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Department of the Navy Programmatic Considerations of Product Support Elements when Employing Hydrogen Fuel to Enable Naval Aviation Capabilities: A PM's Case Study of a Post-Milestone B System

June 2025

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ABSTRACT

This report explores Department of the Navy (DON) programmatic considerations for integrating hydrogen fuel into naval aviation, focusing on challenges and opportunities in the Operations and Sustainment phase of the acquisition life cycle. Despite advancements in hydrogen-enabled prototypes, a defined sustainment framework is lacking. This research analyzes requirements across the twelve Integrated Product Support (IPS) elements to propose a roadmap for operational implementation. A Group 2 unmanned aircraft system (UAS) and Ground Support Equipment (GSE) Rapid Fielding case study examines critical logistical, maintenance, infrastructure, and training needs—especially those beyond traditional Military Occupational Specialties (MOS)—in shipboard and shore-based environments. Findings highlight major technical, regulatory, and logistical barriers to sustaining hydrogen-powered UAS for dispersed Marine Corps units in expeditionary settings in austere environments. The study concludes that successful integration requires developing comprehensive doctrine, streamlining certification pathways, and investment in expeditionary hydrogen technologies. Recommendations include tailored sustainment strategies, leveraging existing infrastructure, employing advanced storage and generation technologies, and delivering targeted training to enhance readiness, enable sustained operations, and align with the DON's long-term energy resilience and sustainability goals.

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ABOUT THE AUTHORS

Lieutenant Colonel Matthew Allen has a Diverse 26-year Marine Corps career spanning enlisted infantry, aviation maintenance, to senior acquisition roles, LtCol Allen currently serves as the Chief of Staff, Deputy Assistant Secretary of the Navy – Air/Ground, under the Assistant Secretary of the Navy for Research, Development and Acquisition, following Command Equivalent position as the Shore Air Traffic Management Deputy Program Manager, where he led a 200+ person team and managed a $720M budget. His career includes operational deployments as a Platoon Sergeant, extensive aviation maintenance and logistics assignments at MALS-31, VMFA-312, and MALS-29, along with a USMC Personnel Exchange Program tour with the Royal Australian Air Force. Acquisition expertise as the RQ-21A "Blackjack" and Unmanned Logistics Systems-Air Military Integrated Product Team Lead and Military Assistant Program Manager for Logistics at PMA-263 and completed a Secretary of Defense Executive Fellowship with Huntington Ingalls Industries. Joint experience with joint deployments, foreign training events, exercise planning/management, and JPME I PME at Naval War College.

Lieutenant Colonel Jacob A.W. Ashbolt currently serves as the Deputy Assistant Chief of Staff G-3 at Headquarters, 4th Marine Aircraft Wing (MAW), while concurrently augmenting two aviation squadrons, both rotary and fixed-wing. A career Marine Corps aviator, he was designated a Naval Aviator in 2009 after earning dual Aviation degrees from Purdue University and commissioning via Officer Candidate School in 2006. He has amassed over 3,400 mishap-free flight hours across multiple platforms, deploying multiple times in support of Operation ENDURING FREEDOM, Unit Deployment Programs, Marine Rotational Force-Darwin, and HA/DR missions. Transitioning into acquisition and logistics domains, he led the Navy's TH-73A Advanced Helicopter Trainer System Program and Production Mitigation Team, overseeing the fleet-wide modernization from the TH-57B/C to the TH-73A across TRAINING WING FIVE. He holds a Lean Six Sigma Green Belt, Advanced Acquisitions Studies Certification, and is currently pursuing a Master of Science in Program Management and Program Manager Certification through the Naval

Postgraduate School. A lifelong learner and advocate for innovation in defense acquisition, LtCol Ashbolt’s career reflects a commitment to advancing aviation readiness and integrating sustainable technology solutions within the DoD enterprise.

Emily G. Pence is an engineer at the Naval Surface Warfare Center Carderock Division, focused on advancing operational energy research and development initiatives. Ms. Pence supports the Director of Innovation, Technology Requirements, and Test & Evaluation (OPNAV N94) to identify, mature, and integrate energy technologies for shipboard application. Ms. Pence has been instrumental in supporting Navy's directed energy efforts and overseeing the integration of large-scale energy storage systems into the fleet. Her work directly contributes to modernizing naval operations, ensuring mission readiness, and aligning emerging technologies with future naval requirements.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAF	Adaptative Acquisition Framework
ACE	Air Command Element
AGL	above ground level
AMTCS	Aviation Maintenance Training Continuum System
ANSI	American National Standards Institute
ASI	aviation skills identifier
AWH	automatic water harvesting
BID	Built-in Diagnostics
BIT	Built-in Test
BUPERS	Bureau of Naval Personnel
C2	command and control
CAA	Clean Air Act
CBM+	Condition-Base Maintenance Plus
CDD	Capability Development Document
CLS	Contractor Logistics Support
CM	configuration management
CMMC	Cybersecurity Maturity Model Certification
CONOPS	concept of operations
CPC	Corrosion Prevention and Control
CSE	common support equipment
CWA	Clean Water Act
DIL	disconnected, intermittent, and limited
DLMS	Defense Logistics Management Standards
DoD	Department of Defense
DoDI	Department of Defense Directive
DoDI	Department of Defense Instruction
DOE	Department of Energy
DON	Department of the Navy
DON-EI	Department of the Navy Office of Energy Infrastructure
DOT	Department of Transportation

EASA	European Union Aviation Safety Agency
EDR	endpoint detection and response
EHOSS	Expeditionary Hydrogen Operations for Sustainable Systems
EIS	Environmental Impact Statement
EMD	Engineering and Manufacturing Development
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FMECA	Failure Modes, Effects, and Criticality Analysis
FRC	Fleet Readiness Center
GCSS-MC	Global Combat Support System-Marine Corps
GSE	ground support equipment
HAZMAT	hazardous material
IEP	Installation Energy Plan
IETM	Interactive Electronic Technical Manual
IPS	integrated product support
IPT	integrated product team
IT	Information Technology
ITEP	Integrated Training and Education Plan
IUID	Item Unique Identification
JCALS	Joint Computer-Aided Acquisitions and Logistics Support
JTDI	Joint Technical Data Integration
LCSP	Life Cycle Sustainment Plan
LRU	Line Replaceable Unit
M&RA	Manpower and Reserve Affairs
MAGTAB	Marine Air-Ground Tablet
MARCORLOGCOM	Marine Corps Logistics Command
MARCORSYSCOM	Marine Corps Systems Command
MCA	Major Capability Acquisitions
MEF	Marine Expeditionary Force
MERIT	Maintenance Engineering Requirements and Improvement Tool
METCAL	meteorology and calibration
MOS	Mission Occupational Specialty

