughout this journey.

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Hana Alnajjar

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Summary

Amid increasing environmental regulations and societal pressures, the aviation industry is urgently seeking sustainable propulsion technologies to mitigate its environmental impact. particularly in light of ambitious international climate targets such as those outlined in the ACARE Flightpath 2050 vision. Hydrogen hybrid-electric propulsion systems (HHEPS) present a compelling alternative, combining hydrogen fuel cells, batteries, and electric motors to improve efficiency and reduce emissions. This research investigates how advancements in HHEPS from the maritime and trucking sectors can be adapted to meet aviation's specific requirements, with a particular emphasis on the Netherlands' role as a leader in sustainable aviation through initiatives like "Aerospace in Transition."

The Netherlands has positioned itself as a hub for green technology, actively supporting cross-sector technology transfer to accelerate sustainable innovation in aviation. This study aligns with these national objectives by examining how technological developments in HHEPS from maritime and trucking can contribute to aviation's sustainability goals. Through an extensive literature review, the study addresses key components of hydrogen hybrid-electric systems, such as fuel cells, hydrogen storage, and refueling infrastructure. Comparative case studies—including the SF-BREEZE hydrogen fuel cell ferry, Hyundai Xcient Fuel Cell truck, and Nikola Tre fuel cell vehicle—provide insights into power requirements, operational capacity, infrastructure needs, and essential competencies in areas like fuel cell maintenance, system safety, and performance monitoring. These case studies allow for a comprehensive evaluation of which aspects of HHEPS technology and know-how can be transferred effectively to aviation.

Using a systems engineering approach, this research systematically breaks down HHEPS to assess the hardware, power needs, and operational characteristics across sectors. Methodologies such as data analysis, expert interviews, and cross-sector case studies enable a detailed assessment of these systems, identifying both the technical and operational requirements for aviation applications. Findings indicate that hydrogen storage solutions and high-speed refueling infrastructure advancements from the trucking and maritime sectors offer promising opportunities for adaptation. High-pressure composite tanks used in the Hyundai Xcient and Nikola Tre meet aviation's need for compact, lightweight hydrogen storage, while rapid refueling systems developed for trucks provide a robust model for meeting aviation's fast turnaround requirements at airports.

However, critical challenges remain. Thermal management emerges as the most complex issue, as aviation's weight constraints make solutions like large-scale heat exchangers—effective in maritime contexts—impractically heavy. In addition, adapting ventilation systems for altitude-sensitive hydrogen release requires specialized solutions that can handle rapid pressure changes and extreme temperature fluctuations encountered in high-altitude flight. These aviation-specific challenges underscore the need for further development in lightweight thermal management and altitude-capable safety systems to ensure reliable hydrogen integration in aviation.

This research offers a strategic roadmap to guide the aviation sector in adopting HHEPS. Recommendations include targeted investments in hydrogen refuelling infrastructure at airports, collaborative efforts with regulatory bodies such as EASA and FAA to establish safety and certification standards, and ongoing R&D focused on lightweight thermal management systems and advanced hydrogen storage materials. Proposed initiatives, such as pilot projects, partnerships with industry stakeholders, and extensive testing, aim to refine HHEPS technologies for aviation-specific applications and provide a foundation for future advancements.

Beyond these technical insights, this study contributes to the Strengthening Ecosystems for Aviation (SEA) initiative, reinforcing the value of cross-sector collaboration to build a resilient, knowledge-rich ecosystem for sustainable aviation. By leveraging innovations and competencies from maritime and trucking, the aviation industry can accelerate its transition to hydrogen propulsion, aligning with SEA's mission of fostering collaboration across industries, regulatory bodies, and research institutions.

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List of abbreviations

Abbreviation	Full Term
AAM	Advanced Air Mobility (FAA program)
ABB	ASEA Brown Boveri
ASME	American Society of Mechanical Engineers
BMS	Battery Management System
BoP	Balance of Plant
CARB	California Air Resources Board
CCS	Carbon Capture and Storage
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DC	Direct Current
EASA	European Union Aviation Safety Agency
EMS	Energy Management System
FAA	Federal Aviation Administration
FCEV	Fuel Cell Electric Vehicle
GF LiT	Growth Fund project "Aerospace in Transition"
GHG	Greenhouse Gas
GH2	Gaseous Hydrogen
GTI	Gas Technology Institute
HHEPS	Hydrogen Hybrid Electric Propulsion System
HIOKI	HIOKI E.E. Corporation
HRS	Hydrogen Refueling Station
HVAC	Heating, Ventilation, and Air Conditioning
H_2	Hydrogen (gaseous)
IAAC	International Air Transport Association
ICAO	International Civil Aviation Organization
IEC	International Electrotechnical Commission
IGF Code	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
IATA	International Air Transport Association
LG Chem	LG Chemical
LH2	Liquid Hydrogen
MEA	Membrane Electrode Assembly
MF Hydra	Motor ferry hydra
MSA	Mine Safety Appliances
NASA	National Aeronautics and Space Administration
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NZE	Net Zero Emissions

PBS	Product Breakdown Structure
PCU	Power Control Unit
PDU	Power Distribution Unit
PED	Pressure Equipment Directive
PEM	Proton Exchange Membrane
PID	Proportional-Integral-Derivative
PMSM	Permanent Magnet Synchronous Motor
PTC	Positive Temperature Coefficient
PV	Photovoltaic
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SEA	Strengthening Ecosystems
SMR	Steam Methane Reforming
SoC	State of Charge
TE	TE Connectivity
TI	Texas Instruments
TRB	Transportation Research Board
TRL	Technology Readiness Level
U.S. DOE	United States Department of Energy
VFD	Variable Frequency Drive
WP	Work Package
WTC	World Trade Centre

Table 1 List of Abbreviations

1. Introduction

1.1 Background

The Netherlands has firmly established itself as a key player in the global aviation market, supported by a robust ecosystem of research institutions, field labs, SMEs, large industries, and a supportive government. This ecosystem, while strong, faces the urgent need to transition toward sustainable aviation—a shift critical not only for environmental impact reduction but also for sustaining the competitiveness and innovativeness of the Dutch aerospace sector.

Sustainable aviation represents the future of the aerospace industry as the world becomes increasingly aware of climate change and the environmental toll of human activities. The aviation sector, in particular, is under significant pressure to reduce its carbon footprint and pioneer greener technologies. This pressure is encapsulated in initiatives like the ACARE Flightpath 2050 vision, which seeks to achieve a 75% reduction in CO_2 emissions, a 90% reduction in NOx emissions, and a 65% reduction in perceived noise by 2050. Meeting these ambitious goals requires adopting cutting-edge technologies, improving fuel efficiency, and integrating alternative energy sources, such as hydrogen and electric propulsion, to align with international climate agreements like the Paris Agreement and ensure the long-term viability of aviation.

One of the most promising strategies to accelerate this transition is through cross-sectoral technology transfer, leveraging innovations from other industries. The Netherlands is uniquely positioned to capitalize on this approach due to its diverse, advanced technological landscape across sectors like automotive, energy, ICT, high-tech equipment, and maritime. Each of these sectors has pioneered progressive technologies and infrastructures that offer potential applications for aerospace. For instance, advancements in hydrogen storage and fuel cells from the maritime and truck sectors may align closely with the specific needs of aviation. By fostering collaboration across these industries, the Dutch aviation ecosystem can access new technologies and competencies that may currently be missing within aerospace.

This project, part of the Growth Fund initiative "Aerospace in Transition" (GF LiT), specifically within the "Strengthening Ecosystems" (SEA) sub-project, aims to bridge these gaps. Its primary objective is to identify and adapt missing technologies, competencies, and infrastructures from sectors like maritime and truck to the aviation industry, enhancing the Dutch aerospace ecosystem and expediting sustainable technology adoption.

By systematically examining the power requirements, critical components, and operational aspects of hydrogen hybrid-electric propulsion systems, along with the challenges and opportunities in transferring this technology from maritime and truck sectors to aviation, this research addresses a pressing need for sustainable aviation practices. Ultimately, the study aspires to contribute insights that support a competitive, sustainable aviation future in the Netherlands.

1.2 Problem description

The transportation sector remains a significant contributor to global greenhouse gas emissions, encompassing sub-sectors such as road, rail, shipping, aviation, and pipeline transport. According to recent data (Ritchie & Roser, 2024), emissions from these sub-sectors have shown a consistent rise over the decades, with road transport accounting for the largest share. In recent years, however, road transport has shown improvements, mainly due to cleaner technologies like electric vehicles and stricter emissions regulations. In contrast, aviation and maritime transport continue to be major emitters, with aviation standing out due to its slower adoption of low-emission technologies.

Aviation sector emissions are particularly concerning, given the anticipated 5-8% annual growth in air traffic measured in passenger kilometers. This growth underscores the urgent need for sustainable aviation advancements. Without significant technological interventions, aviation's share of global emissions could rise, potentially surpassing other sectors in environmental impact. Data from "Our World in Data" illustrates this trend, highlighting the persistent and growing challenge that aviation poses to global emissions reduction efforts.

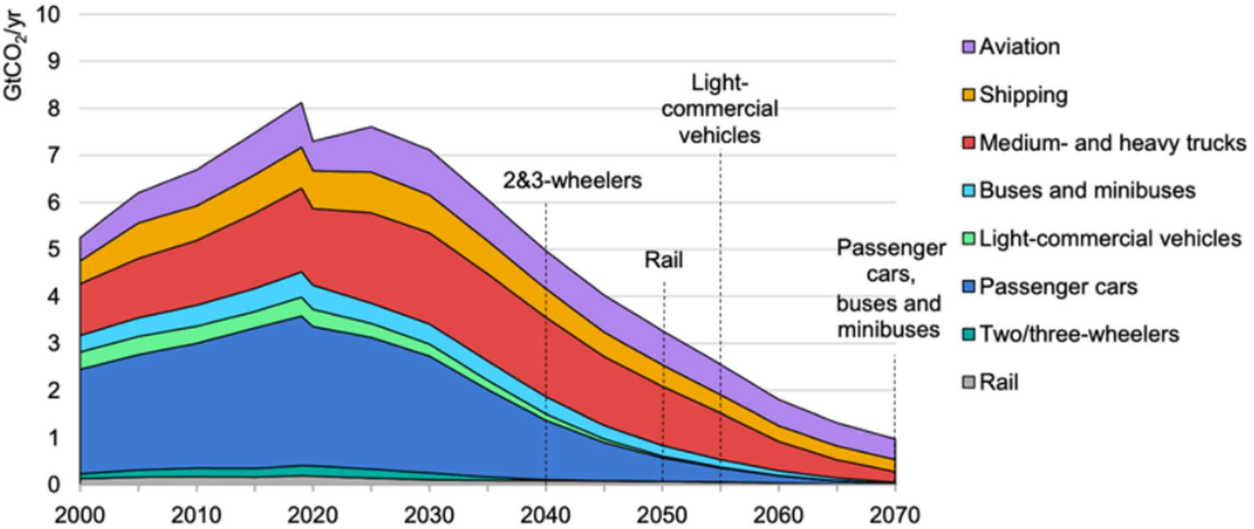

Figure 1 Global CO2 emissions in transport by mode in the sustainable development scenario, 2000-70 (Ritchie & Roser, 2024)

Hydrogen hybrid-electric propulsion systems are emerging as a promising technology to address this issue. These systems combine hydrogen fuel cells with electric driveline systems to power vehicles, utilizing an electrochemical reaction between hydrogen and oxygen to produce electricity. This process emits only water and heat as byproducts, making it an environmentally friendly solution. The electricity generated powers electric motors, and batteries can store excess energy to provide additional power as needed, enhancing the system's overall energy efficiency and reliability.

A key focus of this project is the potential to adapt these hybrid-electric propulsion technologies—originally developed for the maritime and truck sectors—to aviation. Specifically, advanced Balance of Plant (BoP) systems, including liquid hydrogen (LH2) conditioning, thermal and power management, and fuel cell-electromotor integration, show strong potential for aerospace applications. These technologies aim not only to reduce emissions but also to improve energy efficiency, making them critical for achieving sustainability in aviation. However, the transition to sustainable aviation poses significant challenges. Technologies must often undergo extensive adaptation to meet aviation's rigorous safety and performance standards. Moreover, many of these technologies are at a low Technology Readiness Level (TRL), complicating development, testing, and certification within constrained timeframes. Despite these challenges, the pressing need for sustainable solutions in aviation underscores the importance of leveraging cross-sectoral innovations.

This project seeks to bridge these gaps by systematically exploring how hydrogen hybrid-electric propulsion technologies can be adapted from maritime to aviation applications. Through a comprehensive analysis of technologies from the maritime and truck sectors, this project aims to facilitate the Dutch aviation ecosystem's transition toward sustainability by integrating these cross-sectoral technologies and expertise, addressing the critical need for sustainable aviation solutions.

1.3 Objectives

The primary goal of this graduation project is to bolster the aerospace ecosystem and hasten the shift toward sustainable aviation by leveraging cross-sectoral competencies, infrastructure, and technologies. The specific objectives are outlined as follows:

- Identify Missing Technologies and Infrastructure: This project aims to conduct an extensive survey to pinpoint critical technologies, competencies, and infrastructures that are absent in the aerospace sector but present in other Dutch sectors, particularly maritime and road transport (focusing on barges and lorries). The goal is to catalogue these resources and assess how they can be customized to meet the specific needs of aviation.
- Strengthening the Aerospace Ecosystem: By integrating adapted hybrid electric propulsion technologies and balance of plant from sectors like maritime and road transport, this project seeks to enhance the robustness and sustainability of the aerospace industry. The objective is to introduce innovative approaches that improve the environmental impact and efficiency of aerospace operations.
- Identify Opportunities and Hurdles: This includes recognizing potential advantages and challenges associated with adapting maritime hybrid electric technologies for aviation use. The aim is to ensure a comprehensive understanding of the feasibility and practical implementation aspects, facilitating a smoother transition.
- Supporting Sustainable Aviation Transition: The project intends to accelerate sustainable aviation practices by utilizing identified and modified cross-sectoral innovations. This involves leveraging new technologies to enhance energy efficiency in the aerospace industry, reduce carbon emissions, and meet or surpass global sustainability standards.
- Develop a Thorough Understanding of Implementation Challenges: Investigate potential barriers to the aerospace industry's adoption of these new technologies and propose viable solutions. This includes evaluating the technological, economic, regulatory, and integration challenges associated with incorporating these innovations into existing aeronautical systems.
- Technological Scalability: Assess the scalability of adapted technologies for use across various aerospace applications, from small unmanned aerial vehicles to large commercial aircraft. This entails examining different power requirements, potential integration challenges.
- Foster Cross-Sectoral Collaboration: Encourage and facilitate deeper collaboration between the aerospace industry and other sectors such as automotive, energy, maritime, and ICT. This collaboration aims to promote a continuous exchange of knowledge and innovations, thereby driving long-term technological advancements within the aerospace sector.

1.4 Research Questions

Main Research Question

- How can the aviation sector leverage the expertise and advancements in hydrogen hybrid-electric propulsion technology developed in the maritime and truck sectors to meet its specific requirements and constraints?

Sub Research-Questions

The following sub questions are systematically investigated across the three sectors—maritime, truck, and aviation—not merely within isolated chapters but throughout the entire scope of the report:

1. What are the power requirements and dynamic characteristics of hybrid-electric propulsion systems?
2. What are the critical components and hardware used in these systems, and who are the suppliers?
3. How were the solutions in each sector developed, and what competences were needed?
4. What development tools and test infrastructures are used?
5. What are the operational aspects of these systems, including regulatory and certification requirements, operational procedures, competences for operation, safety systems, and maintenance practices?
6. What are the latest developments in hybrid-electric propulsion technologies?
7. What are the opportunities and commonalities between maritime, truck, and aviation hybrid-electric propulsion systems?
8. What are the hurdles and challenges in transferring hybrid-electric propulsion technology from maritime and truck sectors to aviation?
9. How can the potential for technology transfer to the aviation sector be validated?

1.5 Scope and boundaries

- The primary focus will be on examining and adapting the know-how and technologies from the maritime sector to the aviation sector.

- The truck sector will be considered only if it is determined to be time-efficient and does not compromise the project's timeline and deliverables.

- Emphasis will be placed on identifying and leveraging hydrogen hybrid-electric propulsion systems and their components.

- The project will cover power requirements, dynamic characteristics, system hardware, development processes, operational aspects, and new developments in the relevant sectors.

- The study will also explore the regulatory and certification requirements, competences for operation, safety systems, and maintenance practices for the adaptation of these technologies to aviation.

- While the focus includes technologies at various levels of maturity, priority will be given to those at low Technology Readiness Levels (TRLs) that show significant potential for advancement and application in aerospace.

- The project will primarily concentrate on technologies from the maritime sector. Innovations from other sectors such as automotive, energy and high-tech equipment may be considered but are not the main focus.

- Only technologies directly related to hybrid electric propulsion systems in vessels will be considered. Broader maritime technologies not applicable to propulsion will be excluded.

- The scope is limited to the Dutch aviation and maritime ecosystems, emphasizing local competences, technologies, and infrastructures.

- The scope will be influenced by the availability and accessibility of data from maritime and aerospace sectors. Confidential or proprietary information may limit the depth of analysis.

- project timeline imposes limits on the extent of research, analysis, and validation that can be conducted. Prioritization of tasks will be necessary to meet deadlines.

- While the project will consider regulatory and certification pathways, it will not engage in actual certification processes.

- Along with both the agreement of the intern and the company supervisor, time limitation can determine the scope further in the project whether to limit or expand on it.

2. Research Methodology

This chapter outlines the research methodology used to explore the feasibility of hydrogen hybrid-electric propulsion systems (HHEPS) for sustainable aviation. To address the primary research questions and objectives, various methods were employed, including literature review, case studies, interviews, and surveys. These methodologies were selected to ensure a comprehensive analysis of both technical and practical aspects of technology transfer from maritime and truck sectors to aviation. Each method serves a specific purpose in supporting the data collection, analysis, and validation processes, as detailed in the following table.

The table below provides an overview of each methodology used in this study, including descriptions, purposes, research instruments, and the sections of the report where each is addressed.

Methodology	Description	Purpose	Research Instrument	Addressed
Literature Review	Comprehensive review of existing academic papers, industry reports, and regulatory documents.	To gather foundational knowledge on hybrid-electric propulsion technologies and identify relevant technologies from the maritime and truck sectors.	- Academic databases - Industry reports - Regulatory documents-	Chapter 3: Literature Review
Project Meetings and Conferences	Attend relevant meetings and conferences within the industry.	To engage with experts and gather current insights and trends in sustainable aviation practices.	Notes, conference agendas, presentation materials.	Physical/online Weekly project meetings with stakeholder
Interviews	Conducting structured interviews with industry experts from the maritime, truck, and aviation sectors.	To gain insights into the development, implementation, and operational aspects of hybrid-electric propulsion systems.	- Interview guide - Recording devices - Transcription tools	Chapter 2: Research Methodology, Chapter 4: Data Collection and Analysis Chapter 8: Technical Analysis
Surveys	Distribution of questionnaires to industry professionals and stakeholders.	To collect quantitative data on the current use, challenges, and potential for technology transfer of hybrid-electric propulsion systems.	- Online survey tools (ex: Google Forms, excel)	Chapter 4: Data Collection and Analysis
Desk Research	Analysis of secondary data, including market analysis, company reports, and technical specifications.	To understand the technological components, suppliers, and market dynamics related to hybrid-electric propulsion systems.	- Market analysis reports - Company websites - Technical specifications	Chapter 3: Literature Review Chapter 9: System Supplier(s), Chapter 6: Power Requirements and Characteristics
System Analysis	Detailed examination of the hydrogen hybrid-electric propulsion system (HHEPS), analyzing each component's compatibility and adaptability for aviation needs.	To identify specific technological adaptations and enhancements required for successful HHEPS integration in aviation.	-hierarchy breakdown of the system	Chapter 7: Functional Breakdown of HHEPS Chapter 8: technical analysis

Validation Studies	Conducting feasibility studies and validation of technology transfer potential through expert feedback and pilot studies.	To validate the practical applicability and effectiveness of transferring technologies from maritime and truck sectors to aviation.	- Pilot study protocols - Feedback forms - Analysis software	From Chapter 10: Case Studies, to Chapter 15: Technology Translation and Adaptation
Case studies	In-depth examination of specific hydrogen hybrid-electric propulsion systems in maritime and truck sectors.	To analyze real-world applications and gather performance data for potential adaptation in aviation	- Case study reports - Company documentation - Companies products -Performance gap analysis templates	Chapter 10: Case studies
SWOT Analysis	Analyzing the strengths, weaknesses, opportunities, and threats related to technology transfer.	To evaluate the overall potential and risks associated with adopting hybrid-electric propulsion systems in aviation.	- SWOT analysis framework - Data collection sheets	Chapter 16: Challenges and Hurdles

Table 2 Research Methodology

The methodologies chosen for this research provide a well-rounded approach to exploring the feasibility of hydrogen hybrid-electric propulsion systems (HHEPS) in aviation, utilizing a mix of qualitative and quantitative methods. By combining literature review, industry case studies, interviews, surveys, and validation studies, this chapter outlines a comprehensive framework that enables both a technical and practical assessment of HHEPS technology transfer.

The literature review, which follows, will delve deeper into the theoretical and technological foundations of hydrogen propulsion systems. It sets the stage for this research by examining existing studies, regulatory frameworks, and key advancements in the maritime and truck sectors. This foundational knowledge will serve as a reference point for interpreting the data gathered and insights obtained through the methods described here, guiding the analysis in subsequent chapters.

3. Literature Review

Hydrogen hybrid-electric propulsion presents an innovative solution for achieving sustainable transportation by integrating hydrogen fuel cells with electric propulsion systems. Hydrogen, as a clean energy carrier, generates only water and heat as byproducts, drastically reducing greenhouse gas emissions. This review examines the core technologies underpinning hydrogen hybrid-electric systems, focusing on their applications in aviation while drawing insights from maritime and trucking sectors. Understanding the properties and types of hydrogen is crucial for evaluating its potential as an energy source. The following sections detail the unique characteristics of hydrogen, categorize its types based on production methods, and analyse the implications for aviation's specific requirements.

Hydrogen Properties

The properties of hydrogen play a crucial role in its application across various sectors, including aviation. The following table summarizes the key properties of hydrogen and their relevance to transportation (Informatics, n.d.):

Property	Value	Relevance to Aviation and Transportation
Gravimetric Energy Density	~120 MJ/kg	High energy per unit mass helps reduce overall aircraft weight.
Volumetric Energy Density	8.5 MJ/L (liquid hydrogen)	Low density requires large storage volumes, impacting aircraft design.
Storage State	Liquid (-253°C) or Compressed (350-700 bar)	Impacts tank insulation, design, and storage requirements.
Flammability Limits	4-75% in air	Wide limits require strict safety protocols to avoid ignition.
Autoignition Temperature	~500°C	Low ignition energy necessitates stringent spark and leak control.
Leakage and Dispersion	High (due to small molecular size)	High leakage risk requires advanced containment and leak-detection systems.
Specific Heat Capacity (Cp)	28.84 J/(mol·K) at 298.15 K	Affects energy release rates and temperature control in engines.
Flame Speed and Temperature	High flame speed, ~2045 K combustion temperature	Requires heat-resistant materials and careful temperature management.
Environmental Impact	Produces water vapor only	Zero CO_2 emissions; water vapor emission has high-altitude climate impact.
Hydrogen Embrittlement	High susceptibility	Requires materials tested for long-term exposure to hydrogen.
Corrosion and Oxidation	Can accelerate material degradation	Essential to select durable materials to maintain structural integrity.
Perceptual Properties	Colourless, tasteless, odorless	Affects leak detection as hydrogen is undetectable by human senses without instrumentation

Table 3 Key Hydrogen Properties, Values, and Their Relevance to Aviation and Transportation

Types of Hydrogen

Hydrogen is categorized into several types based on its production methods and environmental impact. Understanding these types is crucial for assessing their applicability in various sectors, including aviation. The following hierarchy illustrates the different types of hydrogen along with the methods by which they are produced, which include (National Grid, 2023):

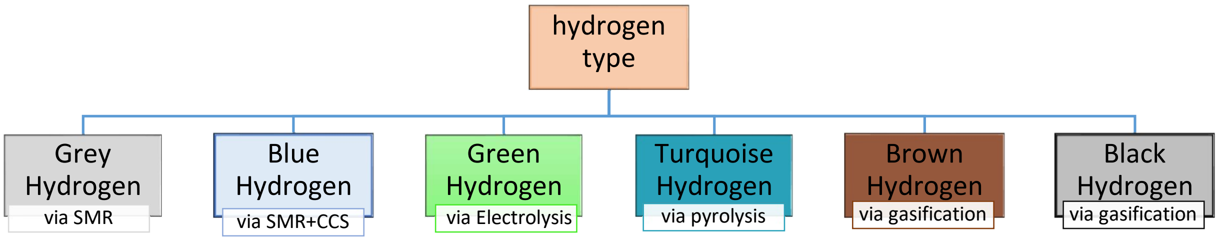

Table 4 Hierarchy of Hydrogen Types

The following table summarizes the key types of hydrogen, detailing their production methods, brief explanations, and relevance to aviation. This information is crucial for understanding how each type aligns with sustainability goals and the specific requirements of hydrogen hybrid-electric propulsion systems (HHEPS).

Type	Production Method	Brief Explanation	Relevance to Aviation
Grey Hydrogen	Via Steam Methane Reforming (SMR)	Produced from natural gas, resulting in significant CO_2 emissions.	Less favourable for sustainability goals; needs improvement for aviation use.
Blue Hydrogen	Via SMR with Carbon Capture and Storage (CCS)	Similar to grey hydrogen but incorporates CCS to capture CO_2 emissions.	More sustainable option for aviation; supports emissions reduction targets.
Green Hydrogen	Via Electrolysis using Renewable Energy	Generated by splitting water into hydrogen and oxygen using renewable energy sources, resulting in zero emissions.	The most favourable option for clean aviation energy; essential for sustainability.
Turquoise Hydrogen	Via Methane Pyrolysis	Produces hydrogen and solid carbon without CO_2 emissions, representing an innovative approach to hydrogen production.	A promising future option for aviation; potential for reduced environmental impact.
Brown Hydrogen	Via Coal Gasification	Produced from lignite coal, leading to high CO_2 emissions and environmental concerns.	Unsuitable for aviation's sustainability goals; not environmentally friendly.
Black Hydrogen	Via Coal Gasification	Derived from hard black coal, also generating significant CO_2 emissions.	Unsuitable for aviation's sustainability goals; environmentally detrimental.

Table 5 Overview of Hydrogen Types, Production Methods, and Relevance to Aviation

The production methods of hydrogen, particularly Green Hydrogen, are directly relevant to the development of hydrogen hybrid-electric propulsion systems (HHEPS). As the aviation sector seeks to reduce its carbon footprint, green hydrogen offers a sustainable solution for powering aircraft.

In the next section, we will explore the key components of HHEPS, highlighting how hydrogen fuel cells, storage solutions, and energy management systems utilize these hydrogen types. This understanding is critical for advancing sustainable aviation technologies and aligning with global decarbonization efforts

- Key Components

1. Hydrogen Fuel Cells: Hydrogen fuel cells are central to hybrid-electric systems, converting chemical energy from hydrogen into electrical energy through an electrochemical process. The three primary types are Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), and Alkaline Fuel Cells (AFCs). PEMFCs are best suited for aviation due to their high efficiency, low operating temperature, and compact design (Maurice, 2023). In contrast, SOFCs provide high thermal efficiency but are less suitable for mobile applications due to their high operational temperatures (Lily, 2024). AFCs, though cost-effective, struggle with CO_2 contamination, limiting their use in aviation.

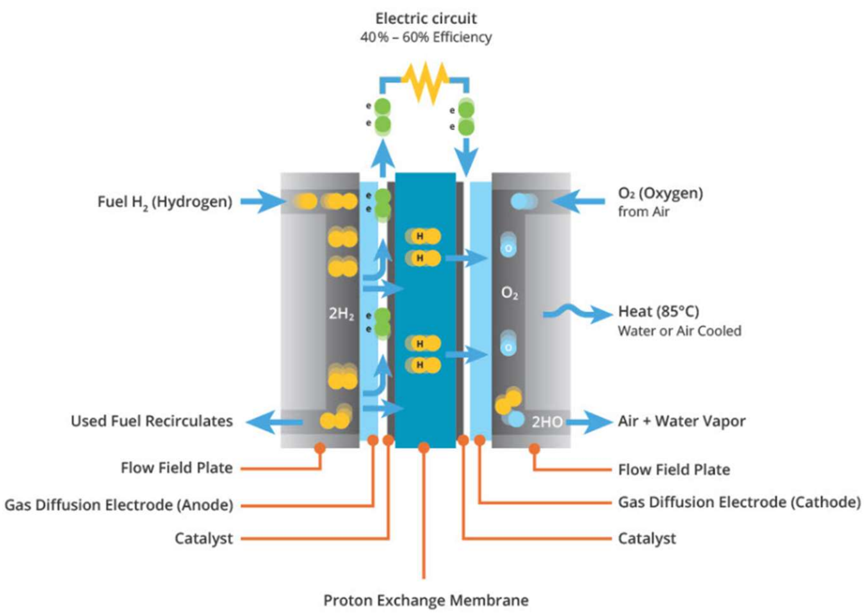

Figure 2 schematic of PEMFC operation (Maurice, 2023)

Proton Exchange Membrane Fuel Cell (PEMFC): PEMFCs are favoured in transportation applications due to their low operating temperature (around 80°C), high power density, and fast start-up time. They are utilized in both maritime and automotive applications because of their compact size and ability to generate substantial amounts of power efficiently

PEMFCs operate by splitting hydrogen into protons and electrons as shown in Figure 2 schematic of PEMFC operation (Maurice, 2023). Protons pass through the proton exchange membrane, while electrons flow through an external circuit, generating electricity. The protons, electrons, and oxygen from the air combine at the cathode to produce water as a byproduct. PEMFCs offer efficiencies ranging from 40% to 60%.

2. Hydrogen Storage: Hydrogen storage is a critical challenge for aviation due to the trade-offs between energy (gravimetric) density (energy per mass) and volumetric density (energy per volume). The comparison graph of various fuels shows that hydrogen has nearly three times the energy content of gasoline, hydrogen, while offering excellent gravimetric density, has a relatively low volumetric density, especially in compressed form at 350 or 700 bar as shown in Figure 3 . This means that hydrogen, whether stored as gas or liquid (LH_2), requires larger tanks than traditional fuels like gasoline or diesel.

In aviation, liquid hydrogen (LH_2) offers higher energy density per volume compared to compressed hydrogen but necessitates cryogenic storage systems capable of maintaining extremely low temperatures (-253°C). These systems are complex and add weight, which is a significant limitation for aircraft design. In comparison, compressed hydrogen, while simpler to store in high-pressure tanks, takes up more space, limiting its practical use in aviation where both weight and volume must be minimized.

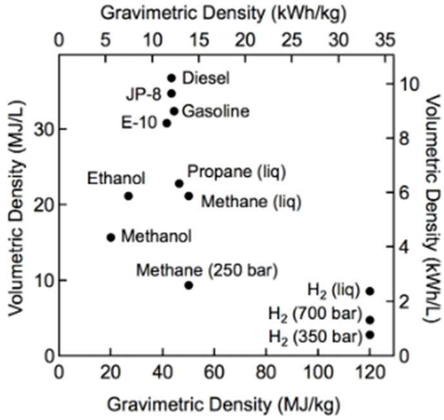

Figure 3 Comparison of specific energy gravimetric density and volumetric density for several fuels based on lower heating values. (Hydrogen Storage, n.d.)

Property	Hydrogen (H_2)	Liquid Hydrogen (LH_2)
State	Gaseous	Liquid
Storage	Stored in high-pressure tanks	Stored in insulated cryogenic tanks
Energy Density	Lower energy density compared to LH_2	Higher energy density, allowing for more compact storage
Temperature	Room temperature	Approximately -253°C
Transportation	Requires high-pressure systems	Requires specialized cryogenic transport systems
Safety Considerations	Flammable, requiring standard safety protocols	Flammable and extremely cold, requiring specific handling protocols to prevent cryogenic burns
Applications	Used in various applications, including fuel cells	Primarily used in aerospace and long-range applications

Table 6 Differences Between Hydrogen (H_2) and Liquid Hydrogen (LH_2)

Table 6 as previously referenced outlines the key differences between gaseous hydrogen (H_2) and liquid hydrogen (LH_2), illustrating that while LH_2 is more space-efficient, its storage requires insulated cryogenic tanks to prevent boil-off and ensure safe handling. Both storage methods face the challenge of providing enough hydrogen to power aircraft over long distances while minimizing impact on weight and space.

To overcome these issues, research is being directed toward alternative storage technologies like solid-state hydrogen storage (e.g., metal hydrides), which could offer a more compact and safer solution for aviation. Additionally, New advancements in composite materials are emerging to address this challenge. Lightweight composite tanks, particularly those made from fiber-reinforced polymers, have been identified as a promising solution for storing hydrogen in aviation. These materials not only reduce tank weight but also improve resistance to the extreme temperatures required for cryogenic storage, which can cause traditional materials to crack or fail over time (Jo.Rich, 2022)

3. Electric Motors: Electric motors are essential in hydrogen hybrid-electric propulsion systems, where they convert electrical energy from hydrogen fuel cells or batteries into mechanical energy to propel the aircraft. These motors must deliver high performance while minimizing weight, as aviation applications demand the highest possible power-to-weight ratios to maintain efficiency and performance during critical flight phases like take-off and climbing.

Permanent magnet motors are widely being considered as a choice for hybrid-electric aircraft due to their high efficiency, compact size, and reliability, refer to Figure 4 Schematic of a permanent magnet motor (Wikipedia contributors, 2024) for a schematic of the motor These motors use strong permanent magnets to generate torque, which allows for high power output with minimal energy losses. Their ability to deliver consistent torque across a wide range of speeds makes them ideal for the variable demands of aircraft propulsion. Integrated with energy management systems (EMS), these motors efficiently manage power from both fuel cells and batteries, optimizing energy use throughout the flight.

While permanent magnet motors dominate current aviation applications, future developments in motor technology, such as superconducting motors, promise further advancements in power density and efficiency, which will be covered in the Chapter 14: Latest developments section.

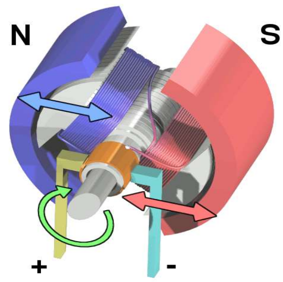

Figure 4 Schematic of a permanent magnet motor (Wikipedia contributors, 2024)

4. Battery Systems: Batteries play a vital role in hybrid-electric aircraft by providing supplemental power during critical phases of flight, such as take-off and climb. Lithium-ion batteries are the most common choice due to their high energy density and relatively low weight, essential for meeting aviation's strict weight and efficiency requirements. These batteries store energy produced by the fuel cells and discharge it as needed during periods of peak demand, ensuring continuous and reliable power delivery throughout the flight (Chunhua Zheng; Weimin Li; Quan Liang, 2018).

Emerging technologies, such as Cuberg's lithium-metal batteries, offer significantly higher energy density—up to 80% more than traditional lithium-ion batteries—and promise better performance in aviation applications. These batteries, while not yet fully integrated into commercial hybrid-electric aircraft, represent the next step in aviation energy storage. For a more detailed discussion of Cuberg's technology, see the Latest Developments section (Vanzieleghem, n.d.)

5. Energy Management Systems (EMS): The EMS in hydrogen hybrid-electric propulsion is even more crucial than in traditional electric systems. It balances power between fuel cells, batteries, and electric motors based on real-time demands. In a hydrogen setup, the EMS must efficiently manage variable hydrogen flow rates to fuel cells while ensuring battery charge levels are maintained to meet power surges during high-energy demand phases. Additionally, the EMS must manage the cooling and thermal management systems for both fuel cells and batteries, as hydrogen fuel cells operate at different thermal parameters than batteries.

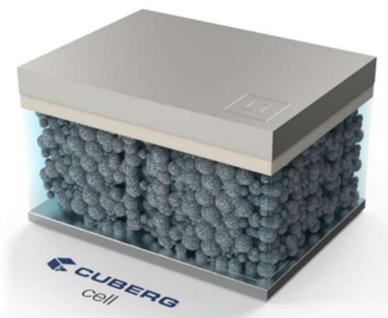

Figure 5 Conceptual Cuberg cell architecture (Vanzieleghem, n.d.)

Comparative Requirements and Gaps for HHEPS Across Sectors

Hydrogen hybrid-electric propulsion systems (HHEPS) have gained traction in both the maritime and truck sectors as a means of reducing emissions and enhancing sustainable energy use. However, adapting these systems to aviation presents unique challenges. This section provides a comparative analysis of the specific requirements across maritime, truck, and aviation sectors, followed by a gap analysis to highlight areas where further research and development are needed for aviation applications.

The table below outlines key HHEPS requirements across the maritime, truck, and aviation sectors. Each sector has distinct operational needs, infrastructure demands, and technical constraints. The common requirements across all sectors are highlighted in green, while aviation-specific needs emphasize the additional adaptations required for effective implementation in aircraft.

Requirement	Maritime	Truck	Aviation
Weight Constraints	Allows for large, heavy hydrogen storage tanks due to fewer weight restrictions.	Uses compressed hydrogen tanks, moderate weight limitations per truck standards.	Requires ultra-lightweight hydrogen storage solutions to meet strict weight and balance limits.
Energy Density	High energy density needed to support extended maritime operations	High energy density needed for long-haul trips	High energy density needed to maximize range with minimal weight
Hydrogen Refuelling Infrastructure	Limited refuelling infrastructure at select ports; cryogenic facilities in some locations.	Limited hydrogen refuelling stations in specific regions, with emerging facilities in Europe and California.	No existing refuelling infrastructure at airports; requires cryogenic refuelling facilities with high-volume, aviation-safe storage.
Thermal Management	Standard cryogenic insulation and basic thermal management at sea level.	Minimal thermal management, as trucks operate at stable ground-level temperatures.	Requires advanced high-altitude thermal management to counter low temperatures and pressure.
Certification and Safety Standards	Compliance with regional maritime safety standards, some flexibility for prototypes.	Regional safety standards; more flexibility in certification for hydrogen systems.	Requires strict certification from FAA/EASA, with impact resistance, leak prevention, and ignition resistance testing.
System Redundancy	Low redundancy requirements; generally single-system reliance.	Basic backup systems, but redundancy requirements are low compared to aviation.	High redundancy required, with multiple backup systems for safety-critical operation in flight.
Altitude-Related Adaptations	Not applicable due to sea-level operations.	Not applicable due to ground-level operation.	Requires high-altitude adaptations, including insulation for hydrogen storage and pressure adjustments for fuel cells.

Table 7 Comparative Analysis of HHEPS Requirements Across Maritime, Truck, and Aviation Sectors

Aviation-Specific Challenges

Performance Under Extreme Conditions

Research on the operational performance of Proton Exchange Membrane Fuel Cells (PEMFCs) and Alkaline Fuel Cells (AFCs) in high-altitude aviation environments is limited. Reduced atmospheric pressure and temperature (down to -60°C at cruising altitude) affect efficiency and durability. Targeted studies are essential to quantify these impacts and optimize fuel cell performance under these specific aviation conditions, as ground-level applications do not face the same environmental extremes.

Hydrogen Storage for Aviation

- Weight and Space Constraints: Current cryogenic hydrogen storage tanks typically weigh between 200-300 kg for ground-based applications, such as trucks and stationary systems, with a storage capacity of 5-10 kg of hydrogen. For aviation, storage systems must reduce tank weight by at least 50% to approximately 100-150 kg to meet payload requirements. Research into alternative storage technologies, such as metal hydrides and advanced composite materials, could provide lighter solutions suitable for aircraft.
- Thermal Management: High-altitude conditions demand advanced thermal management in hydrogen storage. Systems must withstand temperature fluctuations from around 20°C at ground level to -60°C at altitude. Effective insulation and active heating mechanisms are necessary to maintain hydrogen storage integrity, an area requiring further research to ensure system reliability in flight.

Regulatory Framework

- Lack of Standards: Aviation lacks dedicated standards for hydrogen fuel systems, unlike maritime and trucking sectors. Key regulatory needs include standards for leak detection, emergency protocols, and altitude-specific safety testing, essential to safely integrate hydrogen into aviation.
- Certification Processes: Existing certification processes, designed for conventional fuels, do not accommodate hydrogen's unique properties. Adaptations in certification criteria are vital to validate hydrogen fuel systems' impact resistance, leak prevention, and redundancy in flight (European Union Aviation Safety Agency, 2021).

Integration with Existing Systems

- Infrastructure Compatibility: Hydrogen integration in aviation requires modifications to current refuelling infrastructure, which is primarily designed for kerosene-based fuels. Hydrogen refuelling would necessitate cryogenic handling systems and enhanced fire suppression measures specific to hydrogen's characteristics
- Training and Competencies: Introducing hydrogen into aviation operations requires specialized training for ground and flight crews, maintenance teams, and emergency responders. Developing these competencies is critical to operational readiness and safe hydrogen handling, especially given aviation's stringent safety standards.

Cross-Sectoral Knowledge Transfer

- Learning from Other Industries: Although the maritime and truck sectors offer relevant insights, structured mechanisms for transferring knowledge to aviation are currently limited. Case studies from these sectors need systematic analysis to identify best practices adaptable to aviation, particularly in areas like thermal management, storage design, and refuelling protocols. Establishing collaborative research initiatives across these industries could expedite hydrogen technology adoption in aviation.

Together, these challenges emphasize the need for aviation-specific adaptations to make hydrogen propulsion viable. The following chapters will assess the feasibility of these adaptations and explore strategies required for implementing hydrogen hybrid-electric propulsion systems in aviation.

Chapter 4: Data Collection and Analysis of survey

This chapter summarizes the results of a survey conducted among professionals in the maritime and aviation sectors, focusing on hydrogen hybrid-electric propulsion systems. The survey aimed to gather insights into the development challenges, perceived risks, and potential for technology transfer between these sectors. The findings provide a comprehensive view of current hydrogen technology usage, the main hurdles to broader adoption, and its future potential. Detailed responses and diagrams are provided in Appendix A: Assignment Description

BackgroundThe Netherlands, with its knowledge and research institutions, including field labs, small and medium-sized companies, large industry and a committed government, has a strong position in the current aviation market. However, this ecosystem needs to be strengthened in order to successfully accelerate the transition to sustainable aviation. Competences, technologies and infrastructure are needed that cannot be found in the current aviation ecosystem, but can be found in other Dutch sectors, such as automotive, energy, high-tech equipment, ICT and maritime. By intensifying cross-sectoral and sector-wide cooperation, the Dutch (aviation) ecosystem will be enabled to accelerate the intended transition and realize the earning capacity. This study is part of the Growth Fund project “Aerospace in Transition” (GF LiT), sub project SEA “Strengthening Ecosystems”.

Objectives:
The aerospace ecosystem will be strengthened and the transition to sustainable aviation will be accelerated by identifying and disseminating missing technologies, competences and infrastructures that are available in other sectors.

Challenges
Many technologies, competences and infrastructures are developed for specific applications. The use in other sectors and or applications may look obvious, however, without a thorough understanding of the requirements that has driven the initial development and the set of requirements for the new applications, implementation maybe hampered. A second challenge is that many technologies in the journey to sustainable aviation are at low TRL, making it less
easy to identify what is missing. Nevertheless, the complexity of the transition to sustainable aviation in combination with the limited time to develop, test and certify new solutions urges the use of all available cross-sectoral building blocks.

Approach
Interviews, attending project meetings, conferences, etc.
Desk research including analysis of reports and literature.

Deliverables
Survey of technologies developed in the GF LiT
Analysis of missing technologies, competences and infrastructures
Identifying cross-sectoral technologies, competencies and infrastructures that could fill the gaps Capture the relevant information in a database.

