# Shaping the Future of Aviation:
# GKN Aerospace’s Approach to Hybrid Propulsion Systems

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# Nomenclature

| | |
|---|---|
| **R&D** | Research and Development |
| **OEM** | Original Equipment Manufacturer |
| **PLC** | Product Life Cycle |
| **ATI** | Aerospace Technology Institute |
| **PEM** | Proton-exchange Membrane |
| **AM** | Additive Manufacturing |
| **MOF** | Metal-organic Framework |
| **eVTOL** | Electric Vertical Takeoff and Landing |
| **CAGR** | Compound Annual Growth Rate |
| **UAM** | Urban Air Mobility |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **SAF** | Sustainable Aviation Fuel |
| **IP** | Intellectual Property |
| **PCM** | Phase-change Material |
| **AI** | Artificial Intelligence |
| **PSO** | Particle Swarm Optimisation |
| **DED** | Particle Swarm Optimisation |

## Executive Summary

This report explores GKN Aerospace's innovative strategy in sustainable propulsion systems, focusing on their revolutionary role in achieving zero-emission aviation. GKN Aerospace is a leading Tier 1 supplier in the aerospace industry, highlighting its strategic collaborations and emphasis on sustainability. The current product developed and prototyped is hydrogen propulsion systems, which address critical engineering challenges like achieving zero-emission aviation by 2050. Programs such as H2GEAR and H2JET illustrate GKN's targeted approach to different aviation segments.

External influences are also discussed through a PESTEL analysis, identifying political support through initiatives like the UK Jet Zero Strategy and societal demand for sustainable air travel. Technological and economic challenges, including competition from Airbus and ZeroAvia and the high cost of green hydrogen, are analyzed alongside regulatory factors that shape the industry and patent strategies.

This report also provides foresight into scientific and technological advancements necessary for the success of hydrogen propulsion. The focus on cryogenic hydrogen storage underscores innovations in materials like MOFs, dynamic thermal management, advanced manufacturing techniques, and end-of-life sustainability solutions.

Lastly, the conclusion suggests actionable insights. By leveraging these technological advancements and addressing external factors, GKN Aerospace can become a leader in the transition to sustainable aviation. The strategic priorities outlined in this report are to position GKN at the forefront of the industry's evolution over the next two decades.

*Keywords*: GKN Aerospace, Sustainability, Aviation, Hydrogen, Propulsion, Foresight, PESTEL, Material, Manufacturing.

# 1 Introduction

This section provides an overview of GKN Aerospace, its role in the aerospace industry, and its commitment to its current products, future innovations, and sustainability. By understanding the company's market, capabilities, and strategic direction, the context for its development of hydrogen propulsion systems becomes evident.

## 1.1 Overview of GKN Aerospace

GKN Aerospace is a globally recognized Tier 1 component supplier in the aerospace sector. As shown in Figure 1, GKN operates in 38 manufacturing sites across 12 countries, the company supports over 90% of the world's flights, positioning itself as a cornerstone of the global aerospace supply chain. Its diverse portfolio spans propulsion systems, aerostructures, fuselages, electrical systems, and engineering services, catering to major organizations, including Airbus, Boeing, Lockheed Martin, and Northrop Grumman (Melrose 2022). In 2023, GKN Aerospace reported £3.35 billion in sales and holds over 650 active patents, underscoring its technological dominance. The company serves three primary markets: Civil Aviation (70% of revenue), Defense (25%), and Adjacent Markets (5%), including space exploration. More than 70% of which it acts as a sole source supplier. This diverse market engagement enables GKN to remain resilient, niche, and adaptable to evolving industry demands (Bureau van Dijk 2024).


Figure 1: GKN Aerospace's Global Footprint (Taken from GKN (2022))

# 2 Current Product: Hydrogen Propulsion Systems

GKN Aerospace continues to establish itself in developing hydrogen propulsion systems as part of its strategic commitment to sustainable aviation (ATI 2022). These systems, currently in the prototype phase, represent a critical innovation aimed at reducing the environmental footprint of air travel while addressing regulatory and market pressures for cleaner technologies. Through collaborative initiatives and extensive R&D, GKN addresses key challenges such as energy storage, thermal management, and operational scalability (Wood et al. 2024). This section explores the current status of GKN hydrogen propulsion technologies, partnerships, and their alignment with market needs and sustainability goals.

## 2.1 Overview of GKN Aerospace Initiatives

Current hydrogen propulsion systems developed by GKN Aerospace remain in the advanced research and prototype stage, showcasing functionality but requiring improvements in efficiency and cost-effectiveness for commercial deployment. GKN conducts several programs targeting different aspects of hydrogen-powered aviation, this can be mapped across the Product Life Cycle (PLC) in Table 2. The H2GEAR program, co-funded by the UK ATI, was noted by Hales et al. (2023) to focus on hydrogen-electric propulsion for sub-regional aircraft. It employs Proton-exchange Membrane (PEM) fuel cells combining hydrogen, oxygen, and water to produce power, shown in Equation 1, and lightweight cryogenic hydrogen storage systems to provide zero-emission power. Positioned in the Introduction phase, this program emphasizes foundational subsystem validation.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Electricity} + \text{Heat} \tag{1}$$

H2JET, in contrast, targets mid-sized aircraft using hydrogen combustion technologies, mapped to the Growth phase in Table 2. Although less efficient than hydrogen-electric systems, are easier to integrate into existing aircraft designs. This adaptability supports quicker implementation but results in nitrogen oxide (NOx) emissions, reinforcing hydrogen-electric systems as the long-term solution for zero-emission aviation (RISE 2024). The HyFIVE program, involving the University of Manchester, focuses on developing liquid hydrogen fuel systems that can be scaled across multiple aircraft platforms, positioned at the introduction phase (Sampson 2024). Similarly, the H2FlyGHT project aims to design and integrate a 2-megawatt cryogenic hydrogen-electric propulsion system. The University of Manchester contributes significantly to these efforts by advancing hyperconducting motor coil technologies to enhance efficiency (Aerospace 2024). GKN's approach reflects a commitment to addressing hydrogen propulsion's technical and operational challenges, bridging the gaps outlined in the PLC stages. While these systems are not yet commercially available, their progress demonstrates significant potential for future market readiness.

| PLC Stage | GKN Initiatives | Focus | Key Milestones |
|---|---|---|---|
| **Introduction** | H2GEAR, HyFIVE, H2FlyGHT | **H2GEAR:** PEM fuel cells for hydrogen-electric propulsion targeting sub-regional aircraft. **HyFIVE:** Development of scalable liquid hydrogen storage systems for various aviation platforms. **H2FlyGHT:** High-power cryogenic hydrogen-electric systems with hyperconducting motor coils for regional aircraft. | Subsystem validation, laboratory testing, and ground-based demonstrations. |
| **Growth** | H2JET | Scalable hydrogen combustion systems for mid-sized commercial aircraft; short-term market scalability leveraging existing airframes. | Subsystem integration into aircraft designs, early Original Equipment Manufacturer (OEM) adoption. |
| **Maturity** | None currently | Broad adoption of hydrogen propulsion (regional, medium, and long-haul markets). | Widespread deployment and operational optimization in the mid-2040s. |
| **Decline** | Future Alternatives | Potential replacements with next-generation hydrogen hybrids. | Post-2050 exploration of advanced technologies to replace current systems. |

Table 2: PLC of GKN Hydrogen Propulsion Systems (Own work summarised from sources in Chapter 2.1)

## 2.2 Current Hydrogen Technologies

Developing hydrogen propulsion systems requires integrating advanced engineering solutions to overcome key storage, conversion, and system performance challenges. Among the critical technologies under development are cryogenic hydrogen storage, additive manufacturing (AM), and fuel cell integration (Aerospace 2023).