MRA	Manpower Requirements Analysis
MRL	Manufacturing Readiness Level
MSDS	Material Safety Data Sheet
MSL	mean sea level
MTA	Middle Tier of Acquisitions
MTT	Mobile Training Team
NAVAIR	Naval Air Systems Command
NAVFAC	Naval Facilities Engineering Systems Command
NAVSEA	Naval Sea Systems Command
NCCA	Navy Center for Cost
NCDOC	Navy Cyber Defense Operations Command
NDE	Navy Data Environment
NDS	National Defense Strategy
NEC	Naval Enlisted Classification
NFPA 2	NFPA, standards on hydrogen technologies
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NOBLE	Naval Operational Business Logistics Enterprise
NRL	Naval Research Laboratory
NSN	National Stock Number
NSS	National Security Strategy
OSA	open system architecture
OSHA	Occupational Safety and Health Administration
PdM	predictive maintenance
PHA	potential hazard analysis
PHM	Prognostics and Health Management
PHS&T	Packaging, Handling, Storage, & Transportation
PLM	production life cycle management
PM	Program Manager
PMCS	preventative maintenance checks and services
POM	Program Objective Memorandum
PPE	personal protective equipment
PSM	Product Support Manager

RCM	Reliability Centered Maintenance
RCRA	Resource Conservation and Recovery Act
RMF	Risk Management Framework
ROD	Record of Decision
RRL	Ready Relevant Learning
RSP	Readiness Spares Packages
SBIR	Small Business Innovation Research
SBTT	Small Business Technology Transfer
SDS	Safety Data Sheet
SMR	Steam Methane Reforming
SOFA	Status of Forces Agreement
SRA	Shop Replaceable Assembly
SWaP	size, weight, and power
TALSA	Training and Logistics Support Activity
TDP	Technical Data Package
TFMMS	Total Force Manpower Management System
TO&E	Table of Organization and Equipment
TRL	Technology Readiness Level
TTP	tactics, technique, and procedures
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicles
UFC	Unified Facilities Criteria
USMC	United States Marine Corps
USN	United States Navy
VAMOSC	Visibility and Management of Operating and Support Costs
VR/AR	Virtual Reality/Augmented Reality
WAWF	wide are workflow

I. INTRODUCTION

Chapter I establishes the foundation of the research presented in this paper. It begins by providing an overview of the research context and clearly articulating the specific problem being addressed. Following the problem statement, the chapter outlines the central research questions that guide the investigation. Finally, it details the overall research approach, and the analytical methodologies employed to answer these questions and achieve the study's objectives.

A. PROBLEM STATEMENT

To effectively address global energy demands and impending fossil fuel shortfalls while also adhering to emergent Department of Defense (DoD) strategic energy policies, this research focuses on the emergent adoption of hydrogen as a viable alternative fuel source for naval aviation. While military aviation applications of hydrogen reach technological maturation in various prototypes, a clear structure for the widespread implementation, logistical framework, and sustained use of this technology in naval aviation is lacking. This thesis aims to identify and analyze the primary sustainment challenges that a program manager (PM) and product support manager (PSM) will need to address to enable the Operations and Sustainment phase of a hydrogen enabled unmanned aircraft system within the next two to three years. These sustainment challenges will be addressed within the twelve IPS framework to capture the logistical complexities of hydrogen fuel in naval environments, the development of robust safety and operational protocols for hydrogen-powered aircraft, and the need for strategic infrastructure investment, including hydrogen generation and refueling. This research will involve a sustainment roadmap review of a hydrogen-enabled Group 2 unmanned aircraft system test-case scenario that analyzes the logistical, maintenance, and operational aspects of its sustainment. By addressing these programmatic sustainment challenges and creating a framework of programmatic considerations for PSMs and PMs, our hydrogen research can contribute to a sustainable and efficient energy infrastructure for naval aviation, reducing reliance on fossil fuels, mitigating environmental impacts, and enhancing naval aviation capabilities, including potential advantages like increased endurance and reduced signature, in contested logistics environments. This research will help the Department of the Navy position itself as a leader in hydrogen fuel adoption while ensuring the continued operational effectiveness of its naval aviation forces.

B. RESEARCH OBJECTIVE AND QUESTIONS

The objective of this research is to provide a comprehensive analysis of the challenges and barriers associated with implementing and sustaining hydrogen technology for Naval aviation capabilities. By identifying gaps in policies, guidelines, and standards, this research will provide guidance to program managers and decision-makers. Feasible recommendations will be detailed in a test-case IPS breakout for the utilization and fielding of hydrogen technology in Naval aviation, with a specific focus on logistical challenges of hydrogen generation, storage, and transportation. By addressing these challenges and creating a cohesive knowledge resource, this research can support a sustainable and efficient energy supply chain for naval aviation by reducing reliance on fossil fuels and mitigating environmental impacts. The findings will provide valuable insights into the technical, economic, and logistical feasibility of hydrogen fuel, enabling informed decision-making and the development of effective policies and technologies that will position DON as a leader in hydrogen fuel adoption while ensuring the continued operational effectiveness of its Naval aviation forces.

- **Objective One:** Understand the product support limitations of hydrogen technology for energy in an emergent unmanned aviation use case (operations and sustainment within the next two to three years), in terms of logistics policy, sustainment aspects, and technical feasibility.
- **Objective Two:** Consider an emergent, unmanned aviation-specific system as a case study for hydrogen energy solutions to be a program manager's Life Cycle Sustainment Plan (LCSP) primer (via the twelve sustainment IPS elements) to highlight key challenges and solutions to enable future hydrogen-enabled aviation systems.

1. Primary Research Question

- How can DON accelerate transition to hydrogen fuel as a primary energy source for unmanned naval aviation operations in the Operations and Sustainment phase of acquisitions while mitigating current technical, regulatory, and logistics barriers?

2. Secondary Research Questions

- What specific Integrated Product Support elements require unique consideration and adaptation to facilitate successful transition to hydrogen fuel within unmanned naval aviation?
- What are the challenges to acquire and transition hydrogen fuel technology through the Engineering and Manufacturing Development phase, Production, Fielding, Deployment and Operational Support phases of acquisition?
- How can the DON collaborate with industry, academia, and international partners to develop standardized regulations and safety protocols to enable unmanned naval aviation hydrogen fuel applications?