Presentation of the approach and the results to the GF LiT participants

Company supervisor:

Peter Kortbeek
06 5139 1114

Appendix B: Survey questions

Note: The truck sector was not included in the survey due to decisions made early in the research internship. While the truck sector is highly relevant to hydrogen propulsion, the initial focus was on the maritime and aviation sectors as they were considered more applicable at the time.

The survey garnered responses from 20 professionals, including engineers, researchers, consultants, and executives, with experience ranging from less than one year to over 20 years. This diversity of roles and experiences provided a well-rounded perspective on the current state of hydrogen propulsion across industries. The majority of respondents expressed a strong interest in hydrogen technology as a solution for future propulsion systems, driven primarily by global decarbonization efforts. Most respondents worked with Proton Exchange Membrane (PEM) Fuel Cells, widely regarded as the most viable hydrogen technology for both maritime and aviation. Other systems like Solid Oxide Fuel Cells (SOFCs) and Hybrid Electric Gas Turbines were also mentioned, though PEMFCs dominated the feedback due to their scalability and efficiency.

- Key Findings

Several technical challenges were consistently highlighted by respondents, with technology maturity being the most pressing. Many professionals pointed out the need for advancements in fuel cell efficiency, reliability, and overall readiness for large-scale deployment, especially in aviation where certification processes are stringent. The lack of a robust regulatory framework in aviation was also emphasized as a significant barrier, with respondents citing the complexity of certification processes as a major obstacle to the adoption of hydrogen propulsion systems.

The survey further revealed that insufficient hydrogen refuelling infrastructure is a critical challenge, particularly for long-range applications in aviation. This issue is compounded by safety concerns surrounding hydrogen storage and handling, which are especially pertinent in the aviation sector due to the risks posed by high-altitude operations. These challenges are visually summarized in Figure 6, where infrastructure limitations (30%) and technology maturity (25%) emerged as the most frequently cited barriers to broader adoption.

- Risks and Cross-Sector Transfer

Survey respondents also identified several risks associated with adopting hydrogen propulsion technologies, including high initial investment costs and the need for significant public and private sector funding to build the necessary infrastructure. Regulatory hurdles were frequently mentioned, particularly in aviation, where the slow and complex certification processes are viewed as a potential bottleneck. Additionally, concerns about hydrogen availability were raised, with respondents stressing the need for scaling up green hydrogen production to meet future demand.

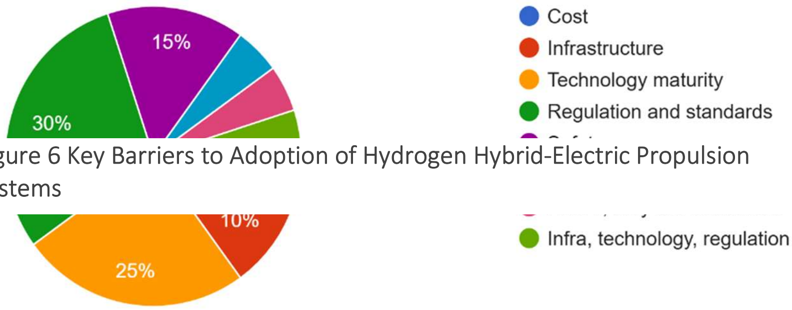

Figure 6 Key Barriers to Adoption of Hydrogen Hybrid-Electric Propulsion Systems

Several respondents saw potential for cross-sector technology transfer, especially from the maritime sector to aviation. The most frequently cited factors for successful transfer included technological compatibility and regulatory harmonization, though some respondents noted that aviation's unique weight and space constraints complicate the transfer of maritime technologies. One respondent remarked, "The largest difference between maritime and aviation is aviation's need for lightweight systems," underscoring how critical weight reduction is for aircraft design. Another noted that aviation's reliance on liquid hydrogen (LH_2) presents additional storage challenges, saying, "Aviation requires liquid hydrogen, which makes it extremely difficult."

The critical factors for technology transfer are outlined in Figure 7, which shows that certification and validation processes (55%) and technological compatibility (35%) are viewed as essential for success.

- Future Outlook

Looking ahead, respondents were optimistic about advancements in hydrogen propulsion technology over the next 5-10 years. Improvements in fuel cell efficiency, especially through Low-Temperature PEM Fuel Cells (LTPEMFC) and High-Temperature PEM Fuel Cells (HTPEMFC), were frequently mentioned as key drivers of progress. Additionally, advancements in hydrogen storage, particularly for aviation, are expected to make hydrogen more practical for long-haul flights. Respondents were hopeful that small hydrogen-electric aircraft could be operational within the next decade, though large-scale commercial applications may take longer to develop due to infrastructure and regulatory challenges.

The survey results provide a clear overview of the current state of hydrogen hybrid-electric propulsion systems in the maritime and aviation sectors. While hydrogen is recognized as having significant potential,

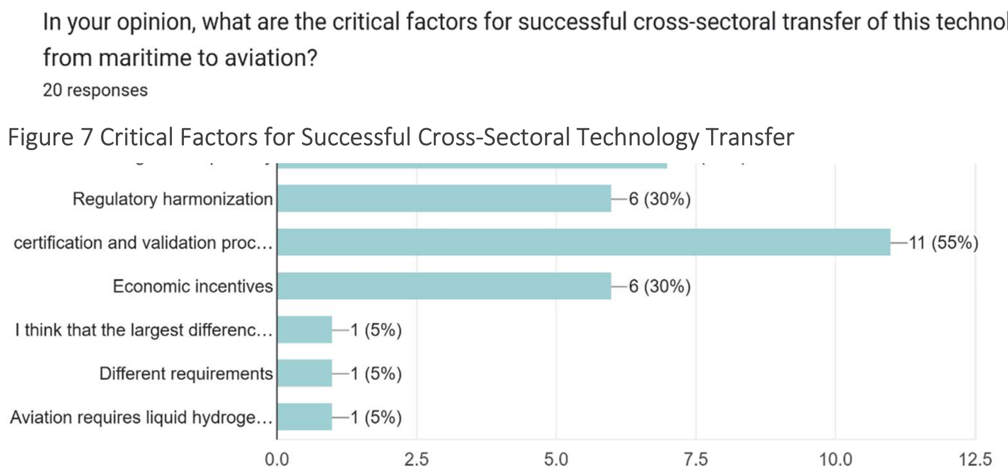

Figure 7 Critical Factors for Successful Cross-Sectoral Technology Transfer

the survey identified several barriers, including technology maturity, infrastructure development, and regulatory alignment. The insights gained from the survey will guide the following chapters, especially regarding opportunities for cross-sectoral technology transfer and addressing existing knowledge gaps. For further context and the full survey data representation, refer to Appendix A: Assignment Description

BackgroundThe Netherlands, with its knowledge and research institutions, including field labs, small and medium-sized companies, large industry and a committed government, has a strong position in the current aviation market. However, this ecosystem needs to be strengthened in order to successfully accelerate the transition to sustainable aviation. Competences, technologies and infrastructure are needed that cannot be found in the current aviation ecosystem, but can be found in other Dutch sectors, such as automotive, energy, high-tech equipment, ICT and maritime. By intensifying cross-sectoral and sector-wide cooperation, the Dutch (aviation) ecosystem will be enabled to accelerate the intended transition and realize the earning capacity. This study is part of the Growth Fund project “Aerospace in Transition” (GF LiT), sub project SEA “Strengthening Ecosystems”.

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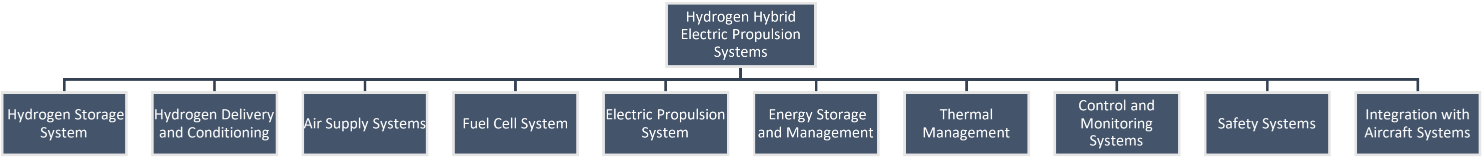
Appendix B: Survey questions

Chapter 5: Comprehensive Overview of Hydrogen-Based Hybrid Electric Propulsion Systems for Aircraft



1. Hydrogen Storage and Management

Hydrogen storage and management encompass the storage of hydrogen in a manner that enables safe and efficient power generation. For hydrogen gas, this typically means high-pressure tanks that store hydrogen at pressures up to 700 bar, utilizing advanced composite materials for strength and lightweight construction. For liquid hydrogen, cryogenic tanks maintain the hydrogen at -253 °C with vacuum insulation to minimize heat transfer and prevent boil-off. Safety measures such as pressure relief devices, hydrogen sensors, and ventilation systems ensure that the hydrogen is stored securely, and any leaks are managed effectively.

2. Hydrogen Delivery and Conditioning

Hydrogen delivery and conditioning systems are responsible for getting the stored hydrogen to the fuel cells at the correct pressure and state. In contrast, for hydrogen gas, compressors increase the pressure to ensure a consistent flow. For liquid hydrogen, cryogenic pumps transfer it to vaporizers that convert it to gas. Pressure regulators control the hydrogen pressure delivered to the fuel cells, ensuring it remains within safe and optimal operating limits. These systems play a vital role in upholding the efficiency and safety of the hydrogen supply to the fuel cells.

3. Air Supply Systems

Air supply systems provide the necessary oxygen for the fuel cells to operate. Air compressors ensure a steady supply of compressed air, which is filtered to remove impurities that could hinder performance. Humidifiers add moisture to the air to maintain optimal humidity levels within the fuel cells, which is essential for the efficient operation and longevity of the proton exchange membrane (PEM) fuel cells.

4. Fuel Cell System

The fuel cell system is the heart of the propulsion system, converting hydrogen and oxygen into electricity through electrochemical reactions. Proton Exchange Membrane (PEM) fuel cells are commonly used due to their high efficiency and power density. They consist of a membrane electrode assembly (MEA) that includes a proton-conducting membrane, electrodes, and catalyst layers. Gas diffusion layers ensure the uniform distribution of hydrogen and oxygen. Solid-oxide fuel cells (SOFC) may also be used for higher efficiency at higher operating temperatures.

5. Electric Propulsion System

The electric propulsion system transforms the electrical energy that the fuel cells produce into mechanical energy to power the aircraft's fans or propellers. This system includes electric motors comprising a stator and rotor to generate rotational motion. Control electronics manage the motor’s speed and torque to ensure optimal performance. Auxiliary motors power other systems, such as pumps and compressors, that are necessary for the operation of the propulsion system.

6. Energy Storage and Management

Energy storage and management systems ensure a stable and reliable power supply. Lithium-ion batteries store energy and provide additional power during peak demands, such as takeoff or acceleration. A Battery Management System (BMS) monitors and manages the health, charge, and discharge cycles of the batteries. Power electronics, including inverters and converters, manage the flow of power between the fuel cells, batteries, and electric motors. An Energy Management System (EMS) optimizes the distribution of power to ensure efficiency and reliability.

7. Thermal Management

Thermal management systems maintain optimal operating temperatures for fuel cells, batteries, and electric motors. Cooling systems, including heat exchangers, coolant pumps, and radiators, transfer heat away from critical components. For cryogenic systems, insulation materials such as vacuum layers and multi-layer insulation minimize heat transfer to maintain the low temperatures needed for liquid hydrogen storage. Effective thermal management is essential to prevent overheating and ensure the longevity and efficiency of the propulsion system.

8. Control and Monitoring Systems

Control and monitoring systems ensure the safe and efficient operation of the entire propulsion system. Sensors monitor various parameters, such as pressure, temperature, and hydrogen concentration. Actuators control the flow of hydrogen, air, and coolant based on real-time data. Centralized control units, equipped with microcontrollers and software algorithms, process sensor data and execute control commands to optimize system performance and safety. These systems are critical for maintaining operational stability and responding to any anomalies.

9. Safety Systems

Safety systems are integral to managing the risks associated with hydrogen propulsion. Leak detection systems use hydrogen sensors to identify leaks quickly, triggering alarms and emergency responses. Ventilation systems ensure that any leaked hydrogen is safely dispersed away from critical areas. Fire suppression systems detect and extinguish fires promptly, using appropriate suppression agents that do not react with hydrogen. These safety measures are essential to protecting the aircraft, crew, and passengers. This integration is vital for ensuring the efficient and safe operation of hydrogen-powered aircraft.

10. Integration with Aircraft Systems

Integration with aircraft systems involves ensuring that the hydrogen propulsion system fits seamlessly into the existing aircraft architecture. Structural integration includes the secure mounting of hydrogen storage tanks and other components, as well as the use of aerodynamic fairings to minimize drag. Avionics integration involves communication interfaces that facilitate data exchange between the propulsion system and the aircraft's control systems. Display systems provide real-time information to pilots about the status and performance of the hydrogen propulsion system.

Chapter 6: Power requirements and characteristics

Hybrid-electric propulsion systems combine electric motors with traditional or alternative power sources, such as internal combustion engines or hydrogen fuel cells, to enhance efficiency and reduce emissions. The power requirements and dynamic characteristics of these systems differ significantly across the maritime, truck, and aviation sectors due to variations in operational demands, load conditions, and environmental factors. The following section outlines the detailed power requirements and dynamic characteristics for each sector, including real-world examples.

Maritime Sector

Power Requirements

In the maritime sector, the power demand of a vessel is primarily determined by its size, weight, and operational profile. The required power depends heavily on the vessel's mission (coastal ferry, container ship, or tanker), its cruising speed, and its cargo capacity. Typical power requirements for different types of vessels are as follows:

- Ferries and Coastal Vessels:
  - Power Output: Ranges from 300 kW to 3 MW depending on vessel size and operational range. Ferries, which often operate on fixed routes, typically require lower power outputs because they engage in repetitive operations over relatively short distances.
  - Example: The **Water-Go-Round** ferry, a hydrogen fuel cell-powered vessel, uses two 300 kW electric motors and 360 kW fuel cells to provide sufficient propulsion power for a cruising speed of 22 knots (Gallucci, 2023).
- Cargo Ships and Tankers:
  - Power Output: Ranges from 15 MW to over 80 MW for large container ships or tankers. These vessels require significantly more power due to their size, the drag resistance of water, and the weight of cargo. For example, the **HMM Algeciras**, one of the largest container ships in operation, has a power output of approximately 60 MW for its propulsion. (*"HMM Algeciras "*, n.d.)
- Cruise Liners:
  - Power Output: Typically, between 40 MW and 70 MW to support both propulsion and the energy-intensive hoteling operations for passengers (lighting, HVAC, and other amenities).

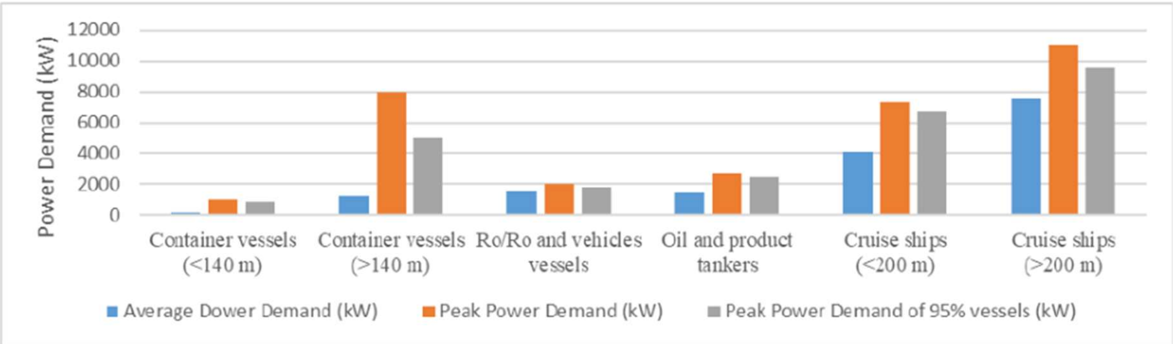


Figure 8 Power demand of different types of ships (Sadiq, Ali, Terriche, Mutarraf, Hassan, Hamid, Ali, Sze, Su, & Guerrero, 2021)

To illustrate power requirements further, Figure 8 shows average and peak power demands for different vessel types, providing insight into how hybrid systems might reduce peak energy needs for these vessels.

Maritime vessels, including cargo ships, ferries, and cruise liners, operate under highly variable load conditions influenced by environmental factors and cargo weight. Hybrid-electric systems offer a potential solution to enhance fuel efficiency and reduce emissions across various operational modes.

Dynamic Characteristics

- Load Variability:
  Maritime vessels, especially large cargo ships, experience significant load variability due to changes in water resistance, cargo weight, and sea conditions. The power requirements can fluctuate significantly depending on the vessel's operating conditions (e.g., cruising speed, wind, and wave resistance).
- Operational Modes:
  Ships typically operate in multiple modes:
  - Cruising Mode: Continuous, steady power is required over long distances. For hybrid-electric systems, fuel cells or batteries can provide supplemental power during these periods to optimize fuel efficiency.
  - Maneuvering Mode (Ports/Harbors): Lower power output is required during docking, maneuvering, or idle times. Hybrid systems, including batteries, are often used to reduce emissions during these phases.
  - Idling: Ships often spend time idling in ports, where hybrid systems can engage to minimize fuel use and emissions.
- Start/Stop Frequency:
  Ships typically operate for extended periods (days or weeks) with minimal start-stop cycles. Unlike trucks or aircraft, ships prioritize endurance and efficiency for long voyages, which hybrid systems can support by offering auxiliary power during low-demand phases.

Truck Sector

Power Requirements

Trucks, particularly those used for heavy-duty applications, require significant amounts of power to transport goods over long distances. The power needed by hybrid-electric trucks varies based on load, road conditions, and operational range.

- Long-Haul Trucks:
  - Power Output: Ranges from 250 kW to 500 kW for hybrid-electric trucks designed for long-distance freight transport. For example, the Hyundai Xcient Fuel Cell truck is equipped with two 90 kW fuel cells (totalling 180 kW) and a 350-kW electric motor, providing the necessary power for heavy-duty operations (*XCIENT Fuel Cell Truck | Hydrogen Truck | Hyundai Motor Company*, n.d.).
  - These trucks typically carry large hydrogen tanks or battery packs to provide extended ranges (over 400 km on a single charge/refuel).
- Urban Delivery Trucks:
  - Power Output: Typically, between 100 kW and 200 kW for smaller delivery trucks operating in urban environments.

Dynamic Characteristics

- Load Variability:
  Trucks experience significant fluctuations in load, depending on the cargo being transported and the terrain. Power requirements change dynamically when trucks traverse steep inclines or flat

roads. The hybrid-electric systems need to provide sufficient torque for heavy loads while offering regenerative braking to recover energy during deceleration.

- Acceleration and Deceleration:
  Trucks, particularly in urban settings, undergo frequent acceleration and deceleration due to traffic conditions and stop-and-go operations. Hybrid systems must accommodate these dynamic changes in power demand by providing rapid power when accelerating and utilizing regenerative braking systems during deceleration to recharge the battery or support the fuel cell system.
- Start/Stop Frequency:
  Urban trucks experience frequent stop-start cycles, particularly during deliveries. The ability to switch between electric motors (for short trips or idling) and fuel cells (for longer distances) is critical for optimizing fuel use and reducing emissions in city environments.

Figure 4 illustrates the difference in energy consumption between diesel and electric trucks. While hybrid-electric trucks are not purely electric, they share many of the same energy efficiency advantages. This comparison emphasizes the potential energy savings and emissions reductions hybrid-electric trucks can achieve. By reducing overall energy consumption and harnessing technologies like regenerative braking, hybrid systems help achieve sustainability goals while maintaining operational efficiency.

Example: The Hyundai Xcient fuel cell truck uses two 90 kW hydrogen fuel cells that power an electric motor for heavy-duty freight applications. This hybrid system allows the truck to deliver high torque during acceleration and maintain efficiency during long hauls.

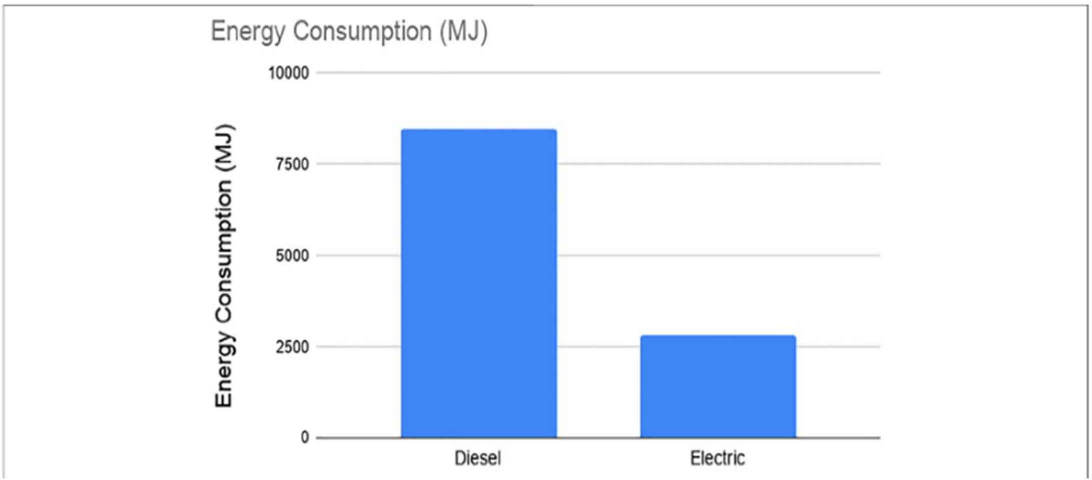


Figure 9 Energy consumption comparison between diesel and electric trucks (Elangovan, Kanwhen, Dong, Mohamed, & Rojas-Cessa, 2021)

Aviation Sector

Power Requirements

Aircraft power requirements vary widely depending on the size, type, and propulsion technology used. While traditional jet-powered aircraft dominate the regional and large commercial segments, advances in hydrogen (H2) hybrid-electric propulsion introduce new ways to achieve reduced emissions and higher efficiency. This chapter focuses on the power requirements for three categories of aircraft: regional jet aircraft, large commercial aircraft, and the emerging class of hydrogen hybrid-electric aircraft. Each class presents distinct challenges and opportunities in terms of power demand, energy storage, and propulsion efficiency

- Conventional jet propulsion

- Regional jets: are typically designed for short- to medium-haul routes, with seating capacities between 19 and 130 passengers (*Regional Aircraft*,2024). These aircraft require moderate power, especially during take-off and climb, while maintaining fuel efficiency over short distances.
    - Take-off Power: Regional jets like the Embraer E175 produce between 13,000 and 14,200 pounds of thrust, which translates to 8 MW to 10 MW of power during take-off (Wikipedia contributors, 2024)
    - Cruising Power: At cruising altitude, power demand decreases significantly. For the Embraer E175, cruising power is typically around 4 MW to 6 MW (*E175 - Embraer*, 2024).

- Large commercial aircraft are designed for long-haul international flights, typically carrying 200 to 400 passengers. These wide-body jets demand significant power during take-off and maintain high power output during cruise to ensure efficient long-range travel.
    - Take-off Power: Aircraft like the Boeing 787 Dreamliner generate 265.3–360.4 kN (59,600–81,000 lbf) of thrust. (Wikipedia contributors, 2024)

- Hybrid systems

The power requirements for aircraft, especially hybrid-electric configurations, are highly dependent on the size of the aircraft, the range of the flight, and the altitude at which it operates. Aviation has the most stringent power and weight requirements due to the need to minimize mass and optimize efficiency.

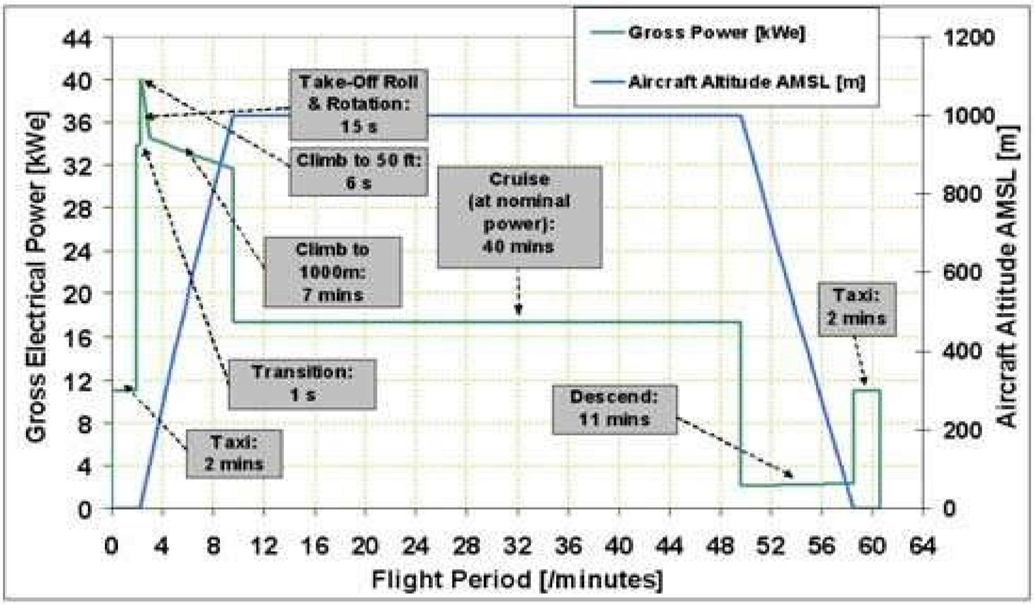
- Regional Aircraft (19–50 seats):
    - Power Output: Ranges from 500 kW to 2 MW for regional aircraft that typically operate on short-haul routes. For example, the Ampaire Electric EEL hybrid-electric aircraft combines a conventional engine with a 250-kW electric motor to power flights up to 200 miles. Future hydrogen-powered regional aircraft may require fuel cells capable of producing 1 MW or more for flights of up to 1,000 km.
- Large Commercial Aircraft (50+ seats):
    - Power Output: Large commercial aircraft, such as those envisioned by Airbus ZeroE, may need power outputs in the range of 5 MW to 20 MW depending on the aircraft size and flight range. These aircraft would likely use a combination of hydrogen fuel cells and gas turbines to generate the necessary power for take-off, cruising, and landing.

Dynamic Characteristics

Hybrid-electric propulsion systems in aviation face unique challenges due to the dynamic nature of aircraft power requirements across different flight phases. These challenges must be addressed to optimize efficiency, weight, and space for future sustainable aviation technologies

Flight Phases:
Aircraft have distinct power requirements during different flight phases, including:

- Take-off and Climb: Take-off demands the highest power output, as aircraft engines must generate enough thrust to overcome gravity and achieve lift. Hybrid-electric propulsion systems must be capable of delivering maximum power rapidly.



Acceleration Requirement: Typically, jet engines need between 20 to 60 seconds to go from 0% to 100% power, depending on the size and type of the engine. For hybrid-electric systems, this response time could be improved to meet the rapid acceleration demands during take-off.

- Cruise: Once at cruising altitude, power requirements stabilize at significantly lower levels compared to take-off. Cruise power generally ranges from 25% to 40% of maximum take-off power, depending on the aircraft model. The graph below illustrates the relationship between required cruise power and cruise speed, as well as the power required for climbing at different speeds (rate of climb, or R/C).

This graph shown in Figure 10 illustrates the variations in gross electrical power (kWe) required by a hybrid-electric aircraft across key flight phases. It highlights power demands during the take-off roll (36 kWe for 15 seconds), initial climb (sustained power to reach 50 ft in 6 seconds), and ascent to 1,000 m (continuous power for 7 minutes). During cruise, power stabilizes around 32 kWe for 40 minutes, showcasing optimal efficiency. The graph also depicts reduced power requirements during descent (11 minutes) and taxi (2 minutes). This visual representation emphasizes the dynamic power management essential for hybrid-electric propulsion in aviation.

- Descent and Landing: Power requirements decrease sharply during descent. Hybrid-electric systems could utilize regenerative braking to recover energy during landing, although this technology is still under development for aviation.

Weight and Space Constraints:
Weight and space are critical factors in aviation, especially for hybrid-electric aircraft, which must balance the additional weight of batteries, fuel cells, and hydrogen storage systems with the need to maintain efficient flight performance.

Figure 10 Gross Electrical Power Requirements During Flight Phases powered by fuel cell (Romeo et al., 2012)

- Power-to-Weight Ratio: Conventional aircraft engines have a power-to-weight ratio of 0.3 to 0.6 kW/kg. This is considerably lower than power-to-weight ratios for trucks and maritime vessels, due to the stringent weight limitations in aviation.
    - Comparisons with Trucks and Ships: In contrast, heavy-duty trucks may have a power-to-weight ratio of 2 to 5 kW/kg, while ships may operate in a range of 0.1 to 1.0 kW/kg, depending on their size and operational profile. The significantly different environments (land vs. sea vs. air) lead to these variations in power-to-weight needs.

- Start/Stop Frequency:
  Aircraft typically have low start/stop frequencies due to the extended periods of operation during flights. However, systems must be capable of handling rapid power changes during take-off and descent.

Example: The Airbus E-Fan X hybrid-electric demonstrator aircraft, which was equipped with a 2 MW electric motor, highlighted the potential of hybrid systems to meet the high-power demands of large aircraft during critical flight phases like take

Sector	Power Requirements (kW/MW)	Dynamic Characteristics
Maritime	- Ferries: 300 kW – 3 MW - Cargo Ships: 15 MW – 80 MW - Cruise Liners: 40 MW – 70 MW	- High load variability due to cargo and sea conditions - Low start/stop frequency - Emphasis on endurance -Maritime applications typically experience more consistent load demands during operation, particularly for large cargo ships and liners. Variability is generally less than that seen in aviation, where power needs fluctuate significantly across different phases of flight.
Truck	- Long-Haul: 250 kW – 500 kW - Urban Trucks: 100 kW – 200 kW	- Frequent acceleration/deceleration - High load variability - Frequent stop/start cycles
Aviation	- Regional Aircraft: 500 kW – 2 MW - Commercial Aircraft: 5 MW – 20 MW	-Distinct power phases (take-off, cruise, landing) - Strict weight and space limitations - Minimal start/stop cycles

Table 8 Comparison Table: Power Requirements and Dynamic Characteristics

Chapter 7: Functional Breakdown of Hydrogen/Liquid Hydrogen Hybrid Electric Propulsion System

In the pursuit of sustainable aviation, hybrid electric propulsion systems using hydrogen (H2), or liquid hydrogen (LH2) offer a promising solution to reduce carbon emissions and improve fuel efficiency. These systems integrate multiple advanced technologies to provide clean, efficient, and reliable power for aircraft. This comprehensive breakdown provides a detailed functional analysis of an H2 or LH2 hybrid electric propulsion system, outlining its main functions, sub-functions, and the detailed components involved. The analysis is structured to cover four primary functions: providing efficient propulsion, ensuring safety and reliability, managing thermal conditions, and monitoring and controlling system operations. Each section will be explored in detail to offer a thorough understanding of the system's complexity and sophistication.

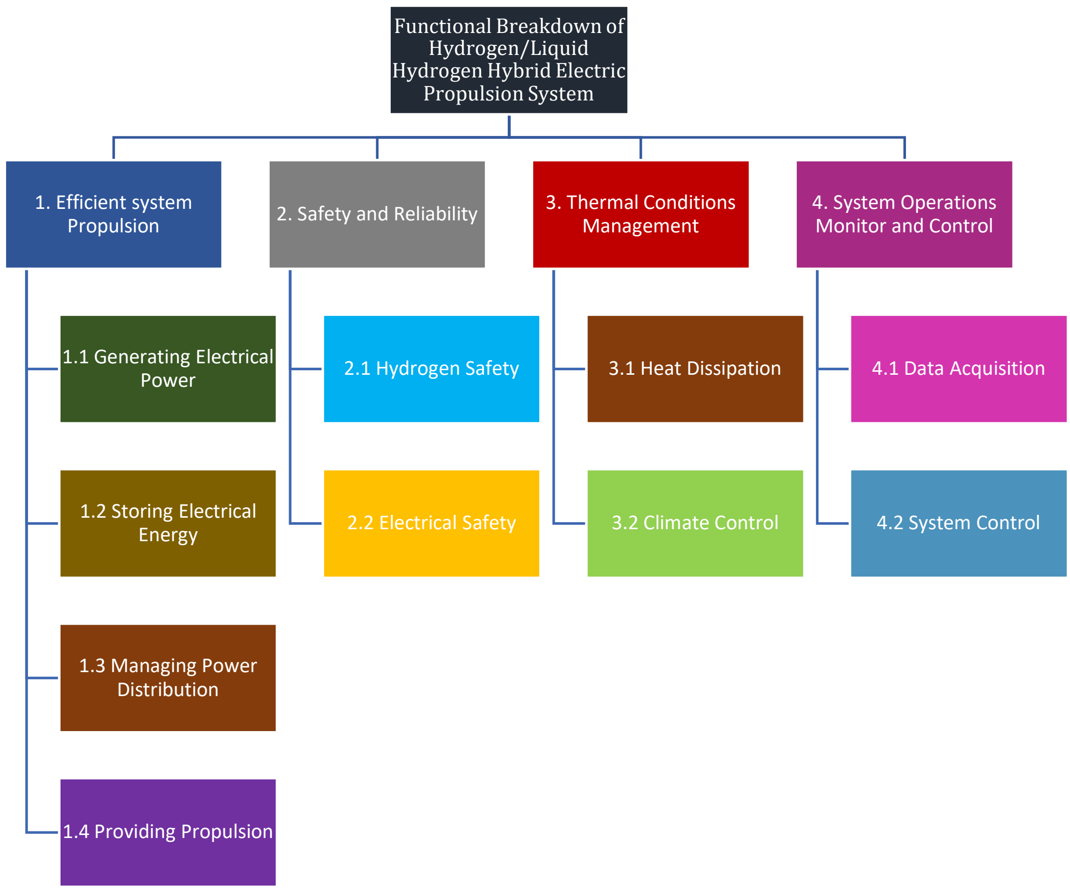


Figure 11 Comprehensive breakdown of the core functions and sub-functions of the Hydrogen Hybrid-Electric Propulsion System (HHEPS)

Overview of Core Functions

1. Efficient Propulsion:
   The core function of a hydrogen hybrid-electric propulsion system is to convert chemical energy into electric power for propulsion. This is achieved through hydrogen fuel cells, which generate electricity via an electrochemical reaction between hydrogen and oxygen, and electric motors that drive the propellers or fans. The power generated by the fuel cells is either stored in lithium-ion batteries for later use or immediately consumed, depending on the phase of flight. Proton Exchange Membrane (PEM) fuel cells, due to their high efficiency and fast response, are commonly used in these systems. Liquid hydrogen, which has a higher energy density than

gaseous hydrogen, is crucial for long-range applications, such as transcontinental flights, check 3. Literature Review.

2. Safety and Reliability:
   Safety is critical in aviation, and hydrogen introduces specific challenges. Hydrogen storage in either gaseous or liquid form requires robust containment systems. Liquid hydrogen (LH_2) is stored at cryogenic temperatures (~-253°C), and any leaks must be detected and contained immediately due to hydrogen's high flammability. Aircraft must incorporate fail-safes and redundant systems to manage the risks of hydrogen leaks or fuel cell malfunctions. Pressure and temperature sensors continuously monitor the system to ensure safe operation. Advanced insulation is used to prevent hydrogen boil-off, ensuring safe and efficient storage during long flights.
3. Thermal Conditions Management:
   Thermal management is a critical aspect of both hydrogen fuel cells and electric motors, as they generate significant heat. Effective cooling systems are required to prevent overheating, particularly during high-power operations such as take-off. Fuel cells function optimally within a narrow temperature range, and heat exchangers are employed to maintain that range. LH_2 also requires complex cryogenic systems to ensure it stays at its low boiling point. Hybrid systems must ensure thermal equilibrium between these various components, as maintaining LH_2 at cryogenic temperatures while managing heat from fuel cells requires advanced systems integration
4. System Operations Monitoring and Control:
   Monitoring and controlling the entire hybrid-electric system is critical for ensuring continuous, efficient operation. Real-time monitoring systems gather data on fuel levels, temperature, pressure, and electrical power output. An advanced Energy Management System (EMS) coordinates power distribution between the fuel cells, batteries, and electric motors, adapting to varying power demands during different flight phases. During take-off and climb, for example, power from both the fuel cells and batteries may be combined to meet peak power demands, while during cruise, the system can switch to fuel cells for more stable, efficient energy output.

Hydrogen and liquid hydrogen hybrid-electric propulsion systems present a promising pathway for sustainable aviation, combining advanced fuel cell technology, energy management systems, and cutting-edge thermal management to significantly reduce emissions. However, the successful implementation of these systems depends on overcoming key challenges, including safe hydrogen storage, efficient power management, and maintaining reliability in varying flight conditions. As we continue to explore the complexities and nuances of these systems, the next chapter will provide a technical analysis of the entire hydrogen hybrid-electric system, offering a deeper dive into the specific components, operations, and performance factors essential for the future of zero-emission aviation.

For detailed analysis, please refer to the following sections:

- Chapter 8: Technical analysis

In this chapter, a comprehensive technical analysis of hydrogen hybrid-electric propulsion systems in aviation is presented, applying systems engineering principles such as hierarchical decomposition. Drawing insights from real-world projects like ZeroAvia's and Airbus's ZeroE, this structured approach breaks down the system into core functions and sub-functions, highlighting the key components. The analysis explores hydrogen fuel cell technology, energy storage solutions, power management systems, and mechanical propulsion mechanisms, focusing on how these subsystems integrate seamlessly to achieve high efficiency, low emissions, and operational reliability in aviation. The different colors used in the diagrams are intended to distinguish various functions clearly, linking them to the main system shown in Figure 11, making it easier to track their roles within the overall propulsion architecture. Each component discussed aligns with ongoing developments in hydrogen aviation technologies.

- 8.1: System Propulsion 0
- 8.2 Safety and Reliability0
- 8.3 Thermal Conditions Management0
- 8.4 System Operations Monitor and Control 0

Chapter 8: Technical analysis

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8.1: System Propulsion

The primary function of the **propulsion system** is to provide efficient and sustainable propulsion for aircraft. This involves the generation and storage of electrical power through hydrogen fuel cells and batteries, as well as the conversion of this electrical power into mechanical power to drive the aircraft's propulsion system. The analyses presented in this chapter focus on detailing the processes and components involved in power generation, its distribution, and conversion to mechanical energy, ensuring efficient and reliable aircraft operation.

The hierarchical decomposition of the system (as shown in Figure 11) details how each of these processes is interconnected. It demonstrates how **power generation**, **storage**, **distribution**, and **propulsion** components work together seamlessly to create a system that meets the rigorous performance and safety standards required for sustainable aviation.

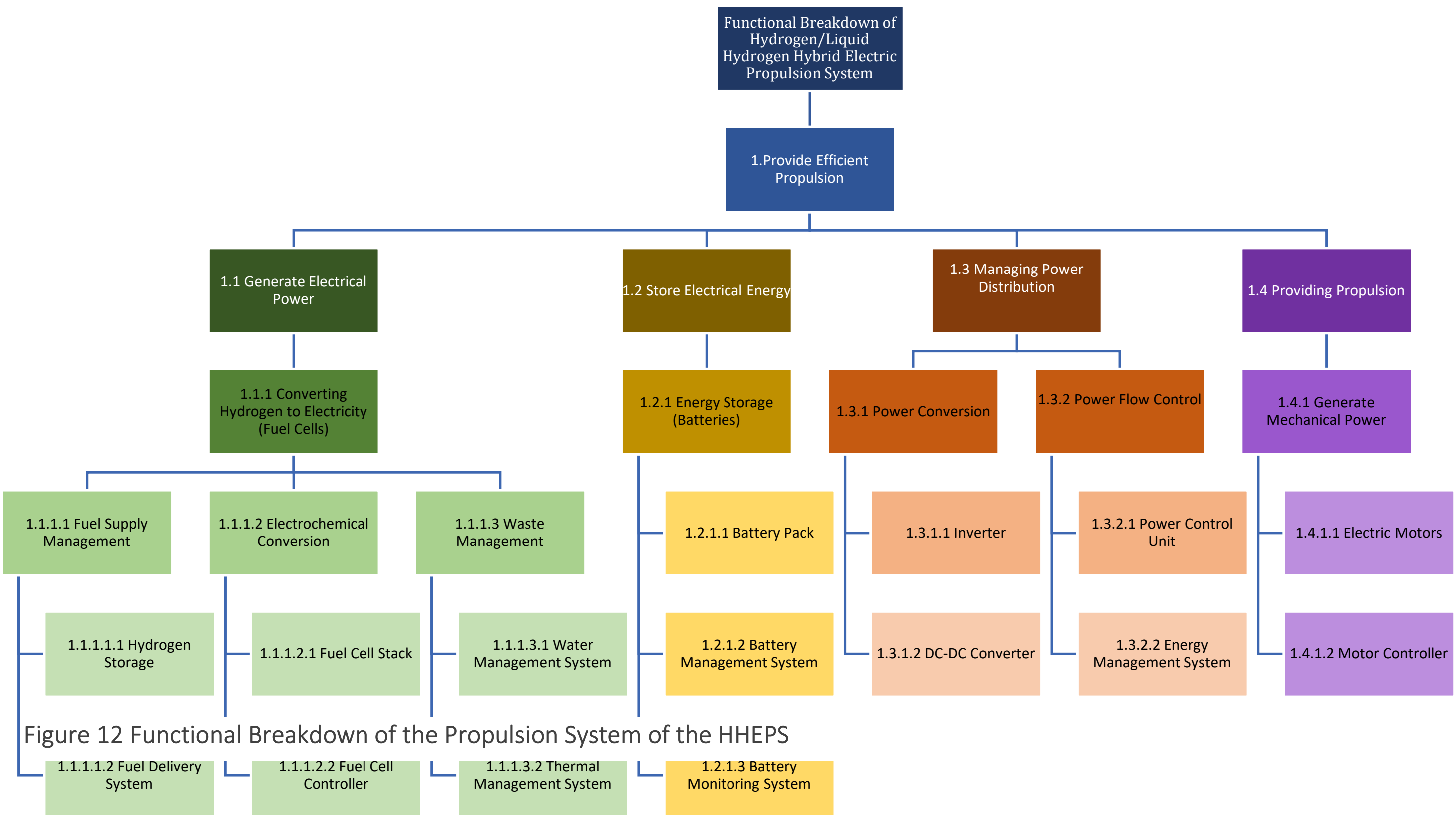

Figure 12 Functional Breakdown of the Propulsion System of the HHEPS

1.1 Generating Electrical Power

The generation of electrical power in an H2 or LH2 hybrid electric propulsion system is a critical function that involves the conversion of hydrogen into electricity through fuel cells. This process is essential for providing the necessary energy to power the aircraft's electric motors and other onboard systems. The generation of electrical power encompasses several sub-functions, including fuel supply management, electrochemical conversion, and waste management. Each of these sub-functions plays a vital role in ensuring the efficient and reliable production of electrical power. This section explores these sub-functions and their associated components in detail.

Converting Hydrogen to Electricity (Fuel Cells)

At the core of the electrical power generation system is the fuel cell, which converts hydrogen into electricity through an electrochemical reaction. In this process, hydrogen reacts with oxygen, generating electricity, water, and heat as byproducts. This sub-function involves managing the precise supply of hydrogen to the fuel cells, optimizing the electrochemical conversion process, and handling the system's thermal and water byproducts to ensure efficiency and longevity

This section explores the sub-functions related to hydrogen fuel cell conversion, including how hydrogen is delivered, the components that facilitate the electrochemical reactions, and how byproducts like water and heat are managed.