**Cryogenic Hydrogen Storage** is essential for hydrogen aviation, as it enables hydrogen to be stored as a liquid at -253°C. GKN's current prototypes use fibre-reinforced polymer composites such as metal hydrides to construct lightweight, durable tanks capable of withstanding extreme thermal stresses. Insulation systems are being enhanced with aerogel-based materials, which provide superior thermal resistance and reduce hydrogen boil-off (Jakob & Qorri 2021, White et al. 2017).

GKN uses **AM** to produce complex, high-precision components for hydrogen propulsion systems. This includes direct metal laser sintering (DMLS), a process that allows for the fabrication of intricate geometries using lightweight aluminium alloys and titanium (Billberg et al. 2017). AM enables the fabrication of multiple functionalities into a single part, such as incorporating cooling channels into the structure of cryogenic tanks. This approach reduces the components required, minimizes production errors, and decreases material waste by up to 90% (Hegab et al. 2023). The hydrogen-electric propulsion systems developed under GKN and other institutions rely on **PEM fuel cells** to convert hydrogen into electricity. These fuel cells are designed to operate with 60-70% efficiency, providing reliable energy for electric motors (Lamy 2016).

However, material limitations, space consumption, and thermal management complexities remain significant challenges. The reliance on high-cost advanced materials and the need to maintain -253°C in cryogenic systems add both technical and financial constraints. Additionally, integrating storage, insulation, and fuel delivery systems through AM presents a promising avenue for efficiency gains. Despite these opportunities, scalability challenges in AM processes and hydrogen boil-off losses during extended storage present threats to operational readiness, as detailed in Table 3. These technologies highlight the current engineering expertise and endeavours that GKN Aerospace prioritizes to ensure that it remains at the forefront of sustainable hydrogen aviation innovation (Hallstedt et al. 2023, Wood et al. 2024).

| **Category** | **Details** |
|---|---|
| **Strengths** | Efficient cryogenic storage with aerogel-based insulation reducing boil-off by 30%; Precision manufacturing with AM reducing material waste by up to 80%; High-efficiency PEM fuel cell integration. |
| **Weaknesses** | Dependence on high-cost materials like aerogels and alloys; Complex thermal management at -253°C; Huge space required for storage and thermal management systems |
| **Opportunities** | Advances in materials like (Metal-organic Framework) MOFs to improve storage density and reduce boil-off; Integration of storage, insulation, and fuel delivery through AM. |
| **Threats** | Scalability of AM processes; Hydrogen boil-off limiting long-term storage efficiency. |

Table 3: SWOT Analysis of Current Hydrogen Technologies (Own work summarised from sources in Chapter 2.2)

## 2.3 Market

These technologies exemplify the engineering rigour required to address the challenges of hydrogen propulsion, ensuring that GKN Aerospace remains at the forefront of sustainable aviation innovation. GKN'sydrogen propulsion systems are designed to serve three key markets shown in Figure 2: Civil aviation, defence, and urban air mobility (UAM), each offering unique opportunities and challenges.

**Civil Aviation** accounts for 70% of GKN's revenue. Partnerships with major manufacturers, such as Airbus, allow GKN to contribute to initiatives like ZEROe, which aims to launch hydrogen-powered commercial aircraft by 2035. GKN provides critical components, including cryogenic storage tanks and lightweight aerostructures, standardising compatibility with next-generation aircraft (Retallack et al. 2023, Aerospace 2023).

**Defence** sector, hydrogen propulsion supports the development of unmanned aerial vehicles (UAVs) and tactical aircraft. Hydrogen-powered UAVs offer reduced thermal and acoustic signatures, increasing their stealth and reconnaissance capabilities. While defence contributes 25% of GKN's revenue, its high-performance and adaptability demands allow GKN to showcase the versatility of its hydrogen technologies (Aerospace 2023).

**Adjacent** sector, according to Precedence (2023) the UAM market is projected to reach $2 billion by 2032, growing at a CAGR OF 27.4% driven by urban congestion, improved mobility, and reduced travel times. Current electric vertical take-off and landing (eVTOL) have low range and are not cost-effective; thus, hydrogen-powered eVTOL aircraft are expected to play a key role in this market. GKN's modular hydrogen fuel cell systems and lightweight aerostructures provide the range and efficiency required for urban air mobility solutions, whether from hydrogen fuel storage or hydrogen-electric conversion efficiency (Xiang et al. 2024, Ng, Patil & Datta 2021).


Figure 2: GKN Aerospace's Propulsion System Market. (Taken from Andersson (2023))

## 2.4 User Needs

Current hydrogen propulsion systems address critical needs across the aviation industry, including sustainability, operational efficiency, and regulatory compliance (Aerospace 2023). Sustainability is driven by internal and external stakeholders demand solutions that align with global decarbonization goals. Hydrogen propulsion eliminates $CO_2$ emissions and significantly reduces fuel consumption, meeting environmental and operational objectives (Petrescu et al. 2020).

Operational efficiency is highlighted as airlines and defence consumers require balanced performance with cost-effectiveness. Hydrogen's high energy density enables longer flight ranges than battery-electric, making it viable for sub-regional to long-haul aviation. GKN's modular cryogenic storage systems ensure scalability and adaptability across diverse aircraft platforms. Regulatory compliance to ensure hydrogen propulsion aligns with global aviation standards, including ICAO and EASA's 2050 net-zero targets. GKN's technologies address emerging safety and performance regulations, ensuring long-term viability (Mithal & Rutherford 2023, Aerospace 2023). Further discussed in Chapter 3.