C. METHODOLOGY

This research examines the sustainment and policy pressure experienced by the Navy to adopt energy efficient technologies and ensure access to sufficient and secure energy sources. Hydrogen as an energy source will be examined in terms of technology efficiency, energy security, and operational performance. The fundamentals of hydrogen technologies in terms of production, storage, transportation, and performance will be detailed. Next, the research will detail hydrogen for energy in a naval capacity by reviewing existing technologies and current challenges.

The research will then delve into the DoD's acquisition framework to provide insight on how hydrogen technology would be acquired and sustained in Naval applications. The focus of the research will be analyzing qualitative and quantitative data regarding the use of hydrogen for energy in Naval applications through the sustainment acquisition life cycle and IPS element guidebook to understand system support needs. A case study approach to examine the acquisition process of an emergent hydrogen enabled aviation system will be used as a test case for research and data collection for emplacing into the current Navy Training and Logistics Support Activity (TALSA) model of training, employment, and sustainment. Key information, obstacles, and recommendations will be broken out into the twelve IPS to enable future program managers to successfully integrate, operate, and sustain hydrogen-based technologies in additional naval aviation applications.

D. SCOPE AND LIMITATIONS

The scope of the paper is an analysis on the sustainment considerations to enable employment of a hydrogen enabled aviation platform within the next two to three years. Case study research is focused on a test case scenario based around the Naval Research Laboratory (NRL) Hybrid Tiger Platform as an emergent, hydrogen aviation programmatic use case as a Middle Tier of Acquisitions (MTA) Rapid Fielding in the acquisitions process with particular emphasis on the Operations and Sustainment phase requirements. Due to the emergent nature of hydrogen into the DON energy ecosystem, the authors will focus on the sustainment requirements for unmanned system employment as a bridge to broader aviation employment of hydrogen.

E. ORGANIZATION

This paper is organized into six chapters.

- **Chapter I:** This chapter introduces the paper and describes the problem being addressed along with the research questions to be answered. The research approach and analysis methodologies are outlined in this chapter.
- **Chapter II:** This chapter provides background information that describes the need for the Navy to adopt energy efficient technologies, details existing hydrogen technologies and challenges, and describes specific DoD sustainment considerations. Gaps in current knowledge around hydrogen technologies for Naval aviation are captured here.
- **Chapter III:** This is the literature review section of the paper where research is presented and analyzed to determine the current state of hydrogen energy for Naval unmanned applications. Background data on the sustainment requirements to support an example unmanned system employment via ship and shore-based operations (e.g., Hybrid Tiger, Avari Hermes unmanned aircraft system test-case examples) via the Navy's TALSA and Fleet sustainment support will be collected and presented.
- **Chapter IV:** This chapter introduces the paper organizational context and methodology to reach findings and analysis.
- **Chapter V:** This chapter discusses the findings of the research, implications of the findings, and recommendations to successfully sustain and employ hydrogen technology for unmanned naval aviation. A review of the twelve IPS (foundational to the LCSP for any program) will be generated based on the unmanned employment scenario to specific units within the DON.
- **Chapter VI:** This chapter concludes the paper with a summary of the findings, conclusion remarks, and recommended areas for future research.

II. BACKGROUND

Chapter II provides essential background information necessary to understand the context and significance of this research. It begins by describing the compelling need for the U.S. Navy to adopt more energy-efficient technologies. Subsequently, it delves into existing hydrogen technologies, discussing their current state and identifying associated challenges. The chapter also incorporates specific DoD sustainment considerations relevant to the adoption of new energy sources. Crucially, this chapter highlights and captures the current gaps in knowledge regarding the application of hydrogen technologies specifically within the domain of Naval unmanned aviation.

A. ENERGY TRANSITION FOR THE DEPARTMENT OF DEFENSE

The U.S. DoD is experiencing increased challenges as new threats emerge due to changes in global politics and the rapid evolution of technologies. The 2022 National Defense Strategy directly calls out the need to "make reducing energy demand a priority and seek to adopt more efficient and clean-energy technologies that reduce logistics requirements in contested or austere environments" (U.S. Department of Defense [U.S. DoD], 2022). This call to action is driving efforts to develop resilient and interoperable energy supply chains. Four specific lines of effort that are called out in DoD policy are Energy Demand Reduction, Energy Substitution and Diversification, Supply Chain Resilience, and Enterprise-wide Energy Visibility (Under Secretary of Defense for Acquisition and Sustainment [USD(A& S)], 2023).

DON's response to higher level calls to action from the DoD is outlined in the Department of Navy Operational Energy Goals (Department of the Navy Operational Energy [DON OE], 2019). The Navy has identified an increased fuel demand of 14% by 2030 as a result of increased demand of weapons systems, force structure, and distributed maritime operations. The Navy is combatting this by enhancing "lethality and effectiveness of forces through energy resiliency, operational reach, and time-on-station of forward presence naval forces" (DON OE, 2019). Specific goals to use energy more effectively in platforms, reduce logistics requirements, and increase the efficiency of Navy platforms are called out to aid the Naval fuel distribution system by removing single points of failure. The Navy has aligned its goals to the National Defense Strategy and Department of Defense Operational Energy Strategy (DON OE, 2019).

Recent changes to force posture and capabilities are driving the need to reduce energy demanded by military platforms. Capability development activities, from requirements development to acquisition, and through sustainment are needed to drive increased energy supportability and reduced energy demand throughout the Joint Force (DON OE, 2019). The U.S. Department of Defense is currently assessing its capabilities and platforms, modernization efforts, and technology development programs to determine the best paths to enhance combat capabilities through the reduction of operational energy demand. New energy supply chains are being developed to reduce energy demand and sustainment requirements to support operations in contested environments (USD(A&S), 2023).

Hydrogen fuel emerges as a pivotal enabler to meet the challenges of energy demand reduction and increased energy supportability (USD(A&S), 2023). Its potential to significantly reduce the military's reliance on traditional fossil fuels offers a pathway to alleviate logistical burdens through potential for localized production and reduced dependence on extensive supply lines. Furthermore, hydrogen offers high energy density solutions as a direct source of fuel or as an energy storage method, allowing for flexible implementation (EASA, 2024). The adaptability of hydrogen solutions makes it an extremely attractive solution that can enable warfighters to operate within a contested environment with a reduced logistical load as compared to traditional fossil fuels. A dynamic solution for energy access and security is crucial to enabling DoD to respond to the changing contested landscape (USD(A&S), 2023).