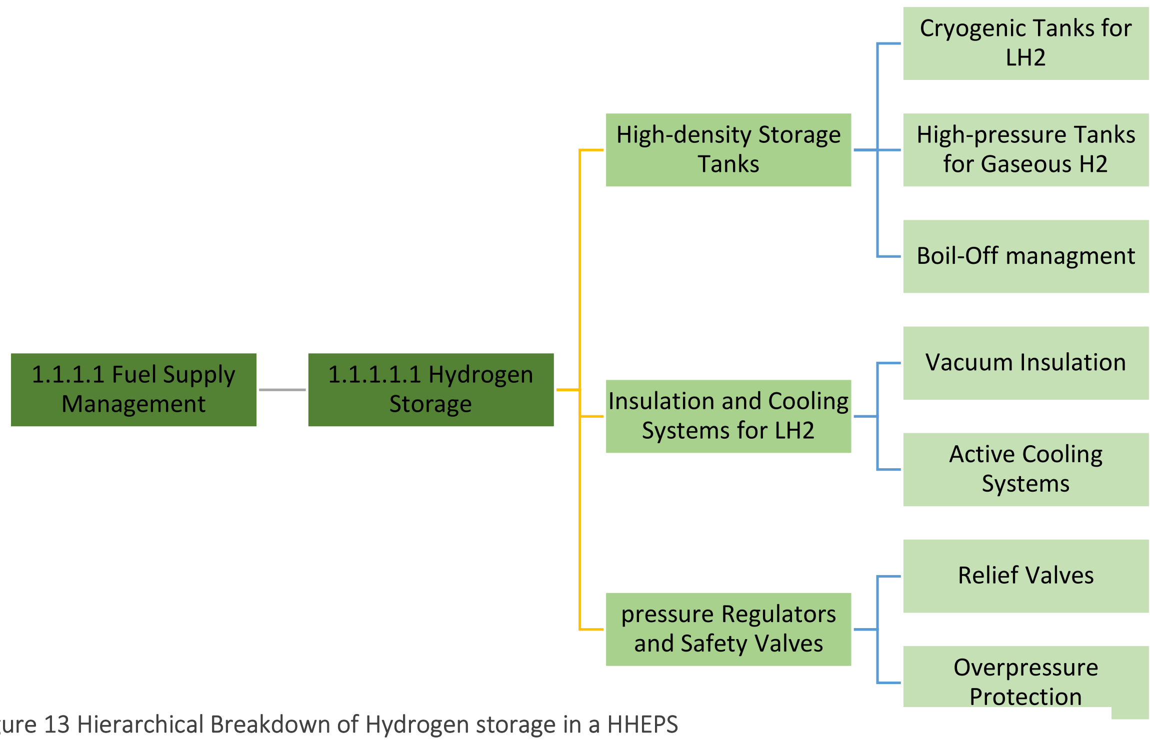

Figure 13 Hierarchical Breakdown of Hydrogen storage in a HHEPS

1.2.1.1 Fuel Supply Management

Fuel supply management ensures that hydrogen is safely stored, delivered efficiently to the fuel cells, and maintained at the proper pressure and flow rate to generate consistent electrical output. This process must take into account both liquid hydrogen (LH_2) and gaseous hydrogen (H_2) storage systems, depending on the aircraft's operational requirements.

1.2.1.1.1 Storing Hydrogen Safely and Efficiently (Hydrogen Storage)

Hydrogen storage is critical for aviation, where lightweight materials and efficient storage solutions are essential.

High-density Storage Tanks: These are essential for storing hydrogen. Cryogenic tanks are used for LH2, while high-pressure tanks are employed for gaseous H2. In this hierarchical decomposition, hydrogen storage is the first critical component of the fuel supply function. Where Hydrogen is stored in:

- Cryogenic Tanks for LH2: These tanks maintain extremely low temperatures to keep hydrogen in its liquid state, requiring advanced insulation and cooling systems, typically it Store hydrogen at cryogenic temperatures of -253°C in vacuum-insulated tanks. LH_2
- High-pressure Tanks for Gaseous H2: Designed to safely contain hydrogen at high pressures, these tanks are reinforced to withstand extreme conditions, typically store hydrogen at pressures ranging from 350 to 700 bar. These tanks are made of lightweight composite materials like carbon fiber to reduce weight while withstanding high pressure.

Boil-Off Management: Refers to the evaporation of liquid hydrogen due to heat transfer, which can occur if not properly insulated.

- Management Strategies:
  - Re-condensation Systems: Technologies that capture and re-condense boil-off hydrogen to return it to the storage tank.
  - Vent Systems: Systems designed to safely vent excess hydrogen to prevent pressure buildup.

Insulation and Cooling Systems for LH2: These systems ensure that cryogenic tanks remain at the required low temperatures.

- Vacuum Insulation: Provides a thermal barrier to minimize heat transfer and maintain the low temperature of liquid hydrogen.
- Active Cooling Systems: Utilize refrigeration technology to maintain the cryogenic conditions necessary for LH2 storage.

Pressure Regulators and Safety Valves: These components manage the pressure within the storage tanks and ensure safe operation.

- Relief Valves: Automatically release excess pressure to prevent tank rupture, ensuring safety.
- Overpressure Protection: Additional safety mechanisms are in place to handle unexpected pressure increases.

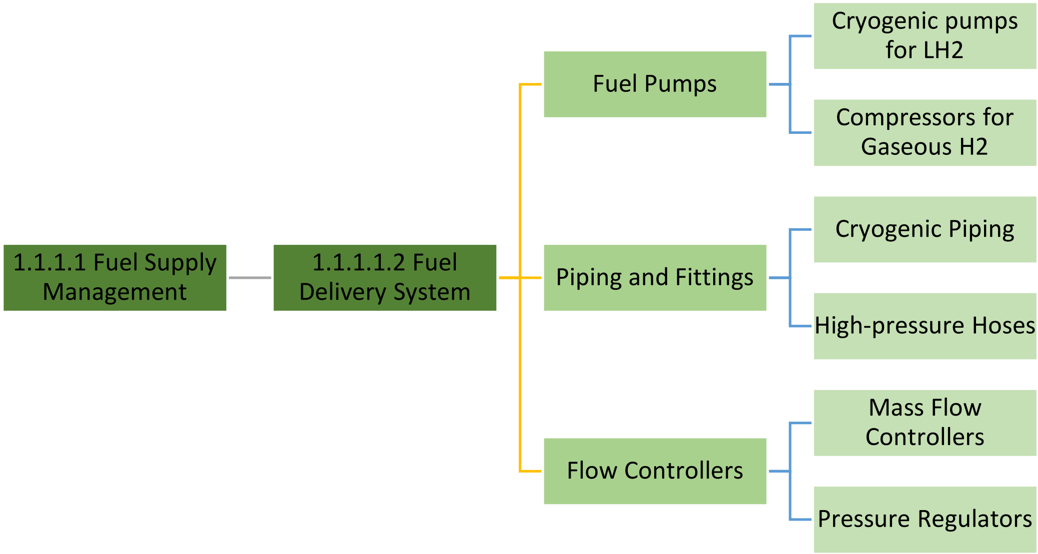

Figure 14 Hierarchical Breakdown of the Fuel Delivery System in HHEPS

1.1.1.1.2 Deliver Hydrogen to the Fuel Cell (Fuel Delivery System)

Efficient hydrogen delivery is crucial for maintaining consistent fuel cell performance. The fuel delivery system comprises:

Fuel Pumps: These are essential for moving hydrogen from the storage tanks to the fuel cells.

- Cryogenic Pumps for LH2: Specifically designed to handle extremely low temperatures and pump liquid hydrogen efficiently.
- Compressors for Gaseous H2: Increase the pressure of gaseous hydrogen for effective delivery to the fuel cells.

Piping and Fittings: These transport hydrogen from the storage tanks to the fuel cells.

- Cryogenic Piping: Specialized pipes capable of handling extremely low temperatures without compromising structural integrity.
- High-pressure Hoses: Designed to safely transport gaseous hydrogen under high pressure.

Flow Controllers: These regulate the flow rate of hydrogen to the fuel cells, ensuring that the supply matches the required power output.

- Mass Flow Controllers: Precisely measure and control the flow rate of hydrogen to the fuel cells.
- Pressure Regulators: Maintain consistent hydrogen pressure to ensure stable fuel cell operation.

1.2.1.2 Electrochemical Conversion

The Electrochemical Conversion process is the heart of the hydrogen hybrid-electric propulsion system, where hydrogen is converted into electricity in the Proton Exchange Membrane Fuel Cell (PEMFC). This involves splitting hydrogen molecules and generating electrical power while managing byproducts like water and heat. The fuel cell stack, consisting of components like membrane electrode assemblies (MEAs) and catalyst layers, facilitates the reaction, while the fuel cell controller regulates voltage and current to ensure efficient performance. This section explores the detailed steps of this conversion process and the systems that ensure its optimal operation, refer to figure 15.

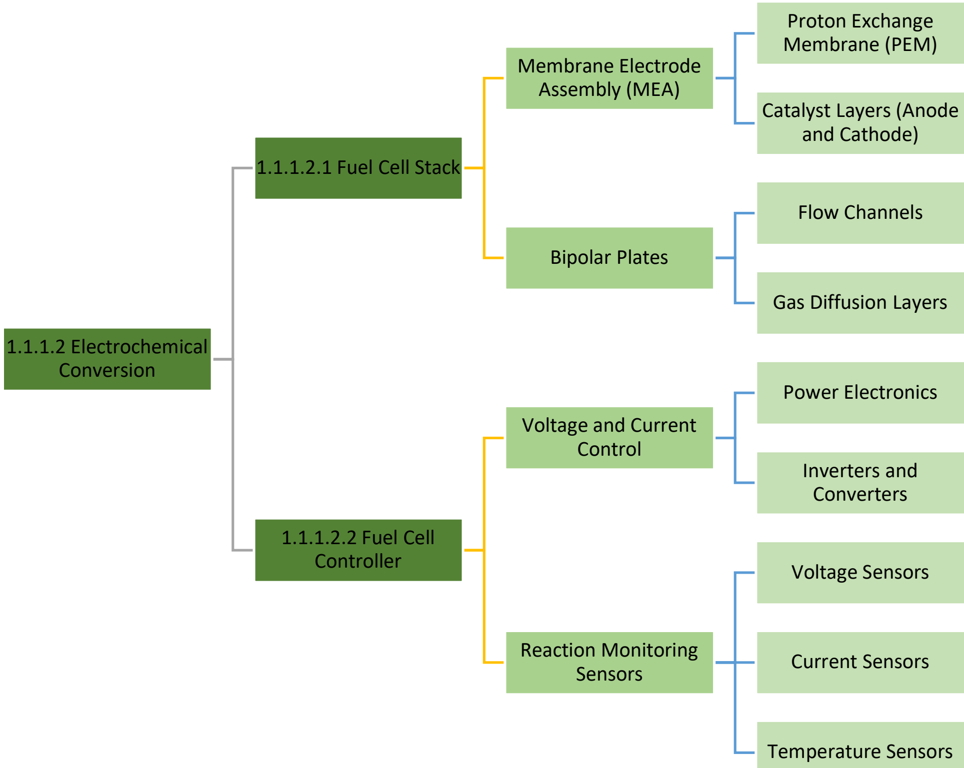

Figure 15 Hierarchical breakdown of the electrochemical conversion process

1.1.1.2.1 Converting Hydrogen and Oxygen into Electricity, Water, and Heat (Fuel Cell Stack)

The fuel cell stack is the core component where the electrochemical reactions take place:

Membrane Electrode Assembly (MEA): The MEA is the central element of the fuel cell where the electrochemical reactions occur.

- Proton Exchange Membrane (PEM): Conducts protons while acting as an insulator for electrons, essential for the electrochemical reaction.
- Catalyst Layers (Anode and Cathode): Facilitate the electrochemical reactions on both sides of the membrane, enabling the production of electricity.

Bipolar Plates: These plates distribute gases uniformly across the MEA and conduct electricity within the fuel cell stack.

- Flow Channels: Designed to ensure uniform distribution of hydrogen and oxygen across the MEA.
- Gas Diffusion Layers: Enhance the transport of gases to the catalyst layers, ensuring efficient reactions.

1.1.1.2.2 Managing the Fuel Cell Reaction Process (Fuel Cell Controller)

The fuel cell controller manages the entire reaction process to ensure optimal performance:

Voltage and Current Control: Essential for ensuring the fuel cells operate efficiently.

- Power Electronics: Convert and manage the electrical output from the fuel cells.
- Inverters and Converters: Convert the DC output from the fuel cells to AC, if necessary, and manage voltage levels.

Reaction Monitoring Sensors: Continuously monitor the performance and condition of the fuel cells.

- Voltage Sensors: Measure the electrical potential across the fuel cells to monitor performance.
- Current Sensors: Monitor the flow of electric current, ensuring it remains within safe operating limits.
- Temperature Sensors: Ensure the fuel cells operate within safe temperature ranges to prevent overheating.

1.1.13 Waste Management

Managing the byproducts of the electrochemical conversion process, such as water and heat, is essential for maintaining system efficiency and safety.

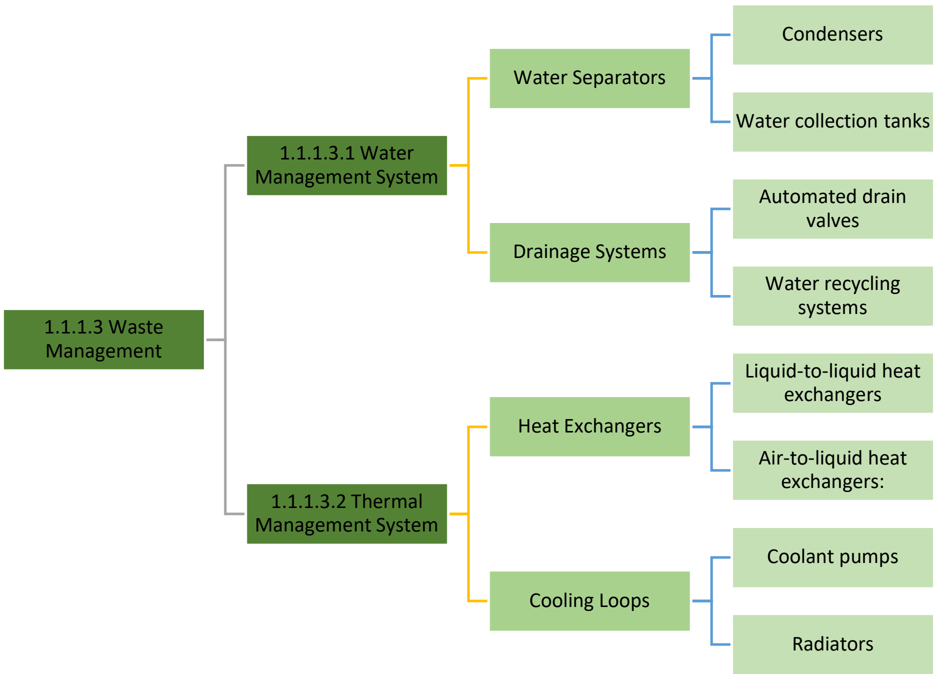

Figure 16 Functional breakdown of the waste management in a HHEPS

1.1.1.3.1 Remove Water Produced by the Fuel Cell (Water Management System)

Effective water management is critical to prevent flooding and maintain optimal fuel cell performance:

Water Separators: Extract water produced during the electrochemical reaction.

- Condensers: Cool the exhaust gases to condense and separate water vapor.
- Water Collection Tanks: Store the separated water safely.

Drainage Systems: Remove excess water from the system to maintain optimal performance.

- Automated Drain Valves: Periodically release accumulated water to prevent flooding.
- Water Recycling Systems: Reuse the water in other parts of the system if possible, enhancing efficiency.

1.1.1.3.2 Dissipate Heat Generated (Thermal Management System)

Effective thermal management is essential to prevent overheating and ensure the longevity of the fuel cells:

Heat Exchangers: Transfer heat from the fuel cells to the cooling medium.

- Liquid-to-Liquid Heat Exchangers: Utilize a coolant to absorb and remove heat from the fuel cells. In maritime applications, freshwater cooling systems may be employed to maintain optimal thermal conditions.
- Air-to-Liquid Heat Exchangers: Use air to cool the liquid coolant, facilitating efficient heat dissipation. This is particularly important in aviation, where thermal management must account for varying atmospheric conditions and high altitudes.

Cooling Loops: Circulate coolant to remove heat from the fuel cells and maintain optimal operating temperatures.

- Coolant Pumps: Ensure continuous movement of the coolant through the system.
- Radiators: Dissipate heat from the coolant into the surrounding air, maintaining efficient cooling.

1.2 Storing Electrical Energy

Storing electrical energy in an H_2 or LH_2 hybrid electric propulsion system is essential for ensuring a stable and reliable power supply to the aircraft, particularly during peak demand phases such as take-off and climb. This involves advanced battery technologies that store excess electricity generated by fuel cells, as well as energy recovered through regenerative braking systems. The energy storage function is broken down into multiple sub-functions, including **battery packs**, **energy management**, and **monitoring system**. Each component within the system plays a critical role in maintaining energy availability and efficiency, as shown in the hierarchical decomposition diagram, figure 11. This section will explore these sub-functions and components, detailing how they interact to store and supply electrical energy effectively

1.2.1 Energy Storage (Batteries)

Energy storage in batteries is essential for maintaining a consistent power supply, particularly during periods of high demand or when the fuel cells alone cannot meet the power requirements. This sub-function involves the storage, management, and monitoring of electrical energy in batteries.

1.2.1.1 Store Electricity for Use During High Demand Periods (Battery Pack)

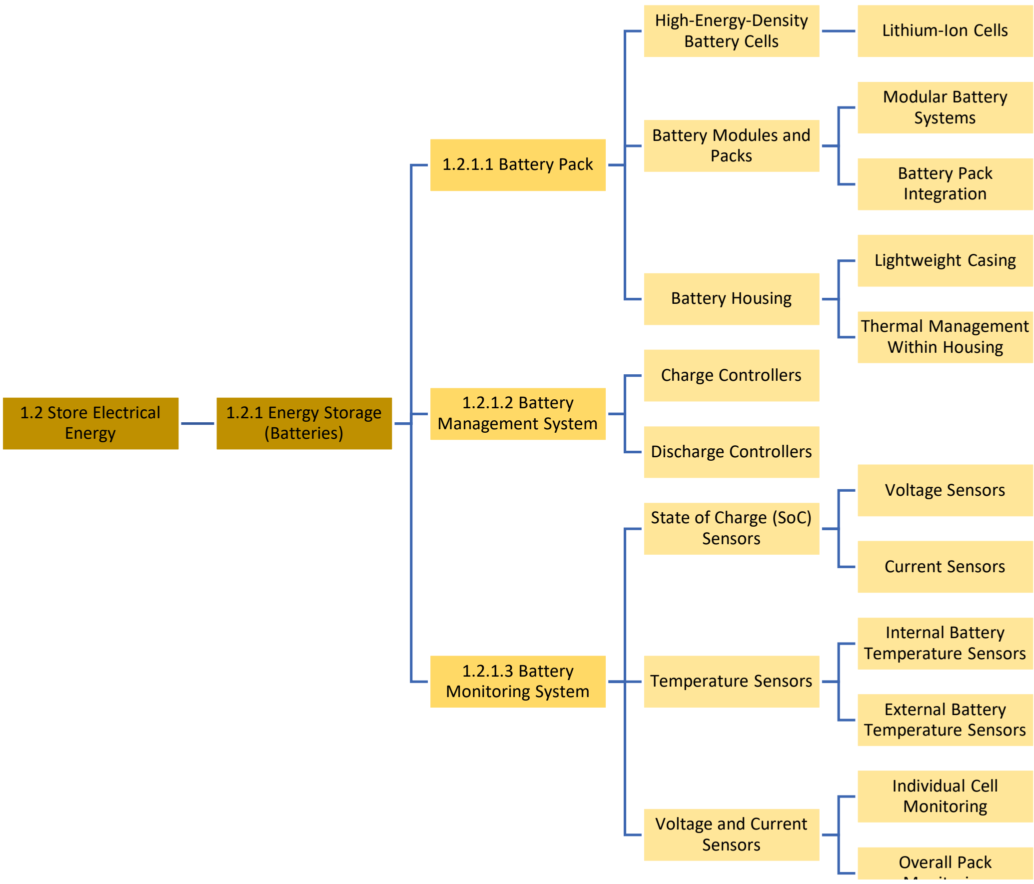

Figure 17 Functional breakdown of Storing Electrical Energy in a HHEPS

The battery pack is the primary component responsible for storing electrical energy. It is composed of individual battery cells organized into modules and packs, which are then integrated into the aircraft's power system.

1.2.1.1.1 High-Energy-Density Battery Cells: These cells are designed to store large amounts of energy in a compact form factor, which is crucial for aviation applications where weight and space are at a premium.

- Lithium-Ion Cells: Widely used due to their high energy density, efficiency, and relatively long-life cycle.

1.2.1.1.2 Battery Modules and Packs: Battery cells are assembled into modules, which are then combined to form battery packs.

- Modular Battery Systems: Facilitate easier maintenance, replacement, and scalability of battery capacity.
- Battery Pack Integration: Ensures that the battery packs are securely mounted and integrated into the aircraft's power system, providing stability and safety during operation.

1.2.1.1.3 Battery Housing: The structural enclosure that protects the battery cells and modules from physical damage and environmental factors.

- Lightweight Casing: Made from advanced materials to minimize weight while providing robust protection.
- Thermal Management Within Housing: Ensures that the battery cells are kept within optimal temperature ranges to maintain performance and safety.

1.2.1.2 Manage Battery Charging and Discharging Cycles (Battery Management System)

The Battery Management System (BMS) is responsible for overseeing the charging and discharging processes, ensuring that the battery operates efficiently and safely.

1.2.1.2.1 Charge Controllers: Regulate the charging process to ensure the batteries are charged efficiently without overcharging, which can damage the cells.

1.2.1.2.2 Discharge Controllers: Manage the discharge process to ensure that the power supply from the batteries is stable and meets the aircraft's power demands.

1.2.1.3 Monitor Battery Health and Status (Battery Monitoring System)

Continuous monitoring of the battery system is essential to ensure safety, reliability, and optimal performance.

1.2.1.3.1 State of Charge (SoC) Sensors: Measure the amount of charge remaining in the batteries, providing critical information for managing power usage.

- Voltage Sensors: Monitor the electrical potential of each battery cell to detect any anomalies.
- Current Sensors: Measure the flow of electric current to ensure it remains within safe operating limits.

1.2.1.3.2 Temperature Sensors: Track the temperature of the battery cells to prevent overheating and ensure they operate within safe temperature ranges.

- Internal Battery Temperature Sensors: Measure the temperature inside the battery cells.
- External Battery Temperature Sensors: Monitor the temperature of the battery pack's exterior.

1.2.1.3.3 Voltage and Current Sensors: Provide detailed information about the electrical status of the battery pack, helping to detect and address any issues promptly.

- Individual Cell Monitoring: Ensures that each cell within the battery pack is operating correctly.
- Overall Pack Monitoring: Provides a comprehensive overview of the entire battery pack's performance.

1.3 Manage Power Distribution

Effective power distribution is essential for ensuring that the generated and stored electrical energy is delivered efficiently to the various systems and components of an H2 or LH2 hybrid electric propulsion system. This function involves converting, regulating, and controlling the flow of electricity between the fuel cells, batteries, and electric motors. Using the hierarchical decomposition in figure x, this section explores the sub-functions and components involved in power distribution, including inverters, voltage regulators, and power controllers, highlighting how they work together to maintain efficient energy flow and operational stability.

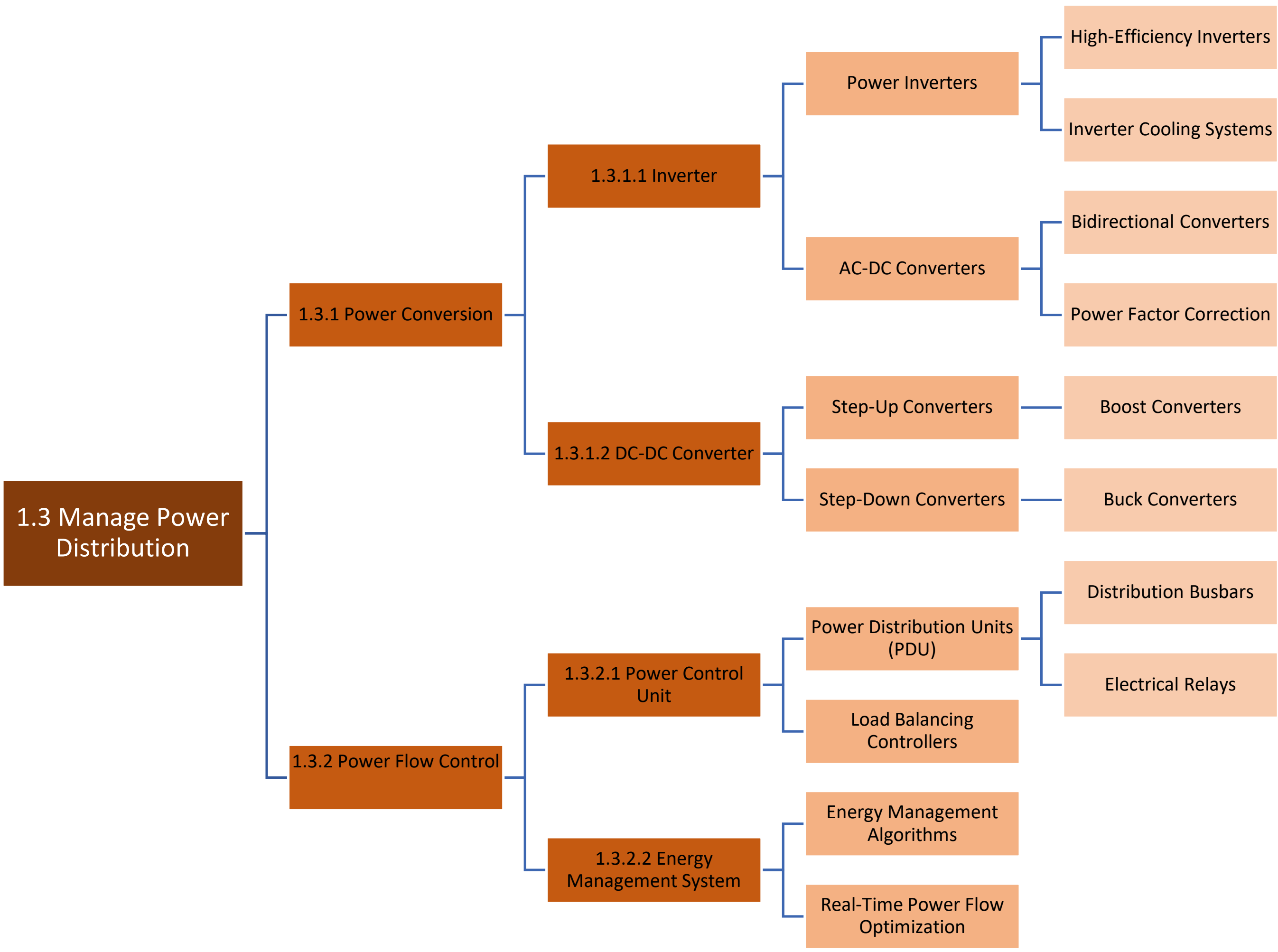

Figure 18 Hierarchical decomposition of the power distribution function in HHEPS

1.3.1 Power Conversion

Power conversion is a critical aspect of power distribution, as it involves converting the electrical power generated by the fuel cells and stored in the batteries into the appropriate form and voltage levels required by the aircraft's systems and motors.

1.3.1.1 Convert DC Power to AC for Motors (Inverter)

Electric motors typically require AC power, while fuel cells and batteries generate DC power. Inverters are used to convert DC power to AC power.

1.3.1.1.1 Power Inverters: Devices that convert DC power from the fuel cells and batteries into AC power for the electric motors.

- High-Efficiency Inverters: Ensure minimal energy loss during the conversion process, which is critical for maintaining overall system efficiency.
- Inverter Cooling Systems: Integrated cooling mechanisms to dissipate heat generated during the conversion process, ensuring reliable operation.

1.3.1.1.2 AC-DC Converters: While primarily for converting DC to AC, some systems may require bidirectional conversion for certain applications.

- Bidirectional Converters: Allow power to flow in both directions, enabling regenerative braking systems to convert kinetic energy back into electrical energy.
- Power Factor Correction: Ensures that the AC power supplied to the motors is of high quality and suitable for optimal motor performance.

1.3.1.2 Regulate Voltage Levels for Different Components (DC-DC Converter)

Different systems and components within the aircraft may require different voltage levels. DC-DC converters are used to adjust the voltage levels to match the requirements of various components.

1.3.1.2.1 Step-Up Converters: Increase the voltage level of DC power to meet the needs of high-voltage components.

- Boost Converters: Used to step up the voltage for components that operate at higher voltages, ensuring they receive sufficient power.

1.3.1.2.2 Step-Down Converters: Decrease the voltage level of DC power to match the requirements of low-voltage components.

- Buck Converters: Used to step down the voltage for components that operate at lower voltages, protecting them from overvoltage conditions.

1.3.2 Power Flow Control

Controlling the flow of electricity between the fuel cells, batteries, and electric motors is essential for maintaining a balanced and efficient power distribution system.

1.3.2.1 Control the Flow of Electricity Between Fuel Cells, Batteries, and Motors (Power Control Unit)

The Power Control Unit (PCU) is responsible for managing the distribution of electrical power from the fuel cells and batteries to the electric motors and other systems.

1.3.2.1.1 Power Distribution Units (PDU): Centralized units that distribute electrical power to various subsystems and components.

- Distribution Busbars: Conductive bars that serve as central points for power distribution, ensuring efficient and reliable delivery of electricity.
- Electrical Relays: Switches that control the flow of electricity to different circuits, enabling or disabling power as needed.

1.3.2.1.2 Load Balancing Controllers: Devices that manage the distribution of electrical loads to ensure that no single component is overloaded by Real-Time Load Distribution: Dynamically adjusts the distribution of power based on current demand and system conditions. And Peak Load Shaving: Reduces the load during peak demand periods to prevent overloading and maintain system stability.

1.3.2.2 Ensure Balanced and Efficient Power Distribution (Energy Management System)

The Energy Management System (EMS) is responsible for optimizing the overall power distribution to ensure that the system operates efficiently and reliably.

1.3.2.2.1 Energy Management Algorithms: Advanced algorithms that analyze system conditions and optimize power distribution accordingly by Optimization Algorithms that Continuously adjust power distribution to maximize efficiency and performance and Predictive Load Management that Uses predictive models to anticipate future power demands and adjust distribution pre-emptively.

1.3.2.2.2 Real-Time Power Flow Optimization: Ensures that power is distributed in the most efficient manner possible, based on real-time data by Dynamic Power Allocation that Adjusts the allocation of power to different components based on real-time demand and system status and Efficiency Maximization that Continuously seeks to maximize the efficiency of the power distribution system, reducing losses and improving performance.

1.4 Propulsion

Providing propulsion is the final and most critical step in the power distribution chain of an hydrogen hybrid-electric propulsion system. This stage involves converting electrical energy generated by the fuel cells and stored in the batteries into mechanical energy to drive the aircraft's propulsion systems. Through electric motors, this mechanical energy is used to generate thrust and propel the aircraft efficiently. In this section, we explore the sub-functions and components that facilitate this energy conversion process, including the role of electric motors, propellers, and thrust management systems, which ensure smooth and reliable propulsion. The hierarchical decomposition of this system illustrates how each sub-function contributes to the efficient generation of mechanical power.

1.4.1 Generate Mechanical Power

The conversion of electrical energy into mechanical energy is essential for propulsion. This sub-function involves the use of electric motors, which are controlled and optimized to ensure efficient power delivery.

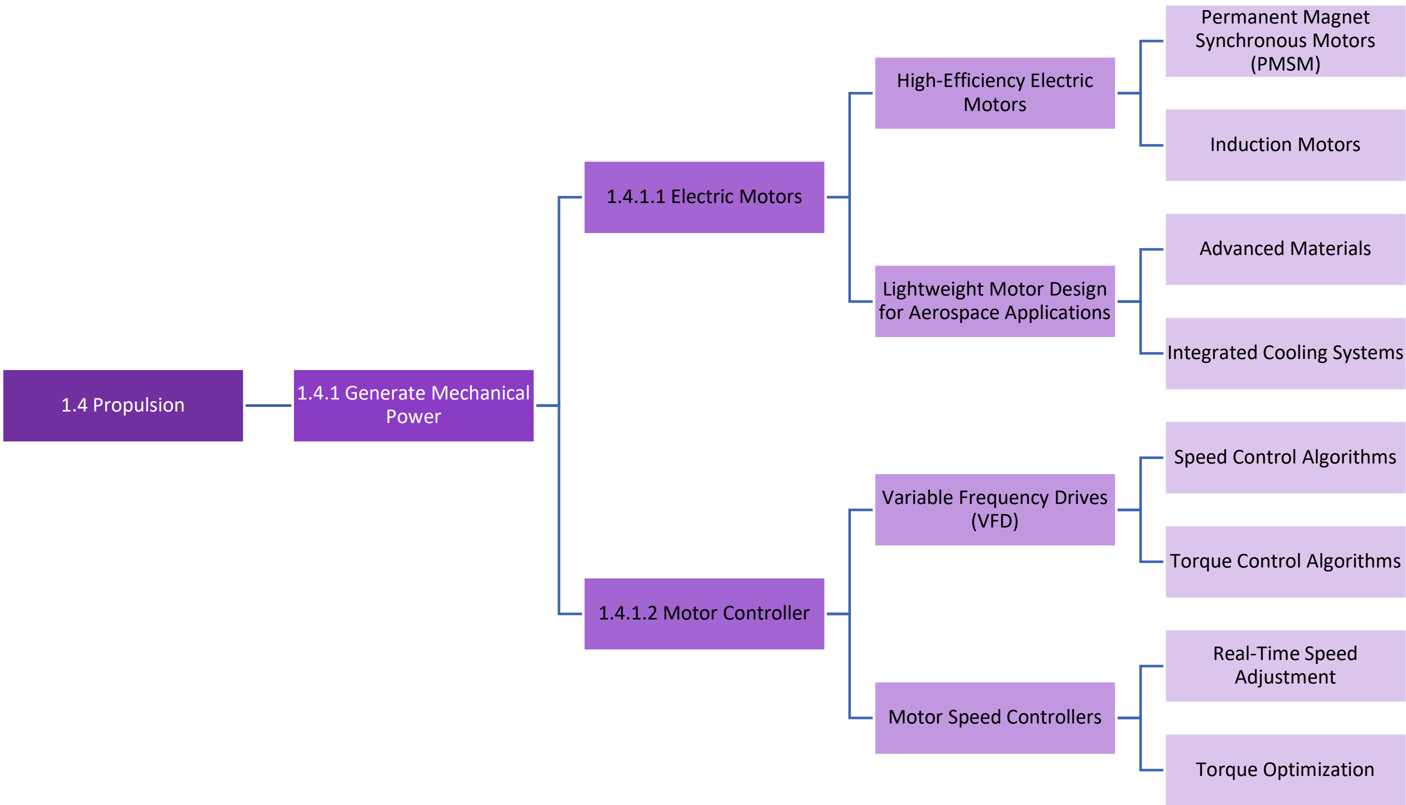

Figure 19 Hierarchical decomposition of the Propulsion function in HHEPS

1.4.1.1 Convert Electrical Energy into Mechanical Energy (Electric Motors)

Electric motors are the primary components responsible for converting electrical energy into mechanical energy, which is then used to propel the aircraft.

1.4.1.1.1 High-Efficiency Electric Motors: Motors designed to maximize efficiency, reducing energy losses and improving overall performance.

- Permanent Magnet Synchronous Motors (PMSM): Known for their high efficiency and power density, making them ideal for aviation applications.
- Induction Motors: Robust and reliable motors that can be used in various propulsion applications.

1.4.1.1.2 Lightweight Motor Design for Aerospace Applications: Motors must be designed to be lightweight to meet the stringent weight requirements of aviation.

- Advanced Materials (Carbon Fiber, Lightweight Alloys): Used in motor construction to reduce weight without compromising strength and durability.
- Integrated Cooling Systems: Ensure that motors operate within safe temperature ranges, preventing overheating and maintaining performance.

1.4.1.2 Control Motor Speed and Torque (Motor Controller)

Motor controllers are essential for managing the performance of electric motors, ensuring they operate efficiently and respond appropriately to the demands of the propulsion system.

1.4.1.2.1 Variable Frequency Drives (VFD): Devices that control the speed and torque of the electric motors by varying the frequency and voltage of the power supplied to the motors.

- Speed Control Algorithms: Advanced algorithms that adjust the motor speed based on real-time performance requirements and flight conditions.
- Torque Control Algorithms: Ensure that the motor produces the necessary torque to meet propulsion demands, optimizing performance and efficiency.

1.4.1.2.2 Motor Speed Controllers: Manage the speed of the electric motors, ensuring they operate at the optimal speed for different phases of flight.

- Real-Time Speed Adjustment: Continuously adjusts motor speed based on current conditions and power requirements.
- Torque Optimization: Balances torque production with energy consumption to maximize efficiency.

8.2 Safety and Reliability

Ensuring safety and reliability is a critical aspect of hybrid-electric propulsion systems utilizing hydrogen as a fuel source. This requires comprehensive safety protocols to manage hydrogen storage, high-voltage electrical systems, and the unique challenges presented in aviation. Implementing robust safety measures—such as hydrogen leak detection, fire suppression systems, and redundant control mechanisms—ensures secure fuel handling and consistent operation. Fault detection and real-time monitoring play vital roles in maintaining reliability, minimizing risks, and preventing potential failures.

To further clarify the safety structure, Figure X presents a hierarchical breakdown of the sub-functions and components involved in ensuring system safety and reliability. This visual diagram illustrates the interactions between the key systems—such as hydrogen containment, electrical safety systems, and fault management—highlighting how each layer contributes to the overall integrity and longevity of the propulsion system. Together, these systems safeguard both the aircraft and its occupants, ensuring that safety and reliability are upheld throughout all phases of operation.

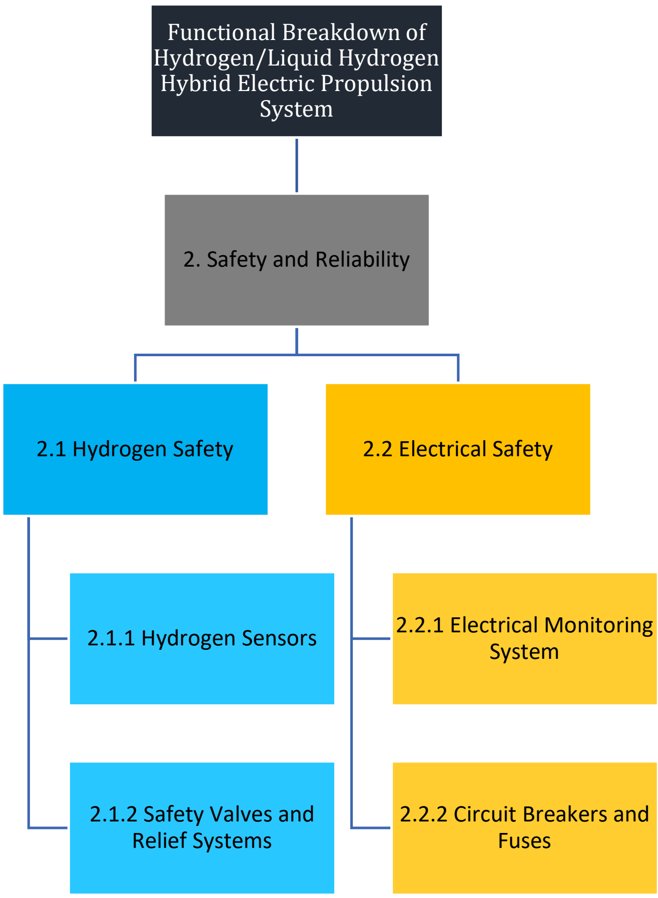

Figure 20 a hierarchical breakdown of the safety and reliability functions in a HHEPS

2.1. Hydrogen Safety

Hydrogen safety is critical due to the highly flammable nature of hydrogen. Proper detection and management of hydrogen leaks, along with secure storage and handling protocols, are essential to prevent accidents and ensure safe operation. Refer to figure 21.

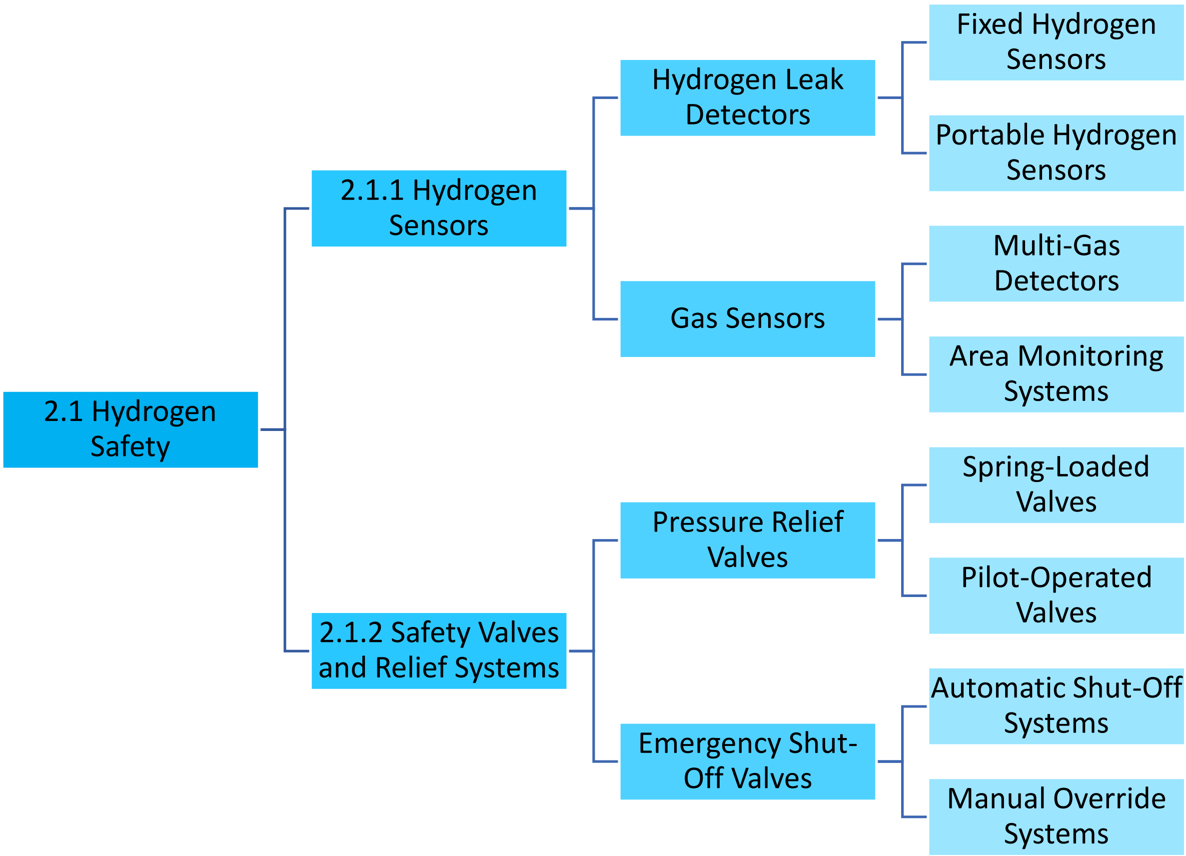

Figure 21 Hydrogen safety breakdown in a HHEPS

2.1.1 Detecting and Managing Hydrogen Leaks (Hydrogen Sensors)

Detecting hydrogen leaks promptly and accurately is crucial for preventing potential hazards. This sub-function involves the use of advanced sensors to detect and manage hydrogen leaks.

2.1.1.1 Hydrogen Leak Detectors

Specialized sensors designed to detect the presence of hydrogen in the air, signaling potential leaks.

- Fixed Hydrogen Sensors: Installed at key locations throughout the aircraft, providing continuous monitoring for hydrogen leaks.
- Portable Hydrogen Sensors: Handheld devices that allow maintenance personnel to check for hydrogen leaks in various locations.