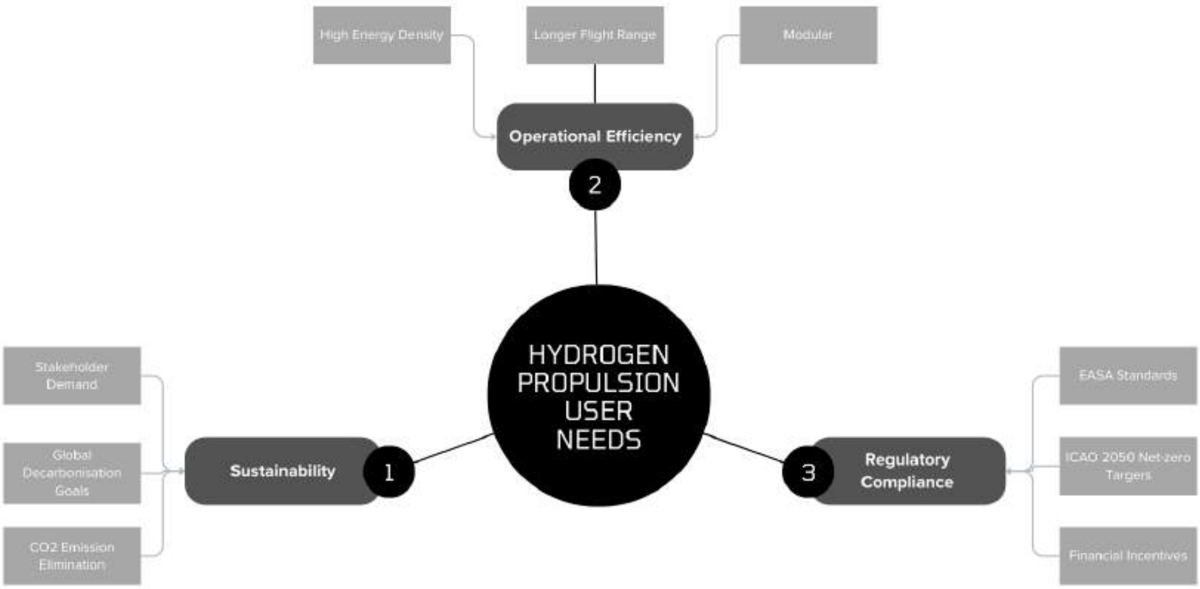


Figure 3: Hydrogen Propulsion System User Needs. (Own Work)

## 2.5 Sustainability across the lifecycle

GKN Aerospace integrates sustainability considerations throughout the lifecycle of hydrogen propulsion systems, from manufacturing to disposal. In manufacturing, GKN's use of fibre-reinforced polymer composites currently reduces material consumption by 30%. Additionally, the accuracy of AM minimizes waste by up to 90%, enhances resource efficiency, and lowers production costs. However, these advanced processes remain energy-intensive, often reliant on non-renewable sources (Jakob & Qorri 2021).

In operational use, hydrogen propulsion eliminates $CO_2$ and particulate emissions, with hydrogen-electric systems completely removing harmful byproducts. However, releasing water vapour as a byproduct at high altitudes can contribute to contrail formation, exacerbating radiative forcing (Boretti 2021). Addressing these secondary impacts will require optimized flight paths and advanced system designs. Cryogenic hydrogen storage tanks allow for higher-density storage, reduce boil-off losses, and enhance operation efficiency; the energy required for hydrogen state transformation and the absence of widespread infrastructure for hydrogen transportation and refuelling remain significant challenges (Jakob & Qorri 2021).

Lastly, its end-of-life management GKN designs its systems for modular disassembly and recovery, with advanced thermochemical recycling achieving 90% material recovery for composites. While these innovations reduce waste and support a circular economy, scaling these processes globally requires further technological and economic advances (Senthilnathan 2024, PLY & JW 2020). GKN Aerospace's hydrogen lifecycle approach showcases a commitment to sustainability. It balances resource efficiency and emission reduction with the need to overcome new challenges that emerge as the adoption of hydrogen propulsion systems becomes widespread.

| **Lifecycle Phase** | **Technological Advances** | **Sustainability Impacts and Challenges** |
|---|---|---|
| **Manufacturing** | Fibre-reinforced polymer composites, AM using DMLS | Reduces material usage by 30% and waste by 80%, but remains energy-intensive and reliant on non-renewable sources. |
| **Operational Use** | Hydrogen-electric systems, Cryogenic storage systems | Eliminates $CO_2$ emissions but contributes to contrail formation. Limited infrastructure for hydrogen refueling and storage. |
| **End-of-Life Management** | Modular design for disassembly, Thermochemical recycling | Achieves 90% material recovery and supports a circular economy, but global scalability remains a challenge. |

Table 4: Sustainability Impacts of Hydrogen Propulsion Systems Across the Lifecycle (Own Work)

# 3 External Influences

Hydrogen propulsion systems for aviation face varying external influences. These factors, while outside GKN Aerospace's direct control, profoundly impact the development, scalability, and adoption of this transformative technology. This section provides a detailed assessment of these influences using a PESTEL framework.

## 3.1 Identification of External Factors

The external factors influencing hydrogen propulsion systems can be categorized into six elements:

1. **Political:** Government policies, funding, national security, and international collaborations support hydrogen infrastructure.

2. **Environmental:** Urgency to mitigate carbon emissions while addressing secondary effects like contrail-induced radiative forcing.

3. **Societal:** Consumer demand for zero-emission travel and public perceptions of hydrogen safety.

4. **Technological:** Advances in hydrogen technologies, competing technologies, and GKN competitors.

5. **Economic:** Cost barriers in hydrogen production, hydrogen infrastructure, and scalability.

6. **Legal:** Regulatory frameworks, certification processes, and intellectual property protection.

## 3.2 PESTEL Analysis

### 3.2.1 Political Factors

Political commitment to decarbonization plays a crucial role in advancing hydrogen propulsion systems. Initiatives such as European Green Deal, with over €1 trillion allocated to sustainable initiatives, and the UK Jet Zero Strategy, which co-funds projects like GKN's H2GEAR, highlight strong governmental support and financial incentives (Commission 2019, Department for Transport 2022). Global coalitions like the Clean Skies for Tomorrow Alliance further position hydrogen as a staple of sustainable aviation (Forum 2020).

Hydrogen-related technologies for defense applications, such as UAVs and tactical aircraft mentioned in Chapter 2.3, add complexity due to their national security implications. These systems, critical for reducing and acoustic signatures, are politically sensitive, especially amid geopolitical tensions. Edler et al. (2023) discussed technological sovereignity as an innovation policy. Nations often restrict technology sharing to safeguard proprietary innovation, NDAs for individuals working on the technology are mandatory, complicating international collaboration (Soboń et al. 2021).

Different regional policies further challenge hydrogen adoption. While Europe leads in hydrogen initiatives, countries like the U.S. and China prioritize Sustainable Aviation Fuel (SAF), delaying global standardization. Standardized international policies are essential for scaling hydrogen-powered aircraft.

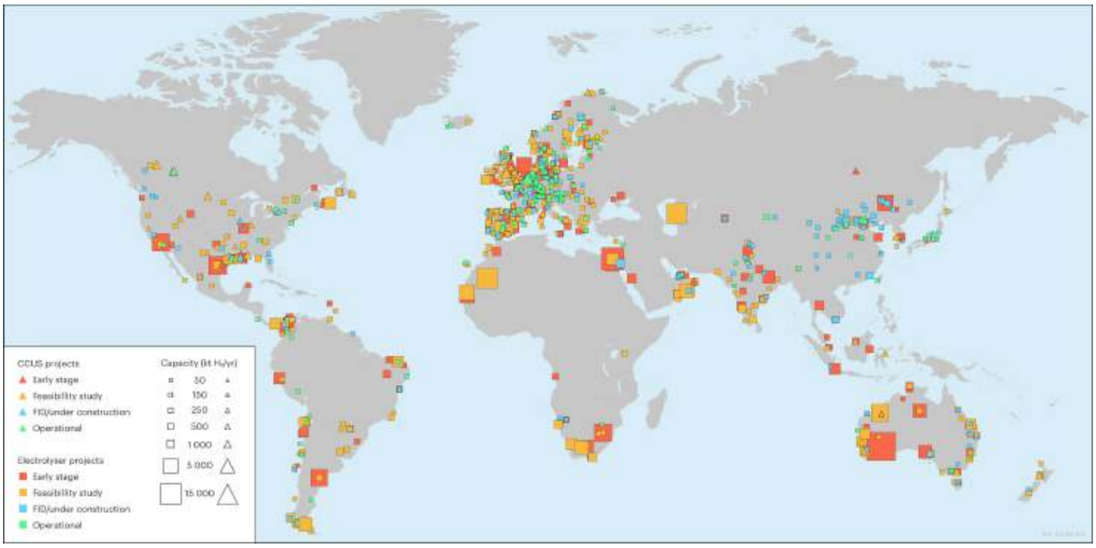


Figure 4: Map of Announced Hydrogen Power Projects by Country (Taken from IEA (2023))

### 3.2.2 Environmental Factors

Hydrogen propulsion directly addresses aviation's environmental challenges, which account for approximately 4% of all global warming to date, by eliminating $CO_2$ and particulate emissions during operation (Gössling & Humpe 2020). However, as mentioned in Chapter 2.5, water vapour released at high altitudes forms contrails and contributes to global warming (Lee et al. 2009). Studies from Penner et al. (1999) suggest contrail mitigation strategies, such as optimising flight altitudes, are essential.