B. ALTERNATIVE FUEL SOURCE IMPERATIVE AND THE LOGISTICS CHALLENGE

The operational effectiveness of the DoD is intrinsically linked to a robust and sustainable logistics network (USD(A&S), 2023). The current reliance on fossil fuels to power military vehicles, aircraft, and bases creates a significant logistics burden, marked by complex supply chains and vulnerabilities, as highlighted by the Department of Defense's position as the largest consumer of petroleum in the U.S. (Crawford, 2019). Addressing this logistical challenge is paramount for maintaining strategic advantage and ensuring mission readiness in an increasingly complex global landscape. The Department's prioritization of reducing energy demand through the adoption of efficient technologies necessitates a fundamental shift towards cleaner energy sources (USD(A&S), 2023).

The Department of Defense is dependent upon energy resilient forces and weapons systems for mission success. Continuous access to secure power is key to meeting defense goals during times of competition, crisis, and conflict (DON OE, 2019). The rise in logistical challenges in contested environments highlights the need for DoD to understand its energy use and challenges associated with technology and infrastructure. The current military's requirements for energy-dense, liquid fuels for mobile applications highlights the reliance on fossil fuels to support operations (USD(A&S), 2023). The DoD predominantly uses fossil fuels to power ships, aircrafts, and bases, making it the largest consumer of petroleum in the United States (Crawford, 2019). The Department of Defense's historical fuel demand and expenditures are shown in Table 1. The Navy has consistently been the second largest consumer of petroleum-based liquid fuel, behind the Air Force (Department of Defense [DoD], 2023).

Table 1. Department of Defense Fuel Demand and Expenditures by Service. Source: Department of Defense (2023).

		FY15	**FY16**	**FY17**	**FY18**	**FY19**	**FY20**	**FY21**
Operational Energy Demand, Million Barrels	Army	7.3	7.1	7.6	9.2	9.0	8.1	7.3
	Navy	28.5	28.5	28.4	26.0	28.1	27.9	27.0
	Air Force	52.0	49.6	49	51.9	45.3	41.2	43.0
	Marines	0.2	0.2	0.2	0.5	.38	0.4	0.3
	Other DoD	0.5	0.4	0.3	0.9	.77	0.3	0.7
	Total Demand	**88.6**	**85.7**	**85.5**	**88.5**	**83.6**	**77.6**	**78.4**
	Expenditures (Billions)	**$14.1**	**$8.7**	**$8.2**	**$9.1**	**$11.0**	**$9.20**	**$7.91**

The Department of Defense is a significant consumer of fossil fuels, reducing its flexibility and operational capability (DoD, 2023). This reliance on traditional fuels for combat vehicles, aircraft, and facilities presents strategic vulnerabilities. Mitigating DoD's reliance on fossil fuels through the enhancement of energy access and security requires the exploration of alternative fuels (DON OE, 2019). Hydrogen presents a promising solution by offering a high energy density fuel that can be produced locally and used for various operations. Hydrogen fuel cells can power vehicles and generators, producing only water as a byproduct, and significantly reducing emissions (Ross, 2006).

Hydrogen can be synthesized from renewable sources like solar and wind power, offering a pathway to a more sustainable and resilient military (Motlow, 2021). While challenges remain regarding hydrogen production, storage, and infrastructure development, its potential to meet DoD's diverse energy needs makes it a critical area for research and investment. Changes in policy can be leveraged to drive the maturation of hydrogen technology (Modelo, 2021). The demand signal for an alternative fuel source like hydrogen is felt across DoD and internationally. It is not a unique demand, as there is currently a global shift towards the exploration of hydrogen as alternative fuel (U.S. Department of Energy [DOE], 2022).

C. GLOBAL HYDROGEN LANDSCAPE

Several countries have launched national hydrogen strategies to accelerate the adoption of hydrogen fuel as a primary alternative energy source. In 2017, Japan established a Basic Hydrogen Strategy that aims to make Japan a world leader in hydrogen technology, with a focus on hydrogen-powered vehicles and fuel cells (METI, 2017). Australia developed a National Hydrogen Strategy in 2019 that is focused on making Australia a global hydrogen supplier by leveraging its renewable energy resources (COAG Energy Council, 2019). In 2020, the European Union (EU) announced its Hydrogen Strategy, setting out a roadmap for scaling up renewable hydrogen production and infrastructure (European Commission, 2020). In that same year, China committed to developing a hydrogen economy, with substantial investments in hydrogen fuel cell technology and infrastructure (Li et al., 2022).

The global focus on fossil fuel depletion and emphasis upon alternative fuel sources has led to an increase in funding and policy directives aimed at reducing dependency on unsustainable fuel sources for both countries and their militaries (United Nations, 2015). Internationally, partnerships with allies and global energy initiatives accelerate hydrogen research and infrastructure development, reinforcing the strategic importance of alternative fuels (Li et al., 2022). Within the U.S., efforts prioritizing the transition to clean energy technologies have positioned hydrogen fuel as a key enabler in achieving carbon neutrality (U.S. Department of the Navy, 2022). Specifically, the DoD is leading efforts to integrate hydrogen technologies into operations to meet operational needs while aligning with national security and defense strategies. By embracing hydrogen fuel, the DoD aims to enhance military capabilities and contribute to broader environmental objectives (U.S. Department of the Navy, 2022).

The EU is developing and implementing strategies to launch them to achieve real, at scale, deployment of hydrogen (European Commission, 2022). European Union initiatives articulate a clear strategic intent for accelerating hydrogen adoption, setting significant targets to bolster capacity and production. By 2030, the aim is to install a minimum of 40 GW of electrolyzer capacity and achieve an annual clean hydrogen production volume of ten million tons (European Commission, 2022). These ambitious goals are foundational to enabling the widespread deployment of renewable hydrogen throughout the EU economy by 2050, including in sectors that are inherently difficult to decarbonize. Such objectives highlight the critical recognition that sustained investment in research and innovation is indispensable for clean hydrogen to fulfill its potential as a pivotal component of the green transition (European Commission, 2022).