2.1.1.2 Gas Sensors

Multi-gas detectors capable of detecting hydrogen along with other potential hazardous gases, enhancing overall safety.

- Multi-Gas Detectors: Devices that can detect multiple gases, including hydrogen, methane, and carbon monoxide, providing comprehensive safety monitoring.
- Area Monitoring Systems: Networked sensors that monitor large areas for gas leaks, ensuring widespread coverage and safety.

2.1.2 Providing Safe Storage and Handling of Hydrogen (Safety Valves and Relief Systems)

Safe storage and handling of hydrogen are paramount to prevent accidents and ensure the integrity of the hydrogen system. This sub-function involves the use of safety valves and relief systems.

Pressure Relief Valves

Valves that automatically release excess pressure from the hydrogen storage tanks to prevent overpressure conditions.

- Spring-Loaded Valves: Common type of pressure relief valve that opens when the internal pressure exceeds a preset limit.
- Pilot-Operated Valves: Designed for higher-pressure applications, these valves offer precise pressure management and are typically found in systems that require careful modulation of hydrogen pressure.

Emergency Shut-Off Valves

Valves that can quickly isolate the hydrogen supply in the event of a leak or other emergency, preventing further release of hydrogen.

- Automatic Shut-Off Systems: These systems automatically trigger the isolation of hydrogen in response to specific fault conditions, such as leaks or sensor-detected issues. Their rapid response capability makes them essential in high-risk environments like aircraft or large-scale hydrogen storage facilities.
- Manual Override Systems: While automated systems are crucial, manual override capabilities are also necessary for human operators to intervene when needed, adding a layer of control for safety personnel in emergency situations.

2.2 Electrical Safety

Electrical safety is critical for preventing electrical faults, short circuits, and other hazards that can compromise the safety and reliability of the propulsion system. This sub-function includes monitoring electrical systems and isolating faulty components to ensure safe operation, as show in figure 22.

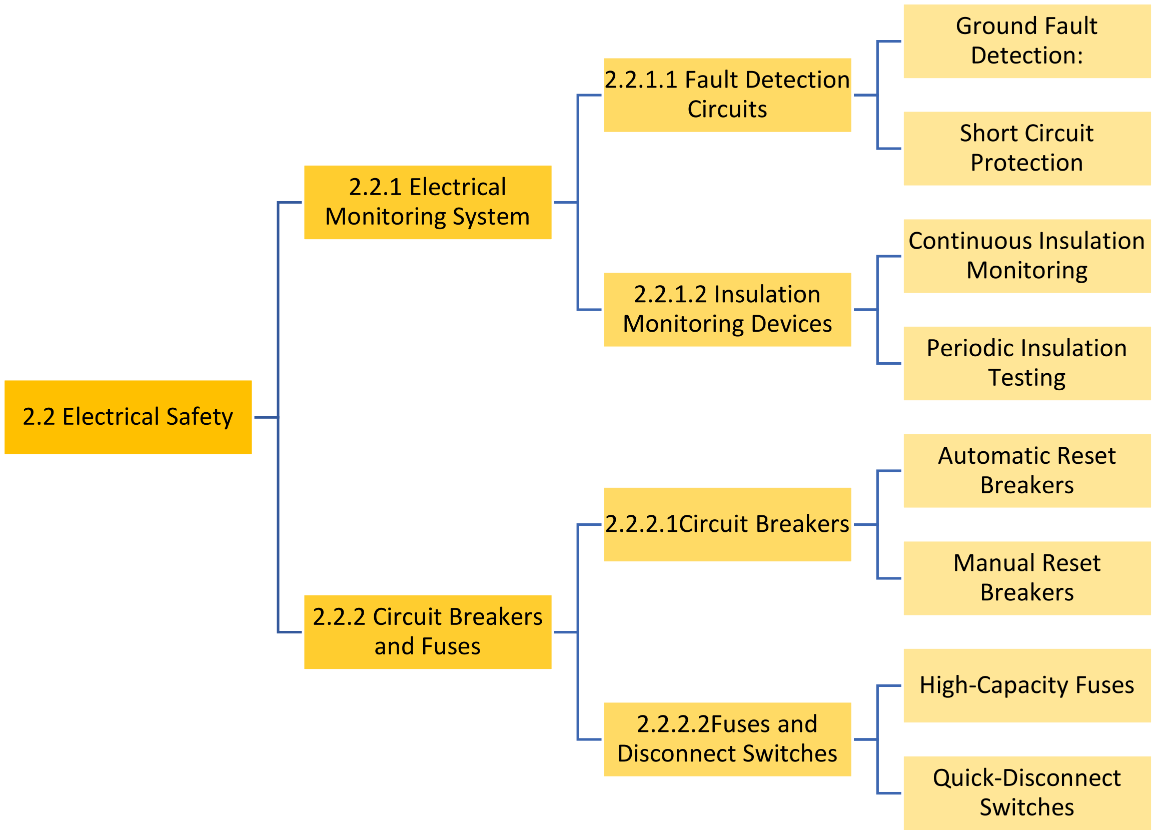

Figure 22 Electrical safety breakdown in a HHEPS

2.2.1 Electrical Monitoring System

The electrical monitoring system continuously tracks the status of the electrical circuits to detect abnormalities or potential failures. Monitoring these circuits is vital for identifying issues before they escalate into more severe problems.

2.2.1.1 Fault Detection Circuits

These circuits are essential for identifying electrical faults such as ground faults or short circuits that can occur within the system.

Ground Fault Detection: Detects unintended electrical connections between the system and the ground, which can lead to dangerous current flows.

Short Circuit Protection: Protects the system from excessive current due to short circuits, which could otherwise cause overheating or fires.

2.2.1.2 Insulation Monitoring Devices

These devices monitor the integrity of the insulation within the electrical system, which is crucial for preventing leaks or electrical faults due to deteriorating insulation.

Continuous Insulation Monitoring: Real-time tracking of insulation health to detect potential failures before they occur.

Periodic Insulation Testing: Regular testing of insulation to ensure it meets the necessary safety standards over time.

2.2.2 Circuit Breakers and Fuses

Circuit breakers and fuses provide essential protection by isolating faulty electrical circuits and preventing damage to the system.

2.2.2.1 Circuit Breakers

Circuit breakers are essential for automatically shutting down a circuit in the event of an overload or short circuit.

Automatic Reset Breakers: Automatically reset after isolating the fault, reducing downtime.

Manual Reset Breakers: Require human intervention to reset, ensuring that faults are fully addressed before resuming operation.

2.2.2.2 Fuses and Disconnect Switches

These components provide fast protection against overcurrent conditions, minimizing the risk of fire or equipment damage.

High-Capacity Fuses: Designed to handle large amounts of current, they blow or "open" when the current exceeds safe levels.

Quick-Disconnect Switches: Allow for fast and safe disconnection of electrical circuits in case of an emergency or for maintenance purposes.

8.3 Thermal Conditions Management

Managing thermal conditions is critical for the optimal performance and safety of a hydrogen-based hybrid-electric propulsion system. The system generates substantial heat from fuel cells, power electronics, and other components, which must be carefully managed to maintain efficient operation. The two main sub-functions involved in thermal management are heat dissipation and temperature control. Heat dissipation focuses on removing excess heat to prevent overheating, while climate control ensures that components such as batteries operate within their optimal temperature ranges.

- Figure 23 illustrates the hierarchical breakdown of the thermal management system, outlining how **heat dissipation** is achieved through components like **liquid-to-liquid heat exchangers**, while **Battery temperature control** is maintained using **cooling loops**. Together, these systems work to regulate the thermal conditions within the propulsion system, ensuring stable operation even in varying flight conditions.

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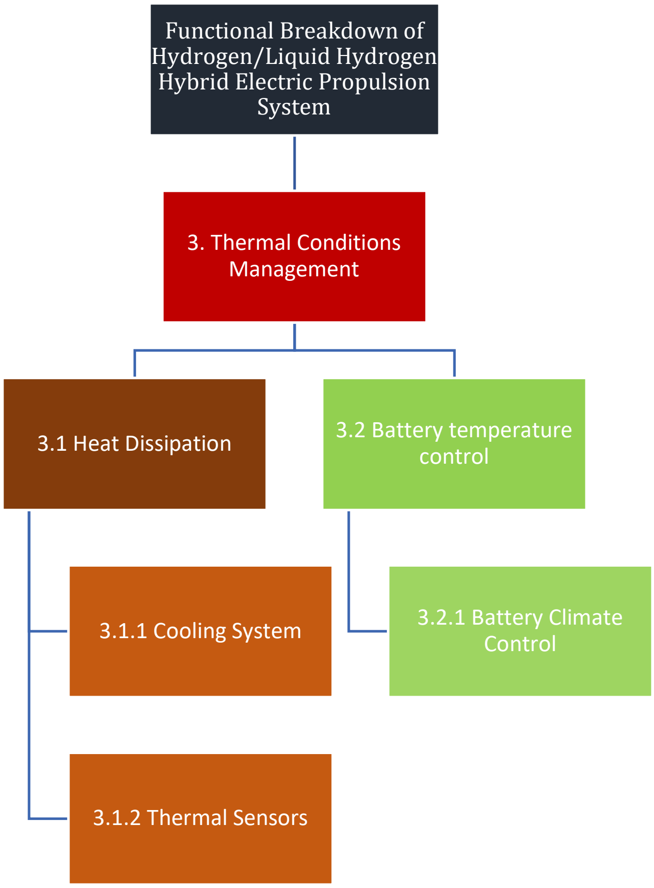

Figure 23 Hierarchical breakdown of thermal condition management in a HHEPS

3.1 Heat Dissipation

Dissipating excess heat generated by the fuel cells and power electronics is essential to prevent overheating and ensure the long-term reliability of the propulsion system. The heat dissipation function relies on two primary sub-functions: the cooling system, which actively removes heat from critical components, and thermal sensors, which monitor temperatures in real-time to ensure the system operates within safe limits. Both sub-functions are critical to maintaining stable thermal conditions and preventing damage from excessive heat.

Figure 24 presents the hierarchical breakdown of the heat dissipation system, highlighting how cooling loops and heat exchangers work in conjunction with thermal sensors to regulate and dissipate heat effectively.

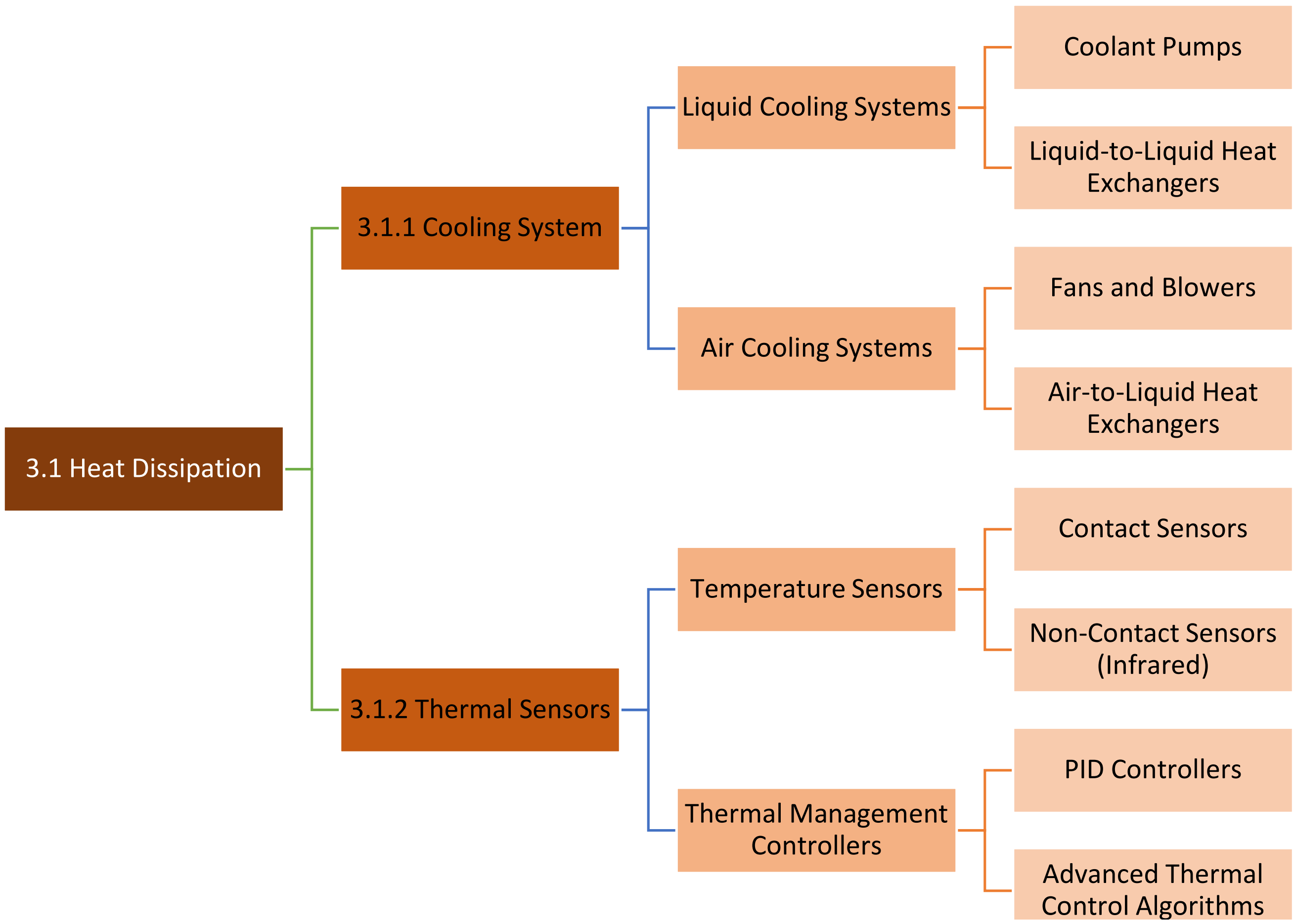

Figure 24 functional breakdown of the heat dissipation function in a HHEPS

3.1.1 Remove Excess Heat from Fuel Cells and Power Electronics (Cooling System)

The cooling system is responsible for removing excess heat from the fuel cells and power electronics to maintain optimal operating temperatures.

3.1.1.1 Liquid Cooling Systems

These systems use liquid coolant to absorb and remove heat from the components.

- Coolant Pumps: Ensure continuous circulation of the coolant throughout the system.

- Liquid-to-Liquid Heat Exchangers: Transfer heat from the coolant to another liquid medium, facilitating efficient heat removal.

Air Cooling Systems

These systems use air to dissipate heat from the components.

- Fans and Blowers: Enhance air circulation around the components, increasing heat dissipation efficiency.
- Air-to-Liquid Heat Exchangers: Use air to cool the liquid coolant, improving overall thermal management.

3.1.2 Ensure Optimal Operating Temperatures for All Components (Thermal Sensors)

Maintaining optimal operating temperatures for all components is critical for ensuring system reliability and performance.

Temperature Sensors

Devices that monitor the temperature of various components to ensure they remain within safe operating ranges.

- Contact Sensors: Measure the temperature directly from the component surfaces.
- Non-Contact Sensors (Infrared): Measure the temperature without direct contact, providing quick and accurate readings.

Thermal Management Controllers

Systems that regulate the cooling process based on temperature readings to maintain optimal conditions.

- PID Controllers: Use Proportional-Integral-Derivative control algorithms to adjust cooling system parameters in real-time.
- Advanced Thermal Control Algorithms: Provide precise temperature regulation to optimize the performance and safety of the propulsion system.

3.2 Battery Temperature control

Maintaining a controlled climate for the battery system is critical to ensure optimal performance and prevent failures due to overheating or excessive cooling. The battery temperature control system monitors and regulates the temperature of the battery packs to ensure they remain within the safe operating range.

Figure 25 illustrates the hierarchical breakdown of the temperature control system, showing the subcomponent of the function to maintain stable battery temperatures.

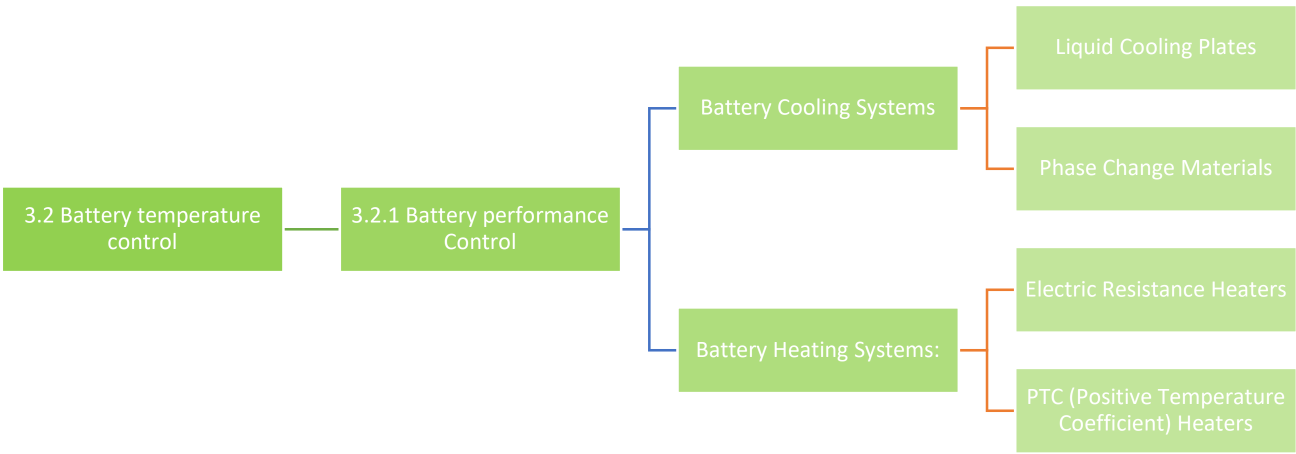

Figure 25 Functional breakdown of the battery temperature control function in a HHEPS

3.2.1 Maintain Comfortable Operating Environment for Batteries (Battery Climate Control)

Effective climate control for batteries involves cooling and heating systems to keep the batteries within their optimal temperature range.

3.2.1.1 Battery Cooling Systems

These systems ensure that the batteries do not overheat during operation.

- Liquid Cooling Plates: Absorb heat from the batteries and transfer it to the cooling liquid.
- Phase Change Materials: Materials that absorb heat by changing their phase, helping to regulate battery temperature.

3.2.2.2 Battery Heating Systems

These systems ensure that the batteries are kept warm in cold conditions to maintain their performance.

- Electric Resistance Heaters: Provide direct heating to the batteries using electrical energy.
- PTC (Positive Temperature Coefficient) Heaters: Self-regulating heaters that increase resistance as temperature rises, preventing overheating.

8.4 System Operations Monitor and Control

Monitoring and controlling system operations are crucial for the efficient and safe functioning of an H2 or LH2 hybrid electric propulsion system. This involves continuous data acquisition, real-time processing, and decision-making to ensure optimal performance and quick response to any anomalies. Effective monitoring and control help maintain the system's reliability, efficiency, and safety. This section explores the essential sub-functions and components involved in monitoring and controlling system operations.

Figure 26 illustrates the hierarchical breakdown of the monitoring and control systems, highlighting key sub-functions such as data acquisition and system control. Together, these components ensure seamless operation, enabling real-time adjustments and enhancing overall system performance

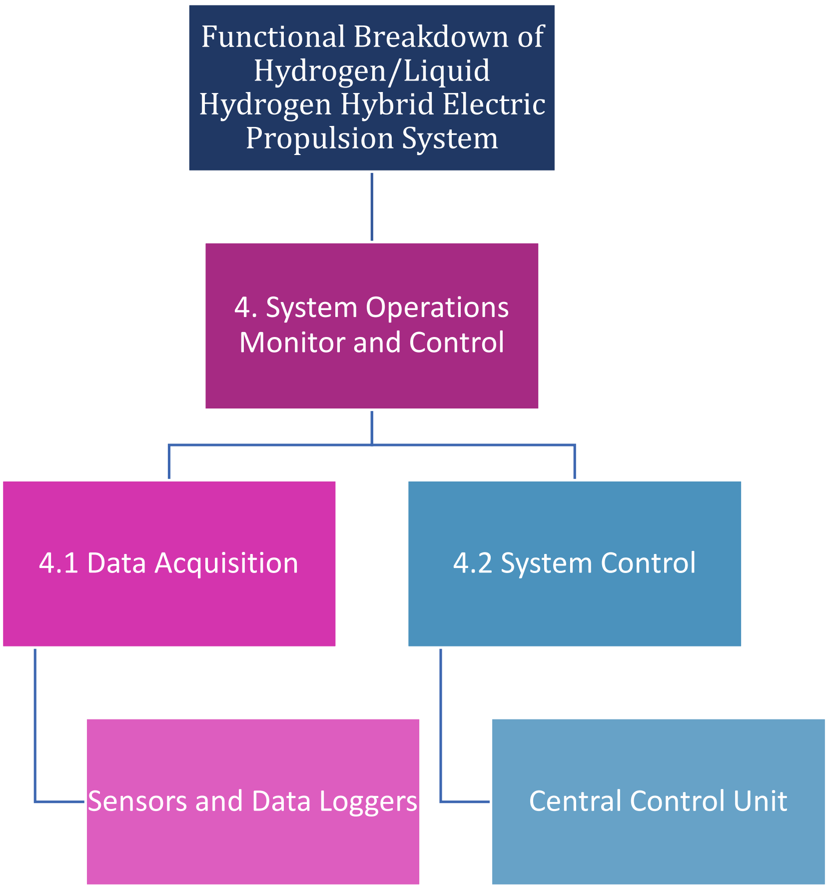

Figure 26 hierarchical breakdown of the monitoring and control operational systems

4.1 Data Acquisition

Collecting real-time data from all components of the propulsion system is crucial for continuously monitoring performance, detecting potential issues, and enabling informed decision-making. This sub-function involves the integration of sensors throughout the system—monitoring critical parameters such as temperature, pressure, electrical output, and fuel levels. The data gathered is processed in real time, providing essential input to the system's control mechanisms for quick adjustments and fault detection.

Figure 27 illustrates how the data acquisition sub-function is integrated into the broader system operations, showing how various sensors feed into the control and monitoring architecture, enabling optimal system performance.

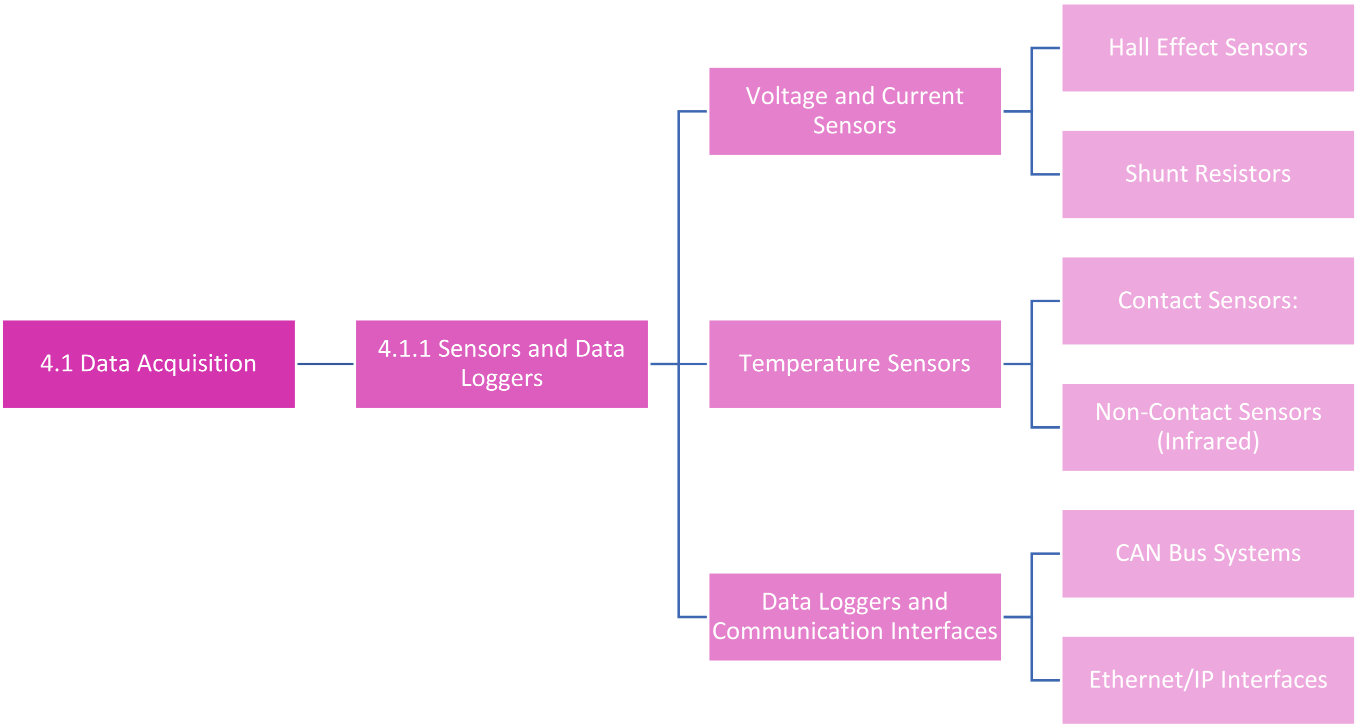

Figure 27 Functional breakdown of the Data Acquisition function in a HHEPS

4.1.1 Collect Real-Time Data from All Components (Sensors and Data Loggers)

The data acquisition system uses various sensors and data loggers to gather real-time information from the propulsion system.

4.1.1.1 Voltage and Current Sensor

Monitor the electrical parameters of the system to ensure stable operation.

- Hall Effect Sensors: Measure the magnetic field generated by current flow to determine the current in a conductor.
- Shunt Resistors: Measure voltage drop across a known resistance to calculate current.

4.1.1.2 Temperature Sensors

Monitor the temperature of critical components to prevent overheating and ensure optimal performance.

- Contact Sensors: Directly measure the temperature from component surfaces.
- Non-Contact Sensors (Infrared): Provide quick and accurate temperature readings without direct contact.

4.1.1.3 Data Loggers and Communication Interfaces

Devices that collect, store, and transmit data from the sensors to the central control unit.

- CAN Bus Systems: Standardized communication protocol for automotive applications, ensuring reliable data transfer.
- Ethernet/IP Interfaces: High-speed communication interfaces for transmitting large amounts of data.

4.2 System Control

Processing collected data and making real-time operational decisions are essential for maintaining optimal system performance and safety in a hydrogen hybrid-electric propulsion system. The central control unit processes data using control algorithms and decision-making logic, while operators interact through dashboard interfaces and control panels to ensure safe and efficient system operation.

Figure 28 illustrates the hierarchical breakdown of the system control architecture, highlighting the interaction between the control algorithms, PID control, and human-machine interfaces.

4.2.1 Process Data and Make Operational Decisions (Central Control Unit)

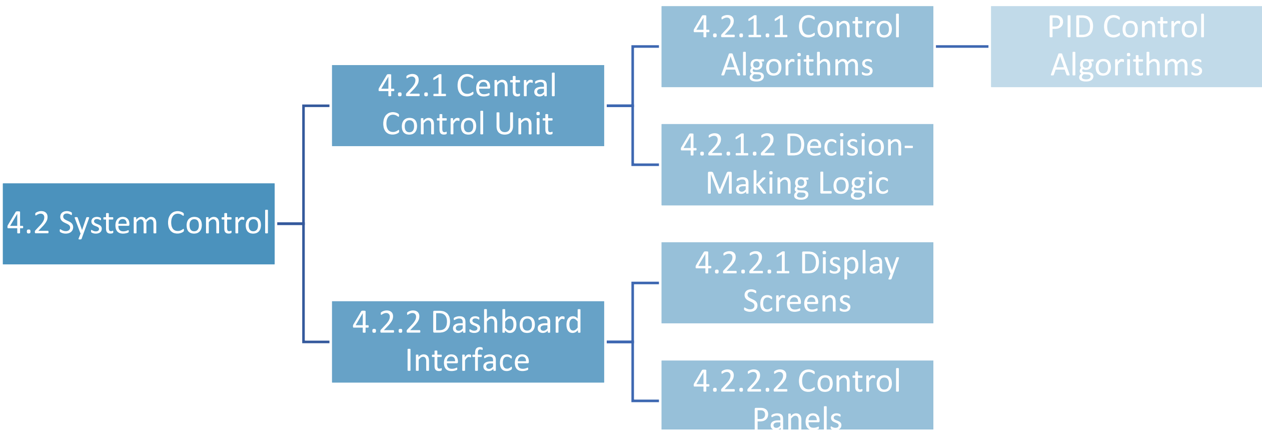

Figure 28 Functional breakdown of the system control function in a HHEPS

The central control unit (CCU) is the brain of the propulsion system, processing data and making real-time decisions to ensure optimal performance.

4.2.1.1Control Algorithms

Advanced algorithms are used to process data and control system operations.

- PID Control Algorithms: Proportional-Integral-Derivative controllers that adjust system parameters to maintain desired performance.

4.2.1.2 Decision-Making Logic

The logic used by the CCU to make real-time decisions based on data inputs and control algorithms.

4.2.2 Provide User Interface for System Status and Control (Dashboard Interface)

A user-friendly interface is essential for monitoring system status and manually controlling operations when necessary.

4.2.2.1 Display Screens

Provide real-time information about system performance, status, and any detected anomalies.

- LCD Displays: Standard displays that provide clear and detailed information.
- OLED Displays: Advanced displays that offer higher contrast and better visibility in various lighting conditions.

4.2.2.2 Control Panels

Allow operators to interact with the system, make adjustments, and respond to alerts.

- Touchscreen Interfaces: Provide intuitive and easy-to-use controls for adjusting system parameters and navigating through different screens.
- Physical Buttons and Switches: Provide manual control options for critical functions, ensuring reliability even in challenging conditions.

By focusing on these essential sub-functions and components, this section provides a clear understanding of how system operations are monitored and controlled in an H2 or LH2 hybrid electric propulsion system. Effective data acquisition and real-time control are crucial for maintaining the system's performance, safety, and reliability.

This chapter provided a detailed technical breakdown of the hydrogen hybrid-electric propulsion system, focusing on key aspects like power generation, thermal management, and system control. Through hierarchical decomposition of the functions, we examined how each sub-function interacts to ensure efficient and safe operation. In the next chapter, we will explore the system suppliers responsible for developing and providing these essential components, bridging the technical understanding with real-world applications and industry collaboration.

9. System supplier(s)

This chapter provides a concise table of potential suppliers for the key components of the hydrogen/liquid hydrogen hybrid-electric propulsion system. Each supplier was selected based on their expertise in relevant corresponding technologies, ensuring they are capable of supporting the functions and components outlined in Chapter 8.

The supplier list was developed by reviewing industry reports, existing hydrogen propulsion projects, and technical documentation. Cross-referencing suppliers from similar sectors like maritime and trucking ensured the list is sufficiently comprehensive and aligned with the system's requirements. This table helps bridge the technical analysis to practical sourcing options, illustrating the commercial viability of these systems

- PROVIDING EFFICIENT PROPULSION

1. Providing Efficient Propulsion					
system Component	Sub-Component	Suppliers	Description	Industries	Website
1.1 Generate Electrical Power					
Converting Hydrogen to Electricity (Fuel Cells)	Fuel Supply Management				
	Hydrogen Storage	Linde	Offers comprehensive solutions for hydrogen storage, including high-pressure gaseous and cryogenic liquid hydrogen storage.	Marine, Aviation, Automotive	Hydrogen | A Linde Company (linde-engineering.com)
		Air Liquide	Provides advanced cryogenic and compressed hydrogen storage solutions.	Marine, Aviation, Automotive	https://www.airliquide.com/
	Hydrogen Production	H2B2 Electrolysis Technologies	Involved in hydrogen production and storage solutions.	Maritime	H2B2 Electrolysis Technologies
		Nel Hydrogen	Specializes in hydrogen production, storage, and distribution solutions.	Marine, Aviation, Automotive	Nel Hydrogen | Proven technology. Trusted partner.
		Thyssenkrupp	Provides hydrogen storage solutions, including high-pressure tanks.	Marine, Aviation, Automotive	Products (thyssenkrupp.com)
	Fuel Delivery System	Swagelok	Provides a range of high-quality fittings, valves, and delivery systems suitable for hydrogen.	Marine, Aviation, Automotive	High-Quality Fluid System Solutions & Components | Swagelok
		Parker Hannifin	Offers robust and reliable hydrogen delivery components and systems.	Marine, Aviation, Automotive	Leading the Way in Innovations in Global Industries | Parker
Electrochemical Conversion					
	Fuel Cell Stack	Ballard Power Systems	Specializes in PEM fuel cell stacks used in various transportation applications.	Marine, Aviation, Automotive	Fuel Cell & Clean Energy Solutions | Ballard Power

		Plug Power	Provides advanced hydrogen fuel cell stacks for transportation and stationary applications.	Marine, Aviation, Automotive	Home - Plug Power
		Horizon Fuel Cell Technologies	Specializes in hydrogen fuel cell systems for various applications.	Marine, Aviation, Automotive	Horizon Fuel Cell Technologies
	Fuel Cell Controller	Bosch	Offers advanced control units for managing fuel cell operations.	Automotive, Aviation	Invented for life | Bosch Global
		Siemens	Provides control systems for fuel cells and other power systems.	Marine, Aviation, Automotive	Siemens
Waste Management					
	Water Management System	Veolia	Provides water management solutions, including systems for recycling and managing water produced by fuel cells.	Marine, Aviation, Automotive	Hydrogen production | Veolia Water Technologies
		GE Water & Process Technologies	Offers advanced water management and treatment systems.	Marine, Aviation, Automotive	GE Companies: Next Generation and Future | General Electric
	Thermal Management System	Grundfos	Manufactures high-efficiency coolant pumps and other components for thermal management.	Marine, Aviation, Automotive	Grundfos | Water is and has always been at the heart and soul of Grundfos. Our promise to the world is to respect, protect, and advance the flow of water.
		Honeywell	Provides advanced thermal management solutions, including cooling systems and components.	Aviation, Automotive	Honeywell - The Future Is What We Make It
1.2 Store Electrical Energy					
Energy Storage (Batteries)	Battery Pack	LG Chem	Leading supplier of high-energy-density lithium-ion battery packs.	Automotive, Aviation	Advanced Materials | By applicable industry | Product | LG Chem
		Panasonic	Provides high-performance lithium-ion and other battery technologies.	Automotive, Aviation	Lithium ion Batteries - Products - Panasonic Energy Co., Ltd.

	Battery Management System	Panasonic	Offers advanced battery management systems to monitor and manage battery performance.	Automotive, Aviation	Lithium ion Batteries - Products - Panasonic Energy Co., Ltd.
		Bosch	Supplies reliable battery management systems for various applications.	Automotive, Aviation	Powering the Present and Future with Battery Management Systems | Bosch Global Software Technologies PVT LTD (bosch-softwaretechnologies.com)
	Battery Monitoring System	Texas Instruments	Provides a range of sensors and monitoring solutions for battery systems.	Automotive, Aviation	Analog | Embedded processing | Semiconductor company | TI.com
		Analog Devices	Offers advanced battery monitoring and management solutions.	Automotive, Aviation	Mixed-signal and digital signal processing ICs | Analog Devices
1.3 Manage Power Distribution					
Power Conversion	Inverter	ABB	Offers high-efficiency inverters suitable for converting DC to AC power.	Marine, Aviation, Automotive	ABB Group. Leading digital technologies for industry — ABB Group (global.abb)
		SMA Solar Technology	Provides reliable and efficient inverter solutions.	Marine, Automotive	Willkommen bei SMA: Wechselrichter- & Photovoltaik-Lösungen | SMA Solar
	DC-DC Converter	Delta Electronics	Provides reliable DC-DC converters for various voltage levels.	Marine, Aviation, Automotive	Welcome to Delta (deltaww.com)
		Vicor Corporation	Specializes in high-performance DC-DC conversion solutions.	Automotive, Aviation	Modular Solutions For Your Power System | Vicor Corporation (vicorpower.com)
Power Flow Control	Power Control Unit	Bosch	Supplies advanced power control units for managing power distribution in automotive and aviation applications.	Automotive, Aviation	Invented for life | Bosch Global
		Siemens	Offers comprehensive power control and management systems.	Marine, Aviation, Automotive	Siemens
	Energy Management System	Siemens	Provides comprehensive energy management systems for optimizing power flow and efficiency.	Marine, Aviation, Automotive	Siemens

		Schneider Electric	Offers advanced energy management and automation solutions.	Marine, Aviation, Automotive	Schneider Electric Global | Global Specialist in Energy Management and Automation (se.com)
1.4 Providing Propulsion					
Generate Mechanical Power	Electric Motors	Siemens	Provides high-efficiency electric motors designed for aviation and other demanding applications.	Marine, Aviation, Automotive	Siemens
		YASA Motors	Specializes in compact and lightweight electric motors suitable for aviation.	Aviation, Automotive	YASA Limited | Axial Flux Motors for electric vehicles
	Motor Controller	Curtis Instruments	Offers advanced motor controllers for precise control and optimization of electric motors.	Automotive, Aviation	Curtis Instruments, Inc. | World leading electric vehicle technology, integrated EV systems and engineering support.
		Nidec Corporation	Provides reliable motor control solutions for various applications.	Automotive, Aviation	NIDEC CORPORATION

Table 9 Suppliers for Hydrogen/Liquid Hydrogen Hybrid Electric Propulsion System Components

❖ 2. Safety and Reliability

2. Safety and Reliability					
System Component	Sub-Component	Suppliers	Description	Industries	Website
2.1 Hydrogen Safety					
Hydrogen Sensors	Leak detection				
		Honeywell	Provides advanced hydrogen sensors for leak detection and safety monitoring.	Automotive, Aviation, Marine	Gas Leak & Flame Detection | Honeywell
	Gas sensors	Teledyne	Offers gas detection systems including hydrogen sensors.	Automotive, Aviation, Marine	Gas Detection Systems - Flame and gas detector, hazardous gas detection monitors | Teledyne GFD (teledynegasandflamedetection.com)
		MSA Safety	Specializes in gas detection sensors,	Automotive, Aviation, Marine	MSA Safety | Netherlands

			including hydrogen sensors.		
		Figaro	Offers a wide range of gas sensors including hydrogen sensors for various applications.	Automotive, Aviation, Marine	Gas Sensors / FIGARO Engineering inc. World leader in gassensing innovation (figarosensor.com)
Safety Valves and Relief Systems					
		Swagelok	Offers a wide range of safety valves and relief systems suitable for hydrogen.	Automotive, Aviation, Marine	High-Quality Fluid System Solutions & Components | Swagelok
		Parker Hannifin	Provides robust safety valves and relief systems for hydrogen applications.	Automotive, Aviation, Marine	Leider in bewegings- en besturingstechnologieën | Parker
		Emerson	Supplies safety valves and pressure relief systems designed for hydrogen applications.	Automotive, Aviation, Marine	Trusted Partner in Helping to Solve the Biggest Challenges of Modern Life | Emerson NL
2.2 Electrical Safety					
Electrical Monitoring System	Monitoring devices and systems				
		Siemens	Provides advanced electrical monitoring systems to ensure safety and reliability.	Automotive, Aviation, Marine	Siemens
		Schneider Electric	Offers comprehensive electrical monitoring and safety solutions.	Automotive, Aviation, Marine	Schneider Electric Global | Global Specialist in Energy Management and Automation (se.com)
		Rockwell Automation	Provides comprehensive electrical safety systems and	Automotive, Aviation, Marine	Smart Manufacturing Industrial Automation | Rockwell Automation

			monitoring solutions.		
		ABB	Supplies electrical monitoring systems for various industrial applications.	Automotive, Aviation, Marine	ABB Group. Leading digital technologies for industry — ABB Group (global.abb)
Circuit Breakers and Fuses	Circuit Breakers				
		Eaton	Supplies a range of circuit breakers and fuses for electrical safety.	Automotive, Aviation, Marine	Electrical and Industrial | Power Management Solutions | Eaton
		Littelfuse	Provides reliable fuses and circuit breakers for protecting electrical systems.	Automotive, Aviation, Marine	Circuit Protection, Fuses, Power Control & Sensing Solutions - Littelfuse
		Schneider Electric	Offers a comprehensive range of circuit breakers and fuses for safety applications.	Automotive, Aviation, Marine	Schneider Electric Global | Global Specialist in Energy Management and Automation (se.com)

Table 10 Suppliers for Hydrogen/Liquid Hydrogen Hybrid Electric Propulsion System Components - Safety and Reliability

- 3. THERMAL CONDITIONS MANAGEMENT

3. Thermal Conditions Management					
system Component	Sub-Component	Suppliers	Description	Industries	Website
3.1 Heat Dissipation					
Cooling System	3.1.1 Cooling System				
	Liquid Cooling Systems	Grundfos	Provides high-efficiency coolant pumps and other components for thermal management.	Marine, Aviation, Automotive	Grundfos | Water is and has always been at the heart and soul of Grundfos. Our promise to the world is to respect, protect, and advance the flow of water.
		Honeywell	Offers advanced cooling systems and components for thermal management.	Automotive, Aviation	Honeywell - The Future Is What We Make It

		Danfoss	Specializes in cooling solutions for various industrial applications.	Marine, Aviation, Automotive	Engineering Tomorrow | Danfoss
	Coolant Pumps	Grundfos	High-efficiency pumps for circulating coolant throughout the system.	Marine, Aviation, Automotive	Grundfos | Water is and has always been at the heart and soul of Grundfos. Our promise to the world is to respect, protect, and advance the flow of water.
		Johnson Controls	Provides a wide range of HVAC and thermal management solutions, particularly for automotive applications.	Marine, Aviation, Automotive	Johnson Controls | Johnson Controls
	Heat Exchangers	Alfa Laval	Specializes in heat exchangers for efficient thermal transfer.	Marine, Aviation, Automotive	Heat transfer, Separation, Fluid handling | Alfa Laval
		Kelvion	Offers advanced heat exchanger solutions for various applications.	Marine, Aviation, Automotive	Heat Exchangers: Cooling & Heating Systems | Kelvion
	Air Cooling Systems	Ebm-papst	Provides fans and blowers to enhance air circulation and heat dissipation.	Automotive, Aviation, Marine	ebm-papst – energy-saving fans and motors from the world market leader – engineering a better life (ebmpapst.com)
		Sunon	Offers a range of fans and blowers for efficient air cooling.	Automotive, Aviation, Marine	sunon.com/eu/index.aspx
Thermal Sensors					
	Temperature Sensors	Texas Instruments	Provides a range of sensors and monitoring solutions for thermal management.	Automotive, Aviation	Analog | Embedded processing | Semiconductor company | TI.com
		Sensirion	Offers advanced environmental and flow sensors for precise thermal management.	Automotive, Aviation, Marine	Home (sensirion.com)
		TE Connectivity	Supplies high-quality thermal sensors for various applications.	Automotive, Aviation, Marine	TE Connectivity: Connectors & Sensors for a Connected, Sustainable Future
	Thermal Management Controllers	Siemens	Provides control units for regulating thermal management systems.	Automotive, Aviation, Marine	Siemens

		Panasonic	Offers thermal management controllers to maintain optimal operating temperatures.	Automotive, Aviation	Panasonic - heating and cooling systems - United Kingdom
3.2 Climate Control					
Battery Climate Control					
	Battery Cooling Systems	LG Chem	Provides battery packs and climate control solutions to maintain optimal battery temperature.	Automotive, Aviation	LG Chem
		A123 Systems	Known for advanced lithium-ion battery solutions with integrated thermal management features	Automotive, Aviation, Marine	A123 Systems
		Panasonic	Offers battery management systems including climate control for batteries.	Automotive, Aviation	Panasonic - heating and cooling systems - United Kingdom
		Bosch	Supplies battery management and climate control systems to ensure battery safety and performance.	Automotive, Aviation	Invented for life | Bosch Global
	Battery Heating Systems	Valeo	Specializes in thermal management systems including climate control for automotive batteries.	Automotive	Valeo - Smart technology for smarter mobility
		Webasto	Provides battery heating solutions to ensure optimal performance in cold conditions.	Automotive, Aviation	Webasto Group - Feel the Drive

Table 11 Suppliers for Hydrogen/Liquid Hydrogen Hybrid Electric Propulsion System Components - Thermal Conditions Management

- 4. System Operations Monitor and Control

4. System Operations Monitor and Control					
System Component	Sub-Component	Suppliers	Description	Industries	Website
4.1 Data Acquisition					
	Sensors				

Sensors and Data Loggers		Honeywell	Provides a wide range of sensors for monitoring various system parameters.	Automotive, Aviation, Marine	Honeywell - The Future Is What We Make It
		Bosch	Offers advanced sensors for data acquisition and monitoring in vehicles.	Automotive, Aviation	https://www.bosch.com
		Texas Instruments	Supplies sensors for temperature, pressure, and other critical parameters.	Automotive, Aviation, Marine	Analog | Embedded processing | Semiconductor company | TI.com
Data Loggers		National Instruments	Provides high-performance data logging solutions for various applications.	Automotive, Aviation, Marine	Test and Measurement Systems, a part of Emerson - NI
		HIOKI	Specializes in advanced data loggers for precise data acquisition.	Automotive, Aviation, Marine	Hioki : Corporate | World-class Test & Measurement Equipment
		Yokogawa	Known for advanced data acquisition systems and industrial automation solutions		Yokogawa Electric Corporation
		Fluke	Offers reliable data loggers and monitoring tools for industrial applications.	Automotive, Aviation, Marine	Fluke Corporation: Fluke Electronics, Calibration and Networks
4.2 System Control					
Control unit and dashboard interface		Siemens	Provides advanced control units for managing and monitoring system operations.	Automotive, Aviation, Marine	Siemens
		Bosch	Supplies central control units for integrated system control and monitoring.	Automotive, Aviation	https://www.bosch.com
		Schneider Electric	Offers comprehensive control units and automation solutions.	Automotive, Aviation, Marine	Schneider Electric Global | Global Specialist in Energy Management and Automation (se.com)
		Honeywell	Provides control systems for managing complex operations in various industries.	Automotive, Aviation, Marine	Honeywell - The Future Is What We Make It

Table 12 Suppliers for Hydrogen/Liquid Hydrogen Hybrid Electric Propulsion System Components - System Operations Monitor and Control

Chapter 10: Case studies

This chapter presents several case studies of hydrogen-based hybrid-electric propulsion systems across different sectors, demonstrating real-world applications of the technologies discussed in previous chapters. The case studies, including:

- Maritime
    - SF-Breeze
    - Water-Go-Round,
    - MF Hydra
- Truck
    - Hyundai Xcient
    - Nikola Tre

Serving as practical examples of how the concepts of hydrogen storage, power distribution, safety management, and system control are applied in diverse environments. By analysing these cases, we can better understand the challenges, advancements, and opportunities in the integration of hydrogen propulsion technologies.