Another issue is the scalability of hydrogen production. Electrolysis, the primary method for producing green hydrogen in PEM, Chapter 2.2, currently operates at 60-70% efficiency and relies heavily on renewable energy. Innovations like solid oxide electrolysers could increase efficiency to over 80%, reducing the carbon footprint of hydrogen production (Hauch et al. 2020).


Figure 5: Global Aviation's Contribution to Global Warming (Taken from Environment (2016) adapted from Lee et al. (2009))

### 3.2.3 Societal Factors

Societal demand for sustainable travel is rising. From IATA (2022) surveys, Figure 6 reveal that 60% of passengers prioritise sustainability when choosing airlines. Public pressure on airlines to adopt zero-emission technologies is reshaping manufacturing priorities, favouring sustainable propulsion systems.

However, public acceptance of hydrogen propulsion systems depends on addressing concerns about hydrogen safety and affordability. Transparency through programs like the HyFlyer II demonstration flights will be critical in building consumer trust (EMEC 2024).

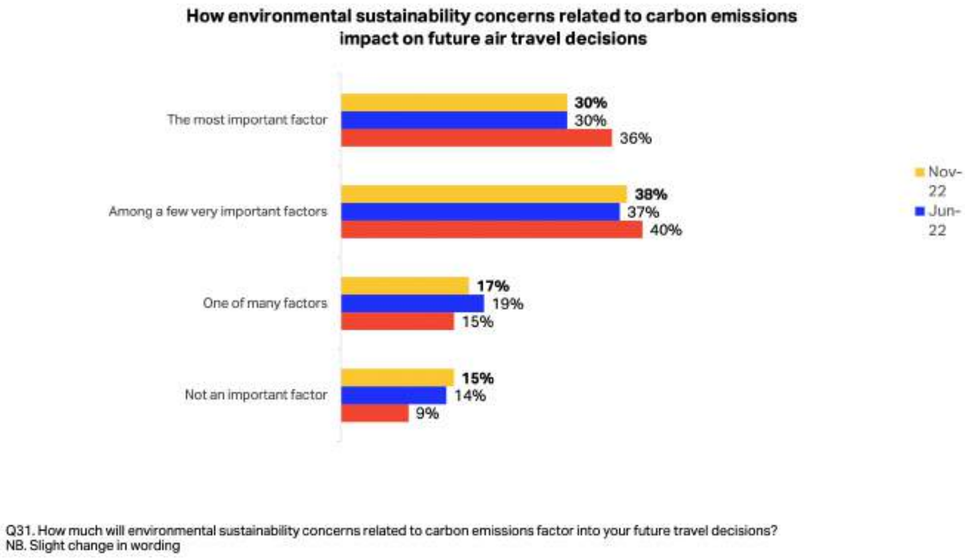


Figure 6: Environmental Sustainability Concerns Affect Travel Decisions (Taken from IATA (2022))

#### 3.2.4 Technological Factors

Technological innovation is both a driver and a challenge for hydrogen propulsion. Cryogenic hydrogen storage remains a critical area, with materials like metal-organic frameworks (MOFs) offering the potential to increase hydrogen density and reduce tank weight (Ren et al. 2015). Advances in topology optimisation via AM and fuel cells also enable more lightweight and efficient systems (Billberg et al. 2017, Lesmana et al. 2024).

Competitor activity underscores the need for accelerated innovation. Rolls-Royce's H2ZERO program explores hydrogen combustion engines, while ZeroAvia's Dornier 228 trials demonstrate its hydrogen-electric system's high Technology Readiness Level (TRL) (Rolls-Royce & easyJet 2022, ZeroAvia 2024). Airbus's ZEROe initiative, targeting standardisation and commercial hydrogen aircraft by 2035, is one of the few that intensifies competitive pressures (Airbus 2024).

| Company | Program | TRL Level | Explanation |
|---|---|---|---|
| GKN Aerospace | H2GEAR | 4-5 | Focuses on hydrogen-electric propulsion for sub-regional aircraft; prototypes are undergoing functional testing. |
| GKN Aerospace | H2JET | 5-6 | Targets mid-sized aircraft with hydrogen combustion technologies, demonstrating scalability for near-term commercial applications. |
| Rolls-Royce | H2ZERO | 3-4 | Hydrogen combustion engines are in concept validation stages; aiming for niche market segments. |
| ZeroAvia | Dornier 228 Trials | 6-7 | Demonstrated successful test flights; close to pre-commercial deployment for hydrogen-electric sub-regional aircraft. |
| Airbus | ZEROe Initiative | 2-3 | Feasibility study phase, targeting commercial hydrogen aircraft by 2035. |

Table 5: TRL Comparison: GKN Aerospace vs Competitors (Own Work)

Additionally, technologies like SAF and battery-electric propulsion present technological alternatives to hydrogen propulsion systems. SAF offers a short-term solution and compatibility with existing jet engines and infrastructure. However, it still produces $CO_2$ emissions and relies on expensive and resource-intensive production processes, limiting long-term sustainability (Ng, Farooq & Yang 2021). Similarly, battery-electric propulsion, demonstrated by companies like Eviation's Alice, is viable, yet the low energy density of batteries, coupled with recycling challenges, restricts its application (Hardee 2024). In contrast, hydrogen propulsion provides zero operational emissions, greater energy density than batteries, and the potential to decarbonise short and long-haul flights, making it a more comprehensive solution for sustainable aviation (Aerospace 2023).

| Technology | Advantages | Disadvantages | Applications/Readiness |
|---|---|---|---|
| Hydrogen Propulsion | Zero $CO_2$ emissions; high energy density; decarbonizes both short- and long-haul flights | Limited infrastructure; high costs; boil-off losses in cryogenic storage | Near-term solutions for sub-regional and mid-sized aircraft with long-term scalability. |
| Sustainable Aviation Fuel (SAF) | Compatible with existing engines and infrastructure; short-term drop-in solution | Produces $CO_2$; resource-intensive production; high costs | Immediate solution but unsustainable for long-term decarbonization. |
| Battery-Electric Propulsion | Zero operational emissions; suitable for short-haul flights | Low energy density; weight limits; recycling challenges | Limited to short-haul flights; currently in demonstration phases (e.g., Eviation's Alice). |

Table 6: Technological Comparison: Hydrogen Propulsion vs Alternatives (Own Work)

#### 3.2.5 Economic Factors

Economic constraints significantly influence hydrogen propulsion adoption. The current cost of green hydrogen production, at $4-6 per kilogram, remains a barrier to competitiveness with kerosene (Council & Company 2023). The Hydrogen Council projects that achieving $1 per kilogram is optimal for widespread utilisation but will require economies of scale and renewable energy expansion ( IRENA). As seen in Figure 7, as companies invest and focus more on hydrogen fuel its price will surely depreciate over the years.