By further comparison, the EU's Aviation Safety Agency (EASA), equivalent to the Federal Aviation Administration (FAA), has nested their own prioritization of transitioning to hydrogen-based fuel sources (EASA, 2024). The EASA is focusing on two main scenarios – the gross carbon emissions reduction in aviation to reach zero carbon emissions in the long term and a reduction of all emissions in aviation to reach emission free to zero emission. As a participant in the Clean Aviation Partnership, EASA remains at the heart of action with certification teams working with the Clean Hydrogen initiative. The Clean Aviation Partnership has been reinforced by the EU to help towards lowering emissions in aviation. Their goal is to enable aircraft and engines to exploit hydrogen's potential as a non-drop-in alternative zero-carbon fuel, particularly liquid hydrogen (EASA, 2024).

China, recognized as the largest producer and consumer of hydrogen globally, is significantly expanding its hydrogen capabilities (Li et al., 2022). As of 2020, China's hydrogen production reached thirty-three million tons annually, with coal gasification accounting for over 60% of production (Li et al., 2022). Despite its current reliance on fossil fuels, China's strategic commitment toward a low-carbon economy is clearly outlined in its recent hydrogen development plan (2021–2035). This plan targets producing between 100,000 to 200,000 tons of renewable hydrogen annually by 2025 and aims to establish a comprehensive hydrogen industry spanning transportation, energy storage, and industrial sectors by 2035 (Li et al., 2022).

Furthermore, China's hydrogen strategy identifies significant investment in electrolytic hydrogen plants, with several large-scale renewable-powered electrolyzer projects already operational and many others planned, showcasing China's rapid scale-up of green hydrogen production capacity (Li et al., 2022). China is actively pursuing hydrogen applications in transport, particularly in fuel cell vehicles, demonstrated during the 2022 Winter Olympics in Beijing with the deployment of approximately 1,000 domestically produced hydrogen fuel cell buses (Li et al., 2022). China faces substantial sustainability and logistical challenges, particularly regarding water resource management and infrastructure development. Given its uneven water distribution, key economic centers experience significant water scarcity, raising concerns about the viability of scaling electrolytic hydrogen production without substantial infrastructure investments (Li et al., 2022).

Despite these challenges, China has expressed strong intentions for international collaboration, particularly in hydrogen technology development, supply chain establishment, and standardization, though it does not currently prioritize exporting hydrogen due to high domestic demand (Li et al., 2022). China's aggressive approach positions it as a key player in global hydrogen technology development, paralleling efforts seen within the EU and highlighting its competitive ambition to establish leadership in hydrogen production and utilization (Li et al., 2022). This competitive stance necessitates strategic consideration from the U.S. and specifically the Department of the Navy, to ensure alignment and preparedness in the rapidly evolving global hydrogen economy. The U.S. government can drive hydrogen implementation and accelerate the innovation needed to refine hydrogen technologies though the development and implementation of policy and regulations (U.S. DoD, 2022).

D. HYDROGEN ENVIRONMENTAL REGULATIONS

The rapid expansion of the hydrogen industry necessitates the development of more specific and robust regulatory frameworks (Tashie-Lewis & Nnabuife, 2021). Currently there is a lack of comprehensive federal regulations that target hydrogen as an alternative fuel source. There are linkages between existing environmental statutes, such as the Clean Air Act (CAA), the Clean Water Act (CWA), and the Resource Conservation and Recovery Act (RCRA), which provide a foundation for regulating certain aspects of hydrogen activities (Tashie-Lewis & Nnabuife, 2021). For instance, the CAA regulates emissions from hydrogen production facilities, particularly those utilizing fossil fuel feedstocks, while the CWA governs wastewater discharges from electrolysis processes. The RCRA addresses the handling and disposal of hazardous materials associated with hydrogen storage and handling (Tashie-Lewis & Nnabuife, 2021).

At the federal level, agencies such as the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) are actively engaged in developing guidance and regulations related to hydrogen (Environmental Protection Agency, 2025). The EPA is exploring the potential for incorporating hydrogen into existing air quality regulations and developing methodologies for assessing the life cycle greenhouse gas emissions of hydrogen pathways (Environmental Protection Agency, 2025). The DOT, through its Pipeline and Hazardous Materials Safety Administration, is focusing on developing safety standards for hydrogen transportation and storage, particularly for pipelines and high-pressure storage systems (Department of Transportation, 2024).

One critical aspect of hydrogen fuel adoption is the growth in international environmental regulations and standards that can exert considerable influence on the future of hydrogen development and regulations (European Commission, 2022). The EU has adopted a comprehensive hydrogen strategy that includes stringent sustainability criteria for hydrogen production and utilization. The EU's Renewable Energy Directive and related regulations set forth requirements for the life cycle greenhouse gas emissions of renewable hydrogen (European Commission, 2022). These international standards can influence U.S. regulatory development and shape global trade in hydrogen technologies.

For the Department of the Navy, navigating the evolving regulatory landscape requires proactive engagement with federal and state agencies, as well as a thorough understanding of international standards (DON OE, 2019). Conducting detailed environmental impact assessments, implementing robust leak detection and prevention systems, and adhering to best practices for hydrogen handling and storage are crucial for ensuring the environmentally responsible integration of hydrogen technologies. The development of clear and consistent environmental regulations will be essential for realizing the full potential of hydrogen as a sustainable energy solution for the DON and beyond (Balli & Caliskan, 2022). Hydrogen potential can be more readily realized when regulations are in place to drive the maturation of hydrogen technology.

E. HYDROGEN TECHNICAL BACKGROUND

Addressing the significant climate-driven initiatives and the strategic imperatives outlined by the DoD necessitates the exploration of alternative energy sources to reduce greenhouse gas emissions and enhance operational resilience (U.S. DoD, 2022). Hydrogen is a promising candidate due to its potential for sustainable production, high energy density, and compatibility with many military applications. To capitalize on hydrogen's potential effectively, it is essential to understand the technical aspects of hydrogen generation, storage, and transportation, which includes diverse methods and need for technological advancements.

1. Generation

Elemental hydrogen is highly reactive and quick to bond with other elements, making it exceedingly rare to find it in its natural form (International Energy Agency [IEA], 2021). To use hydrogen as a fuel source, the hydrogen atom must be split from the compound it exists in. The most abundant source of hydrogen on Earth is in water, and the second largest is hydrocarbons commonly found in coal, natural gas, and petroleum (IEA, 2021). There are several processes for hydrogen extraction water and fossil fuels, and the technology for hydrogen generation is advancing rapidly. The primary methods of hydrogen generation are electrolysis, Steam Methane Reforming, biomass gasification, photocatalysis, and thermochemical water splitting (IEA, 2021).