The structure of the case studies follows a consistent template, focusing on key aspects such as power requirements, safety and reliability, and operational performance. This template was developed using a combination of industry reports and academic resources to ensure a comprehensive analysis. Each case study is examined through the lens of the system functions and components outlined in earlier chapters, providing a practical demonstration of how these theoretical concepts work in real-world settings.

By analysing these case studies, we bridge the technical analysis and supplier information with real-world examples, offering valuable insights into the practical implementation of hydrogen propulsion systems. These case studies not only validate the technical discussions from earlier chapters but also highlight potential areas for future development and cross-sectoral learning.

10.1.1 Water-Go-Round: Pioneering Hydrogen Fuel Cell Technology

Objectives

The Water-Go-Round project sought to prove that hydrogen fuel cells could be a viable, clean-energy alternative for the maritime industry. The goal was to build the first hydrogen fuel cell-powered ferry that operated with zero emissions while maintaining the speed, range, and capacity necessary for commercial viability. The project aligned with California's commitment to reducing greenhouse gas emissions.

Solutions

The Water-Go-Round project implemented hydrogen fuel cell technology as the primary source of power for the ferry. Hydrogen fuel cells produce electricity by combining hydrogen and oxygen in an electrochemical reaction, with water being the only byproduct. This power system was complemented by lithium-ion battery packs to store excess energy and provide additional power during peak demand periods.

Key components included:

- Hydrogenic fuel cells for clean energy generation.
- XALT Energy lithium-ion batteries for energy storage.
- Hexagon Composites hydrogen storage tanks.
- Bae Systems propulsion systems to integrate and optimize power from fuel cells and batteries.

The ferry was built by Bay Ship & Yacht and underwent sea trials to validate its performance in real-world conditions.

Industry: Maritime Transport

Product: Hydrogen Fuel Cell Ferry

location: California

Goal: To develop the world's first commercial hydrogen fuel cell-powered ferry, reducing emissions and leading the transition to clean energy in maritime transport.

"For over 10 years, we have been committed to developing new technology that benefits the environment while maintaining commercial efficiency. Water-Go-Round exemplifies our vision for a sustainable maritime future."

Joseph W. Pratt, CEO, Golden Gate Zero Emission Marine

Benefits and Results

The Water-Go-Round project has significantly advanced hydrogen fuel cell technology in maritime transport, offering substantial environmental and operational benefits., including:

- Environmental Sustainability: The ferry set a new standard for reducing emissions in maritime transport, aligning with global climate goals and regional regulations like those in California.
  - The ferry's zero-emission design contributes significantly to improving air quality in coastal and port areas, helping meet California's stringent air quality standards. The ferry prevents approximately 750 metric tons of CO_2 from entering the atmosphere annually.
- Operational Cost Efficiency: While the initial investment in hydrogen fuel cells is high, the long-term savings in fuel and maintenance costs make hydrogen-powered vessels economically viable. Hydrogen fuel cells have fewer moving parts than diesel engines, reducing the frequency and cost of repairs.
  - The ferry achieved a speed of 22 knots and demonstrated a range of 300 nautical miles per refueling. This performance validated hydrogen fuel cells as a reliable power source for commercial ferry operations.
- Scalability: The technology demonstrated by the Water-Go-Round is scalable and can be applied to a wide range of vessel types, including cargo ships and other passenger vessels. This opens the door for widespread adoption of zero-emission maritime transport.
- Zero Emissions: The ferry successfully operated with zero CO_2, NO_x, or particulate matter emissions, highlighting the effectiveness of hydrogen fuel cell technology in eliminating greenhouse gas emissions from maritime operations

Key system specification

- Primary Propulsion: Hydrogen Fuel Cells
- Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells.
- Power Output: 3 x 120 kW fuel cells, totaling 360 kW.
- Secondary Power Source: Battery System
- Battery Capacity: 100 kWh lithium-ion battery pack
- Electric Motor Output: 2 x 300 kW
- Hydrogen Type: Compressed Hydrogen (H_2)
- Storage Capacity: 250 kg of hydrogen
- Storage Pressure: Stored at 250 bar (3,600 psi)
- Speed: Achieves speeds of around 22 knots
- Range: 300 nautical miles per refueling.

More detailed specifications are available in Appendix X

At a Glance

Challenges

- High upfront cost of hydrogen fuel cell systems.
- Limited hydrogen refuelling infrastructure.
- Ensuring operational efficiency under varying maritime conditions.

Motivation of choice

- This case study focuses on using hydrogen for urban water transportation, an area increasingly relevant due to urbanization and the need for sustainable solutions in congested areas. Understanding this model is crucial for exploring similar applications in urban air mobility.

- It showcases innovative uses of hydrogen technology in everyday services, providing insights into public acceptance and operational challenges that can be translated to aviation.

10.1.2 SF-BREEZE - Hydrogen Fuel Cell High-Speed Passenger Ferry

Figure 29 SF-Breeze ferry (SAN FRANCISCO BAY HYDROGEN FUEL CELL POWERED ELECTRIC FERRY FERRIES ZERO CARBON SF BREEZE WATER GO ROUND, n.d.)

Industry: Maritime Transport

Product: Hydrogen Fuel Cell-Powered High-Speed Ferry

location: San Francisco Bay Area, California

Goal: To develop and demonstrate a high-speed, zero-emission hydrogen fuel cell ferry that meets the requirements of commercial passenger transportation.

Objectives

The SF-BREEZE (San Francisco Bay Renewable Energy Electric Vessel with Zero Emissions) project set out to design and build a high-speed hydrogen fuel cell ferry capable of servicing passengers across the San Francisco Bay. The main objectives were to:

- Zero Emissions: Eliminate greenhouse gas emissions by using hydrogen fuel cells.
- High Performance: Develop a ferry capable of high-speed operations, comparable to traditional diesel ferries.
- Environmental Compliance: Meet stringent California regulations for emission reductions and air quality improvement.
- Scalable Technology: Prove that hydrogen fuel cells can be scaled for larger maritime applications, such as commercial ferries and cargo vessels.

Solutions

The SF-BREEZE ferry was designed to use Proton Exchange Membrane (PEM) hydrogen fuel cells for propulsion. The ferry concept integrated hydrogen storage, fuel cell power, and electric propulsion in a single, high-performance vessel that could achieve high speeds while carrying a significant passenger load (Sandia National Laboratories, 2016).

- Hydrogen Fuel Cells: The PEM fuel cells were supplied by Proton OnSite, designed to convert hydrogen into electricity, producing only water and heat as byproducts.
- Hydrogen Storage: Compressed hydrogen storage tanks, provided by Hexagon Lincoln, allowed for the safe and efficient storage of high-pressure hydrogen, ensuring enough fuel for the ferry's intended range and operational needs.
- Propulsion System: The ferry employed an electric propulsion system, integrating power from the fuel cells to drive electric motors that ensured efficient and quiet operation. The design allowed for high-speed service, similar to conventional diesel-powered ferries.

The SF-BREEZE project shows that high-speed hydrogen fuel cell vessels are not just a possibility, but a reality. This technology can compete with diesel ferries on every front, while offering the advantage of zero emissions."

— Randy K. Iwasaki, Executive Director, Contra Costa Transportation Authority

- Energy Efficiency: The ferry's hybrid system, combining fuel cells and battery storage, optimized energy use. Batteries helped to store excess power generated by the fuel cells and provided additional energy during peak demand, such as when accelerating or traveling at top speed.

Benefits and Results

- The ferry offers zero-emission operations, drastically reducing greenhouse gas emissions and air pollution, directly improving the air quality in the San Francisco Bay area.
- High-speed performance comparable to conventional diesel ferries ensures that passengers do not experience any trade-offs between speed and environmental sustainability. The ferry achieves a top speed of 35 knots, making it competitive in commercial maritime services.
- Scalability and innovation: The project demonstrates that hydrogen fuel cell technology can be scaled for larger vessels and offers a clean alternative to diesel-powered ferries, paving the way for future innovations in the maritime industry.

Key system specifications

- Primary Propulsion: Hydrogen Fuel Cells
- Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells
- Power Output: 4.92 MW total from hydrogen fuel cells (equivalent to approximately 6,600 horsepower)
- Secondary Power Source: Battery System (Conceptually Possible)
- Electric Motor Output: Approximately 4.92 MW, matching the fuel cell power output for high-speed ferry operations.
- Hydrogen Type: Compressed Hydrogen Gas (H2)
- Storage Capacity: 1,200 kg of hydrogen
- Storage Pressure: Stored at 350 bar (5,000 psi)
- Speed: Achieves a speed of approximately 35 knots
- Range: can travel up to 100 nautical miles

More detailed specifications are available in Appendix C1

At a Glance

Challenges

- Ensuring hydrogen fuel cell technology could meet the performance standards required for high-speed ferries.
- Developing hydrogen refuelling infrastructure to support the ferry's operational needs.
- Addressing the high initial costs associated with hydrogen fuel cells and their integration into maritime vessels.

Motivation of choice

- This hydrogen fuel cell ferry operates in a real-world context, providing valuable data on operational efficiency, reliability, and performance. These metrics are critical for assessing the viability of similar technologies in aviation.

- The operational range of SF-BREEZE offers benchmarks for regional aviation, particularly for short-haul flights. Analyzing this ferry's performance aids in understanding how to adapt technology for the aviation sector.

10.1.3 MF Hydra - World’s First Hydrogen-Powered Ferry

Figure 30 MF-Hydra ferry (CleanTech, 2023)

Industry: Maritime Transportation

Product: Hydrogen-Powered Ferry

Location: Norway

Goal: To develop and operate the world’s first liquid hydrogen-powered ferry for regular commercial use, contributing to Norway’s push for zero-emission maritime transport.

Objectives

The MF Hydra, developed by Norled, is an innovative hydrogen-powered ferry that aims to lead the maritime industry toward a sustainable, zero-emission future. The main objectives of the project were to:

- Zero Emissions: Develop the world’s first liquid hydrogen-powered ferry, eliminating greenhouse gas emissions from ferry operations.
- Scalability: Demonstrate that hydrogen fuel technology can be scaled for regular commercial maritime operations.
- Compliance with Regulations: Meet stringent environmental regulations imposed by the Norwegian government and international maritime organizations, including the International Maritime Organization (IMO).

Solutions

The MF Hydra is powered by liquid hydrogen fuel cells, which provide a sustainable and scalable solution for maritime transport. The ferry's hybrid hydrogen system allows for smooth and efficient operations while ensuring zero emissions.

- Hydrogen Fuel Cells: The ferry utilizes Ballard Power Systems hydrogen fuel cells that convert liquid hydrogen into electricity, providing clean energy for the vessel's propulsion. The fuel cells generate electricity without emitting harmful pollutants, with water being the only byproduct.
- Liquid Hydrogen Storage: Linde Engineering provided liquid hydrogen storage tanks that allow for safe and efficient storage of hydrogen at low temperatures. This ensures that the ferry has sufficient fuel for its voyages and can meet operational demands.
- Electric Propulsion System: The ferry integrates Corvus Energy battery packs to supplement the fuel cells, optimizing energy use during peak power demands. The electric motors provide reliable and efficient propulsion for ferry operations.
- Energy Efficiency: The hybrid system combines hydrogen fuel cells and battery packs to maximize energy efficiency and reduce operating costs over time, while ensuring that the ferry can meet its high-performance standards.

"The MF Hydra is not just a ferry, it’s a game-changer in the fight against climate change. This project proves that hydrogen fuel cells can power large commercial vessels without sacrificing performance, paving the way for a cleaner maritime industry."

— Hege Økland, CEO of Norled.

Benefits and Results

- Zero Emissions: The ferry operates with zero emissions, significantly contributing to Norway's ambitious goal of reducing its carbon footprint in the maritime sector. This achievement showcases the potential of hydrogen to replace fossil fuels in the transportation industry.
- Operational Viability: The ferry is capable of transporting 300 passengers and 80 cars, proving that hydrogen technology can power large commercial vessels without compromising on capacity or performance. Its successful deployment shows that hydrogen-powered vessels are viable for regular ferry services.
- Scalability and Innovation: The success of the MF Hydra serves as a model for further adoption of hydrogen in maritime transport, inspiring future developments in zero-emission vessels worldwide. The ferry's design can be replicated or adapted for other maritime applications, including larger vessels and cargo ships.

Key system specification

The MF Hydra project achieved significant milestones in advancing hydrogen fuel technology for the maritime industry:

- Primary Propulsion: Hydrogen Fuel Cells
- Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells
- Power Output: 2 x 200 kW fuel cells, totalling 400 kW
- Secondary Power Source: Battery System
- Battery Capacity: 1.36 MWh lithium-ion battery pack
- Hydrogen Type: Liquid Hydrogen (LH2)
- Storage Capacity: The MF Hydra is equipped with an 80 m³ liquid hydrogen tank, which can store approximately 70 kg of liquid hydrogen
- Storage Pressure: Stored at cryogenic temperatures to maintain liquid state.
- Speed: 9 knots

More detailed specifications are available in Appendix C2

At a Glance

Challenges

- Ensuring the safe storage and handling of liquid hydrogen in a maritime environment.
- Developing hydrogen refuelling infrastructure to support regular ferry operations.
- Meeting regulatory requirements and gaining approval from maritime authorities for hydrogen use.

Motivation of choice

- MF Hydra serves as an excellent example of a hybrid propulsion system utilizing hydrogen fuel cells. This technology is directly applicable to aviation, as it highlights the integration of different power sources to optimize efficiency

- The focus on zero-emission operations aligns with global sustainability goals in transportation. Studying this case helps understand how hydrogen solutions can significantly reduce emissions in aviation.

10.1.4 Comparison of Hydrogen-Powered Hybrid Ferries: MF Hydra, Water-Go-Round, and SF-BREEZE

The transition to hydrogen-powered vessels is an essential step toward achieving sustainability in maritime transport. The MF Hydra, Water-Go-Round, and SF-BREEZE are three notable examples of hydrogen-powered hybrid ferries, each designed to meet the unique demands of their operational environments. This comparison highlights their specifications, operational capabilities, and technological innovations, showcasing the diverse applications of hydrogen fuel in maritime transport.

Aspect	MF Hydra	Water-Go-Round	SF-BREEZE
Type	Passenger and Car Ferry	Passenger Ferry	High-Speed Passenger Ferry (Concept)
Owner/Operator	Norled (Norway)	Golden Gate Zero Emission Marine (USA)	U.S. Department of Transportation / Sandia National Laboratories (USA)
Location of Operation	Norwegian Fjords	San Francisco Bay, USA	San Francisco Bay, USA
Passenger Capacity	300 passengers	84 passengers (reconfigurable)	150 passengers
Vehicle Capacity	80 cars	N/A	N/A
Primary Propulsion	Hydrogen Fuel Cells (PEM)	Hydrogen Fuel Cells (PEM)	Hydrogen Fuel Cells (PEM)
Power Output (Fuel Cells)	2 x 200 kW (400 kW total)	3 x 120 kW (360 kW total)	4.92 MW total (approx. 6,600 horsepower)
Battery Capacity	1.36 MWh	100 kWh	Not specified (conceptual, possible integration in future iterations)
Electric Motor Output	2 x 410 kW	2 x 300 kW (600 kW total)	4.92 MW
Hydrogen Storage Type	Liquid Hydrogen (LH2)	Compressed Hydrogen (H2)	Compressed Hydrogen (H2)
Hydrogen Storage Capacity	Approx. 80 cubic meters (LH2) (70.85 kg/m³)	250 kg (compressed at 250 bar)	1,200 kg (compressed at 350 bar)
Storage Pressure	Stored as liquid at cryogenic temperatures	250 bar (3,600 psi)	350 bar (5,000 psi)
Range	Several days (depending on operation)	1-2 days (depending on operation)	Approx. 100 nautical miles
Speed	Approx. 10 knots	Cruising: 12 knots, Top Speed: 22 knots	Designed for up to 35 knots (high-speed)
Operational Focus	Long-haul ferry services in fjords	Short-haul ferry services in urban bay area	High-speed passenger ferry routes in the San Francisco Bay Area

Refueling Infrastructure	Developing LH2 bunkering in Norway	Compressed hydrogen refueling stations in California	Planned hydrogen bunkering infrastructure for compressed hydrogen at Bay Area ports
Emissions	Zero emissions (water vapor only)	Zero emissions (water vapor only)	Zero emissions (water vapor only)
Safety Systems	Leak detection, fire suppression, emergency venting	Leak detection, fire suppression, emergency venting	Leak detection, fire suppression, emergency venting
Pioneering Technology	First liquid hydrogen ferry in the world	First hydrogen-powered ferry in the USA	Concept designed to showcase scalability of hydrogen fuel cells for high-speed ferries
Technology Demonstrated	Viability of LH2 for long-haul maritime transport	Viability of compressed hydrogen for short-haul passenger ferries	Conceptual model to demonstrate high-power hydrogen applications for fast ferries

Table 13 Comparison of Hydrogen-Powered Hybrid Ferries

The MF Hydra, Water-Go-Round, and SF-BREEZE illustrate the diverse applications of hydrogen-powered hybrid ferries, each tailored to specific operational environments. The MF Hydra is optimized for long-haul services utilizing liquid hydrogen, while the Water-Go-Round focuses on short-haul operations with compressed hydrogen. The SF-BREEZE serves as a conceptual design aimed at showcasing the scalability of hydrogen fuel for high-speed ferries. Collectively, these projects demonstrate the flexibility of hydrogen as a zero-emission fuel source and lay the groundwork for further advancements in sustainable maritime transport and its potential applicability in other sectors, including aviation.

10.2 Truck case studies

10.2.1 Hyundai Xcient Fuel Cell: Leading the Charge in Zero-Emission Heavy-Duty Transportation

Figure 31 (Hyundai Motor Puts XCIENT Fuel Cell Electric Trucks into Commercial Fleet Operation in California, n.d.)

Objectives

The Hyundai Xcient Fuel Cell truck is a groundbreaking initiative aimed at transforming heavy-duty transportation through hydrogen fuel cell technology. As part of Hyundai's vision for a zero-emission future, the primary objectives of the Xcient Fuel Cell truck project were:

Zero Emissions: Reduce carbon emissions in the logistics and transport industry by replacing diesel-powered trucks with hydrogen fuel cell alternatives.

Commercial Viability: Demonstrate that hydrogen fuel cell trucks can meet the demands of the commercial trucking sector, particularly for long-haul transportation.

Global Leadership in Hydrogen Technology: Position Hyundai as a leader in hydrogen fuel cell technology for heavy-duty vehicles, paving the way for wider adoption globally.

Infrastructure Development: Collaborate with governments and industries to establish hydrogen refuelling infrastructure to support the widespread deployment of hydrogen trucks. (*XCIENT Fuel Cell Truck | Hydrogen Truck | Hyundai Motor Company*, n.d.)

Solutions

The Hyundai Xcient Fuel Cell truck combines innovative hydrogen fuel cell technology with the performance and durability required for heavy-duty transport. The project is a pioneering solution that leverages hydrogen as a clean, efficient, and scalable energy source for long-haul trucks.

Hydrogen Fuel Cells: The Xcient truck is powered by two 190-kilowatt hydrogen fuel cell systems that generate electricity by combining hydrogen and oxygen, with water as the only byproduct. This eliminates harmful emissions and provides a clean energy alternative to diesel engines.

Hydrogen Storage: The truck features seven high-pressure hydrogen tanks, capable of storing a total of 32 kg of hydrogen, giving it a driving range of approximately 400 kilometers (around 250 miles) on a single charge, making it suitable for long-haul transport.

Industry: Heavy-Duty Transportation

Product: Hydrogen Fuel Cell-Powered Truck to create the world's first mass-produced hydrogen-powered heavy-duty truck, aimed at reducing emissions in the transportation and logistics sectors.

Location: Switzerland (initial deployment)

Goal: To create the world's first mass-produced hydrogen-powered heavy-duty truck, aimed at reducing emissions in the transportation and logistics sectors.

"The Hyundai Xcient Fuel Cell truck represents the next step in our journey toward a zero-emission future. With its powerful hydrogen fuel cell system, the Xcient is showing the world that clean transport is possible, even in heavy-duty applications."

— In Cheol Lee, Executive Vice President and Head of Commercial Vehicle Division

Electric Propulsion System: The truck's electric propulsion system, powered by fuel cells, ensures smooth, quiet operation while delivering the necessary torque and power for carrying heavy loads.

Efficiency and Energy Use: The integration of fuel cells and electric systems ensures that the truck maintains high energy efficiency. The vehicle is also equipped with energy recovery systems, such as regenerative braking, to maximize efficiency during operations.

Benefits and results

- Zero-Emission Transport: The trucks eliminate CO2, NOx, and particulate emissions, making them environmentally friendly compared to traditional diesel trucks. Hyundai estimates that over 1,000 metric tons of CO2 have been avoided in Switzerland since their deployment.
- The truck's 400-kilometer range on a single refuelling demonstrates that hydrogen fuel cells can meet the operational demands of long-haul and regional transport, making it a viable alternative to diesel trucks for fleet operators.
- Commercial viability and scalability: Future Growth: Hyundai aims to deploy 1,600 Xcient trucks by 2025, with plans to expand into other markets, including Europe, North America, and Asia. The success of this project paves the way for the global adoption of hydrogen fuel cells in heavy-duty transport.

Key Specifications

- Primary Propulsion: Hydrogen Fuel Cells
- Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells
- Power Output: 2 x 90 kW fuel cells, totaling 180 kW
- Secondary Power Source: Battery System
- Battery Capacity: 72-kWh
- Electric Motor: A single 350 kW electric motor
- Hydrogen Type: Gaseous Hydrogen (GH2)
- Storage Capacity: 31 kg of GH2
- Storage Pressure: 350 bar

More detailed specifications are available in Appendix C3

At a Glance

Challenges

- High costs associated with hydrogen fuel cells and hydrogen infrastructure.
- Establishing a reliable network of hydrogen refuelling stations to support the deployment of hydrogen-powered trucks on a large scale.
- Convincing fleet operators and logistics companies to invest in hydrogen-powered trucks, given the high initial capital expenditure.

Motivation of choice

- As a commercially deployed heavy-duty vehicle, the Hyundai Xcient represents a successful implementation of hydrogen fuel cell technology. This case provides insights into market readiness and the infrastructure required to support hydrogen systems, which are vital considerations for aviation.

- The performance data from this case study offers a benchmark for evaluating the potential of hydrogen fuel cells in larger aircraft, helping to inform design decisions and efficiency targets

10.2.2 Nikola Tre Fuel Cell Electric Vehicle (FCEV): A Hydrogen-Powered Solution for Long-Haul Transportation

Industry: Heavy-Duty Transportation

Product: Hydrogen Fuel Cell-Powered Truck

Location: United States (with plans to expand into Europe)

Goal: To develop a zero-emission hydrogen-powered truck that can meet the needs of long-haul logistics operators.

Objectives

The Nikola Tre FCEV is part of Nikola Motors' vision to revolutionize heavy-duty trucking by transitioning away from diesel-powered engines to clean hydrogen fuel cells. The primary objectives for the Tre FCEV were:

Zero Emissions: Create a heavy-duty truck powered by hydrogen fuel cells to reduce greenhouse gas emissions in long-haul transportation.

Operational Viability: Ensure the truck meets the performance and range requirements for logistics companies, enabling long-distance travel with minimal refueling.

Scalability: Develop a commercially viable truck that can be mass-produced and deployed globally, particularly in Europe and North America, where emission regulations are becoming stricter.

Partnerships for Hydrogen Infrastructure: Collaborate with industry partners to build the necessary hydrogen refueling infrastructure for a network of hydrogen-powered trucks.

solution

The Nikola Tre FCEV truck is designed to offer zero-emission long-haul capabilities using hydrogen fuel cell technology. The truck is a powerful competitor in the heavy-duty sector, offering long-range travel, fast refueling times, and zero emissions.

Hydrogen Fuel Cells: The Nikola Tre FCEV uses a high-capacity hydrogen fuel cell system that generates electricity through an electrochemical process, with water vapor as the only emission. This fuel cell technology enables the truck to meet the performance requirements for heavy loads.

Hydrogen Storage: The truck is equipped with high-pressure hydrogen storage tanks, providing a driving range of up to 500 miles (800 kilometers) per refueling, making it competitive with diesel trucks for long-distance routes.

Electric Propulsion System: The electric propulsion system provides torque and power required for the heavy-duty vehicle, ensuring smooth and quiet operation with performance comparable to traditional diesel engines.

Refueling Time: Hydrogen refueling takes approximately 15-20 minutes, significantly shorter than the time it takes to recharge battery-electric trucks, making the Tre FCEV more operationally efficient for long-haul routes (Motor, 2024).

"The Nikola Tre FCEV is designed to meet the needs of long-haul transportation, providing a clean and efficient solution that can compete with diesel trucks. With zero emissions and a range of up to 500 miles, this truck represents the future of sustainable logistics."

— Mark Russell, CEO of Nikola Motors.

Benefits and Results

Since its debut, the Nikola Tre FCEV has demonstrated several key results:

- Zero-Emission Performance: The truck eliminates greenhouse gas emissions, offering a clean alternative to diesel-powered trucks for long-haul transport.
- Range and Refueling Efficiency: The truck's 500-mile range and short refueling time offer significant advantages over battery-electric trucks for long-haul applications, making it more practical for fleet operators focused on uptime and efficiency.
- Partnerships and Future Expansion: The truck is part of a larger ecosystem of hydrogen infrastructure development, Nikola Motors has partnered with Iveco in Europe and is collaborating with energy companies like Total and Shell to build hydrogen refueling stations. These partnerships are crucial to expanding hydrogen infrastructure and supporting the wider deployment of hydrogen-powered trucks.

Key system specifications

- Primary Propulsion: Hydrogen Fuel Cells
- Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells
- Power Output: 200-kW fuel cell
- Secondary Power Source: Battery System
- Battery Capacity: 164-kWh lithium-ion battery
- Electric Motor: 400 kW
- Hydrogen Type: Gaseous Hydrogen (GH2)
- Storage Capacity: 70 kg of GH2
- Storage Pressure: 700 bar

More detailed specifications are available in Appendix C4

At a Glance

Challenges

- High cost of hydrogen fuel cell systems and building refuelling infrastructure.
- Overcoming the skepticism in the logistics industry regarding hydrogen's viability and reliability.
- Establishing a hydrogen refueling network that can support widespread deployment of hydrogen trucks.

Motivation of choice

- Nikola Tre demonstrates the potential of hydrogen fuel cells in the heavy-duty sector, emphasizing performance and efficiency. This showcases the adaptability of hydrogen technology, which can inspire similar developments in aviation.
- It provides valuable insights into market dynamics, consumer acceptance, and the economic aspects of adopting hydrogen solutions. Understanding these factors is essential for introducing hydrogen-powered aircraft successfully.

10.2.3 Comparison of Hyundai Xcient Fuel Cell Truck vs. Nikola Tre Fuel Cell Electric Vehicle (FCEV)

The comparison between the **Hyundai Xcient Fuel Cell Truck** and the **Nikola Tre Fuel Cell Electric Vehicle (FCEV)** summarizes key insights from their respective case studies, highlighting advancements and the competitive landscape within the heavy-duty hydrogen truck sector. Both vehicles represent significant strides toward sustainable transport solutions, focusing on hydrogen fuel as a clean alternative to traditional fossil fuels. While they cater to the heavy-duty market, their specifications, capabilities, and operational focuses differ in various aspects. This comparison provides an overview of their features, strengths, and potential applications, enabling stakeholders to make informed decisions in the evolving landscape of hydrogen-powered transportation.

Feature	Hyundai Xcient Fuel Cell Truck	Nikola Tre Fuel Cell Electric Vehicle (FCEV)	Key Differences/Similarities
Manufacturer	Hyundai Motor Company	Nikola Motor	Both are hydrogen truck manufacturers; Hyundai has a more established market presence.
Vehicle Class	Heavy-duty truck (long-haul, regional delivery)	Heavy-duty truck (regional, medium haul)	Both target the heavy-duty truck sector, but Nikola focuses more on regional hauls.
Gross Vehicle Weight (GVW)	34,000 kg (34 tons)	37,200 kg (82,000 lbs)	Nikola Tre has a slightly higher GVW, allowing for higher payloads. The **Nikola Tre FCEV** has a longer range than the later.
Payload Capacity	22 tons	22 to 24 tons	Similar payload capacities, with Nikola Tre offering slightly more depending on configuration.
Driving Range	400 to 500 km	Up to 500 miles (approximately 805 km)	Nikola Tre offers a competitive range, with an upper limit based on conditions.
Fuel	Hydrogen (compressed, gaseous)	Hydrogen (compressed, gaseous)	Both trucks use compressed hydrogen.
Hydrogen Storage Capacity	31 kg	Approximately 70 kg	Nikola Tre has significantly more hydrogen storage capacity, contributing to its extended range.
Refueling Time	8 to 20 minutes	Less than 20 minutes	Similar refueling times despite Nikola Tre's larger hydrogen tanks.
Fuel Cell System	2 x 90 kW PEM fuel cell stacks (180 kW total)	200 kW fuel cell power	Nikola Tre offers more powerful fuel cells, providing higher energy output.
Electric Motor	350 kW motor	536 HP (400 kW) electric motor	Nikola Tre has a more powerful motor, supporting its higher payload capacity and longer-range operations.
Energy Storage (Battery)	72 kWh lithium-ion battery	164 kWh lithium-ion battery	Nikola Tre has a larger battery pack, allowing for more efficient energy management.
Hydrogen Tank Pressure	350 bars	700 bars	Nikola Tre uses higher-pressure tanks, allowing for greater hydrogen storage.
Deployment	Available in Europe (since 2020)	Available in Europe and North America (since 2023)	Hyundai Xcient has been operational longer, while Nikola Tre is newer to the market.

Table 14 Comparison of Hyundai Xcient Fuel Cell Truck vs. Nikola Tre Fuel Cell Electric Vehicle (FCEV)

10.3 Overall analysis of the case studies

This section provides a comparative analysis of hydrogen-powered systems in maritime and trucking sectors, focusing on their efficiency, operational range, technology readiness levels (TRL), and applicability to aviation. TRL is a systematic metric used to assess the maturity of a technology, ranging from initial research (TRL 1) to fully operational systems ready for commercial deployment (TRL 9). The relevant system specifications for each case study have already been detailed in Table 9 (Maritime Case Studies) and Table 10 (Truck Sector). Therefore, this analysis will concentrate on the aspects outlined in the tables, assessing the implications of each system's performance and features for potential adaptation to aviation, as discussed later in Chapter 9: Technology Translation.

Case Study	Efficiency	Operational Range	Technology Readiness Level (TRL)	Aviation Applicability
The Water Go Round	Moderate efficiency due to the urban environment; likely lower than larger vessels.	Limited by urban routes, typically under 50 km per trip.	TRL 5-6 (Prototype)	Adaptable for short urban air mobility; insights on urban logistics.
MF Hydra	High efficiency with a hybrid system, optimizing fuel cell and battery use.	Designed for routes of approximately 400 km.	TRL 7 (Demonstration)	Strong applicability for hybrid aircraft; efficient power management.
SF-BREEZE	High efficiency and zero emissions, focused on fuel cell performance.	Operational range around 200-400 km.	TRL 6-7 (Prototype/Demonstration)	Relevant for regional aviation; insights into route planning and efficiency.
Hyundai Xcient Fuel Cell	High efficiency in heavy-duty applications, utilizing fuel cells effectively.	Capable of operating over 600 km on a full tank.	TRL 8 (Commercial Use)	Fuel cell technology applicable for larger aircraft; logistics insights valuable.
Nikola Tre Fuel Cell	High efficiency; focuses on sustainable logistics.	over 805 km on a full tank.	TRL 8 (Commercial Use)	Market acceptance insights useful for hydrogen aviation; performance metrics applicable.

Table 15 Overall analysis of the case studies

- <u>TRL Explanation</u>

TRL 5: Technology Validated in Relevant Environment: Testing occurs in a relevant environment (not just in the lab). This may include simulations or small-scale testing in conditions similar to those it will encounter in real-world applications.

TRL 6: Technology Demonstrated in Relevant Environment: A prototype is developed and demonstrated in an environment that closely resembles the intended operational environment. This step may include more rigorous testing and validation.

TRL 7: System Prototype Demonstrated in Operational Environment: The technology is demonstrated in an operational environment, typically involving a fully integrated prototype. This testing assesses performance under actual conditions.

TRL 8: Actual System Completed and Qualified The technology is complete and has undergone all necessary testing. It is ready for operational use and has been qualified for commercial applications.

- Analysis

The case studies reveal distinct characteristics of hydrogen-powered vessels, each tailored to specific operational contexts. The Water Go Round showcases moderate efficiency due to its urban routing constraints, limiting its operational range to typically under 50 km. However, it provides valuable insights into urban logistics and the potential for short urban air mobility applications.

In contrast, the MF Hydra and SF-BREEZE demonstrate higher efficiencies and greater operational ranges. The MF Hydra, with a range of approximately 400 km and a TRL of 7, highlights strong applicability for hybrid aircraft due to its efficient power management system. Similarly, the SF-BREEZE, achieving a range of 200-400 km, offers relevant insights for regional aviation.

The Hyundai Xcient Fuel Cell Truck and Nikola Tre stand out in the heavy-duty truck segment, both achieving high efficiencies. The Hyundai Xcient operates over 600 km, making its fuel cell technology applicable for larger aircraft. Meanwhile, the Nikola Tre's significant range of over 805 km, along with its commercial readiness, provides market acceptance insights that are valuable for the future of hydrogen aviation.

Overall, these case studies illustrate the diverse applications and technological advancements of hydrogen-powered systems in maritime transport. Each vessel brings unique insights that can inform the development of hydrogen technologies in aviation, showcasing the flexibility and potential of hydrogen as a zero-emission fuel source across various transportation sectors. For a comprehensive comparison of all case studies, including detailed specifications and performance metrics, please refer to Appendix D: Comprehensive Comparison cross-sectoral Hydrogen-Powered Systems.. As we transition into the next chapters, these findings will serve as a foundation for exploring how hydrogen technologies can be effectively integrated and scaled within the aviation industry to address current challenges and enhance sustainable practices

Chapter 11: Solutions and competencies

The aviation sector faces increasing pressure to reduce its environmental footprint while maintaining safety, efficiency, and performance. Hydrogen technologies, particularly hybrid-electric propulsion systems (HHEPS), offer promising pathways to meet these challenges. This chapter synthesizes insights from previous case studies and literature reviews to identify key solutions and competencies essential for the aviation sector to leverage advancements in hydrogen hybrid-electric propulsion technology developed in maritime and trucking sectors.

The information presented here is derived from a comprehensive analysis of various sources, including government reports, industry publications, and academic research Additionally, the chapter incorporates my own analysis techniques, including comparative analysis of case studies such as the MF Hydra and SF-BREEZE, to highlight best practices and lessons learned. By synthesizing this information, the chapter outlines practical approaches, and necessary skill sets to facilitate the adoption of hydrogen technologies in aviation.

Key Solutions

Hydrogen Production

Efficient hydrogen production is foundational for the aviation sector's transition to hydrogen technologies:

- Electrolysis: Utilizing renewable energy sources, such as solar or wind, for electrolysis can produce green hydrogen efficiently. Innovations like Proton Exchange Membrane (PEM) electrolysis achieve efficiencies of up to 70%, presenting a sustainable pathway for hydrogen production suitable for aviation applications (*Home | Hydrogen Program*, n.d.)
- Biomass Gasification: This method converts organic materials into hydrogen, leveraging waste resources to produce clean energy. The Gas Technology Institute has developed systems that produce hydrogen from agricultural waste, contributing to a circular economy (GTI Energy, 2024)

Storage and Distribution

The ability to store and distribute hydrogen safely and efficiently is critical for aviation:

- Storage Solutions: Optimizing storage methods, such as compressed hydrogen at pressures of 700 bar or liquid hydrogen storage, allows for increased energy density.
- Distribution Infrastructure: Establishing a comprehensive hydrogen distribution network is vital to supporting refuelling stations at airports. Initiatives like Germany's Hydrogen Mobility Program showcase public-private partnerships in developing hydrogen infrastructure, which can serve as a model for aviation (*H2 MOBILITY - H2Mobility*, 2022).

Fuel Cell Technology

Advancements in fuel cell technology can significantly enhance aviation performance:

- Efficiency Improvements: Ongoing research into advanced catalyst materials, such as non-platinum catalysts, may lead to significant cost reductions and increased efficiency, potentially exceeding 60% energy conversion rates. This improvement is crucial for hydrogen-powered aircraft (Wang, 2005).
- Modular Fuel Cell Systems: Developing modular fuel cell designs enables scalability, allowing for easy integration into various aircraft types. Companies like Ballard Power Systems are leading efforts to create scalable fuel cell solutions tailored for aviation applications (*Fuel Cell & Clean Energy Solutions | Ballard Power*, n.d.)

Competencies Needed

To effectively implement hydrogen technologies in aviation, several critical competencies are essential:

Technical Skills

- Aerospace Engineering: Engineers must possess advanced skills in aerodynamics, aircraft weight optimization, and propulsion system integration. This involves developing lightweight, energy-dense propulsion systems capable of providing sufficient thrust for all phases of flight.
- Fuel Cell and Hydrogen Technology: Expertise in hydrogen fuel cells is critical, especially in adapting these systems to aviation environments where high power-to-weight ratios are necessary. Engineers need to develop lightweight hydrogen storage solutions (liquid hydrogen or compressed gas) adhering to stringent weight and safety regulations.
- Energy Storage and Power Management: Engineers require specialized knowledge of battery systems to ensure that energy storage meets the aircraft's operational requirements without excessive weight. They also need to design power management systems that balance the use of batteries and fuel cells during distinct phases of flight.
- Cryogenic Systems and Safety: The use of liquid hydrogen (LH_2) in aviation demands expertise in cryogenic engineering. Engineers must ensure the safe handling, storage, and transfer of liquid hydrogen while maintaining system reliability under extreme conditions, such as high altitudes and low temperatures.
- Certification and Regulatory Knowledge: Aviation engineers must work closely with regulators such as EASA and FAA to ensure hybrid-electric systems meet stringent certification standards. This requires a thorough understanding of aviation safety regulations and expertise in aircraft certification processes.

To effectively implement hydrogen technologies in aviation, several critical competencies are essential. The following table summarizes the key competencies, their corresponding development stages, and the necessary qualifications and certifications required for each:

Competence	Development Stage	Specific Tasks and Responsibilities	Relevant Technologies	Potential Challenges
Mechanical Engineering	Design and prototyping	-Design lightweight structures for hydrogen systems -Prototype hybrid-electric aircraft components	CAD Software, Finite Element Analysis (Harris, 2021)	Balancing weight and structural integrity
Chemical Engineering	Production and processing	- Develop processes for efficient hydrogen production - Optimize biomass gasification techniques	Electrolysis Systems (U.S. DOE, 2020), Bioreactors	Ensuring scalability and cost-effectiveness
Aerospace Engineering	Integration and testing	-Conduct aerodynamic analysis for hydrogen aircraft - Test integration of hybrid systems	Wind Tunnels, Computational Fluid Dynamics (NASA, 2022)	Meeting safety and performance regulations
Safety Standards	Safety assessment and compliance	Evaluate safety protocols for hydrogen handling	Safety Management	Navigating complex

		- Ensure compliance with aviation regulations	Systems (NFPA, 2021)	regulatory environments
Research Experience	Research and innovation	Publish findings on hydrogen fuel cell advancements - Engage in cross-sector collaborations	Research Publications, Conferences (Ballard, 2021)	Keeping pace with rapid technological advancements
Sustainability	Sustainability assessment	Assess environmental impact of hydrogen production - Develop sustainability metrics	Life Cycle Assessment Tools (EPA, 2021)	Balancing economic feasibility with environmental goals
Policy Advocacy	Policy development	Advocate for supportive hydrogen policies - Engage with stakeholders for funding opportunities	Policy Frameworks (U.S. Hydrogen and Fuel Cell Program, 2021)	Gaining consensus among diverse stakeholders
Regulatory Compliance	Compliance auditing	Conduct audits to ensure regulatory adherence - Develop compliance documentation	Regulatory Compliance Software (EASA, 2022)	Staying updated with evolving regulations
Project Management	Project execution and monitoring	Manage project timelines and resources - Coordinate multi-disciplinary teams	Project Management Software (PMI, 2021)	Overcoming logistical challenges in project execution
Training and Education	Implementation and training	Develop training programs for hydrogen technologies - Conduct workshops and seminars	Learning Management Systems (National Fire Protection Association, 2021)	Ensuring comprehensive understanding of new technologies

Table 16 Summary of Competencies Needed for Implementing Hydrogen Technologies in Aviation

This table highlights the necessary skills and qualifications that must be developed to support the transition to hydrogen technologies in aviation. Each competency plays a crucial role in ensuring the effective integration of hybrid-electric propulsion systems.