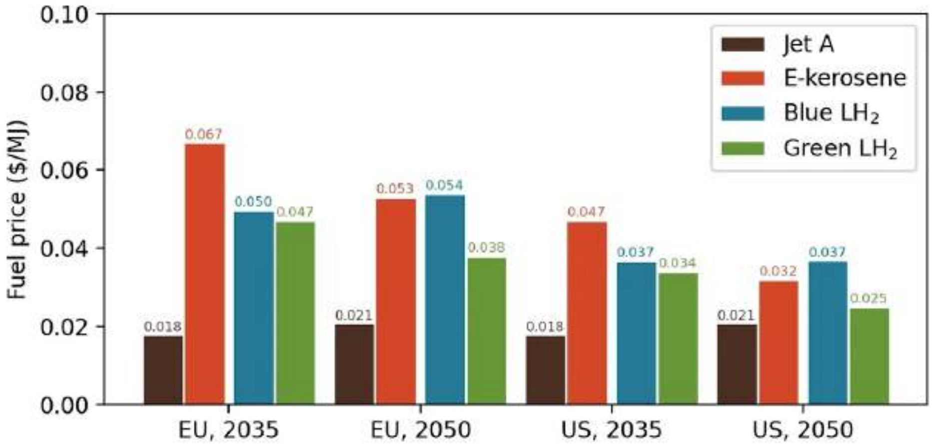


Figure 7: A price comparison of fossil jet fuel (Jet A); synthetic kerosene made from hydrogen and $CO_2$ (e-kerosene); liquid hydrogen derived from natural gas (Blue LH2); and liquid hydrogen made using renewable electricity (Green LH2) in the EU and U.S. (ICCT) (Taken From Canary (2023))

The aviation industry's post-pandemic recovery also affects investment. With airlines operating on tight margins, GKN's modular designs reduce upfront costs, allowing phased adoption of hydrogen propulsion systems. Government subsidies and programs like the ATI's Future Flight Challenge provide funding, incentivising early adoption (ATI 2022).

Infrastructure development plays a key role in the border adoption of hydrogen propulsion. The aviation industry requires significant investment in hydrogen refuelling stations and cryogenic storage facilities at airports. Programs like Hydrogen Airports of the Future are emerging, but many regions need more financial and technical capacity to support these installations. Without global standardisation and investment in infrastructure, hydrogen propulsion will remain a niche market (Apostolou & Xydis 2019).

#### 3.2.6 Legal Factors

The regulatory framework for hydrogen propulsion is still evolving. ICAO and EASA's 2050 net-zero targets provide overarching guidance, but specific certification standards like ISO for hydrogen-powered aircraft remain under development. Establishing safety protocols for cryogenic storage and fuel cell handling is critical (Mithal & Rutherford 2023),.

Intellectual Property (IP) plays a strategic role in GKN's competitive positioning. The company holds multiple patents in the field of hydrogen propulsion systems. However, competitors like Airbus and ZeroAvia also aggressively expand their IP portfolios, potentially creating legal challenges for overlapping technologies (Airbus 2024, ZeroAvia 2024). International collaboration on hydrogen handling standards is equally critical. Fragmented regulations could delay adoption and increase safety risks, necessitating the standardisation of global hydrogen frameworks (Kalanje 2006).

## 3.3 Conclusion

The adoption of hydrogen propulsion systems is shaped by a dynamic environment of external factors, from regulatory frameworks to technological competitors and societal expectations. While political and societal trends favour hydrogen innovation, implementation of this technology remains significant. By addressing these factors with strategic management, GKN Aerospace can maintain its leadership in sustainable aviation.

# 4 Specific Scientific and Technological Developments

Hydrogen propulsion systems have emerged as the leading candidate for achieving net-zero aviation, but its success hinges on breakthroughs in cryogenic hydrogen storage. This technology is foundational to addressing challenges across the lifecycle of hydrogen propulsion, from production and storage to integration and end-of-life recycling. Unlike other aspects, such as fuel cells or aerostructures, cryogenic storage determines the feasibility of hydrogen's energy density, scalability, safety, and operational efficiency. By exploring future advancements in materials, thermal management, and manufacturing techniques, this section provides foresight to innovations that will redefine cryogenic storage systems over the next two decades.

## 4.1 Material

The choice of materials is pivotal in cryogenic storage, especially as mentioned in Chapter 2.2. The hydrogen is stored in a liquid state at -253°C to increase fuel density for storage and transport (White et al. 2017). Future storage tanks will leverage next-generation materials that combine strength, thermal insulation, and sustainability. With their nanoporous structures, MOFs are expected to play a transformative role by enhancing hydrogen absorption and storage capacity (Ren et al. 2015, Zhang et al. 2022). By 2040, hybrid systems combining MOFs with cryogenic storage could reduce tank size and boil-off by 50%, significantly better than the current metal-hydrides of 30% mentioned in Chapter 2.2. This would enable lighter, more efficient, and more compact designs that improve aircraft range and payload efficiency, see Table 7 (Shet et al. 2021).

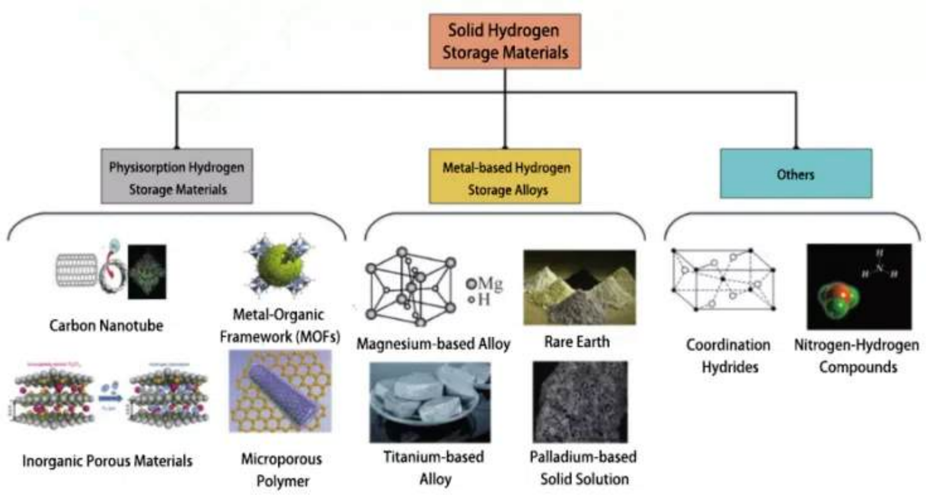


Figure 8: Classification of Solid Hydrogen Storage Materials. This diagram categorizes hydrogen storage materials into physisorption materials (e.g., carbon nanotubes, MOFs, and porous polymers) and metal-based hydrogen storage alloys (e.g., magnesium-based alloys and rare earth elements). Other advanced compounds, such as nitrogen-hydrogen complexes, highlight the diversity in hydrogen storage solutions under research. (Taken From Hydrogen (2024))