The electrolysis process involves splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electricity. If electricity is sourced from renewables such as wind or solar power, the hydrogen produced is considered "green hydrogen" (IEA, 2021). Electrolysis methods are still under development and are not used for mass scale hydrogen production. The efficiency of the technology is low, so significant amounts of energy are required for electrolysis, which drives up the costs. Electrolysis is currently not considered practical for industrial use because of the lacking infrastructure and scalability of technology (Thorson et al., 2022). The Hydrogen Council, a global organization of leading companies committed to leveraging hydrogen for energy, predicts that electrolysis technology for "green hydrogen" production will be widely adopted in 2030 (Hydrogen Council, 2024).

Steam Methane Reforming (SMR) is the most common industrial method for hydrogen production and involves the reaction of natural gas with high-temperature steam (Tang et al., 2023). Much of the commercially available hydrogen in the U.S. is produced via this method, which involves separating hydrogen atoms from methane under extremely elevated temperatures (1,300 o F–1,800 o F). This method is commonly used as it is currently the most cost-effective method with the most mature technology (Tang et al., 2023). The SMR method has been used for decades and has leveraged the availability of natural gas as a primary feedstock to provide readily accessible hydrogen. The well-developed SMR technology has been adopted due to its efficiency of converting natural gas into hydrogen. One drawback of SMR is that it releases carbon dioxide, making it a contributor to global warming (Tang et al., 2023).

Biomass gasification is the process of converting organic materials into a combustible gas mixture called syngas (Lundgren et al., 2025). Organic materials are heated in a low-oxygen environment to produce hydrogen-rich syngas, a more sustainable alternative to fossil fuel-based hydrogen production. Biomass is an extremely abundant resource, especially in rural areas, and results in low net greenhouse gas emissions since biomass recycles carbon (Lundgren et al., 2025). The biomass or feedstock for this process can vary widely, which impacts consistency and the efficiency of gasification. This method requires further maturation to increase efficiency and decrease costs before it is used in large-scale, industrial applications (Lundgren et al., 2025).

Thermochemical water splitting is a method of hydrogen production that uses elevated temperatures, often from nuclear reactors, to split water molecules into hydrogen and oxygen (Agarwal, 2022). This method has been explored for large-scale hydrogen production in energy-intensive environments like military installations. When used with heat sources like concentrated solar power or nuclear reactors, this method has the potential to achieve the highest efficiency compared to other hydrogen production methods. Thermochemical water splitting is still in the research and development phase as there are currently challenges regarding operational complexity, large initial investments, and limited reliability (Agarwal, 2022).

Current trends and global initiatives support the production of "green hydrogen" through electrolysis powered by renewable energy sources (European Commission, 2022). The global focus on climate is driving electrolysis as it can be directly coupled with renewable energy sources such as solar, wind, and hydroelectric power to support decarbonization goals (Yu, 2017). Global climate action plans are focused on the production of green hydrogen through electrolysis, which has led to increasing technological advances. Continuous advancements are focused around decreasing the cost and increasing the performance of electrolyzer technology. Electrolysis technology can be used for small, central, units or can be used for large, industrial-sized solutions, which increases the flexibility of use cases for the end user (Hydrogen Council, 2024). Once the hydrogen has been formed from electrolysis, it must be stored and then transported to the end user, which comes with unique challenges.

2. Storage and Transportation

Hydrogen storage is a critical factor in support of transportation methodologies for both fixed and portable power applications. Storing hydrogen can be challenging due to its high energy mass per volume and its low energy per unit volume (Willige, 2022). Hydrogen takes up about four times as much space as natural gas, making hydrogen compression a common storage method. Hydrogen can be compressed and stored as a gas or in liquid form (Tashie-Lewis & Nnabuife, 2021). For liquid hydrogen storage, the hydrogen needs to be cooled to extremely low temperatures and stored in cryogenic tanks. An alternative hydrogen storage method is materials-based storage, meaning solids and liquids can chemically bind to the hydrogen for easier storage (Willige, 2022). Current storage technologies are energy intensive, inefficient due to hydrogen loss through embrittled materials, and costly. As hydrogen storage technologies mature, hydrogen losses will decrease and the cost of storage will decrease, which will increase the ease of transportability (Alsaba et al., 2023).

The transportation of hydrogen from the point of production to the end user varies per use case (Alsaba et al., 2023). Current infrastructure includes pipelines, trucks, storage facilities, and liquification plants. Hydrogen transportation technologies are evolving to decrease cost and increase efficiency, but initial hydrogen infrastructure for transportation is leveraging the existing natural gas system (Ustolin et al., 2022). Currently, hydrogen transportation is reliant on trucks on the road for shorter distances. Hydrogen transportation via air is being explored, but there is safety challenges associated with this method (Bhuiyan & Siddique, 2025). The cost of hydrogen transportation is a main factor in the chosen method and as infrastructure and storage methods evolve, so will transportation. Methods for transporting hydrogen depend on the storage methods, including compressed hydrogen gas transport, liquid hydrogen transport, and hydrogen carriers (Alsaba et al., 2023).

Compressed hydrogen gas transport occurs when hydrogen is stored at high pressures (350–700 bar) in reinforced cylinders made of steel or composite materials (Guo et al., 2024). These cylinders are then transported to distribution points for end users via trucks. Tube trailers can be used to transport substantial amounts of compressed hydrogen. They are made of multiple high-pressure cylinders mounted on a trailer and can transport larger amounts for longer periods than standard gas cylinders (Alsaba et al., 2023). For industrial areas with significant hydrogen demand, dedicated hydrogen pipelines can be used. Pipelines are suited for large-scale and long-distance transport. Compressed hydrogen gas transport offers the potential for large-scale distribution but requires robust containment materials and infrastructure (Rampai et al., 2024).

Liquid hydrogen transport requires hydrogen to be cryogenically cooled to -432oF and transported in insulated tanks. Highly insulated containers and advanced refrigeration systems are required for transporting liquid hydrogen (Willige, 2022). While liquid hydrogen has a higher energy density than compressed gas, it requires continuous refrigeration to prevent boil-off losses (Schlapbach & Zuttel, 2001). The management of boil-off, or evaporation of hydrogen due to heat ingress, is critical to minimizing losses. Significant energy is required to liquify hydrogen and specialized infrastructure for storing, handling, and transporting it is needed, which increases the overall cost of this method (Alsaba et al., 2023).