Regulatory and Certification Requirements

Understanding the regulatory landscape is vital for the successful implementation of HHEPS in aviation. The following table summarizes the existing certifications and regulations that govern the development and integration of hydrogen technologies:

Regulatory Body	Regulation/Specification	Description	Reference
European Union	Regulation (EU) 2018/1139	Establishes common rules in civil aviation, mandating type certification for all products, including HHEPS.	European Parliament and Council, 2018
	Commission Regulation (EU) No. 748/2012	Sets implementing rules for airworthiness and environmental certification, defining certification processes for HHEPS.	European Commission, 2012
	EASA Certification Memorandum CM-21.A-004	Provides guidance on certification approaches for Electric/Hybrid Propulsion Systems, including flexibility for hydrogen integration.	EASA, 2024
	Special Condition E-19	Addresses specific certification requirements for electric/hybrid propulsion systems, applicable to hydrogen technologies.	EASA, 2021
	Special Condition E-18	Outlines requirements for integrating electric propulsion systems into CS-23 normal-category aeroplanes, potentially relevant for HHEPS.	EASA, 2020
International Standards	ICAO Guidelines	Provides overarching safety and environmental guidelines that influence national regulations for new propulsion technologies.	ICAO, 2021
	ASTM F3338-18	Relates to the design and manufacture of electric propulsion units, applicable to hydrogen propulsion systems.	ASTM International, 2018
National Regulations	FAA Regulations	Regulates the certification of aircraft in the U.S., including those with hydrogen propulsion systems, ensuring compliance with safety and operational standards.	FAA, 2022
Safety and Environmental Standards	EPA Regulations	Sets emissions standards and environmental impact assessments for aviation technologies, including HHEPS.	EPA, 2021
	Safety Management Systems (SMS)	Requires a systematic approach to managing safety risks associated with the implementation of new technologies, including HHEPS.	ICAO, 2013

Table 17 Regulatory and Certification Requirements for Hydrogen Hybrid-Electric Propulsion Systems

Research and Development

Investing in research and development (R&D) is crucial for driving innovation in hydrogen technologies. The aviation sector must prioritize R&D to ensure the successful integration of hydrogen hybrid-electric propulsion systems. Key aspects include:

Collaboration with Research Institutions: Partnerships can foster the development of cutting-edge hydrogen technologies. Collaborative projects involving NASA and industry partners focus on developing hydrogen propulsion technologies for aircraft, yielding valuable insights applicable to the aviation sector (NASA, 2024) Such collaborations can accelerate technological advancements and enhance the reliability and performance of HHEPS.

Focus on Sustainability: R&D efforts should prioritize environmental sustainability by developing processes that minimize carbon footprints in hydrogen production and utilization. For instance, optimizing electrolysis systems to enhance energy efficiency can significantly contribute to sustainability goals in aviation. This focus aligns with global initiatives to reduce greenhouse gas emissions and support the transition to cleaner energy sources.

- Case Studies of Successful Implementations

Previous case studies illustrate successful implementations of hydrogen technologies in maritime and trucking sectors, providing valuable lessons for aviation:

- The MF Hydra and SF-BREEZE showcase how hybrid systems optimize performance, offering models for future hybrid aircraft design. These case studies demonstrate the effectiveness of integrating hydrogen fuel cells with traditional propulsion systems.
- The Hyundai Xcient Fuel Cell Truck exemplifies the use of hydrogen fuel cells in heavy-duty applications, with a range of over 600 km. Insights from this vehicle's logistics and operational efficiency can inform the design and implementation of hydrogen systems in aviation.
- The Nikola Tre offers valuable data on market acceptance and performance metrics, particularly its hydrogen storage capacity and operational range exceeding 805 km. Such metrics can guide future hydrogen applications in aviation, helping to establish benchmarks for performance.
- The Water Go Round demonstrates the importance of adaptability in urban logistics, which can guide the development of short-range hydrogen-powered aircraft for urban air mobility. This adaptability is essential as the aviation sector looks to integrate hydrogen technologies into diverse operational contexts.

The aviation sector's transition to hydrogen technologies requires a multifaceted approach that emphasizes effective solutions and well-defined competencies. By leveraging insights gained from maritime and trucking sectors, aviation can adapt existing hydrogen production methods, storage solutions, and fuel cell technologies to meet its specific challenges. These tables summarizing competencies and regulatory requirements provide essential frameworks for understanding the human and regulatory resources necessary for the successful integration of HHEPS. As we move into the next chapter on Development and Infrastructure, these foundational elements will be crucial in shaping the necessary framework to support the growth and deployment of hydrogen technologies in aviation.

Chapter 12: Development and Infrastructure

The transition to hydrogen hybrid-electric propulsion systems (HHEPS) in aviation requires a robust and specialized infrastructure that encompasses hydrogen production, storage, distribution, and refueling capabilities. Understanding the unique properties of hydrogen, such as its high energy density by weight, low toxicity, and buoyancy, is crucial for effectively integrating hydrogen into energy systems and technologies. Figure 32 summarizes key properties of hydrogen compared to natural gas and gasoline, highlighting its unique characteristics. For a more in-depth examination of hydrogen physical and chemical properties, please refer to the literature review section.

This chapter explores the essential components of hydrogen infrastructure within the aviation sector, emphasizing the technologies, safety considerations, and challenges associated with each aspect. By examining these elements, stakeholders can facilitate the effective implementation of hydrogen technologies and contribute to a sustainable aviation future.

Hydrogen Properties

Understanding the properties of hydrogen is crucial for its effective integration as a fuel source in aviation. The following table summarizes key properties of hydrogen compared to natural gas and gasoline, highlighting its unique characteristics:

	Hydrogen	Natural Gas	Gasoline
Color	No	No	Yes
Toxicity	None	Some	High
Odor	Odorless	Mercaptan	Yes
Buoyancy Relative to Air	14X Lighter	2X Lighter	3.75X Heavier
Energy by Weight	2.8X > Gasoline	~1.2X > Gasoline	43 MJ/kg
Energy by Volume	4X < Gasoline	1.5X < Gasoline	120 MJ/gallon

Figure 32 Comparison of Hydrogen Properties with Natural Gas and Gasoline. (*National Hydrogen and Fuel Cell Emergency Response Training Resource | H2tools | Hydrogen Tools*, n.d.)

This comparison illustrates critical differences in characteristics such as energy density, toxicity, and buoyancy, which are essential considerations for fuel selection in various applications, including aviation.

Hydrogen Production Infrastructure

Hydrogen production infrastructure is a fundamental component supporting the generation of hydrogen fuel necessary for aviation applications. Establishing robust production capabilities is critical to ensuring a reliable and efficient hydrogen supply.

- Types of Hydrogen Production Methods

1. Electrolysis
    - Overview: Electrolysis involves splitting water into hydrogen and oxygen using electrical energy. When powered by renewable energy sources, this method produces green hydrogen, which is crucial for reducing the aviation sector's carbon footprint (*Hydrogen Production | Hydrogen Program*, n.d.).
    - Infrastructure Requirements: Electrolysis facilities for aviation must include substantial electrical infrastructure, high-capacity electrolysers, and sufficient water supply systems.

2. Steam Methane Reforming (SMR)

   - Overview: SMR is the most widely used method for hydrogen production, where natural gas is reacted with steam to produce hydrogen and carbon dioxide. While this method is currently dominant, it generates CO_2 emissions, which may limit its viability in the long term for sustainable aviation (GTI Energy, 2024).
   - Infrastructure Requirements: Facilities utilizing SMR must integrate carbon capture and storage (CCS) technologies to mitigate emissions, aligning with the aviation industry's sustainability goals.

3. Biomass Gasification

   - Overview: Biomass gasification converts organic materials into hydrogen, contributing to a circular economy while producing clean energy. This method can be particularly useful for regions with abundant biomass resources (GTI Energy, 2024).
   - Infrastructure Requirements: Biomass production facilities must be strategically located near feedstock supply chains and equipped with gasification reactors tailored for aviation fuel requirements.

Challenges in Scaling Hydrogen Production for Aviation

- Capital Investment: Establishing hydrogen production facilities often requires significant upfront investment. Securing funding and support for these projects is critical for encouraging growth in the aviation hydrogen economy (*Paving the Way for a Sustainable Future with Hydrogen Energy*, 2024).
- Regulatory Compliance: Facilities must comply with stringent environmental regulations and safety standards specific to the aviation sector (EASA, 2024).

Hydrogen Storage Solutions

Hydrogen storage solutions are critical for ensuring a stable hydrogen supply in aviation, facilitating safe handling, and enabling efficient distribution and refuelling operations.

Types of Hydrogen Storage Methods

1. Compressed Hydrogen Storage

   - Overview: Compressed hydrogen storage involves storing hydrogen gas at high pressures (350 to 700 bar), which is commonly used due to its efficiency (*Hydrogen Storage | Hydrogen Program*, n.d.) For aviation, high-pressure storage must be compatible with aircraft systems.
   - Infrastructure Requirements: High-strength pressure vessels and compressors must be capable of meeting the aviation sector's safety and operational standards.

2. Liquid Hydrogen Storage

   - Overview: Liquid hydrogen (LH_2) is cooled to cryogenic temperatures (-253°C) to increase energy density. This method is particularly relevant for aviation, where weight and space are critical considerations.
   - Infrastructure Requirements: LH_2 storage facilities require cryogenic systems, including insulated storage tanks and vacuum-insulated transfer lines, specifically designed for aircraft fuelling operations.

3. Metal Hydride and Chemical Storage

- Overview: Both metal hydride and chemical hydrogen storage methods can provide safer storage options at lower pressures. These methods may be more suitable for smaller aircraft or specialized applications.
- Infrastructure Requirements: Facilities must include reactors for hydrogen absorption and desorption and systems for maintaining optimal conditions.

Safety Considerations

- Material Selection: All storage systems must be designed using materials resistant to hydrogen embrittlement, especially critical in aviation applications.
- Monitoring and Detection: Implementing real-time monitoring systems for pressure, temperature, and hydrogen concentration is essential to ensure safe operation in aviation environments.

Hydrogen Distribution Systems

Hydrogen distribution systems are vital for transporting hydrogen from production facilities to storage locations and refuelling stations in the aviation sector.

Transportation Methods

1. Pipelines
    - Overview: Hydrogen pipelines are efficient for transporting hydrogen over long distances. They can be constructed specifically for hydrogen or repurposed from existing natural gas infrastructure, although modifications may be necessary (*Hydrogen a Renewable Energy Perspective*, 2019)
    - Infrastructure Requirements: Pipeline systems must utilize robust materials to prevent hydrogen embrittlement, ensuring safety and reliability.
2. Compressed Hydrogen Trucks and Liquid Hydrogen Tankers
    - Overview: For shorter distances or areas not served by pipelines, hydrogen can be transported using specialized high-pressure tank trucks or cryogenic tankers, which are essential for meeting aviation demand (*Gaseous Hydrogen Delivery*, n.d.).
    - Infrastructure Requirements: Both methods require well-designed loading and unloading facilities with adequate safety measures.

Safety Considerations

- Leak Detection Systems: Advanced leak detection and monitoring systems are essential for identifying potential hazards in hydrogen distribution.
- Training and Protocols: Personnel involved in hydrogen distribution must be thoroughly trained in safety protocols and emergency response procedures specific to aviation contexts.

Hydrogen Refuelling Stations

Hydrogen refuelling stations (HRS) are critical infrastructure components that enable the delivery of hydrogen fuel to aircraft, ensuring efficient and safe refuelling operations.

- Bunkering Process

Bunkering is a well-established procedure in the aviation industry, but hydrogen bunkering introduces complexities due to hydrogen's unique properties, whether stored as a compressed gas or as a cryogenic liquid. The bunkering process must be carefully managed to prevent leaks, minimize losses, and ensure the safety of personnel and aircraft.

Figure 33 (Compressed Hydrogen Storage | MAHYTEC, 2023)

1. Compressed Hydrogen Bunkering
    - Process Overview: Involves transferring hydrogen gas from high-pressure storage tanks at refuelling stations into the onboard storage tanks of aircraft. This process requires specialized high-pressure hoses, connectors, and valves (U.S. Department of Energy, 2020).
    - Key Equipment: High-pressure compressors, safety interlocks, and leak detection systems are vital for safe operation.
    - Safety Considerations: Essential safety protocols include pressure relief valves, emergency shut-off systems, and real-time monitoring of hydrogen concentrations.
2. Liquid Hydrogen (LH_2) Bunkering
    - Process Overview: More complex due to the cryogenic nature of LH_2, which must be kept around -253°C. The bunkering process involves transferring LH_2 from cryogenic storage tanks into onboard cryogenic tanks of aircraft, requiring vacuum-insulated pipelines and cryogenic pumps (NASA, 2022).
    - Key Equipment: Cryogenic pumps and multilayer insulation around storage tanks are necessary for maintaining low temperatures.
    - Safety Considerations: Safety measures include boil-off gas management systems, emergency venting systems, and temperature sensors to monitor conditions during transfer.

Figure 34 liquid hydrogen transfer pump (Demaco Holland B.V., 2024)

- Design and Layout of Refuelling Stations

Understanding the design and layout of hydrogen refueling stations is crucial for effective implementation. The following configurations and capacities have been included based on industry standards, particularly the ISO 19880-1:2018 guidelines, which provide specifications for hydrogen fueling stations.

The Gaseous Hydrogen Fueling Station diagram (Figure 35) illustrates the essential components involved in the fueling process. It highlights the interconnected systems for hydrogen supply, storage, and dispensing, which are vital for ensuring the safety and efficiency of operations. This visual representation is important as it helps stakeholders, engineers, and regulatory bodies understand the complexities of hydrogen refueling infrastructure and the integration of various technologies required for safe operation.

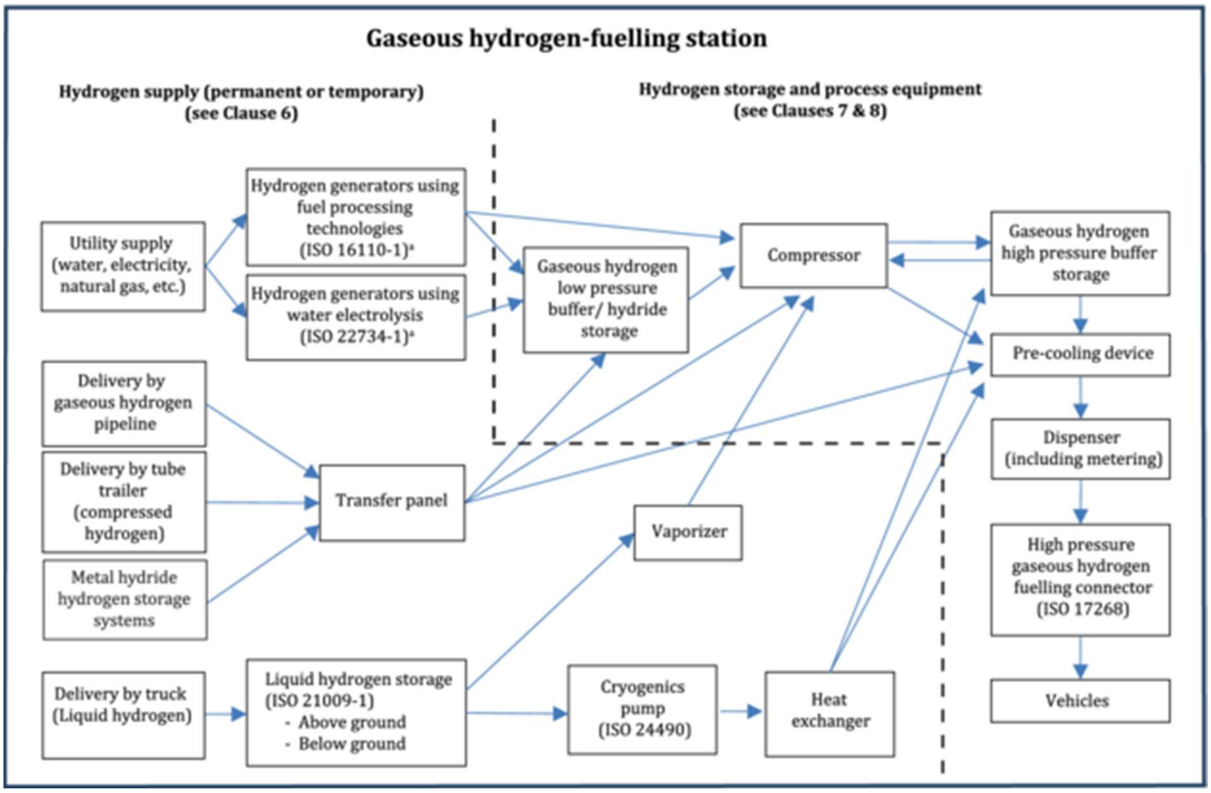

Figure 35 Components of a Gaseous Hydrogen Fuelling Station (International Organization for Standardization, 2018)

1. Station Configuration
   - Compressed Hydrogen Stations: These stations are equipped with high-pressure storage tanks and specialized dispensing units tailored for aircraft fuelling (*Hydrogen Delivery*, n.d.).
   - Liquid Hydrogen Stations: Feature cryogenic storage tanks and vacuum-insulated environments specifically designed for aviation applications (NASA, 2022).
2. Capacity and Scalability
   - HRS must be designed with sufficient storage capacity to accommodate aviation demand and be scalable to support the growing fleet of hydrogen-powered aircraft.

Maritime and Trucking Advancements in infrastructure

As the aviation sector transitions to hydrogen as a primary fuel source, there is significant potential to leverage advancements and systems developed in the maritime and trucking sectors. This section explores how existing technologies, processes, and regulatory frameworks is adapted to support hydrogen infrastructure in maritime and truck sectors.

Adapting Bunkering Processes

The maritime sector has established effective bunkering processes that can be adapted for aviation.

- Example: The MF Hydra, a hydrogen-powered ferry, utilizes specialized high-pressure bunkering systems designed for safe and efficient refuelling of hydrogen fuel cells. These systems incorporate high-pressure hoses, connectors, and valves that handle hydrogen at pressures typically ranging from 350 to 700 bar. Aviation can adopt similar technologies in hydrogen refuelling stations for aircraft, ensuring safety during the transfer process and minimizing the risk of leaks.

Storage Solutions

Innovations in hydrogen storage solutions for heavy-duty trucks provide valuable insights for aviation applications.

- Example: The Nikola Tre, a hydrogen fuel cell truck, utilizes composite pressure vessels designed to store hydrogen at high pressures. These vessels are lightweight and resistant to hydrogen embrittlement, making them ideal for use in aviation (Nikola Corporation, 2024). By adopting similar composite materials and designs, aviation can enhance the efficiency and safety of hydrogen storage for aircraft.

Distribution Systems

The distribution strategies employed in the trucking and maritime sectors offer valuable insights for aviation.

- Example: The Port of Klaipeda is developing hydrogen production and refuelling stations that will supply both compressed hydrogen gas (H_2) and potentially liquefied hydrogen for various applications, including aviation. By implementing hydrogen transport strategies used in trucking, such as using specialized hydrogen transport trucks equipped for high-pressure delivery, the aviation sector can enhance its fuel supply chains (Port of Klaipeda, 2024).
- The use of compressed hydrogen trucks for local distribution can also be adapted for airport hydrogen delivery systems. This model has been successfully employed in regions where infrastructure for hydrogen pipelines is limited, ensuring a continuous supply of hydrogen to refuelling stations at airports (*Gaseous Hydrogen Delivery*, n.d.).

Refuelling Station Technology

The technologies utilized in hydrogen refuelling stations for trucks and vessels can significantly enhance the infrastructure for aviation.

- Example: The Nikola HYLA Hydrogen Refuelling Station is designed to accommodate heavy-duty fuel cell vehicles. This station features advanced dispensing systems and safety monitoring technologies that can be adapted for aviation refuelling operations (Nikola Corporation, 2024). Incorporating these technologies into airport refuelling stations can improve operational efficiency and safety.
- Automated Refuelling Systems developed for maritime applications, such as the automated refuelling technology used in the Hydrogen Refuelling Station at the Port of Rotterdam, could be employed at airports to streamline the refuelling process, reducing the time required for aircraft to refuel and increasing turnaround efficiency (*Air Products to Supply Green Hydrogen Filling Station in 2023*, n.d.).

Regulatory Frameworks

The regulatory frameworks established in the maritime and trucking sectors provide a foundation for developing aviation-specific guidelines.

- Example: The International Maritime Organization (IMO) has developed safety regulations for hydrogen bunkering that include rigorous testing and safety protocols (IMO, 2023). Aviation can benefit from adopting similar regulations tailored to aircraft refuelling operations, ensuring a high standard of safety and operational protocol in hydrogen handling.

- In the trucking sector, the California Air Resources Board (CARB) has set stringent emissions standards that must be met for hydrogen fuel cell vehicles (CARB, 2024). The aviation sector can leverage these regulatory experiences to establish a robust framework for hydrogen safety and emissions management in aircraft.

Collaborative Research and Development

Collaboration between the maritime, trucking, and aviation sectors is crucial for advancing hydrogen technology.

- Example: Collaborative projects involving NASA and industry partners focus on developing hydrogen propulsion technologies for aircraft, yielding valuable insights applicable to other sectors (NASA, 2022). Initiatives such as these encourage sharing of best practices and technology advancements across sectors, which can accelerate the development of hydrogen infrastructure in aviation.

Existing Hydrogen Refueling Stations

As the aviation sector transitions to hydrogen technologies, existing hydrogen refueling stations from the maritime and trucking sectors serve as valuable models for airport operations. The table below highlights key hydrogen refueling stations that exemplify advancements in infrastructure, showcasing features that aviation can adapt to enhance its own refueling capabilities.

Hydrogen Refueling Station	Location	Operational Status	Hydrogen Type	Hydrogen Production	Key Equipment	Power Supply	Charging Infrastructure
Port of Antwerp Hydrogen Station	Port of Antwerp-Bruges, Belgium	Active and part of a broad hydrogen import and distribution network.	H_2 (hydrogen gas) and LH_2 (liquid hydrogen)	Imported as ammonia or methanol, converted back to hydrogen on-site.	High-pressure hydrogen storage and conversion systems.	Sourced from renewable energy for sustainability.	Multifuel stations supporting large-scale hydrogen refueling for maritime use
Nikola HYLA Hydrogen Station	Ontario, California, USA	Fully operational, catering to Class 8 hydrogen fuel cell trucks.	Compressed H_2 (hydrogen gas)	Part of Nikola's extensive hydrogen supply chain and infrastructure.	Modular fueler designed for high-capacity, high-pressure hydrogen dispensing.	Supported by Nikola's integrated distribution network.	Flexible modular and permanent refueling options, suitable for heavy-duty trucks
Port of Klaipeda Hydrogen Station	Klaipeda, Lithuania	Currently in development as part of the Green Port initiative.	Compressed H_2 and potentially liquefied hydrogen	Aims to produce up to 127 tons of green hydrogen per year through 2 MW electrolysis.	Electrolysers, high-pressure storage tanks, and refueling dispensers.	Utilizes renewable energy sources to ensure minimal carbon emissions.	Designed for maritime and terrestrial vehicles, with a sustainability focus.
Shell Hydrogen Station	Wesseling, near Cologne, Germany	The electrolyser is scheduled to begin operating in 2027.	Green hydrogen produced through renewable sources	Shell is building a 100-megawatt renewable hydrogen electrolyser	The facility will include high-capacity electrolysis equipment for hydrogen production, along with advanced storage and dispensing systems.	powered by renewable energy	High-pressure refueling infrastructure compatible with heavy-duty applications.

Table 18 Existing Hydrogen Refuelling Stations

Challenges in Refuelling Infrastructure Implementation

Implementing hydrogen refuelling infrastructure across the aviation sector presents several challenges, including:

1. Technical Challenges
    - High-Pressure and Cryogenic Handling: Managing high pressures for compressed hydrogen refuelling and maintaining cryogenic temperatures for LH_2 is critical. Innovations in material science and technology are needed to ensure safety and efficiency.
2. Logistical Challenges
    - Infrastructure Compatibility: Integrating hydrogen refuelling stations into existing airport infrastructure can be challenging, requiring modifications to accommodate specialized storage and handling systems.
    - Refuelling Time: The time required to refuel hydrogen aircraft can be longer compared to conventional fuels, necessitating efficient scheduling and coordination to minimize operational impacts.
3. Regulatory Challenges
    - Hydrogen refuelling stations must comply with stringent safety regulations that vary by region. Compliance involves extensive documentation and certification processes (EASA, 2024).

The development of hydrogen production, storage, distribution, and refuelling infrastructure is essential for the widespread adoption of hydrogen technologies in the aviation sector. By investing in advanced technologies, optimizing facility designs, ensuring safety, and addressing regulatory challenges, the hydrogen economy can develop robust infrastructure to support the growing demand for clean energy solutions.

Leveraging advancements from the maritime and trucking sectors presents significant opportunities for the aviation industry as it transitions to hydrogen technologies. By adapting successful processes, technologies, and regulatory frameworks, aviation can enhance its hydrogen infrastructure and facilitate a more efficient and sustainable energy future. This cross-sectoral approach will not only improve the operational capabilities of hydrogen in aviation but also contribute to the overall growth of a hydrogen economy.

As the chapter transitions to operational aspects, it is crucial to consider how the established hydrogen infrastructure will function within aviation operations. Understanding the interplay between infrastructure and operational requirements will be vital for effectively implementing hydrogen technologies and maximizing their benefits in the pursuit of sustainable aviation. The subsequent chapter will delve into these operational considerations, exploring how aviation can integrate hydrogen into its daily functions to achieve efficiency and safety in a hydrogen-powered future.

Chapter 13: Operational aspects

The adoption of Hybrid and Hydrogen Electric Propulsion Systems (HHEPS) in aviation represents a transformative step toward sustainable, low-emission flight technologies. Implementing HHEPS requires addressing complex challenges in safety, infrastructure, regulatory compliance, and technical adaptations to ensure seamless integration within the existing aviation ecosystem. This chapter examines these operational aspects in detail, including regulatory requirements, operational procedures, required competencies, safety systems, and maintenance practices. It also includes a comparative analysis with the maritime and trucking sectors, providing insights on how aviation can leverage advancements in hydrogen propulsion technology from these industries. For a comprehensive list of relevant standards and regulations, see Appendix E: Standards and Regulations for HHEPS in Aviation, and for an operational comparison across sectors, see Appendix F: Comparative Operational Aspects of HHEPS in Aviation, Maritime, and Trucking.

1. Regulatory Requirements

The aviation industry is heavily regulated to ensure safety, environmental sustainability, and operational efficiency. HHEPS introduces new regulatory needs, particularly concerning hydrogen fuel handling, cryogenic storage, high-voltage electric systems, and emissions. Key regulatory bodies such as EASA, FAA, and ICAO have started to adapt existing regulations and develop new guidelines. For example, EASA's Special Condition for Hybrid Electric and Hydrogen Aircraft specifies requirements for cryogenic hydrogen storage, fuel cell integration, and electric system fault tolerance. In the U.S., the FAA's Advanced Air Mobility (AAM) Program sets certification standards for hydrogen-electric propulsion, addressing crashworthiness, thermal management, and emergency protocols specific to hydrogen systems in aviation.

To ensure operational consistency, HHEPS must comply with standards such as ISO 19880-1 (hydrogen fuelling stations), IEC 60079-10-1 (classification of explosive atmospheres), and Pressure Equipment Directive (PED) 2014/68/EU for hydrogen storage. These regulatory requirements provide a foundation for safe integration into the aviation sector yet highlight the need for further collaboration between regulatory bodies to ensure cross-sector alignment as HHEPS matures.

2. Operational Procedures

Standardized operational procedures are essential for safely and efficiently implementing HHEPS in aviation, covering hydrogen refuelling, high-voltage battery charging, and component handling. For example, hydrogen refuelling requires specialized protocols to manage cryogenic temperatures and prevent leaks in high-traffic areas like airports. ISO 14687 and ASTM D7650 specify the purity standards for hydrogen fuel, which is crucial for fuel cell efficiency and safety.

Battery charging procedures also demand high-voltage safeguards, as outlined in SAE AS6858, to protect personnel and equipment during routine refuelling and turnaround times. In addition, the IATA Guidance on Hydrogen and SAF Infrastructure offers best practices for hydrogen integration, ensuring compatibility with existing airport infrastructure. Documenting these operational procedures is vital for establishing industry-wide standards that minimize risks and streamline HHEPS operations.

3. Required Competencies for HHEPS Operations

Implementing HHEPS requires a skilled workforce trained in handling hydrogen and electric systems, with competencies that extend beyond conventional aviation expertise. Personnel must be adept in cryogenic hydrogen handling, high-voltage safety, and hydrogen fuel cell maintenance, requiring specific qualifications and certifications. For example, refuelling staff need training on cryogenic storage and leak detection protocols as described in ISO/TR 15916 (safety of hydrogen systems), while maintenance crews must understand high-voltage systems and thermal management, following guidelines like RTCA DO-311A for rechargeable lithium batteries.

Developing comprehensive training programs and certification requirements ensures that personnel meet the industry's stringent safety and operational standards. The documentation of required competencies for HHEPS operations not only promotes safety but also enables efficient scaling as hydrogen technology becomes more prevalent in aviation.

4. Safety Systems

Aviation's operational environment necessitates rigorous safety systems tailored to HHEPS, addressing risks associated with hydrogen storage, high-voltage electric components, and emergency scenarios. Safety systems for hydrogen include leak detection, pressure monitoring, and thermal management, as recommended by ISO 13985 (hydrogen tanks for cryogenic storage) and NEN-EN-ISO 21013-3 (pressure-relief devices for cryogenic systems). These systems are critical for managing the volatile nature of hydrogen, particularly in the confined and pressurized environment of aircraft.

For electric systems, SAE AS6858 and IEC 60079-10-1 outline safety requirements for high-voltage systems and hazardous area classifications, ensuring the containment of electric hazards during regular operation and emergencies. Incorporating these safety systems into HHEPS operations provides a proactive approach to risk management, aligning with aviation's stringent safety requirements.

5. Maintenance Practices

Effective maintenance practices are essential to ensure the long-term reliability and safety of HHEPS components. Hydrogen fuel cells, cryogenic tanks, and high-voltage batteries demand specialized maintenance routines due to their sensitivity to environmental factors and complex operational requirements. For instance, cryogenic tanks require regular inspections for material toughness at low temperatures, guided by NEN-EN-ISO 21028-1. ISO 16111 and ISO 23273 address maintenance requirements for hydrogen storage devices and fuel cells, ensuring equipment durability and safe operation over extended use.

Maintenance staff must adhere to protocols for contamination prevention, battery health monitoring, and fuel cell efficiency checks, as outlined in EN ISO 14952-3 (cleaning of aerospace components). By documenting these maintenance practices, the aviation industry can ensure HHEPS reliability and operational continuity, reinforcing the safe integration of hydrogen technology.

6. Environmental and Performance Testing

HHEPS components in aviation must undergo rigorous environmental and performance testing to confirm resilience under high-altitude conditions, temperature changes, and vibration. RTCA DO-160 specifies environmental testing requirements, addressing the extreme conditions unique to aviation. Hydrogen fuel cell standards like ISO 16111 and ASTM D7650 offer specifications for durability and resilience, essential to meet the demands of aviation's high-performance requirements.

Performance testing also extends to emissions and fuel efficiency, with ISO 14687 ensuring hydrogen purity to reduce emissions without compromising fuel cell performance. Certification standards will likely evolve as HHEPS technology matures, incorporating new testing protocols that allow HHEPS-equipped aircraft to meet environmental and operational targets specific to aviation.

7. Comparison of Operational Aspects: Aviation vs. Maritime and Trucking Sectors

The operational demands of HHEPS vary significantly between aviation, maritime, and trucking sectors due to differences in energy requirements, infrastructure, and safety needs. Aviation, with its stringent energy density and weight limitations, requires high energy-to-weight ratios, unlike the trucking sector, which can accommodate larger hydrogen tanks, or the maritime sector, where fewer weight restrictions allow for larger hydrogen storage solutions. Standards such as NEN-EN-ISO 21028-1 (cryogenic toughness for materials) and SAE AS6858 (high-voltage electric systems) are particularly critical in aviation, where high altitudes and confined spaces pose unique challenges.

Infrastructurally, aviation relies on compact, high throughput refuelling systems within airport environments, whereas trucking benefits from an extensive hydrogen refuelling network along highways, and maritime operations leverage larger port facilities. Safety requirements also differ; aviation faces fluctuating pressures and temperatures that demand specialized safety protocols, while trucking and maritime operate at near-ground levels with more stable conditions. IATA Guidance on Hydrogen and SAF Infrastructure and EN ISO 14952-3 offer insights on safe refuelling and contamination control across sectors.

Despite these differences, the aviation industry can leverage advancements from the trucking and maritime sectors, particularly in hydrogen storage, safety protocols, and infrastructure. Innovations in compressed gas storage for trucking and robust hydrogen fuel handling from maritime applications offer valuable insights, though they must be adapted to meet aviation's high safety and operational standards. For a detailed comparison of these operational aspects, see Appendix B: Comparative Operational Aspects of HHEPS in Aviation, Maritime, and Trucking.

Chapter 14: Latest developments

In the pursuit of advancing hydrogen technologies for aviation, several noteworthy innovations have emerged across the aviation, maritime, and trucking sectors. Each sector, already invested in hydrogen-based propulsion, has developed technologies that meet its unique operational requirements, and many of these can potentially be adapted to meet aviation's stringent standards. This chapter highlights recent advancements in hydrogen production, storage, and utilization technologies from these three sectors, underscoring their potential applicability to aviation. Progress in areas such as circular hydrogen bunkering, high-efficiency fuel cells, solid-state storage, modular configurations, electric motor advancements, and cutting-edge battery technologies demonstrates how emerging innovations are transforming the capabilities of HHEPS. Together, these advancements reflect the role of cross-sector knowledge-sharing in driving sustainable, hydrogen-based propulsion.

Key Innovations in Hydrogen Hybrid-Electric Propulsion Systems by Sector

✈ Aviation-Specific Developments

1. On-Site Hydrogen Production – H2B2 EL600N Generator
   The H2B2 EL600N hydrogen generator represents a cutting-edge solution for on-site hydrogen production through Proton Exchange Membrane (PEM) electrolysis, producing up to 23 kg per hour (or 552 kg daily). With a high purity level of 99.99%, the EL600N is well-suited for aviation fuel cell applications, ensuring quality standards while reducing reliance on external hydrogen suppliers. Its modular, compact design supports installation at airports, and it integrates smoothly with renewable energy sources. This model is ideal for high-demand environments like major airports, where on-site production can meet growing hydrogen needs efficiently and sustainably (*Hydrogen Electrolyser EL600N - H2B2 Electrolysis Technologies*, 2024).

2. High-Efficiency Hydrogen Fuel Cells
   Innovations in fuel cells, particularly high-temperature PEM (HT-PEM) fuel cells and graphene-enhanced fuel cells, are improving HHEPS viability in aviation. HT-PEM cells operate at temperatures between 150-180°C, enhancing efficiency and tolerance to impurities. Additionally, incorporating graphene into PEM fuel cells boosts durability, reduces platinum requirements, and increases power density—essential for aviation's weight-sensitive applications. These advancements directly support aviation's energy demands, especially for sustained power over long flights (Rosli et al., 2017; Dwivedi, 2022).

3. Integrated Power Management Systems (IPMS)
   IPMS utilizes AI-driven algorithms to optimize energy distribution between fuel cells, batteries, and regenerative systems in real time. Such systems ensure that power demands are dynamically managed during flight phases like take-off, cruising, and landing, which vary significantly. IPMS extends system life by balancing power loads and enhancing fuel efficiency, representing a crucial innovation for efficient HHEPS operation in aviation

4. Solid-State Hydrogen Storage Solutions
   Solid-state storage solutions, like metal hydrides, offer high-density hydrogen storage without requiring cryogenic or high-pressure containment. In aviation, such storage could minimize fuel weight and enhance safety. Metal hydrides, for instance, store hydrogen in a stable, low-maintenance form, offering greater energy density and reliability, particularly suited for aircraft with limited space (El Harrak et al., 2024).

5. Electric Motor Advancements in Aviation

   - Axial Flux Permanent Magnet Motors: Axial flux motors, pioneered by companies like YASA, are revolutionizing power density and compactness in electric motors. The YASA 750R motor, for example, used in the Rolls-Royce ACCEL project, achieves power densities of up to 10 kW/kg, making it ideal for aviation where space and weight constraints are critical. This innovation in compact, high-torque motors is particularly advantageous for short- to medium-haul flights, where efficiency and weight reduction are essential (YASA Limited, n.d.).
   - Superconducting Motors: Fully superconducting motors, such as those developed under the ASuMED project, provide power-to-weight ratios up to 20 kW/kg with efficiency rates exceeding 99%. These motors, while still facing challenges in cryogenic cooling, offer transformative potential for large-scale commercial aircraft due to their near-zero electrical resistance. If cooling hurdles are overcome, superconducting motors could substantially reduce emissions and fuel consumption in hybrid-electric aviation (Demaco Holland B.V., 2023).

6. Battery Technology Advancements – Cuberg Lithium-Metal Batteries

Cuberg's lithium-metal batteries mark a significant advancement in aviation energy storage, offering approximately 80% higher energy density compared to conventional lithium-ion batteries. These batteries utilize a high-energy cathode and lithium-metal anode, with a non-flammable electrolyte that addresses safety concerns associated with thermal runaway in traditional lithium-ion batteries. This improvement in both energy density and safety makes them suitable for HHEPS applications, particularly for powering peak demand phases like take-off and climbing. The batteries demonstrated up to a 90% increase in flight time for electric vertical take-off and landing (eVTOL) drones, positioning them as a crucial technology for longer-range hybrid-electric aircraft (*Technology*, 2023).

⛵ Innovations from the Maritime Sector

1. Circular Hydrogen Bunkering Systems Using Metal Borohydride (MBH_4)
   The maritime sector has pioneered a circular bunkering system utilizing metal borohydride (MBH_4) as a solid-state hydrogen carrier. This system allows MBH_4 to react with water onboard to produce hydrogen gas on demand, which is then used in fuel cells. Byproducts, primarily MBO_2 and water, are collected and sent to a regeneration facility to recreate MBH_4, completing the closed-loop system. Figure 36 illustrates this bunkering process for maritime vessels, where fuel is

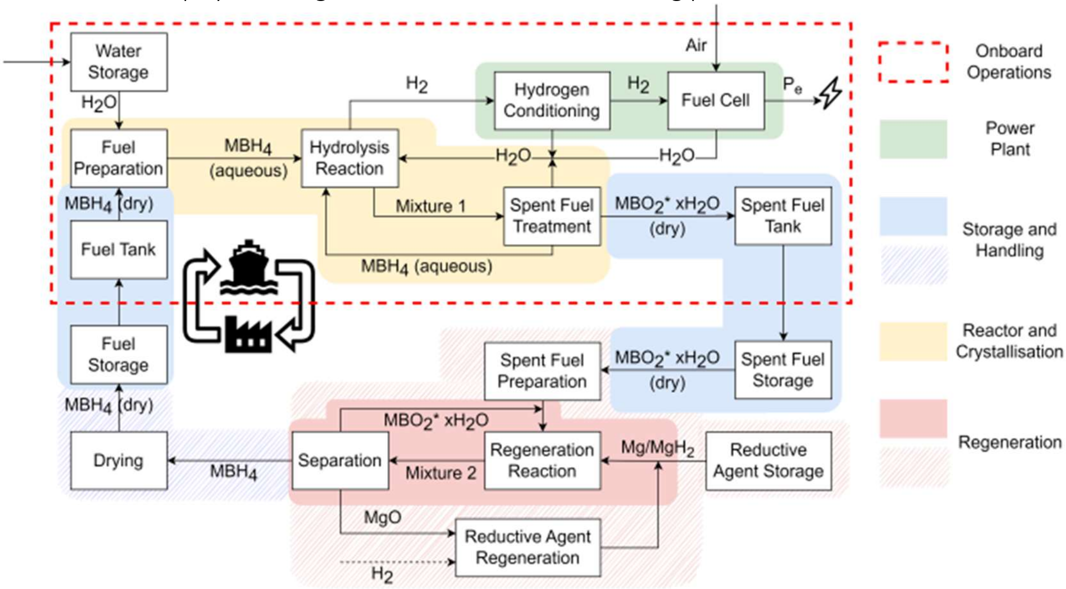

Figure 36 Circular Bunkering Process for a Single Vessel (Towards Hydrogen-fueled Marine Vessels Using Solid Hydrogen Carriers - SH2IPDRIVE, 2024)

continuously cycled and regenerated, providing an innovative model for sustainable hydrogen storage and use. If adapted for aviation, this system could support long-haul flights by reducing reliance on ground-based refuelling and enhancing operational flexibility (SH2IPDRIVE, 2024).

2. Cryogenic Liquid Hydrogen Storage
   Maritime vessels often rely on cryogenic storage to maintain liquid hydrogen at extremely low temperatures (-253°C), which minimizes boil-off and energy loss. These systems use advanced insulation and multi-layered vacuum jackets, allowing for stable, large-scale hydrogen storage over long periods. Aviation could adapt these cryogenic storage systems for onboard fuel tanks, particularly beneficial for long-distance flights where compact, efficient storage is essential.

3. Automated Leak Detection Systems
   Hydrogen leak detection is a critical aspect of maritime hydrogen use, with automated systems employing fiber optic and infrared sensors for real-time monitoring. These systems, proven effective in maritime, can be adapted to monitor hydrogen storage and piping in aircraft, offering continuous monitoring and early detection capabilities essential for onboard safety in aviation (Pixabay et al., 2022).

4. Hybrid Power Management Systems
   Maritime hybrid systems manage power efficiently by integrating fuel cells with batteries, enabling energy capture during low-demand periods and redistribution during peak demand. This method maximizes fuel cell efficiency and can be applied in aviation, where phases like take-off and ascent require peak power. Storing and redistributing energy within hybrid systems in aviation could reduce fuel consumption, increase range, and improve overall energy efficiency (Han et al., 2014).

Innovations from the Trucking Sector

1. Modular Hydrogen Generation Units
   The trucking industry has pioneered modular hydrogen generation units that provide flexible, on-site hydrogen-powered solutions at depots, supporting scalable and adaptable refuelling. An example of this technology is the Huade Hydrogen CarNeu-100 unit, a modular fuel cell system designed for high-efficiency power generation using low-temperature Proton Exchange Membrane (LT-PEM) technology. Operating with 99.97% pure hydrogen, this unit consumes approximately 6 kg of hydrogen per hour and provides a power output of 100 kW, with an efficiency rate of over 92% for power generation and a total efficiency above 47%. The system also generates heat output, capable of delivering hot water at a maximum temperature of 65°C with a flow rate of up to 1.3 tons per hour.

   For aviation, such modular units could be valuable at smaller airports or regional hubs where permanent hydrogen infrastructure is not yet feasible. The CarNeu-100's compact, portable design enables on-demand power generation with flexible output voltages of 380V or 110V AC at 50Hz, making it ideal for varied operational needs. By using systems like the Huade CarNeu-100, airports can scale hydrogen-powered infrastructure efficiently, meeting fluctuating demands without significant investment in permanent facilities, which supports the broader adoption of hydrogen-powered aircraft (*CarNeu-100_Jiangsu HuaDe Hydrogen Energy Technology Co., Ltd.*, n.d.).

2. Hybrid Fuel Cell-Battery Configurations for Peak Power Management
   In trucking, hybrid configurations that integrate fuel cells with high-capacity batteries allow efficient energy management during high-demand phases, like uphill driving or heavy loads. Such systems can be adapted for aviation, where batteries could support fuel cells during take-off and landing, and then recharge during lower-demand cruising. This setup enhances energy efficiency and extends fuel cell life by reducing strain during peak-demand phases, meeting aviation's dynamic energy requirements (Di Ilio et al., 2021).