Graphene-based nanocomposites are another promising innovation. These materials provide exceptional mechanical strength and thermal conductivity, essential for maintaining structural integrity under repeated stress and thermal cycles (Zhou et al. 2016). By incorporating graphene layers into current polymer composites, future tanks could achieve a 40% reduction in thermal losses compared to current systems while extending their operational lifespan (Renteria et al. 2014). To address durability concerns, layering of self-healing polymers is being developed to repair microcrack leaks and prevent embrittlement caused by extreme temperatures (Das et al. 2016). By 2035, these materials could become standard, significantly reducing maintenance costs and enhancing tank safety, especially for long-haul and demanding defence applications.

| **Material Innovation** | **Benefits** | **Projected Impact** |
|---|---|---|
| Metal-Organic Frameworks (MOFs) | Enhance hydrogen absorption and storage capacity; reduce boil-off losses by 50% | Lighter, more efficient tanks; increased aircraft range and payload |
| Graphene-Based Nanocomposites | Provide exceptional mechanical strength and thermal conductivity | Reduce thermal losses by 40%; extend operational lifespan |
| Self-Healing Polymers | Repair microcrack leaks; prevent embrittlement at extreme temperatures | Lower maintenance costs; enhanced safety for long-haul and defense applications |

Table 7: Material Innovations and Their Impact on Cryogenic Hydrogen Storage (Own Work)

## 4.2 Thermal Management in Operation

During operation, thermal management is critical to preserving liquid hydrogen's low temperature, safety and minimizing energy losses. Traditional passive insulation systems, which experience daily energy losses of 0.3% to 2%, are insufficient to meet the dynamic thermal demands of next-generation hydrogen propulsion (Barron 1985, Haselden 1971). PCM offer a groundbreaking solution. Capable of absorbing and releasing large amounts of energy during phase transitions, PCMs can actively regulate and adapt internal tank temperatures, reducing hydrogen boil-off by up to 50% (Oró et al. 2012). By 2040, PCMs integrated into multi-layer insulation systems will ensure a stable thermal environment even under extreme external conditions (Jebasingh & Arasu 2020).

But that is technological, for its control advances in AI will further enhance thermal management. For example, Paulitschke et al. (2017) utilise genetic algorithms such as PSO to simulate and optimize thermal insulation layout in real-time, finding the most efficient configurations for minimizing heat transfer. By analyzing past data from environmental conditions, these control systems could dynamically adjust insulation parameters to eliminate boil-off virtually, achieving maximum hydrogen utilization and operational efficiency by 2045 (Izadi et al. 2022). Also, emerging technologies like quantum dot coating, initially developed for space exploration, could revolutionize thermal insulation (Xu et al. 2022). These coatings reflect radiative heat, reducing the need for thick insulation layers and lowering overall tank weight. By 2040, quantum dot applications could be adapted and aligned with commercial aviation standards, improving fuel efficiency without compromising safety.

| **Technology** | **Advantages** | **Limitations** |
|---|---|---|
| Passive Insulation | Simple, cost-effective; widely used in current tanks. | Energy losses of 0.3%-2% daily; insufficient for dynamic demands. |
| Phase-Change Materials (PCM) | Reduces boil-off by up to 50%; ensures stable internal tank temperatures. | High cost of integration; limited adaptation in aviation applications to date. |
| AI-Controlled Thermal Management | Real-time optimization; eliminates boil-off; maximizes hydrogen utilization. | Requires advanced computational systems; dependent on reliable environmental data. |
| Quantum Dot Coatings | Reflects radiative heat; reduces insulation layer thickness and tank weight. | Experimental stage; high cost and untested commercial aviation readiness. |

Table 8: Comparison of Thermal Management Techniques for Hydrogen Storage

## 4.3 Manufacturing for Sustainability: Redefining Production

Manufacturing advancements will be critical to scaling cryogenic hydrogen storage systems while reducing their environmental footprint, not only for aircraft applications but also for hydrogen infrastructure storage in airports and other locations (Moreno-Benito et al. 2017). Integrating next-generation manufacturing processes will enable greater precision, efficiency, and adaptability, possibly overcoming the technical deficiency mentioned in Chapter 3.2.1 in limited countries to maintain global standardisation (Hoelzen et al. 2022).

By 2035, next-gen AM, such as Directed Energy Deposition (DED), will allow for generative designs that optimise tank geometry, eliminating stair-stepping of current AM, increasing performance and weight reduction (Liu et al. 2021). Real-time feedback mechanisms will ensure the storages are fabricated with minimal defects, enhancing safety and reliability. These techniques are expected to reduce material waste by up to 95%, aligning with circular economy principles.

Future nanomanufacturing technologies will enable molecular-level layering of advanced materials like MOFs and graphene composites, as mentioned in Chapter 4.1. This precision will enhance tank performance while significantly lowering production costs, making cryogenic storage more accessible for widespread aviation applications.

| **Technique** | **Key Features** | **Advantages** | **Limitations** |
|---|---|---|---|
| Traditional Additive Manufacturing | Layer-by-layer material deposition | Cost-effective; widely adopted | Stair-stepping effect reduces precision. |
| Directed Energy Deposition (DED) | Generative designs with real-time feedback | Enhanced performance; reduces material waste by 95% | High initial cost; limited material compatibility. |
| Nanomanufacturing | Molecular-level precision layering | Optimizes material properties (e.g., MOFs, graphene); lowers production costs | Experimental stage; scalability challenges. |

Table 9: Comparison of Manufacturing Techniques for Cryogenic Hydrogen Storage

## 4.4 End-of-Life Sustainability

As cryogenic storage systems end their lifecycle, sustainability considerations will be critical. Current storages, often constructed from non-recyclable composites, pose significant environmental challenges. By 2040, thermochemical recycling processes such as pyrolysis will recover over 90% of high-value materials, such as graphene and MOFs, from decommissioned tanks (**?**). These processes will use heat to break down composite structures into reusable components, reducing landfill waste and aligning with circular economy principles addressed in Chapter 2.5 (Bernatas et al. 2021, Nicolai et al. 2023).

Modular designs will further enhance end-of-life sustainability by enabling easy disassembly of tanks. Structural elements, insulation layers, and thermal coatings can be separated and recycled individually, minimizing disposal costs and environmental impact. In addition, innovations in self-healing materials and coating in Chapter 4.1 will extend tank lifespans, reducing the frequency of replacements and contributing to long-term stability (Comincini 2017).