An alternative to transporting hydrogen as a gas or liquid is hydrogen carriers. Hydrogen carriers can exist as chemical hydrides or solid-state carriers (Motlow, 2021). Chemical hydrides store hydrogen as a chemical compound and have a high storage density relative to liquid or gas storage methods. These chemical hydrides can exist as metal hydrides, ammonia, or chemically bound to liquid organic hydrogen carriers (Klebanoff et al., 2021). Solid-state carriers are different from chemical hydrides because they store hydrogen in the pores of their structure through adsorption. These methods reduce the risks associated with high-pressure or cryogenic storage but require additional processing at the delivery point to extract hydrogen, which increases cost (Ustolin et al., 2022). Research into advanced materials to improve the efficiency of the extraction process is necessary to improve the feasibility of widespread adoption (Klebanoff et al., 2021).

The successful worldwide adoption of hydrogen as an alternative fuel hinges upon increasing efficiency and decreasing the cost of hydrogen generation, storage, and transportation methods (Wang et al., 2023). Another hurdle is the lack of existing hydrogen infrastructure. To support the hydrogen supply chain, major investments need to be made to bolster hydrogen infrastructure (Alsaba et al., 2023). This encompasses facilities and systems needed to support the hydrogen life cycle, including facilities for hydrogen production and storage, pipelines for transport and refueling stations for vehicles. The development of hydrogen infrastructure needs to keep pace with the rapidly evolving production and storage technology for successful large-scale implementation (Alsaba et al., 2023).

3. Infrastructure

The Hydrogen Council predicts that by 2035, critical infrastructure for hydrogen production and deployment could be in place (Hydrogen Council, 2024). Key milestones for infrastructure that support hydrogen transport are regional hubs with refueling stations between 2025 and 2030. By 2030, projections show green hydrogen can be cost competitive to traditional fossil fuels, which will drive global pipeline networks to create an integrated energy system by 2035 (Hydrogen Council, 2024). The increase in global demand of hydrogen is driven by decarbonization goals, but there are hurdles such as cost and technology readiness that could slow infrastructure development.

The future of hydrogen storage and transportation will likely use an integrated approach that is based upon user needs, technological developments, and cost (Klebanoff et al., 2021). It is likely that compressed hydrogen transport will be used for local distribution in cities or industrial hubs. Liquid-hydrogen will likely be used for long-distance transport and large volumes of hydrogen for specific regions with high demands, as specialized tankers and pipelines would be needed. International shipping or transport to regions with limited hydrogen infrastructure would likely leverage hydrogen carriers (Klebanoff et al., 2021).

Currently, hydrogen infrastructure in the U.S. is supported with government and private industry investments (Department of Energy [DOE], n.d.). Infrastructure for hydrogen transportation and storage is limited, and the growth of infrastructure to include pipelines, generation and storage facilities, and refueling stations will require significant investment. Efforts in the U.S. aim to continue the development of hydrogen infrastructure in specific transportation corridors through targeted grants. Seven-billion dollars have been set aside for the development of seven Regional Clean Hydrogen Hubs, with the goal of accelerating the mass adoption of low-cost, clean hydrogen as fuel (DOE, n.d.).

The DoD has expressed interest in hydrogen for its potential to enhance energy security, resilience, and operational capabilities, while industry seeks opportunities for investment and technological advancement (U.S. DoD, 2022). The DoD can leverage efforts focusing on hydrogen production, storage, and transportation to address logistical challenges associated with widespread hydrogen adoption, to ensure a reliable and efficient supply chain of fuel. The growth in the hydrogen sector presents opportunities for partnerships between the DoD and private industry (U.S. DoD, 2022). These partnerships involve joint research and development efforts, pilot programs that demonstrate hydrogen's military applications, and shared utilization of emerging infrastructure, accelerating the transition of hydrogen technology (Joby Aviation, 2024). A key aspect of hydrogen adoption that impacts every life cycle phase is safety. Hydrogen safety needs to be considered during the generation, storage, transportation, and infrastructure development phases to ensure the risks are mitigated (Najjar, 2013).

4. Safety

To ensure the welfare of the warfighters and civilians handling hydrogen through the generation, storage, and distribution phases, the safety risks associated with hydrogen must be fully identified and mitigated (Najjar, 2023). Hydrogen is a highly reactive element and when exposed to oxygen, a significant amount of energy is released in the form of heat and light, or a flame (Guo et al., 2024). Hydrogen is highly flammable and has a low ignition energy, while also having a high flammability range compared to other fuels, which means that hydrogen easily ignites and can burn or explode in mixtures containing as little as 4% hydrogen. This increases the risk of a hydrogen explosion as even a small amount of leakage into the air can create a flammable mixture (Guo et al., 2024).

There is a high probability of hydrogen leakage during storage and transportation. The hydrogen molecule is extremely small, meaning that it can easily leak through seals and any porous materials (Guo et al., 2024). If hydrogen is stored in a confined space, the leaks can lead to an accumulation of hydrogen, which would increase the risk of a fire or explosion. Since hydrogen is lighter than air, it disperses quickly, which rapidly reduces the concentration in open areas, but if proper ventilation is not available, explosive hydrogen clouds can form. Hydrogen leakage during storage and transportation is an elevated risk due to the small molecular size, but also because hydrogen can cause metals to become brittle, leading to structural failures (Guo et al., 2024). The reactivity of hydrogen allows it to diffuse into certain metals and accumulate at areas of high stress and initiate cracks. Once a storage system has cracks, it is mostly useless as it will continue to leak hydrogen and continue to become embrittled. Embrittlement becomes a larger issue when looking at long term hydrogen transportation through international pipelines (Guo et al., 2024).

Other safety risks for hydrogen stem from high-pressure storage tanks or cryogenic temperatures when storing liquid hydrogen (Wang et al., 2023). For the high-pressure storage of gaseous hydrogen, there is a risk of rapid gas release if there are any failures in the pressure containment systems. Flaws in the tank materials could lead to a catastrophic rupture of the tank, which poses severe risks to anyone or objects near it (Wang et al., 2023). For cryogenic storage, there are safety risks of cryogenic burns from direct contact, along with the embrittlement of materials. The evaporation of hydrogen from cryogenic storage tanks is known as "boil-off" and is required to be ventilated or reliquefied to avoid any pressure buildup within the tanks. In the event of a fire, cryogenic hydrogen can quickly change from a liquid to a gas, which causes extreme, rapid pressure increase and could cause the tank to explode (Wang et al., 2023).