3. Lightweight Composite Materials for Hydrogen Tanks
   The trucking sector has pioneered **lightweight composite materials** for hydrogen tanks, significantly reducing vehicle weight while maintaining structural integrity. As illustrated in Figure 37, hydrogen storage tanks are available in various types (Type I to Type V), each with unique material compositions and structural designs. Types IV and V, which use lightweight composite

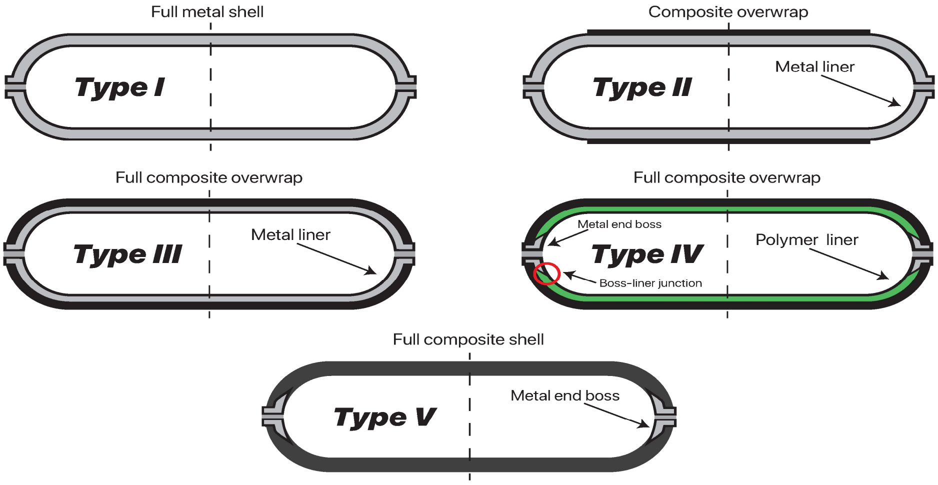

Figure 37 Types of Hydrogen Storage Tanks

   materials and polymer liners, are particularly suitable for high-pressure storage while maintaining a reduced weight, making them ideal for both trucking and aviation applications. In aviation, adapting these lightweight materials for fuel tanks and structural components could enhance fuel efficiency by reducing aircraft weight, a crucial factor in maximizing the range and energy density of hydrogen-electric systems (Halder et al., 2024).

4. Mobile Hydrogen Bunkering Units
   Similar to maritime applications, the trucking sector has implemented **mobile bunkering units** to provide hydrogen refuelling flexibility across various locations, particularly for regions lacking permanent infrastructure. Enapter's approach to mobile hydrogen refuelling exemplifies this concept, using compact, mobile electrolyser units to generate and distribute hydrogen on demand, making refuelling accessible without costly infrastructure investments. These mobile systems allow hydrogen to be produced and supplied where it's needed, enabling flexible distribution at multiple locations and adapting to variable demand.

   For aviation, particularly at smaller or regional airports, adapting mobile hydrogen bunkering units based on Enapter's model could provide a cost-effective and scalable solution. These mobile units would support aviation's transition to hydrogen by enabling decentralized hydrogen supply at airports without the need for dedicated refuelling stations, allowing for adaptable, on-demand refuelling as the sector scales its hydrogen infrastructure (Benz, 2022).

The latest technological advancements in Hydrogen Hybrid Electric Propulsion Systems (HHEPS) — spanning fuel cell innovations, solid-state hydrogen storage, modular configurations, advanced motors, and battery technologies — are transforming hydrogen-electric aviation. Each development contributes to overcoming critical challenges in fuel efficiency, energy density, and safety, bringing HHEPS closer to commercial viability and positioning hydrogen as a foundational element in sustainable aviation. As the aviation industry integrates these technologies, HHEPS will be central to reducing emissions and achieving zero-emission flight, fostering a future where aviation operations align with global sustainability goals.

Building upon these advancements, the following chapter, Technology Translation and Adaptation, explores how the aviation sector can leverage these innovations through insights from maritime and trucking sectors. By examining cross-sector case studies, we will identify how technological expertise from these industries can be adapted to meet aviation's unique demands, accelerating the integration of hydrogen-electric systems and establishing a robust foundation for sustainable aviation solutions

Chapter 15: Technology Translation and Adaptation

This chapter builds on the knowledge gained from extensive research and detailed case studies in the maritime and trucking sectors. Projects like the MF Hydra, SF-BREEZE, Hyundai Xcient Fuel Cell Truck, and Nikola Tre Fuel Cell Electric Vehicle have pioneered hydrogen technologies, providing practical insights into hydrogen storage, thermal management, safety systems, and infrastructure. Although these hydrogen applications operate at sea level or on the road, the aviation sector introduces unique challenges, such as altitude-induced pressure variations, extreme temperatures, and strict weight constraints.

Drawing from these case studies, this chapter explores how hydrogen systems from maritime and trucking can be adapted for aviation. By leveraging cross-sector advancements, the aviation industry can integrate hydrogen propulsion technology more effectively, accelerating the shift toward sustainable air travel.

- <u>Leveraging Maritime and Trucking Advancements for Aviation</u>

The aviation sector stands to benefit significantly from systems developed in the maritime and trucking industries, particularly in hydrogen infrastructure. Several technologies and processes used in these sectors provide a foundation for aviation adaptations:

1. Bunkering Processes: High-pressure hydrogen bunkering systems, like those used in the MF Hydra ferry, can inform aircraft refuelling designs. These systems employ high-pressure hoses, connectors, and safety interlocks to ensure safe and efficient hydrogen transfer, which is crucial for reliable airport operations.
2. Storage Solutions: Innovations in hydrogen storage from heavy-duty trucks, exemplified by the Nikola Tre's use of lightweight composite pressure vessels, offer a pathway to more efficient storage in aviation applications. Additionally, cryogenic storage techniques from maritime, such as those at the Port of Antwerp, provide best practices that can inform liquid hydrogen systems in aircraft.
3. Distribution Systems: Trucking's hydrogen distribution strategies, including specialized transport vehicles, can support hydrogen supply chains for airports. Initiatives like the Port of Klaipeda's hydrogen production and refuelling infrastructure offer valuable logistics insights for aviation.
4. Refuelling Station Technology: Hydrogen refuelling stations, such as the Nikola HYLA Station, equipped with safety monitoring and dispensing systems, can serve as models for aviation refuelling infrastructure. Automated refuelling technology from maritime applications could streamline airport hydrogen operations.
5. Regulatory Frameworks: Safety regulations established by the International Maritime Organization (IMO) for hydrogen bunkering provide a framework that the aviation sector can adopt, helping to ensure safe hydrogen handling and regulatory compliance.
6. Collaborative Research and Development: Collaborative initiatives, such as those involving NASA in hydrogen propulsion technologies, highlight the value of cross-sectoral knowledge sharing. Partnerships like these can accelerate hydrogen infrastructure development and safety standards in aviation.

These cross-sectoral advancements not only inform the technological adaptations needed for aviation but also highlight the importance of collaboration in building a sustainable hydrogen infrastructure.

Specific Adaptations for Aviation

The following sections detail specific adaptations required to tailor maritime and trucking hydrogen technologies to aviation's unique conditions.

1. Helium Integration for Hydrogen Safety

- Current Use in Maritime: Maritime hydrogen systems, such as those in the SF-BREEZE ferry, often use helium to purge hydrogen lines, preventing combustion.
- Adaptation for Aviation: Helium offers advantages for purging in aviation due to its non-reactivity and low freezing point, which remains stable under cryogenic temperatures.
- Proposed Solution: Integrate helium as an inert gas in hydrogen systems to prevent combustion risks. Helium's inert nature and ability to remain gaseous at low temperatures make it ideal for purging lines, creating a safer operating environment in hydrogen-powered aircraft.

2. Pressure Management at High Altitude

- Current Use in Maritime: Maritime systems, such as those in the SF-BREEZE ferry, utilize pressure-relief valves to manage hydrogen expansion due to temperature changes at sea-level pressure.
- Adaptation for Aviation: Rapid pressure drops during ascent (from 1 bar at sea level to approximately 0.2 bar at 35,000 feet) cause hydrogen to expand within storage tanks. Aviation applications therefore require altitude-sensitive pressure-relief valves to handle these rapid pressure changes.
- Proposed Solution: Lightweight, altitude-triggered pressure-relief valves made from titanium alloys could ensure structural integrity during altitude shifts, maintaining safe storage without adding unnecessary weight.

3. Thermal Insulation for High-Altitude Temperature Variations

- Current Use in Maritime: Vacuum-insulated tanks with multi-layer insulation keep liquid hydrogen (LH2) at -253°C, suited to the stable temperatures of sea-level conditions.
- Adaptation for Aviation: Aviation temperatures vary significantly, from +15°C at take-off to -60°C at altitude. Insulation systems must not only maintain cryogenic conditions but also be lightweight to meet aircraft design constraints.
- Proposed Solution: Lightweight aerogel-based insulation or composite vacuum insulation panels (VIPs) offer excellent thermal resistance while reducing weight and bulk. These materials ensure cryogenic hydrogen stability without compromising aircraft weight limitations.

3. Boil-Off Management for Altitude-Induced Expansion

- Current Use in Maritime: In maritime systems, boil-off gas (BOG) management captures evaporated hydrogen and re-condenses it or vents it safely at sea level.
- Adaptation for Aviation: At high altitudes, rapid pressure changes increase the risk of hydrogen boil-off. Aviation systems must be capable of handling altitude-induced boil-off without excessive hydrogen loss.
- Proposed Solution: High-efficiency reliquefication systems paired with adaptive venting systems could capture hydrogen vapor and re-condense it during ascent, minimizing boil-off and loss.

4. Tank Structural Integrity for Dynamic Flight Conditions

- Current Use in Maritime: Cryogenic tanks in maritime use durable materials like stainless steel or CFRP to withstand pressure and thermal changes.

- Adaptation for Aviation: Aircraft tanks must be lighter, able to handle up to 2.5 G forces during take-off, and resistant to rapid thermal fluctuations.
- Proposed Solution: Composite tanks made from carbon-fibber-reinforced polymers (CFRP) or aluminium-lithium alloys would reduce weight. Flexible expansion joints would manage stress from altitude changes, ensuring safe storage.

5. Ventilation Systems for Safe Pressure Regulation at Altitude

- Current Use in Maritime: Maritime systems vent hydrogen at sea level to safely release pressure.
- Adaptation for Aviation: High altitudes demand venting systems that can handle rapid hydrogen expansion due to lower external pressures.
- Proposed Solution: Altitude-sensitive venting systems with automatic adjustments and discharge channels would release hydrogen safely, directing it away from sensitive areas on the aircraft.

6. Redundant Systems for Hydrogen Propulsion

- Current Use in Maritime: Maritime systems integrate redundant hydrogen and electric power sources to ensure uninterrupted operation.
- Adaptation for Aviation: Aviation can implement dual redundancy by using hydrogen and battery power, providing fail-safe operations and continuous propulsion.
- Proposed Solution: Design dual energy pathways with hydrogen fuel cells and battery backup to ensure uninterrupted operation and enhance safety, critical for long-haul flights.

7. Economic Strategies from Maritime Hydrogen Adoption

- Current Use in Maritime: The MF Hydra ferry uses Contracts for Difference (CfD) to offset higher hydrogen costs, making operations economically viable.
- Adaptation for Aviation: Similar economic strategies, such as CfDs, carbon credits, and subsidies, can make hydrogen financially viable for aviation, offsetting initial adoption costs.

8. Regenerative Systems

- Current Use in Trucks: Trucks like the Hyundai Xcient employ regenerative braking, converting kinetic energy to recharge batteries.
- Adaptation for Aviation: Aviation could capture energy during descent and landing rollouts to power auxiliary systems.
- Proposed Solution: A Kinetic Energy Recovery System (KERS) using lightweight flywheel technology could be integrated to recharge batteries during descent, extending operational range.

9. Infrastructure Development and Integration

- Current Use in Maritime: Maritime hydrogen refuelling infrastructure supports efficient vessel operations.
- Adaptation for Aviation: Dedicated hydrogen refuelling zones and high-flow dispensers at airports will be essential.
- Proposed Solution: Modular, high-flow hydrogen refuelling stations would streamline airport refuelling, minimizing downtime and meeting aviation's high fuel demand.

10. Hybrid Integration with Renewable Energy Sources

- Current Use in Maritime: Maritime hybrid systems sometimes incorporate solar or wind power to supplement energy demands.

- Adaptation for Aviation: Integrating renewable energy sources in aviation hybrid systems, such as solar panels for high-altitude flights, could reduce hydrogen fuel consumption.
- Proposed Solution: Develop energy-harvesting systems that draw solar power during flights, reducing reliance on hydrogen and maximizing fuel efficiency, particularly in long-haul operations.

Adapting maritime and trucking hydrogen technologies to aviation offers a practical pathway to sustainable aviation. By leveraging helium for safe hydrogen handling, optimizing cryogenic insulation, developing redundancy systems, and implementing regenerative energy systems, the aviation industry can enhance its hydrogen infrastructure and operational efficiency. These cross-sector innovations underscore the critical role of collaboration in advancing sustainable aviation technology and achieving global climate goals.

Chapter 16: Conclusion

This research highlights the transformative potential of hydrogen hybrid-electric propulsion systems within the aviation sector, addressing both critical environmental challenges and the need for sustainable energy solutions. Through integrating hydrogen fuel cells with electric drive systems, aviation can significantly reduce greenhouse gas emissions, presenting a viable path toward net-zero aviation goals. By adapting technologies from the maritime and trucking sectors, such as high-pressure hydrogen storage and automated refuelling systems, aviation can harness proven innovations to meet its unique operational demands.

The findings indicate that several technologies from maritime and trucking can be adapted to aviation, though some require additional innovation to address aviation-specific challenges. Specifically, high-pressure hydrogen storage systems, such as lightweight composite tanks used in heavy-duty vehicles like the Hyundai Xcient and Nikola Tre, show strong adaptability. These tanks effectively store gaseous hydrogen at high pressures, maximizing storage density while meeting aviation's strict weight constraints. Automated, high-speed refuelling systems from the trucking sector, exemplified by Nikola's HYLA stations, also offer a robust solution for aviation's fast turnaround requirements at airports, with high-speed dispensers and built-in safety protocols.

However, certain technologies present ongoing challenges. Thermal management is the most critical area for adaptation, as aviation's strict weight limits make conventional maritime heat dissipation systems, like large-scale heat exchangers, unsuitable. Maintaining the cryogenic temperatures necessary for liquid hydrogen storage, while also dissipating heat generated by fuel cells, requires lightweight and highly efficient thermal management solutions that are not yet available. While advanced materials like aerogels and composite vacuum panels hold promise, further research is necessary to optimize these for aviation use.

Some elements, such as altitude-sensitive ventilation systems, require entirely new aviation-specific solutions. Unlike maritime and trucking, where systems operate at sea-level pressure, aviation faces rapid altitude changes and lower external pressures, causing hydrogen to expand within storage tanks. This demands a specialized ventilation system that can safely adjust to altitude, vent hydrogen away from sensitive areas, and remain lightweight requirements that exceed current maritime and trucking technology capabilities. As such, dedicated R&D is essential to design venting systems suited to aviation's unique conditions.

In summary, while certain technologies from the maritime and trucking sectors can be directly adapted for aviation—such as high-pressure storage and rapid refuelling—thermal management and high-altitude safety systems will require further innovation to align with aviation's operational requirements. These findings underscore the need for a multi-faceted approach, combining cross-sector adaptation with proactive, aviation-specific development to fully realize hydrogen hybrid-electric propulsion in aviation.

A crucial aspect of advancing hydrogen for aviation lies in developing and optimizing hydrogen storage materials. While substantial progress has been made in creating materials with high hydrogen storage capacities, a deeper understanding of the thermodynamics and kinetics of hydrogen adsorption and desorption is essential. This knowledge will enable the design of safer, more efficient hydrogen storage solutions that are lightweight and compact enough for aviation applications.

This cross-sectoral study not only provides technological insights but also contributes to the Strengthening Ecosystems for Aviation (SEA) initiative by fostering a collaborative environment for sustainable innovation. By integrating maritime and trucking advancements—such as hydrogen storage, refuelling protocols, and safety standards—this research strengthens SEA's mission to create a resilient, cohesive ecosystem that supports sustainable aviation. Cross-sector knowledge transfer and collaboration enrich aviation's competencies, accelerating its ability to develop and deploy hydrogen solutions while reinforcing SEA's objectives for sustainable, competitive aviation.

A key observation from this research is that accessing proprietary data on hydrogen technology remains a significant barrier, as companies often protect their systems. This challenge emphasizes the need for aviation to proactively invest in its own hydrogen development, building the expertise necessary to address aviation-specific challenges. Furthermore, the transition to hydrogen cannot occur in isolation; collaboration across sectors is vital to establish the infrastructure, safety standards, and knowledge exchange required to integrate hydrogen into aviation fully.

To make hydrogen-powered aviation a reality, targeted strategies are essential, including investment in refuelling infrastructure at airports, collaboration with regulatory bodies like EASA and FAA to create safety standards, and continued R&D in lightweight thermal management solutions. These recommendations, detailed in the next chapter, provide a roadmap to support both immediate implementation and long-term innovation for hydrogen in aviation.

For hydrogen to serve as a genuinely sustainable fuel alternative, future studies should examine the full lifecycle impacts of hydrogen production, storage, and consumption. Ensuring that hydrogen reduces emissions not only during operation but throughout its lifecycle is critical for a holistic approach to sustainability in aviation. Research on lifecycle impacts will help validate hydrogen’s role as an environmentally sound fuel, supporting aviation’s commitment to sustainability

In conclusion, while hydrogen hybrid-electric propulsion systems present a promising path toward sustainable aviation, the journey will require proactive development, cross-sector collaboration, and strategic investments. By pursuing lifecycle sustainability, strengthening the SEA ecosystem, and leveraging advancements in hydrogen technology, the aviation industry can lead the shift toward a cleaner, more resilient future, effectively positioning hydrogen as a vital component of global sustainability efforts.

Chapter 17: Recommendations

As hydrogen technology advances in aviation, several strategic and economic considerations are essential for overcoming cost, infrastructure, and market acceptance challenges. Drawing on lessons from maritime and trucking, this chapter outlines recommendations for accelerating hydrogen adoption and ensuring its viability as a sustainable aviation fuel.

1. Economic Mechanisms to Bridge the Cost Gap

One of the primary challenges facing hydrogen adoption in aviation is the significant cost disparity between hydrogen and conventional aviation fuels. To address this, the following economic mechanisms are recommended:

- Contracts for Difference (CfD): Similar to the MF Hydra project in maritime, CfDs could help offset the cost difference between hydrogen and traditional aviation fuels by providing financial compensation when hydrogen prices exceed a baseline level. This mechanism can make hydrogen more affordable, encouraging airlines to transition to cleaner fuel sources.

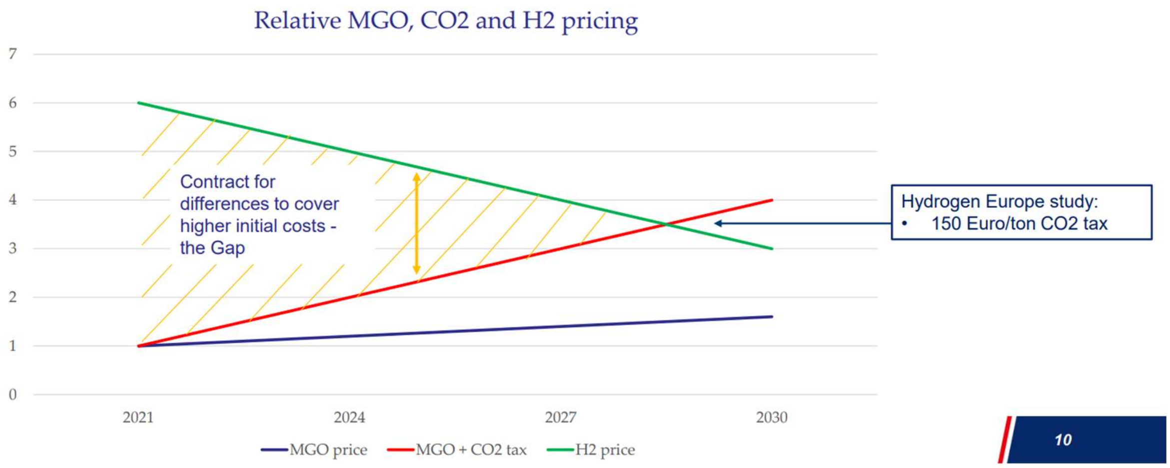

Figure 37 Relative MGO, CO2 and H2 pricing (Østvik et al., 2021)

- Carbon Credits and Tax Incentives: Offering carbon credits and tax benefits to airlines that adopt hydrogen could reduce financial barriers. Airlines could earn carbon credits for hydrogen use, which they could then sell or apply to offset operational costs, providing both an environmental and financial benefit.
- Subsidies and R&D Grants: Governments should consider offering subsidies and research grants focused on hydrogen infrastructure and technology development. This would incentivize private-sector investment in hydrogen solutions, from fuel cell innovations to refuelling infrastructure.

These economic tools will make hydrogen-powered aviation more financially competitive, fostering greater adoption across the industry.

2. Refuelling Infrastructure Development at Airports

Establishing hydrogen refuelling infrastructure at airports is critical for hydrogen-powered aviation to scale. Drawing from hydrogen refuelling practices in trucking and maritime, these infrastructure developments are recommended:

- High-Speed Refuelling Stations: To meet aviation's quick turnaround needs, hydrogen refuelling rates must be faster than current road vehicle standards. It is recommended to develop stations capable of dispensing gaseous hydrogen at approximately 9 kg per minute and liquid hydrogen at up to 111 kg per minute, supporting fast refuelling for regional and larger aircraft.
- Dedicated Hydrogen Refuelling Zones: Airports should designate specific zones for hydrogen refuelling with high-flow dispensers, storage tanks, and safety monitoring systems. This approach

minimizes refuelling time and ensures streamlined, safe handling of hydrogen near runways and terminals.

- Modular, Scalable Infrastructure: Implement modular refuelling stations that can be expanded as demand grows. Modular setups allow airports to start small and scale up as more hydrogen-powered aircraft come into operation, making it cost-effective and adaptable.

3. Leveraging Market Insights from Heavy-Duty Hydrogen Vehicles

The commercial viability and market acceptance of hydrogen vehicles in the trucking sector, such as the Hyundai Xcient and Nikola Tre, offer valuable insights for aviation. The following strategies are recommended to address market and infrastructure concerns:

- Public Awareness and Education: Like the trucking sector, aviation will need to foster public awareness and confidence in hydrogen safety and reliability. Educating passengers, airline staff, and the public on hydrogen safety can reduce resistance and improve market acceptance.
- Phased Introduction of Hydrogen Aircraft: Begin with shorter, regional routes to demonstrate the safety and efficiency of hydrogen-powered aircraft. This phased approach mirrors the strategy of heavy-duty hydrogen trucks, gradually building trust and proving viability before wider deployment on long-haul routes.
- Partnerships with Fuel Suppliers: Collaborate with hydrogen suppliers, as seen in trucking partnerships, to secure a steady hydrogen supply chain for airports. This collaboration can help create efficient logistics and ensure a consistent fuel supply as hydrogen-powered aviation grows.

4. Policies to Support Hydrogen Safety and Certification Standards

Given the stringent safety requirements in aviation, it is essential to adapt regulatory frameworks from maritime hydrogen systems to ensure safe handling, storage, and usage of hydrogen in aviation.

- Adopt Maritime's Hydrogen Safety Protocols: The International Maritime Organization (IMO) provides a valuable regulatory foundation for hydrogen safety protocols that aviation can adapt. Regulations on hydrogen bunkering, leak detection, venting, and fire suppression systems are essential for aviation and should be developed in collaboration with bodies like the International Civil Aviation Organization (ICAO).
- Hydrogen-Specific Certification Processes: Establish a dedicated certification process for hydrogen propulsion systems, from fuel cells to refuelling protocols, ensuring that hydrogen-powered aircraft meet high safety standards. This will enable streamlined certification for hydrogen systems as they become more widely adopted in aviation.
- Support from Civil Aviation Authorities: National and international aviation authorities should work together to develop consistent standards and guidelines for hydrogen technology, ensuring safe and unified adoption across regions.

5. Advanced Refuelling Speed Requirements and Automation

To meet operational demands, hydrogen refuelling must become faster and more efficient. Inspired by practices in the trucking sector, these refuelling recommendations would support seamless integration into aviation operations:

- Automated Refuelling Systems: Automation in refuelling, as seen in maritime hydrogen bunkering, can expedite turnaround times and enhance safety. Airports should invest in automated refuelling systems equipped with remote monitoring and control to manage large-scale hydrogen refuelling efficiently.
- Regular Upgrades and Maintenance: Refuelling stations must be equipped with up-to-date safety and monitoring systems. Regular upgrades and rigorous maintenance protocols, as practiced in the maritime sector, will help prevent accidents and ensure compliance with hydrogen safety standards.

6. Strategic Integration of Renewable Energy Sources

Drawing from maritime applications where solar and wind energy are integrated into hybrid systems, aviation could consider renewable energy to support auxiliary functions:

- Solar Power for Auxiliary Systems: Incorporating solar panels on aircraft for auxiliary power, particularly during high-altitude flights, could reduce hydrogen consumption slightly by supporting non-propulsive systems. This approach could optimize fuel usage without requiring significant changes to aircraft design.
- Ground-Based Renewable Energy Integration: Airports can supplement hydrogen refuelling infrastructure with on-site renewable energy sources, like solar or wind, to power hydrogen production and storage. This setup would reduce reliance on external power grids and support the carbon-neutral goals of hydrogen-powered aviation.

7. Continued Investment in R&D and Cross-Sector Collaboration

The development of hydrogen-powered aviation will require sustained investment in research and development. Collaboration with the maritime and trucking sectors can accelerate progress:

- Joint Research Programs: Initiate collaborative programs with maritime and trucking experts to advance hydrogen storage, insulation, and thermal management technologies. These cross-sector efforts can streamline solutions that meet aviation-specific challenges.
- Demonstration Projects and Testing Facilities: Invest in dedicated testing facilities for hydrogen-powered aircraft to conduct long-term trials, validating performance, safety, and reliability. These projects will build confidence in hydrogen technology and address aviation-specific issues, such as high-altitude performance.
- Continuous Knowledge Exchange: Maintain an ongoing dialogue with hydrogen technology leaders in other sectors to learn from their advancements and address shared challenges. This collaborative approach will help aviation access new innovations and implement the most effective technologies.

8. Continued Research on Technology Translations for Aviation

While several technology adaptations from the maritime and trucking sectors show significant promise, hydrogen-powered aviation is a relatively new field with unique operational and regulatory demands. Further investigation is essential to refine these solutions and address hidden challenges that may arise during their application in aviation.

- Focus on Operational Testing: Conducting extensive operational testing in real-world flight conditions will be crucial to understanding how adapted technologies perform at high altitudes and in variable weather conditions.
- Addressing Aviation-Specific Challenges: Some technologies, while effective in maritime or trucking, may encounter unexpected issues in the aviation environment. This includes challenges related to high-altitude pressure, weight constraints, and rapid temperature shifts.
- Developing Adaptive Solutions: Continued R&D should focus on making these adapted technologies resilient to aviation's dynamic operating conditions, ensuring both safety and performance are maintained. For instance, in the Technology Translation chapter, specific solution for the aviation sector was mentioned, further investigation is required to determine whether these solutions can effectively apply in real-world aviation scenarios. Testing and validation should confirm that these adapted technologies maintain both safety and performance standards under dynamic operating conditions specific to aviation

The aviation industry can make significant strides in sustainable fuel use by adopting hydrogen technology and drawing from the successes and strategies in the maritime and trucking sectors. Through targeted economic incentives, robust infrastructure, regulatory frameworks, and cross-sector collaboration, hydrogen-powered aviation can become viable, paving the way for a greener future in air travel.

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Appendices

Appendix A: Assignment Description

BackgroundThe Netherlands, with its knowledge and research institutions, including field labs, small and medium-sized companies, large industry and a committed government, has a strong position in the current aviation market. However, this ecosystem needs to be strengthened in order to successfully accelerate the transition to sustainable aviation. Competences, technologies and infrastructure are needed that cannot be found in the current aviation ecosystem, but can be found in other Dutch sectors, such as automotive, energy, high-tech equipment, ICT and maritime. By intensifying cross-sectoral and sector-wide cooperation, the Dutch (aviation) ecosystem will be enabled to accelerate the intended transition and realize the earning capacity. This study is part of the Growth Fund project “Aerospace in Transition” (GF LiT), sub project SEA “Strengthening Ecosystems”.

Objectives:
The aerospace ecosystem will be strengthened and the transition to sustainable aviation will be accelerated by identifying and disseminating missing technologies, competences and infrastructures that are available in other sectors.

Challenges
Many technologies, competences and infrastructures are developed for specific applications. The use in other sectors and or applications may look obvious, however, without a thorough understanding of the requirements that has driven the initial development and the set of requirements for the new applications, implementation maybe hampered. A second challenge is that many technologies in the journey to sustainable aviation are at low TRL, making it less
easy to identify what is missing. Nevertheless, the complexity of the transition to sustainable aviation in combination with the limited time to develop, test and certify new solutions urges the use of all available cross-sectoral building blocks.

Approach
Interviews, attending project meetings, conferences, etc.
Desk research including analysis of reports and literature.

Deliverables
Survey of technologies developed in the GF LiT
Analysis of missing technologies, competences and infrastructures
Identifying cross-sectoral technologies, competencies and infrastructures that could fill the gaps Capture the relevant information in a database.

Presentation of the approach and the results to the GF LiT participants

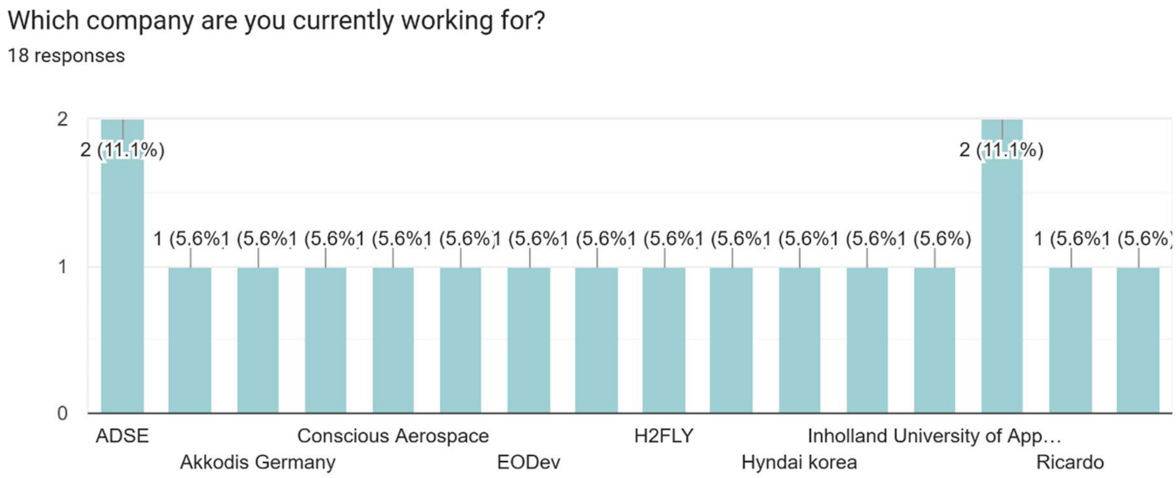
Company supervisor:
Peter Kortbeek
06 5139 1114

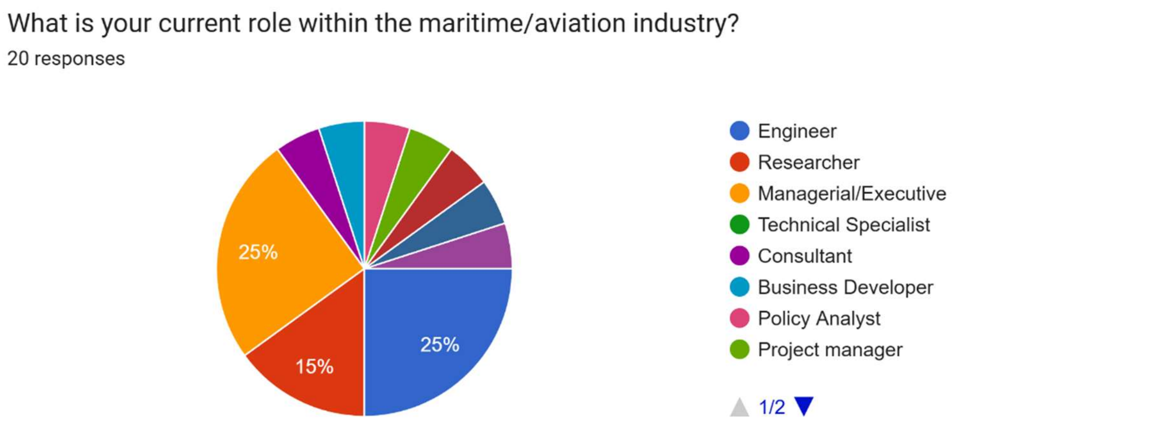
Appendix B: Survey questions

Cross-Sectoral Analysis of Hydrogen Hybrid Electric Propulsion in Maritime and Aviation Industries

This survey aims to gather expert insights into the development, challenges, and potential of hydrogen hybrid electric propulsion systems within the maritime and aviation sectors. As the global emphasis on reducing carbon emissions intensifies, these industries are pivotal in adopting innovative propulsion technologies that could significantly influence environmental outcomes.

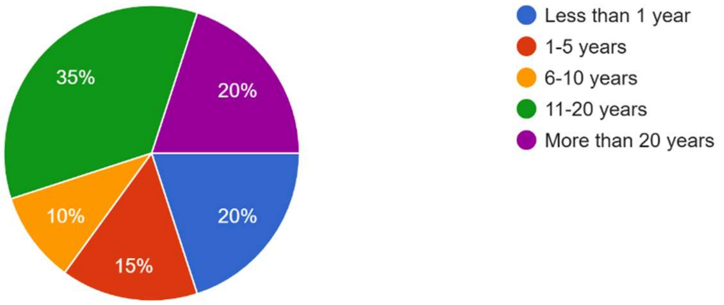
This research is part of a thesis project conducted by Hana Alnajjar, a graduate student at Inholland university. The survey seeks to understand technical barriers, market readiness, and the cross-sectoral applicability of hydrogen technologies from maritime to aviation. The results will provide valuable data to support academic research, influence industry practices, and inform policymaking in sustainable propulsion technologies. Your expertise and responses are crucial in shaping a comprehensive view of the future landscape of hybrid electric propulsion systems.





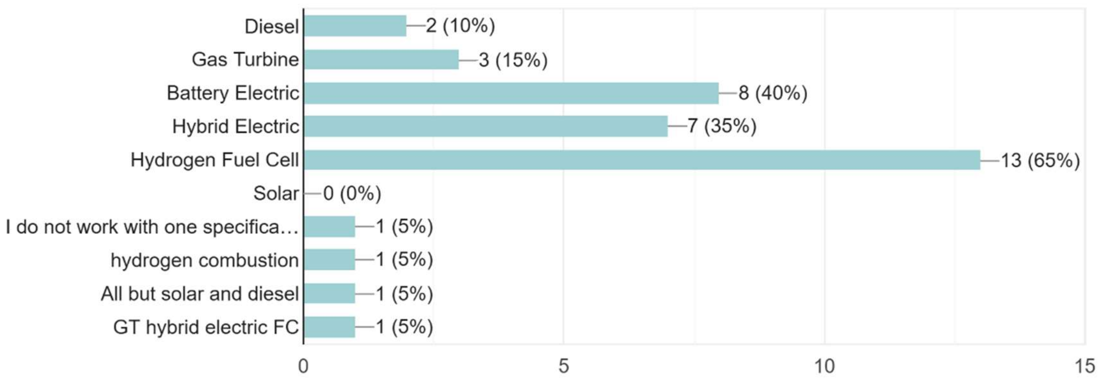
How many years of experience do you have in this industry?

20 responses



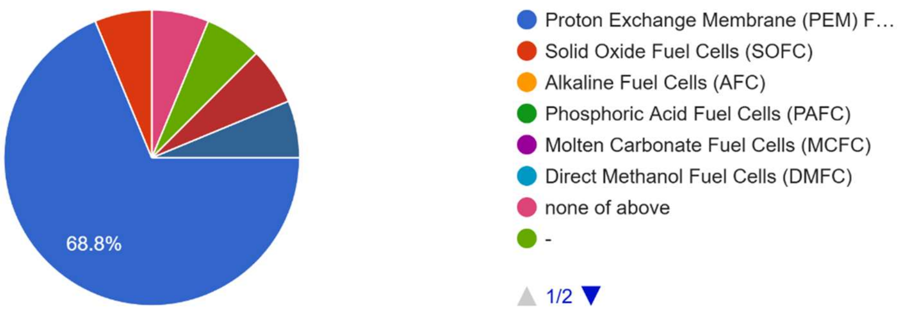
What types of propulsion systems are you currently working with or researching?

20 responses



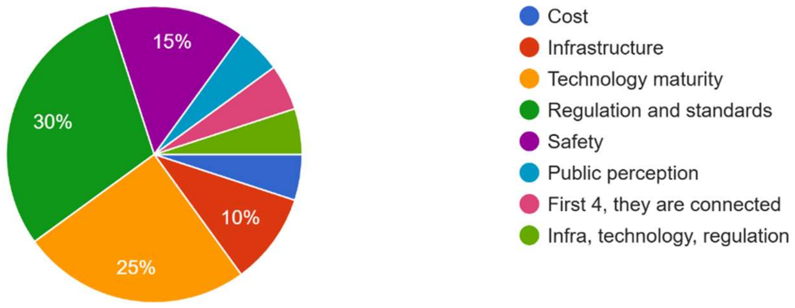
If you selected hydrogen fuel cells, what type are you working with?

16 responses



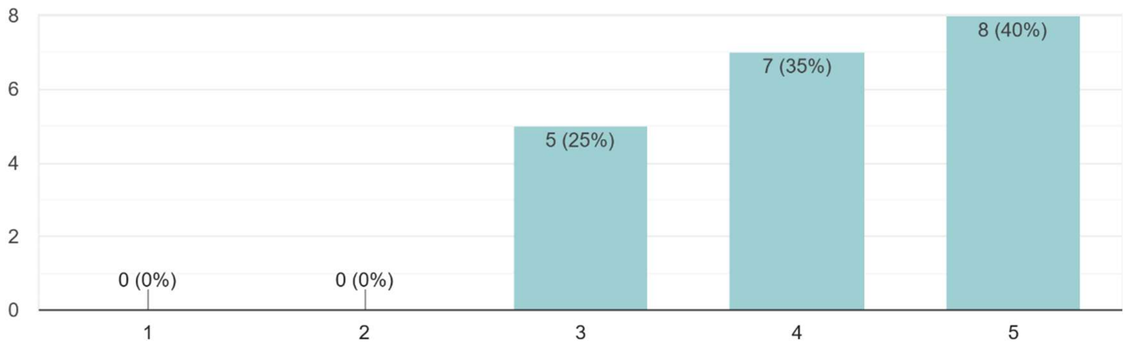
Based on your experience, what are the primary technical challenges in developing and implementing hydrogen hybrid electric propulsion systems?

20 responses



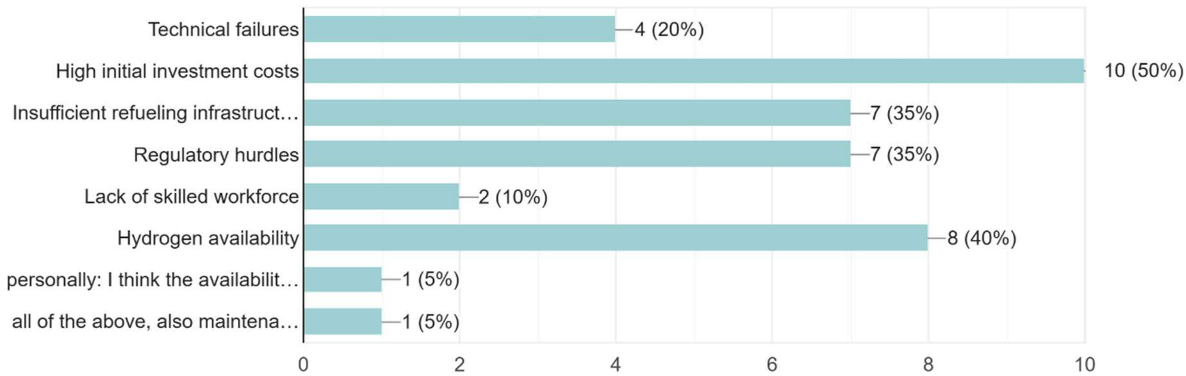
How would you rank the difficulty of the challenges you selected?

20 responses

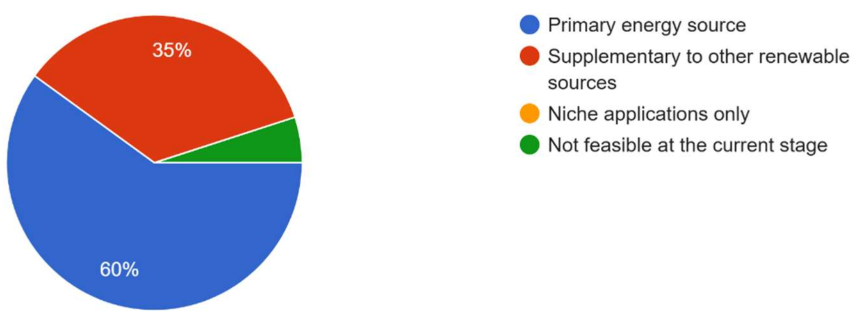


What are the perceived risks associated with the adoption of hydrogen hybrid electric propulsion in your sector?