The sustainability process throughout the lifecycle of cryogenic hydrogen storage systems are summarized in Table 10, which applies the Ellen MacArthur Foundation's Circular Economy framework. This summarises key activities, principles, and their applications across the design, use, and reuse phases.

| Lifecycle Phase | Circular Economy Principle | Application to Cryogenic Hydrogen Storage Systems |
|---|---|---|
| Design | Prioritize materials that are durable, reusable, and recyclable. | Selection of MOFs, graphene composites, and fiber-reinforced polymers ensures high performance and recyclability. Modular tank designs simplify disassembly. |
| Use | Maximize resource efficiency and minimize emissions and waste. | Advanced thermal management systems (e.g., PCMs, AI-driven algorithms) reduce hydrogen boil-off by 50%. Cryogenic tanks improve operational efficiency and safety. |
| Reuse | Recover and repurpose high-value materials to extend resource utility. | Thermochemical recycling (e.g., pyrolysis) achieves over 90% material recovery. Recovered graphene and MOFs are used to produce new tanks. |

Table 10: Circular Economy Framework for Cryogenic Hydrogen Storage Systems (Own Work)

## 4.5 Strategic and Competitive Implications

The competitive landscape for cryogenic hydrogen storage is intensifying, with companies like Airbus and ZeroAvia advancing integrated hydrogen storage technologies and aiming for commercial aviation by 2035 (Airbus 2024, ZeroAvia 2024). These developments highlight the urgency for GKN Aerospace to maintain its leadership through technological innovation and robust intellectual property strategies. GKN's portfolio already covers a variety of hydrogen technologies, as outlined in Chapter 2.2, that provide a strategic advantage. However, the patent activity surrounding hydrogen technologies continues to surge. GKN must accelerate patent filing for the storage systems and the aforementioned emerging innovations in the previous subsections, as its applications cover a wide range from commercial to defence (Justia 2024).

A forward-looking strategy would involve cross-licensing agreements with competitors in areas like thermal management and material science. These agreements could mitigate IP disputes and foster collaborative progress while ensuring GKN retains proprietary control over core technologies (Shapiro 2000). Additionally, GKN should actively monitor and engage in patent pools, particularly in hydrogen propulsion, to safeguard access to critical technologies while strengthening its future position. To further visualise GKN Aerospace's strategic positioning, a Porter's Five Forces analysis is provided in Table 11 dynamics and external pressures shaping this evolving landscape (Pavitt 1982).

| Force | Impact on GKN Aerospace (Patent and IP Focus) |
|---|---|
| Rivalry Among Competitors | **High**: Airbus, ZeroAvia, and Rolls-Royce have filed multiple patents for hydrogen propulsion and cryogenic storage. Airbus's ZEROe program and ZeroAvia's hydrogen-electric systems highlight the need for GKN to expedite its own patent filings and strengthen its IP portfolio. |
| Threat of New Entrants | **Moderate:** While the high R&D costs and expertise required in hydrogen propulsion pose barriers, startups and SMEs often secure niche patents, intensifying competition for specific technological advancements. |
| Bargaining Power of Suppliers | **Moderate:** Dependence on patented materials such as MOFs and advanced composites places GKN at risk of higher costs or licensing requirements, emphasizing the importance of securing in-house patents for critical materials. |
| Bargaining Power of Buyers | **High:** Airlines prioritize cost-effective, scalable hydrogen solutions. Early adopters may demand shared IP rights or licensing agreements to reduce costs, challenging GKN to protect its proprietary technologies. |
| Threat of Substitutes | **Moderate:** Competing technologies like SAF and battery-electric propulsion also involve active patenting, particularly in infrastructure compatibility. GKN must maintain a competitive edge by focusing on hydrogen's long-term benefits and securing broad patents to cover multiple applications. |

Table 11: Porter's Five Forces Analysis Focused on Patents and Intellectual Property (Own Work)

## 4.6 Conclusion

The advancements in cryogenic hydrogen storage, which cover its future materials, thermal management, advanced manufacturing, and end-of-life strategies, highlight its transformative potential as a staple of zero-emission propulsion. By driving innovation in these areas, GKN Aerospace can address immediate challenges and secure its position as a leader in sustainable aviation over the next two decades.

# 5 Conclusion

## 5.1 Conclusion

The revolutionary potential of hydrogen propulsion systems, particularly in advancing sustainable aviation, is established in this report. The foundational overview in Chapter 2.1 shows that GKN Aerospace's collaborative initiatives, such as H2GEAR and H2JET, demonstrate a robust commitment to hydrogen propulsion technologies (Hales et al. 2023, RISE 2024). Though currently impractical, these prototypes are strategically positioned to address market-specific needs for civil, defence, and UAM sectors, as explored in Chapter 2.3. By aligning with global decarbonisation targets, GKN remains critical in meeting the industry's evolving regulatory and operational demands (GKN 2022).

Chapter 3.2 provided various considerations of external influences, highlighting political, economic, and technological factors shaping hydrogen propulsion's future. The competitive landscape, underscored by Airbus's ZEROe program and ZeroAvia's advancements, presents challenges and opportunities (Airbus 2024, ZeroAvia 2024). These external forces emphasise the urgency for GKN to expand its intellectual property portfolio, strengthen collaborations, and accelerate innovation.

From a scientific perspective, Chapter 4 focuses on cryogenic hydrogen storage as the backbone of hydrogen propulsion's life cycle. Future advancements in materials, such as metal-organic frameworks and graphene composites, will significantly improve hydrogen storage density and reduce boil-off losses, ensuring storage efficiency. Thermal management innovations, including control systems and phase-change materials, promise to enhance operational performance under dynamic conditions. Next-generation AM and nano manufacturing will complement these advancements, redefining production efficiency, reducing waste and enabling scalable designs. Integrating end-of-life sustainability measures, such as thermochemical recycling and modular designs, underscores GKN's commitment to a circular economy.

Foreseeing ahead, GKN Aerospace must capitalise on emerging opportunities to maintain its leadership. By 2040, hydrogen propulsion will dominate sub-regional and mid-sized aircraft markets. Strategic foresight suggests that advancements in cryogenic hydrogen storage will catalyse broader adoption across aviation segments, from infrastructure to long-haul flights. Collaborations with academic institutions and competitors, as discussed throughout Chapter 2 and 3, will be pivotal in securing technological innovation and operational standardisation.

In conclusion, hydrogen propulsion systems represent the most viable path toward zero-emission aviation, addressing critical environmental, societal, and regulatory challenges. By leveraging foresight, extensive R&D, and a lifecycle-focused approach, GKN Aerospace is poised to lead the industry's transition to sustainable aviation. The insights and strategic priorities identified in this report provide focus points and a roadmap for the company to navigate the complex interplay of technological innovation, market demands, and competitors over the next two decades.

## 5.2 Future Work

Future direction and development should address the broader ecosystem required for hydrogen propulsion to achieve widespread adoption. While this report focuses on cryogenic hydrogen storage, other components of hydrogen propulsion systems warrant detailed exploration.

1. **Hydrogen Infrastructure:** As discussed in Chapter 3.2.1, developing scalable refuelling systems and robust supply chains to ensure operational feasibility across aviation segments.
2. **Alternative Propulsion Technologies:** Investigating how SAFs or hybrid-electric systems could complement hydrogen propulsion hybrids, particularly for the short term.
3. **Lifecycle Cost Analyses:** Expanding economic modelling to assess cost-efficiency across manufacturing, operation, and recycling stages.
4. **Integration with Aircraft Designs:** Conducting simulation studies to optimize the compatibility of cryogenic storage systems with future hydrogen-powered aircraft.