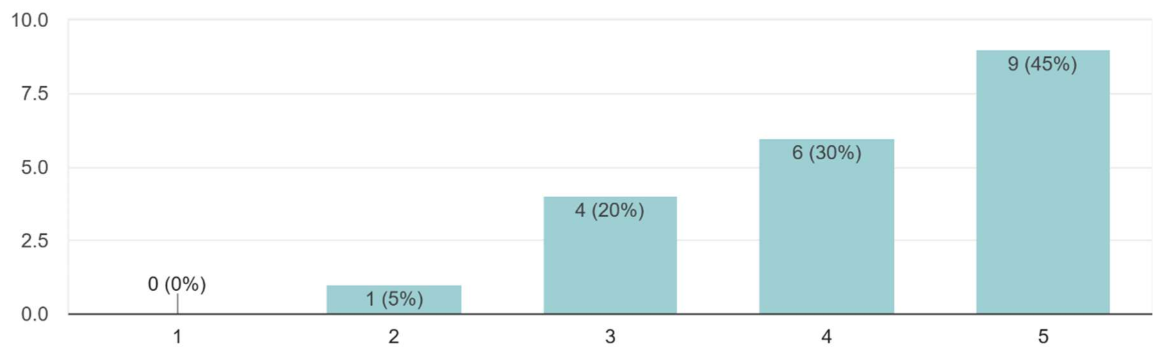
20 responses



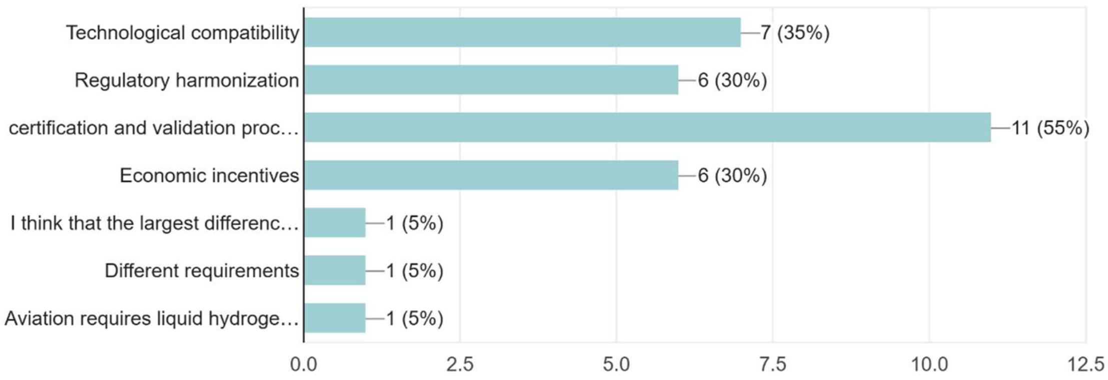
What is the optimal role of hydrogen propulsion in your sector's future energy mix?
20 responses



How do you rate the potential of hydrogen hybrid electric propulsion to transform the maritime/aviation sector?
20 responses



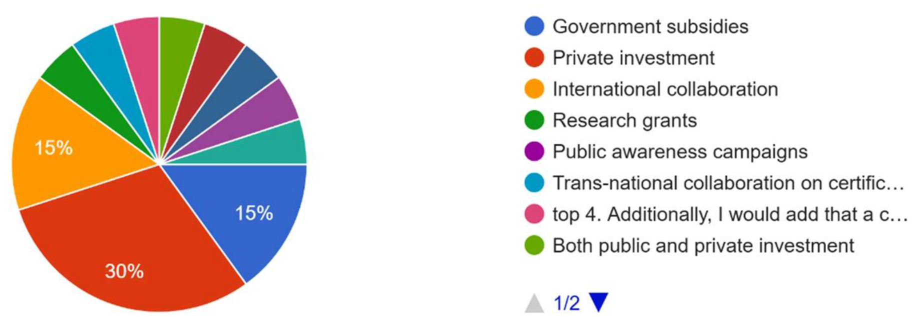
In your opinion, what are the critical factors for successful cross-sectoral transfer of this technology from maritime to aviation?
20 responses



What advancements in hydrogen propulsion technology do you foresee in the next 5-10 years?
17 responses

- Within 5-10 years, first flights on hydrogen. Not sure if commercial flights are already happening though.
- For aviation: Operating small hydrogen electric aircraft (covered under CS-23), first as test- and demonstrator aircraft and later as commercial aircraft (trainers etc). For larger aircraft the first test flights may be performed in this timeframe.
- more reliable, and efficient LTPEMFC & the introduction of competitive HTPEMFC
- adaption in use
- Bi fuel solution
- First application in service
- Production, onboard storage and infrastructure
- From niche to mainstream
- In this time frame it's still challenging
- Increased efficiency
- MW PEM FCS flying regularly, and parts being certified
- Hydrogen propulsion: first plane with passengers will fly in 5 years from now
- Certified high temperature fuel cells. Fully CFRP LH2 storage
- Hydrogen generator to template step by step diesel engine
- Higher power, better efficiencies
- Reduced cost. Improved power density. Improved efficiency and life.
- I hope that progress will be made in producing hydrogen on a large scale with renewable energy sources (otherwise it does not make sense) and I hope that technological solutions will be developed to make it safer.

What kind of support (policy, investment, research, etc.) is needed to accelerate the adoption of hydrogen hybrid electric propulsion in these sectors?
20 responses



What additional insights can you share about the integration of hydrogen propulsion technology in maritime and aviation?
20 responses

- As I said, it seems overlooked that green hydrogen is hard to get, and very expensive. This needs resolve.
- none, sorry. I am under NDA.
- It will certainly start regionally with FC, in the 2030's, then with direct combustion for long haul in maybe the 2040's. FC technology in aviation is more or less where combustion was during the 1940's; we have not experienced the rapid growth stage yet.
- Safety issues have to be addressed early during development requiring upfront investments
- Production really hast to scale up and it will also compute with industry

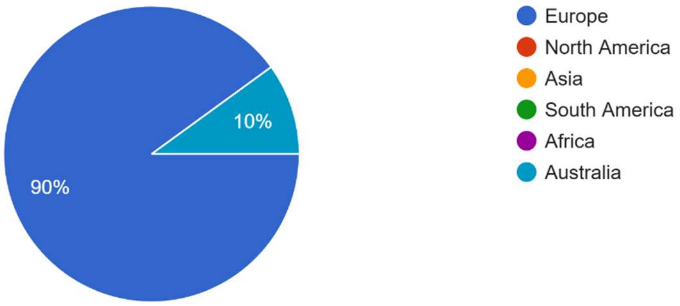
- Maybe primary commonalities in infrastructure and H2 availability
- H2 technologies Will needs further boost to catch up to the dynamic change in climate.
- Maritime seems more do-able, since aviation is weight and volume constraint
- While there is a lot of hydrogen powertrain development currently within the aviation sector, there is still a lack of knowledge in LH2 within the aviation sector
- Regulation is a big hurdle today. The price of hydrogen is too high. The storage, transportation and delivery of h2 is also a big challenge.
- Usage of ultracapacitors
- Challenging to achieve standards and certification requirements. Technically challenging to deliver optimized, high-power systems. But…. Achievable!
- As stated before, Hydrogen will only become a sustainable fuel if it can be produced on a large scale from renewable energy sources.

Do you have any specific recommendations or advice for research areas or practical applications in this field?

20 responses

- Close collaboration with certification bodies
- For hydrogen aviation there are already a number of research projects running. NLR is investing in new hydrogen facilities and universities are doing a lot of research. The main challenge right now is to actually couple this obtained to commercial partners.
- Build systems with compliance in mind and understand your design problem properly before you start with the solution.
- Start with the end in mind taking all life cycle processes seriously
- Weight reduction power density increase
- Not yet
- Continue research about onboard storage and energy conversion
- A lot is already going on. No clear gaps.
- Cryogenic cooling
- H2 Airport infrastructure
- Not really
- Mainly H2 storage and distribution and High Temperature fuel cell PEM
- motivate others to join this field
- Cheap storage and transportation of h2.
- Ultracaps and galvanic isolated systems
- Short with standards and certification requirements
- Don't focus only on hydrogen. Keep searching for alternative solutions!

Which global regions do you think will lead in adopting hydrogen propulsion technologies in the next decade?
20 responses



Please write down the specific companies you may know that are relevant to the topic discussed20 responses

- Oh, so many. Pls check all companies in Luchtvaart in Transitie.
- I already sent you the list of duch hydrogen companies but NLR, Cryoworld, Concious aerospace, Fokker Next gen are the most relevant (semi)commercial parties to me right now.
- ZeroAvia, Universal Hydrogen, Conscious Aerospace, Beyond Aero, Airbus, Fokker Next Gen
- TUD
- Airbus Conscious Collins universal hydrogen
- APUS Airbus
- Wenger Engineering
- Roger, shell
- The list is too long.
- Airbus
- H2Fly, Airbus, maersk, linde
- Universal hydrogen, zero avia
- ZeroAvia Airbus
- Startups like Conscious Aerospace, all companies that have experience with liquid hydrogen distribution, fuel cell companies and of course the big companies like Airbus, Boeing, Rolls Royse (Hydrogen jet fuel). Success with your graduation!
- Airbus, Consious Aerospace, Zero Avia, Fokker next gen, H2fly, PowerCell
- HD
- Eodev
- Ballard
- Ricardo
- NLR, Fokker GKN, TU Delft

Appendix C: System Specifications

C1: The Water Go Round

System specifications

The Water-Go-Round is the first hydrogen fuel cell-powered ferry in the United States, serving as a demonstration of hydrogen propulsion technology for maritime applications. Below are the system specifications and details about its hybrid hydrogen-electric propulsion system (Kammerer, 2019):

General Information:

- Type: Passenger ferry
- Owner/Operator: Golden Gate Zero Emission Marine (GGZEM)
- Location of Operation: San Francisco Bay, USA
- Capacity:
    - Passengers: Approximately 84 passengers
    - Crew: 3 crew members

Propulsion System:

- Primary Propulsion: Hydrogen Fuel Cells
    - Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells.
    - Power Output: 3 x 120 kW fuel cells, totalling 360 kW.
    - Manufacturer: Cummins Hydrogenic
    - Weight: Not found
- Secondary Power Source: Battery System
    - Battery Capacity: 100 kWh lithium-ion battery pack
    - Purpose: Batteries provide supplementary power during peak demand and energy storage for low-speed operations such as docking and maneuvering.
    - Manufacturer: XALT Energy
- Propulsion Motors: Electric motors powered by the combined output of the hydrogen fuel cells and battery system.
    - Electric Motor Output: 2 x 300 kW

Hydrogen Storage System:

- Hydrogen Type: Compressed Hydrogen (H2)
    - Storage Capacity: 250 kg of hydrogen
    - Storage volume: 11.98 m^3 (calculated @298 K room temperature)
    - Storage Pressure: Stored at 250 bar (3,600 psi)
    - Storage Tanks: Composite high-pressure tanks that safely store compressed hydrogen.

Operational Features:

- Range: The Water-Go-Round can operate for up to 2 days on a single fill of hydrogen, depending on operational conditions. It is designed for short-haul routes in San Francisco Bay.
- Refuelling: Hydrogen is refuelled at specialized stations capable of handling compressed hydrogen gas at high pressure.
- Speed: The ferry has a cruising speed of approximately 12 knots (22 km/h) and a top speed of 22 knots (41 km/h).

Environmental Impact:

- Emissions: Zero-emission ferry; the only byproduct of the hydrogen fuel cell system is water vapor.
- Energy Efficiency: The combination of hydrogen fuel cells and batteries results in high energy efficiency, reducing the ferry's overall carbon footprint compared to diesel-powered alternatives.

Safety Systems:

- Leak Detection: The ferry is equipped with hydrogen sensors to detect leaks and has automatic shutdown procedures in case of a breach.
- Fire Suppression: State-of-the-art fire suppression systems are installed to manage potential fires in both the hydrogen and battery compartments.
- Emergency Venting: The compressed hydrogen storage tanks are equipped with emergency venting systems to safely release hydrogen gas in the event of overpressure.

Figure 38 Water-Go-Round vessel (Kammerer, 2019)

Technological and Operational Advancements:

- Pioneering Technology: Water-Go-Round is a pioneering project aimed at demonstrating the viability of hydrogen fuel cell technology for maritime applications. It serves as a pilot project for the development of hydrogen-powered vessels in the United States.
- Hybrid System: The ferry operates on a hybrid system, combining hydrogen fuel cells and batteries to maximize efficiency and minimize emissions during various operational modes (e.g., cruising, docking).

Infrastructure Development:

- Hydrogen Refueling: The ferry has access to refueling infrastructure at ports in the San Francisco Bay area that support compressed hydrogen. This infrastructure is part of California's broader push toward zero-emission transportation technologies.

Conclusion:

The Water-Go-Round is an important milestone in the development of hydrogen-powered maritime vessels in the United States. Its hybrid system, combining hydrogen fuel cells with battery power, enables zero-emission operation in one of the busiest maritime regions in the country. This vessel demonstrates the potential of hydrogen as a clean energy solution for short-haul ferry services and serves as a model for future applications in other types of vessels and routes.

C2: SF-Breeze System

SF-BREEZE System Specifications

The **SF-BREEZE** (San Francisco Bay Renewable Energy Electric Vessel with Zero Emissions) is a concept hydrogen fuel cell-powered high-speed passenger ferry designed to demonstrate the feasibility of zero-emission maritime transportation using hydrogen fuel cells. This project, commissioned by the U.S. Department of Transportation and supported by Sandia National Laboratories, envisions a fully operational hydrogen-powered ferry for the San Francisco Bay Area (Sandia National Laboratories, 2016).

General Information:

- **Type**: High-speed passenger ferry (concept design)
- **Owner/Operator**: U.S. Department of Transportation / Sandia National Laboratories
- **Location of Operation**: San Francisco Bay, USA
- **Capacity**:
  - **Passengers**: 150 passengers

Propulsion System:

- **Primary Propulsion**: Hydrogen Fuel Cells
  - **Fuel Cell Type**: Proton Exchange Membrane (PEM) fuel cells
  - **Power Output**: 4.92 MW total from hydrogen fuel cells (equivalent to approximately 6,600 horsepower)
  - **Manufacturer**: Ballard Power Systems (fuel cell provider for conceptual design)
  - **Total mass of the SF-BREEZE LH2/fuel cell system**: 11,640 kg (LH2 tank) + 32,000 kg (Fuel Cell Power Racks) + 907 (evaporator) = 44,547 kg.
  - **Total volume of the SF-BREEZE LH2/fuel cell system** : 29.76 m3 (LH2 tank) + 64.88 m3 (fuel cells) + 1.73 m3 (evaporator) = 96.37 m^3
  - **Deliverable volumetric energy density**: 791.6 MJ/m^3 .
- **Secondary Power Source**: Battery System (Conceptually Possible)
  - While the SF-BREEZE design primarily focuses on hydrogen fuel cells, future iterations could incorporate batteries for additional energy storage or peak shaving.
- **Propulsion Motors**: Electric propulsion motors powered by hydrogen fuel cells.
  - **Electric Motor Output**: Approximately 4.92 MW, matching the fuel cell power output for high-speed ferry operations.

Hydrogen Storage System:

- **Hydrogen Type**: Compressed Hydrogen Gas (H2)
  - **Storage Capacity**: 1,200 kg of hydrogen
  - **Storage Pressure**: Stored at 350 bar (5,000 psi)
  - **Storage Tanks**: Large composite high-pressure tanks capable of safely storing the compressed hydrogen.

Operational Features:

- **Range**: Approximately 100 nautical miles on a single fill of hydrogen, depending on operational speed and conditions.
- **Speed**: The SF-BREEZE is designed for high-speed ferry service, capable of speeds up to 35 knots (65 km/h), making it suitable for short- to medium-distance passenger routes in the San Francisco Bay Area.

- Route: The vessel is designed to operate on the route between San Francisco and Oakland/Alameda, with potential for expansion to other Bay Area locations.

Environmental Impact:

- Emissions: The SF-BREEZE would be a zero-emission vessel, with the only byproduct of the hydrogen fuel cell system being water vapor, contributing to improved air quality in the San Francisco Bay Area.
- Energy Efficiency: Hydrogen fuel cells offer high efficiency and significant reductions in greenhouse gas emissions compared to conventional diesel-powered ferries, particularly for high-speed operations.

Safety Systems:

- Leak Detection: Equipped with state-of-the-art hydrogen sensors to detect leaks throughout the storage and propulsion systems, with automatic shutdown systems in place to mitigate risks.
- Fire Suppression: Advanced fire suppression systems are included to protect the hydrogen storage tanks and fuel cells in the event of a fire.
- Emergency Venting: The system includes controlled emergency venting protocols for the safe release of hydrogen in case of overpressure.

Technological and Operational Advancements:

- Pioneering Design: The SF-BREEZE is a concept ferry designed to demonstrate the feasibility of hydrogen fuel cells for high-speed maritime operations. It highlights the potential for scaling hydrogen systems to larger, more powerful vessels.
- High Power Density: The ferry's use of hydrogen fuel cells at such high power levels (close to 5 MW) demonstrates that hydrogen can be used not only for small vessels but also for high-speed, high-power applications, expanding the scope of hydrogen-powered vessels.

Infrastructure Development:

- Hydrogen Refueling: The design includes infrastructure plans for refueling compressed hydrogen at San Francisco Bay Area ports. The refueling stations would need to accommodate high-pressure hydrogen gas in large quantities to meet the ferry's operational needs.

Conceptual Insights:

- Scalability: SF-BREEZE aims to show that hydrogen fuel cells can be scaled to meet the demanding power needs of high-speed ferries, with potential implications for larger vessels and other types of maritime transport.
- Decarbonization: The SF-BREEZE concept aligns with California's broader goals of reducing emissions and promoting renewable energy use, especially in high-traffic areas like San Francisco Bay.

C3: MF-Hydra System

MF Hydra System Specifications

General Information:

- Type: Passenger and car ferry
- Owner/Operator: Norled, a leading Norwegian ferry operator
- Location of Operation: Norwegian fjords
- Capacity:
  - Passengers: Approximately 300 passengers (295 currently)
  - Crew members: 8 crew members
  - Vehicles: Up to 80 cars

Propulsion System:

- Primary Propulsion: Hydrogen Fuel Cells
  - Fuel Cell Type: Proton Exchange Membrane (PEM) fuel cells
  - Power Output: 2 x 200 kW fuel cells, totalling 400 kW
  - Manufacturer: Ballard Power Systems (fuel cells)
  - System weight: not explicitly mentioned
- Secondary Power Source: Battery System
  - Battery Capacity: 1.36 MWh lithium-ion battery pack
  - Purpose: Batteries provide backup power, assist during peak demand, and enable energy recovery (e.g., during braking).
  - Manufacturer: Corvus Energy
- Propulsion Motors: Electric motors powered by the combined output of the hydrogen fuel cells and battery system.
  - Electric Motor Output: 2 x 410 kW

Hydrogen Storage System:

- Hydrogen Type: Liquid Hydrogen (LH2)
  - Storage Capacity: The MF Hydra is equipped with an 80 m³ liquid hydrogen tank, which can store approximately 70 kg of liquid hydrogen
  - Storage Pressure: Stored at cryogenic temperatures to maintain liquid state.
  - Storage Tanks: A 20m3 Double-walled, vacuum-insulated cryogenic tanks to safely store LH2

Operational Features:

- Range: The ferry can operate for several days on a full tank of liquid hydrogen, depending on the operational profile and demand.
- Refuelling: Hydrogen is refuelled at designated bunkering stations equipped for cryogenic LH2 refuelling. Norway is developing infrastructure to support LH2 bunkering.
- Redundancy: The ferry has backup systems to ensure continuous operation, including a diesel generator for emergency situations, though it aims to operate primarily on hydrogen.

Environmental Impact:

- Emissions: The MF Hydra is a zero-emission vessel during normal operations, as it emits only water vapor from the hydrogen fuel cells.

- Energy Efficiency: The combination of fuel cells and batteries allows for optimized energy use, reducing overall consumption and emissions compared to traditional diesel-powered ferries.

Safety Systems:

- Leak Detection: Advanced sensors monitor hydrogen systems for any leaks, with automatic shutdown protocols in case of detection.
- Fire Suppression: The ferry is equipped with state-of-the-art fire suppression systems specifically designed for hydrogen and battery systems.
- Emergency Venting: The storage tanks and fuel cells are designed with emergency venting systems to safely release hydrogen in case of overpressure.

Technological and Operational Advancements:

- Pioneering Technology: As the first of its kind, the MF Hydra represents a significant advancement in maritime hydrogen technology, serving as a model for future hydrogen-powered vessels.
- Infrastructure Development: The ferry’s operation is part of a broader initiative to establish a hydrogen-based maritime infrastructure in Norway, including hydrogen production, storage, and refuelling capabilities.

The MF Hydra is a pioneering vessel that demonstrates the potential of hydrogen fuel cells for maritime applications. Its hybrid system, combining hydrogen fuel cells with a robust battery system, allows for efficient, zero-emission operation in the demanding environment of Norwegian fjords. The lessons learned from the MF Hydra's development and operation could be invaluable for other industries, including aviation, looking to adopt hydrogen technology for sustainable transportation (*MF HYDRA CAR FERRY NORWAY LIQUEFIED LIQUIDE HYDROGEN POWERED BALLARD FUEL CELLS NORLED*, n.d.)

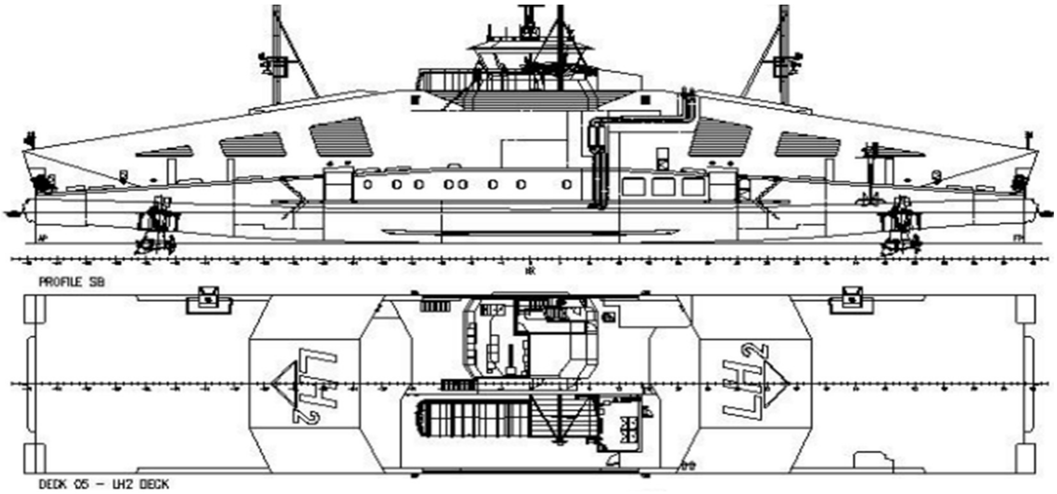


Figure 39 MF Hydra vessel (Hydrogenics, 2021)

C4: XCIENT Fuel Cell Truck system specifications

System specifications

System Overview (*XCIENT Fuel Cell Truck | Hydrogen Truck | Hyundai Motor Company*, n.d.):

- Model: Hyundai Xcient Fuel Cell
- Vehicle Class: Heavy-duty truck (long-haul and regional delivery)
- Gross Vehicle Weight (GVW): 34 tons (for the 4x2 model)
- Driving Range: 400 km (based on real-world conditions)
- Fuel: Hydrogen (compressed, gaseous)
- Hydrogen Storage Capacity: 31 kg of hydrogen
- Refuelling Time: Approx. 8 to 20 minutes (depending on station pressure)

Powertrain and Propulsion System

- Fuel Cell System:
  - Two 90 kW Proton Exchange Membrane Fuel Cell (PEMFC) stacks, providing a total power output of 180 kW. This fuel cell system generates electricity from hydrogen and oxygen, with only water as a byproduct.
- Electric Motor:
  - A single 350 kW electric motor, providing the necessary torque for heavy-duty transportation.
  - Torque Output: 3,400 Nm.
  - The motor ensures efficient acceleration and load management for long-haul trips.
- Energy Storage:
  - The truck is equipped with a 72-kWh battery pack, which acts as a buffer to optimize power delivery between the fuel cell and electric motor.
  - The battery helps manage peak power demands and enhances system efficiency during regenerative braking.
- Transmission:
  - The system integrates an automatic transmission optimized for smooth interaction between the electric motor and mechanical drivetrain.

Hydrogen Storage System

- Hydrogen Tanks:
  - The truck features seven high-pressure hydrogen tanks, offering a total hydrogen capacity of 31 kg.
  - Tank Pressure: 350 bar.
  - Material: The hydrogen tanks are made from carbon fiber-reinforced polymer to ensure both lightweight construction and high safety standards.
- Storage Configuration:
  - The hydrogen tanks are arranged along the truck chassis, carefully balancing weight distribution to maximize vehicle stability and performance.

Thermal Management System

- Cooling System:

- A sophisticated water-cooled system regulates the temperature of both the fuel cell stacks and the electric motor. This system ensures that the fuel cells remain within optimal operating temperature ranges for maximum efficiency, even under high load conditions.
- Battery Thermal Management: The battery pack is also integrated into the cooling system to prevent overheating during high-power operations or regenerative braking.

- Heat Utilization:
    - Waste heat from the fuel cells is used to optimize overall system efficiency, particularly during cold-weather operations, where it helps reduce energy consumption for cabin heating.

Operational Features

- Range:
    - The Xcient Fuel Cell truck offers a driving range of 400 km, providing sufficient range for long-haul applications without the need for frequent refuelling.
- Refuelling Time:
    - The truck's hydrogen tanks can be refilled in 8 to 20 minutes, depending on the pressure at the refuelling station, making it significantly faster to refuel than recharging a battery-electric truck.
- Regenerative Braking:
    - The regenerative braking system recovers energy during deceleration and stores it in the battery pack, improving overall energy efficiency and reducing hydrogen consumption.

Safety Systems

- Hydrogen Safety:
    - The truck is equipped with hydrogen leak detection sensors and a hydrogen safety shutoff system that automatically seals off the hydrogen tanks in the event of a detected leak or crash.
- Crash Safety:
    - The hydrogen tanks are reinforced with carbon fiber to prevent ruptures in the event of an accident. Additionally, the truck's structural design is optimized to protect the hydrogen storage system in high-impact collisions.
- Cooling Safety:
    - The thermal management system includes fail-safes that prevent overheating of the fuel cells and electric motor, ensuring operational safety under all driving conditions.

System Efficiency and Performance

- Fuel Efficiency:
    - The Xcient Fuel Cell truck consumes approximately 7.5 kg of hydrogen per 100 km, making it one of the most efficient heavy-duty trucks in its class in terms of cost per kilometers.
- Performance:
    - The truck's 350 kW electric motor provides enough torque (3,400 Nm) to manage heavy loads on highways and inclines, ensuring smooth and consistent performance.

Operational Considerations

- Infrastructure Compatibility:
    - The truck is compatible with existing 350 bar hydrogen refuelling stations, primarily in Europe and South Korea. As more hydrogen stations are built, especially in North America, the Xcient Fuel Cell will become available in additional markets.
- Deployment:
    - Initial deployment of the Hyundai Xcient Fuel Cell truck began in Switzerland in 2020, where over 46 units are now in operation as part of Hyundai's efforts to commercialize hydrogen-powered freight transport. Further expansion into Europe, the U.S., and other regions is planned as hydrogen infrastructure continues to grow.

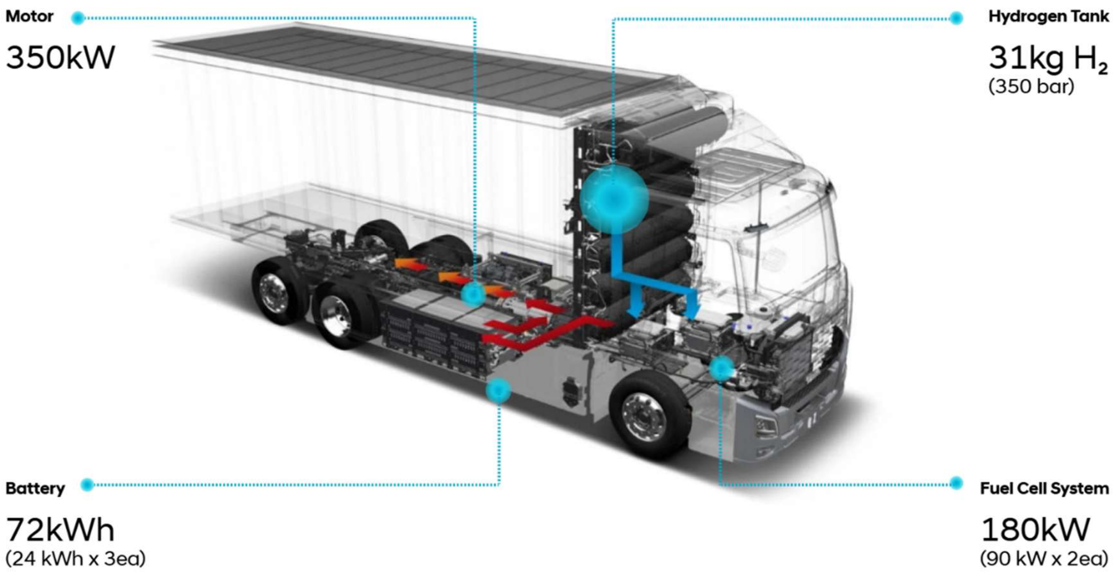


Figure 40(XCIENT Fuel Cell Truck | Hydrogen Truck | Hyundai Motor Company, n.d.)

C5: Nikola Tre Fuel Cell Electric Vehicle (FCEV)

System specification

System Overview ((Motor, 2024):

- Model: Nikola Tre Fuel Cell Electric Vehicle (FCEV)
- Vehicle Class: Heavy-duty truck (regional and medium haul)
- Gross Vehicle Weight (GVW): 37,200 kg (82,000 lbs)
- Driving Range: Up to 500 miles (approximately 805 km)
- Fuel: Hydrogen (compressed, gaseous)
- Hydrogen Storage Capacity: Approximately 70 kg of hydrogen
- Refuelling Time: Less than 20 minutes (at a 700-bar hydrogen refuelling station)

Powertrain and Propulsion System

- Fuel Cell System:
    - The Nikola Tre FCEV is powered by a 200-kW fuel cell power module, which converts hydrogen into electricity to drive the electric motor.
- Electric Motor:
    - A continuous power output of 536 HP (400 kW) provides the necessary torque for heavy-duty transportation.
    - Torque Output: 12,500 ft-lb.
- Energy Storage:
    - The truck features a 164-kWh lithium-ion battery, optimizing power flow between the fuel cell, electric motor, and regenerative braking system.
    - The battery helps manage peak power demands and stores energy captured through regenerative braking.
- Transmission:
    - A single-speed automatic gearbox ensures seamless power delivery from the electric motor to the wheels, providing smooth acceleration and operational efficiency.

Hydrogen Storage System

- Hydrogen Tanks:
    - The truck is equipped with three backpack tanks and two saddle tanks.
    - Total Storage Capacity: Approximately 70 kg of hydrogen.
    - Tank Pressure: 700 bar (high pressure to maximize driving range and enable faster refuelling).
    - Material: Type IV composite tanks made from carbon fiber for high strength and durability.
- Storage Configuration:
    - Hydrogen tanks are mounted in a compact configuration along the truck's chassis, optimizing weight distribution and ensuring vehicle stability.

Thermal Management System

- Cooling System: The fuel cell stacks, and electric motor are supported by a robust thermal management system that maintains optimal operating temperatures.
    - Active cooling loops help ensure efficient operation during both long-distance travel and stop-and-go driving.
- Heat Utilization:

    - Waste heat from the fuel cell system is captured and used for cabin heating, improving overall energy efficiency.

Operational Features

- Range:
    - The Nikola Tre FCEV offers a range of up to 500 miles, suitable for regional hauls.
- Refuelling Time:
    - The truck can refuel its hydrogen tanks in less than 20 minutes at a 700-bar refuelling station.
- Regenerative Braking:
    - The regenerative braking system captures energy during deceleration, increasing overall energy efficiency.

Safety Systems

- Hydrogen Safety:
    - Equipped with hydrogen leak detection sensors and automatic shut-off valves that stop hydrogen flow in case of a leak.
- Crash Safety:
    - Hydrogen tanks are protected by reinforced safety structures to withstand impacts.
- Thermal Safety:
    - Redundant cooling systems ensure safe operating temperatures during high loads and long-distance operations.

System Efficiency and Performance

- Fuel Efficiency:
    - The truck consumes approximately 8 kg of hydrogen per 100 km, offering efficient operation compared to diesel trucks.
- Performance:
    - The electric motor’s 536 HP provides enough torque to handle heavy loads and ensures reliable performance for regional and medium-haul operations.

Operational Considerations

- Infrastructure Compatibility:
    - Designed to be refuelled at 700-bar hydrogen refuelling stations, compatible with infrastructure being developed across Europe and North America.
- Deployment:
    - Initial deployments began in 2023 as part of Nikola’s strategy to enable zero-emission freight transportation in major logistics hubs.

Appendix D: Comprehensive Comparison cross-sectoral Hydrogen-Powered System

Aspect	MF Hydra	Water-Go-Round	SF-BREEZE	Hyundai Xcient Fuel Cell	Nikola Tre Fuel Cell
Type	Passenger and Car Ferry	Passenger Ferry	High-Speed Passenger Ferry (Concept)	Heavy-duty truck (long-haul)	Heavy-duty truck (medium haul)
Manufacturer	Norled (Norway)	Golden Gate Zero Emission Marine (USA)	U.S. Department of Transportation	Hyundai Motor Company	Nikola Motor
Location of Operation	Norwegian Fjords	San Francisco Bay, USA	San Francisco Bay, USA	Europe (since 2020)	Europe and North America (since 2023)
Passenger Capacity	300 passengers	84 passengers (reconfigurable)	150 passengers	N/A	N/A
Vehicle Capacity	80 cars	N/A	N/A	N/A	N/A
Primary Propulsion	Hydrogen Fuel Cells (PEM)	Hydrogen Fuel Cells (PEM)	Hydrogen Fuel Cells (PEM)	Hydrogen Fuel Cells (PEM)	Hydrogen Fuel Cells (PEM)
Power Output (Fuel Cells)	2 x 200 kW (400 kW total)	3 x 120 kW (360 kW total)	4.92 MW total (approx. 6,600 horsepower)	2 x 90 kW (180 kW total)	200 kW
Battery Capacity	1.36 MWh	100 kWh	Not specified	72 kWh	164 kWh
Electric Motor Output	2 x 410 kW	2 x 300 kW (600 kW total)	4.92 MW	350 kW	536 HP (400 kW)
Hydrogen Storage Type	Liquid Hydrogen (LH2)	Compressed Hydrogen (H2)	Compressed Hydrogen (H2)	Compressed Hydrogen (H2)	Compressed Hydrogen (H2)
Hydrogen Storage Capacity	Approx. 80 cubic meters (LH2) (70.85 kg/m³)	250 kg (compressed at 250 bar)	1,200 kg (compressed at 350 bar)	31 kg	Approx. 70 kg
Storage Pressure	Stored as liquid at cryogenic temperatures	250 bar (3,600 psi)	350 bar (5,000 psi)	350 bar	700 bar
Range	Several days (depending on operation)	1-2 days (depending on operation)	Approx. 100 nautical miles	Over 600 km	Over 805 km
Speed	Approx. 10 knots	Cruising: 12 knots, Top Speed: 22 knots	Designed for up to 35 knots	Approx. 90 km/h (55.92 mph)	120 km/h (74.56 mph)
Operational Focus	Long-haul ferry services in fjords	Short-haul ferry services in urban bay area	High-speed passenger ferry routes	Long-haul and regional delivery	Regional and medium haul
Refueling Infrastructure	Developing LH2 bunkering in Norway	Compressed hydrogen refueling	Planned hydrogen bunkering infrastructure	Established infrastructure in Europe	Planned infrastructure in North America

		stations in California	at Bay Area ports		
Emissions	Zero emissions (water vapor only)	Zero emissions (water vapor only)	Zero emissions (water vapor only)	Zero emissions (water vapor only)	Zero emissions (water vapor only)
Safety Systems	Leak detection, fire suppression, emergency venting	Leak detection, fire suppression, emergency venting	Leak detection, fire suppression, emergency venting	Leak detection, fire suppression	Leak detection, fire suppression
Pioneering Technology	First liquid hydrogen ferry in the world	First hydrogen-powered ferry in the USA	Concept designed to showcase scalability of hydrogen fuel cells for high-speed ferries	Established fuel cell technology in trucks	Market-accepted fuel cell technology
Technology Demonstrated	Viability of LH2 for long-haul maritime transport	Viability of compressed hydrogen for short-haul passenger ferries	Conceptual model to demonstrate high-power hydrogen applications	Practical application of hydrogen technology	Viability of hydrogen logistics and operations
Type	Passenger and Car Ferry	Passenger Ferry	High-Speed Passenger Ferry (Concept)	Heavy-duty truck (long-haul)	Heavy-duty truck (medium haul)
Manufacturer	Norled (Norway)	Golden Gate Zero Emission Marine (USA)	U.S. Department of Transportation	Hyundai Motor Company	Nikola Motor
Location of Operation	Norwegian Fjords	San Francisco Bay, USA	San Francisco Bay, USA	Europe (since 2020)	Europe and North America (since 2023)
Passenger Capacity	300 passengers	84 passengers (reconfigurable)	150 passengers	N/A	N/A
Vehicle Capacity	80 cars	N/A	N/A	N/A	N/A

Table 19 Comprehensive Comparison cross-sectoral Hydrogen-Powered System

Appendix E: Standards and Regulations for HHEPS in Aviation

No.	Standard/Regulation	Description	Organization	Reference
1	NEN-EN-ISO 13371	Cryogenic vessels – Couplings for cryogenic service	ISO	ISO Standards
2	ISO 13984	Liquid hydrogen – Land vehicle fueling system interface	ISO	ISO Standards
3	ISO 13985	Liquid hydrogen – Land vehicle fuel tanks	ISO	ISO Standards
4	NEN-ISO 21029-1	Transportable vacuum insulated vessels ≤ 1000L – Design, fabrication, inspection, and tests	ISO	ISO Standards
5	NEN-EN-ISO 21013-3	Pressure-relief accessories for cryogenic service – Sizing and capacity determination	ISO	ISO Standards
6	NEN-EN-ISO 21028-1	Cryogenic vessels – Toughness requirements for materials at temperatures below -80°C	ISO	ISO Standards
7	NEN-EN-ISO 21028-2	Cryogenic vessels – Toughness requirements for materials at temperatures between -80°C and -20°C	ISO	ISO Standards
8	SFAR 88	Fuel tank system fault tolerance evaluation requirements	FAA	FAA
9	Pressure Equipment Directive (PED) 2014/68/EU	Safety requirements for pressure equipment within the EU	European Union	EU Publications
10	ASTM F3063/F3063M-2	Standard for cryogenic systems in aerospace applications	ASTM	ASTM International

11	NASAI CR-2002-211867	Hydrogen Storage for Aircraft	NASA	NASA Publications
12	EC-79	Type-approval of hydrogen-powered motor vehicles	European Union	EU Publications
13	IEC 60079-10-1	Explosive atmospheres – Classification of areas with explosive gas atmospheres	IEC	IEC Standards
14	ISO 14687	Hydrogen fuel – Product specification	ISO	ISO Standards
15	ISO/TR 15916	Basic considerations for the safety of hydrogen systems	ISO	ISO Standards
16	SAE AS6858	Electrical power systems for hybrid-electric and electric aircraft	SAE	SAE International
17	SAE J2719	Hydrogen fuel quality for fuel cell vehicles	SAE	SAE International
18	SAE AS6821	Standards for hydrogen fuel systems in aircraft	SAE	SAE International
19	ISO 16111	Transportable gas storage devices – Hydrogen absorbed in reversible metal hydrides	ISO	ISO Standards
20	ASME B31.12	Hydrogen piping and pipelines	ASME	ASME Standards
21	ICAO Annex 6 Part II	Operation of aircraft – International general aviation	ICAO	ICAO Publications
22	RTCA DO-160	Environmental conditions and test procedures for airborne equipment	RTCA	RTCA Standards
23	IATA Guidance on Hydrogen and SAF Infrastructure	Best practices for hydrogen and SAF integration at airports	IATA	IATA Publications
24	ISO 19880-1	Gaseous hydrogen – Fuelling stations	ISO	ISO Standards

		– General requirements		
25	SAE J2601	Fueling protocols for light-duty gaseous hydrogen surface vehicles	SAE	SAE International
26	SAE ARP 4754A	Guidelines for development of civil aircraft and systems	SAE	SAE International
27	SAE ARP 4761	Guidelines and methods for conducting safety assessment process on civil airborne systems	SAE	SAE International
28	ISO 23273	Fuel cell road vehicles – Safety specifications	ISO	ISO Standards
29	ASTM D7650	Standard test method for purity of hydrogen for fuel cell vehicles	ASTM	ASTM International
30	EN 17127	Outdoor hydrogen refueling stations for vehicles	CEN	CEN Standards
31	EN ISO 14952-3	Aerospace series – Cleaning of parts and assemblies	CEN/ISO	ISO Standards
32	DO-311A	Minimum operational performance standards for rechargeable lithium batteries	RTCA	RTCA Standards
33	EASA CS-LUAS	Certification specifications for large, unmanned aircraft systems	EASA	EASA Publications

Table 20 Standards and Regulations for HHEPS in Aviation

Table A1 provides a comprehensive list of standards and regulations that support the safe and efficient operationalization of HHEPS in aviation. Each entry in this table addresses crucial elements of HHEPS operations, from fuel storage and handling to environmental resilience and safety systems, forming the backbone of safe and effective HHEPS integration in aviation.

Appendix F: Comparative Operational Aspects of HHEPS in Aviation, Maritime, and Trucking

Operational Aspect	Aviation	Maritime	Trucking	References
Fueling Infrastructure	- Dedicated hydrogen refueling stations at major airports with specialized nozzles, cryogenic storage, and pressure controls. - Infrastructure placement critical to minimize downtime.	- Hydrogen bunkering facilities at ports, equipped for high-capacity storage for both compressed and liquid hydrogen. - Space availability allows for larger storage capacity.	- Modular hydrogen refueling stations along major highways and logistics hubs. - Quick-deployment, adaptable systems for different truck types.	Standards: ISO 19880-1 (general fueling), IEC 60079-10-1 (explosive atmospheres), ISO 14687 (hydrogen quality).
Refueling Time	- Refueling takes 30-60 minutes due to safety checks and cryogenic requirements, compared to 10-15 minutes for conventional fuels. - Safety protocols extend time due to high-pressure fueling.	- Typically completed in 15-30 minutes with rapid fueling systems designed for large vessels. - Refueling aligned with port docking schedules.	- Comparable to diesel refueling times (10-15 minutes) due to established protocols and high-capacity dispensers. - Suitable for frequent stops.	Standards: SAE J2601 (refueling protocols), ISO 19880-1 (fuel stations).
Safety Protocols	- Rigorous protocols with mandatory leak detection, flame arrestors, and emergency shutdown systems for hydrogen refueling. - Altitude-specific protocols critical due to pressure changes.	- Fire safety and pressure monitoring systems crucial for onboard and bunkering safety. - Emergency response training required for hydrogen handling.	- Safety training for handling compressed hydrogen; trucks equipped with leak detection and emergency valves. - Consistent protocols for ground-based hazards.	Standards: ISO/TR 15916 (hydrogen safety), SAE AS6858 (high-voltage), IEC 60079-10-1 (explosive atmospheres).
Maintenance Requirements	- Frequent checks on cryogenic tanks, fuel cells, and high-voltage components due to operational and altitude stresses.	- Maintenance performed during dry-docking, with corrosion checks and pressure testing. - Hydrogen systems inspected	- Regular inspections of hydrogen tanks and fuel cells; schedules aligned with vehicle operations for	Standards: RTCA DO-311A (battery safety), EN ISO 14952-3 (component cleanliness), ASME B31.12 (hydrogen piping).

	- Stringent preventative maintenance protocols.	less frequently but comprehensively.	minimal downtime.	
Logistical Challenges	- Limited airport space and strict safety zoning for hydrogen transport and storage. - Requires coordination with air traffic and ground control.	- Complex logistics to supply hydrogen across multiple ports; storage capacity varies by port. - Increased complexity with multi-country regulations.	- Growing hydrogen distribution network; regional regulatory differences pose supply chain challenges. - Logistics hubs require secure transport and refueling.	Standards: IEC 60079-10-1 (zoning for explosive atmospheres), ISO 19880-1 (refueling stations).
Regulatory Compliance	- Compliance with FAA, EASA, ICAO regulations for hydrogen storage, refueling, and emissions. - Environmental targets under CORSIA.	- IMO's MARPOL standards and regional environmental guidelines for hydrogen bunkering and emissions.	- Compliance with DOT and CARB emissions standards; regulated by Hazardous Materials Regulations (HMR) for safe hydrogen transport.	Standards: FAA AAM Program (safety), EASA Special Conditions (hydrogen aircraft), IMO MARPOL (marine pollution).
Operational Flexibility	- Limited flexibility; requires careful scheduling around hydrogen refueling cycles due to high infrastructure demands.	- Flexible refueling options at multiple ports; routes can adjust based on port availability.	- Flexible route planning with refueling at depots and logistics hubs; adaptable infrastructure allows scheduling adjustments.	Standards: SAE J2601 (truck fueling), ISO 19880-1 (general fueling infrastructure).
Environmental Impact Goals	- Focused on zero emissions for compliance with CORSIA and international standards on noise and CO_2.	- Aims to meet IMO targets, reducing sulfur oxides (SOx) and nitrogen oxides (NOx) for maritime emissions.	- Compliance with EU and CARB emissions regulations; emphasis on reducing NOx and particulates.	Standards: ISO 14687 (hydrogen purity), CORSIA (carbon offsetting in aviation), IMO MARPOL (marine emissions).

Table 21 Comparative Operational Aspects of HHEPS in Aviation, Maritime, and Trucking

Table 22 provides a side-by-side comparison of the operational requirements, challenges, and regulatory standards across aviation, maritime, and trucking sectors for HHEPS, allowing readers to understand each sector's unique needs while identifying transferable knowledge and best practices.