## 5.3 Limitations

This report acknowledges certain limitations that constrain the scope of analysis:

1. **Focus on Cryogenic Storage:** The report concentrates on cryogenic hydrogen storage, omitting detailed assessments of fuel cells, combustion systems, and other hydrogen technologies.
2. **Emerging Technologies:** Foresight relies on the scalability of prototypical and speculative technologies such as MOFs and AI-driven control systems, which remain in experimental stages.
3. **Geopolitical and Market Factors:** Volatile external influences, such as policy shifts and market disruptions, may alter the timeline for hydrogen adoption beyond the scenarios envisioned in this report.
4. **Competitive Landscape:** While major competitors are outlined, smaller startups and emerging players with disruptive potential should be covered more deeply.

# 6 Personal Project diary and Gantt plan

## 6.1 Personal diary

The diary captures activities and reflections throughout the project using Gibbs' Reflective Cycle.

**Week 1-2:** Initial Research and Topic Selection The project began with topic selection and formative proposals in early October, gradually transitioning into more profound research and analysis. I decided to report on GKN Aerospace, an interesting sector to analyze. After identifying its integral role in zero-emission aviation, I explored potential topics within GKN Aerospace's operations. I decided to focus on hydrogen propulsion systems, specifically cryogenic hydrogen storage. The visiting lecturer Mark Shaw inspired this focus on hydrogen propulsion when he talked about hydrogen infrastructure and safety. This phase was exciting but overwhelming due to the breadth of available information I should have covered in my courses. Using Gibbs's reflective cycle and consulting with the GTA, I realized the importance of narrowing my scope early to avoid unnecessary complexities. I will allocate more time to clarifying research objectives in future projects.

**Week 3-6:** Report Drafting and Peer Feedback Drafting and building the report was iterative. Chapter 2, detailing the current product, was initially broad, leading to significant revisions based on my lecturer's and peers' comments. Writing about cryogenic storage's lifecycle was rewarding but required detailed technical research, especially on materials like MOFs. Identifying external influences was also crucial, shaping my foresight for the following sections. Challenges included managing word count and ensuring narrative transitions between sections. I eventually realized that breaking the task into smaller, focused parts improved efficiency and quality. If I undertook a similar project, I would establish more precise milestones in the Gantt chart for feedback incorporation.

**Week 7-9:** Integration of Insights During these weeks, I integrated external influences and foresight into the report. The most challenging part was balancing depth with clarity, particularly in Chapter 3. Addressing end-of-life sustainability requires deep research into thermochemical recycling processes, which are currently theoretical. Reflecting on this, I recognized the importance of aligning each section with the project's objectives. I also revised my initial structure to streamline the narrative flow.

**Week 10-11:** Presentation Preparation The preparation for the presentation provided clarity on structuring the report, specifically the subsections, as they are further broken down from the rubric. I outlined GKN's hydrogen propulsion initiatives and external forces. Delivering the presentation was a valuable experience, as it highlighted gaps in my knowledge, particularly around competitor and intellectual property strategies. During the Q&A session, my lecturer emphasized the need to focus on specific engineering challenges, which refined my approach to the scientific and technological section of the report. Reflecting on this, I learned the value of feedback and would proactively seek more early input in similar assignments.

**Week 12:** Review and Submission Finalizing the report involved repetitive proofreading and formatting. Ensuring proper referencing to figures and sections and using Harvard citations across all sections took longer than anticipated. Reflecting on the process, I appreciated the value of creating a detailed Gantt Chart, which helped me manage deadlines effectively. In the future, allocating more time for final review is crucial to catch minor inconsistencies earlier.

## 6.2 Gantt Chart

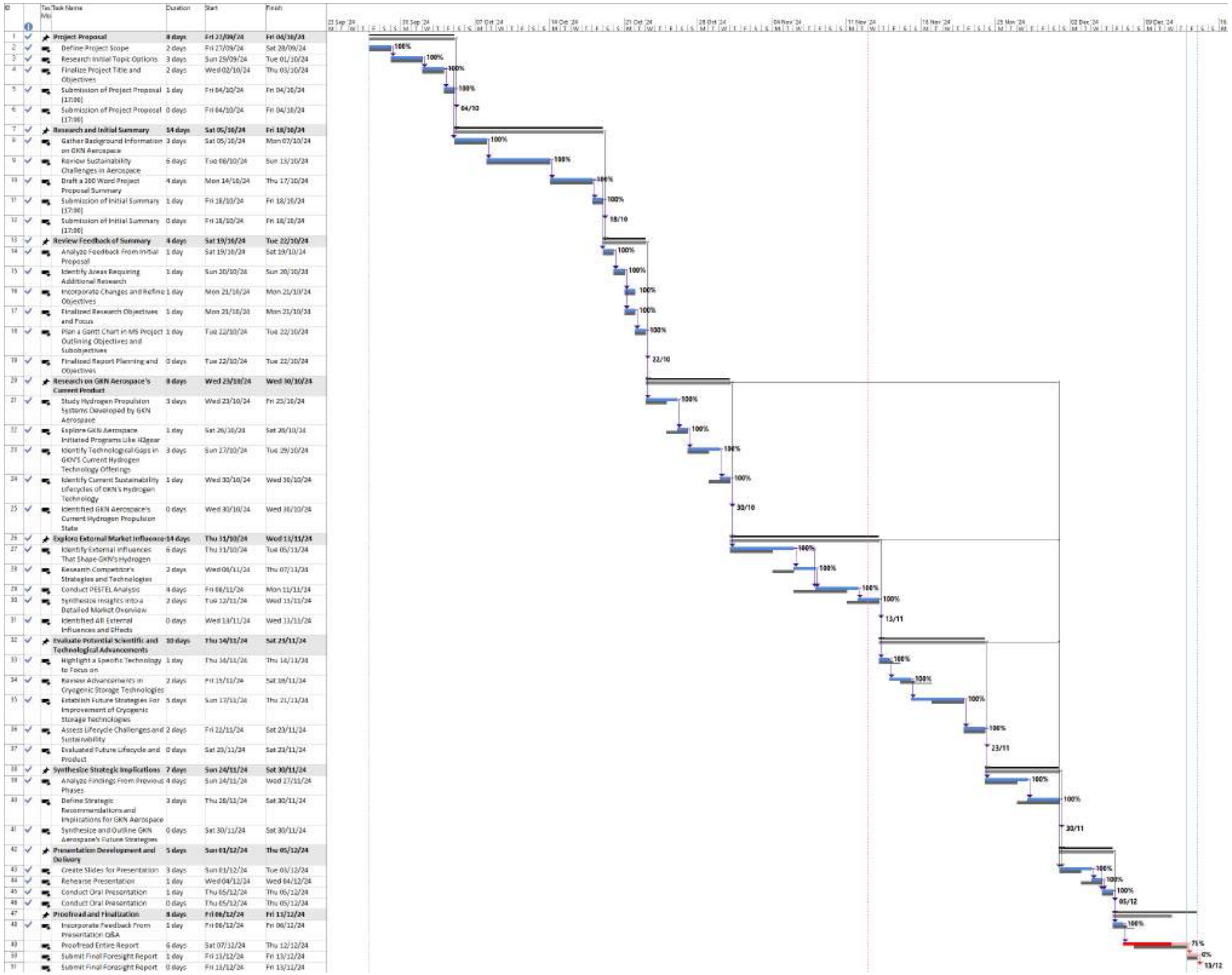


Figure 9: Gantt Chart

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