Hydrogen leakage risks a fire or explosion and is also an asphyxiation hazard. Leakage in a confined space could displace the oxygen in that space and reduce its concentration (Wang et al., 2023). As oxygen levels deplete, the body can experience hypoxia which can result in impaired thinking and coordination, loss of consciousness, and then death as the oxygen levels decrease. Hydrogen is also odorless and colorless by nature, which makes leaks extremely hard to detect without the proper sensing and monitoring systems. The main risks of hydrogen stem from the high flammability, leakage potential, large dispersion, and embrittlement of material. Theses can have severe consequences that result in explosions, structure impairment, and death if not mitigated properly (Wang et al., 2023).

Implementing rigorous safety protocols for the generation, storage, and distribution of hydrogen, while continuously education personnel handling the systems will be key to mitigate threats. Addressing the flammability risks should include implementing extremely sensitive hydrogen sensors to detect leaks and then developing leak mitigation strategies such as high-quality seals, gaskets, and shut-off valves (Guo et al., 2024). Ventilation systems that prevent hydrogen build-up will reduce the likelihood of explosion. In some cases, the use of inert gas such as nitrogen to blanket hydrogen and reduce its exposure to oxygen, which would reduce the risk of ignition, should be considered (Tae, 2021).

Frequent inspection and maintenance of storage and transportation systems can reduce the likelihood of catastrophic failure to storage tanks or pipelines (Tae, 2021). This would also help mitigate the leakage of hydrogen throughout the storage and distribution phases. Proper hydrogen-resistant materials should be selected for all hydrogen applications to mitigate the risk of leaks. Sensors and monitors to identify leaks that activate a controlled ventilation system should be implemented to avoid dispersion. Developing robust regulations and standards for the handling of hydrogen from generation to end-use will be critical for ensuring the safety of the Fleet (Tae, 2021).

Efforts to enhance hydrogen technology are focused on safety and risk mitigation. Developing advanced materials resistant to embrittlement will reduce the likelihood of leaks (Najjar, 2023). Storage methods that protect the user from cryogenic and high-pressure tanks are being explored via enhanced insulation and pressure relief devices. Minimizing personnel exposure to these extreme storage methods through remote operations and isolation should also be used as a mitigation technique. Safety mitigation is key for the Fleet to adopt hydrogen technology (Guo et al., 2024). As hydrogen technology continues to mature, the efficiency of the technology will increase, which will increase the safety aspects.

F. HYDROGEN ENERGY LIMITATIONS

At present, the limitations behind widespread utilization of hydrogen today are cost and technology maturation (International Renewable Energy Association [IRENA], n.d.). The major drivers of cost include technology advancements in generation, storage, transportation, infrastructure development, scaling, and high initial investments. The market demand is focused on green hydrogen production, shown in Figure 1, but this is limited by the efficiency of current technology and its high capital costs. Renewable sources to generate green hydrogen are currently not cost competitive with fossil fuels. As hydrogen generation technology becomes more efficient and the price of energy decreases, producing green hydrogen will be more cost-competitive to fossil fuel sources (IRENA, n.d.).

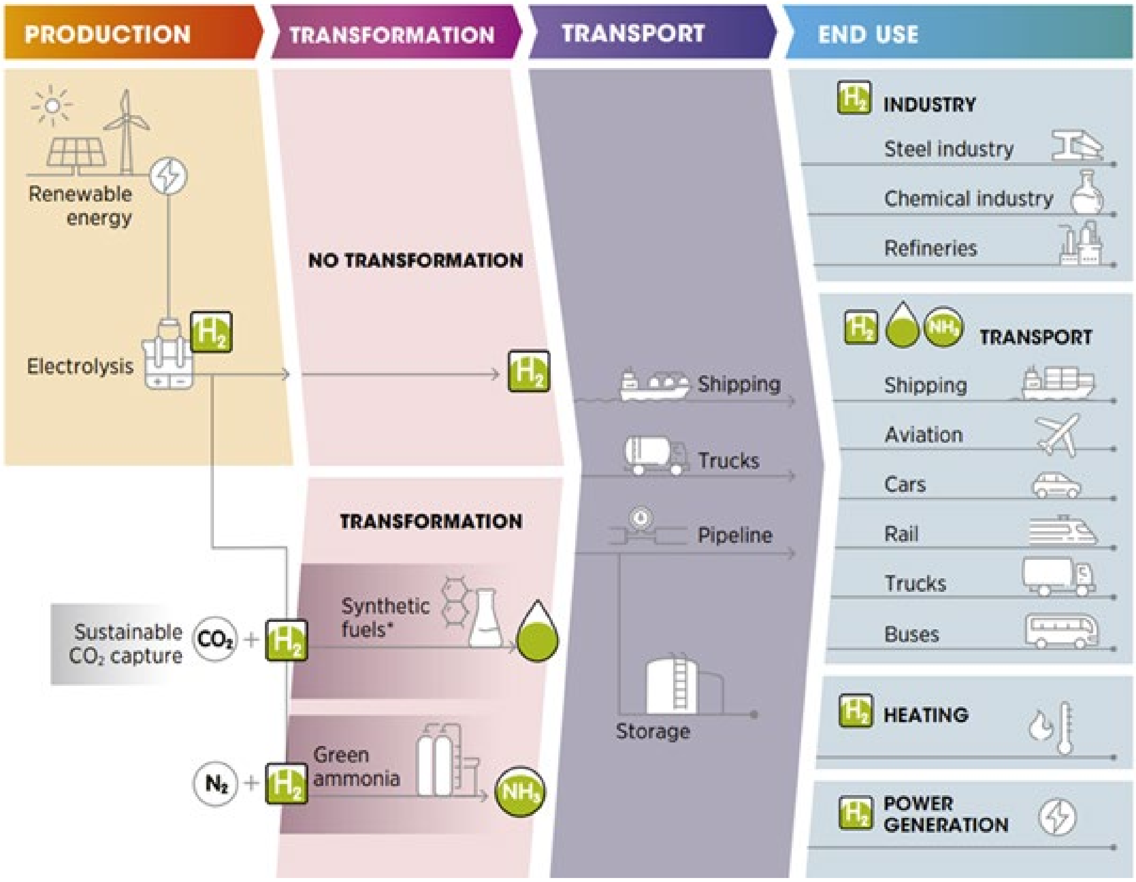

Figure 1. Green Hydrogen Production, Conversion and End Use across the Energy System. Source: International Renewable Energy Association (n.d.).

Technology for storage, production, and distribution of hydrogen has not addressed the loss of hydrogen, which further impacts the feasibility of hydrogen as a mainstream energy source (Miller et al., 2020). Many inefficiencies and complexities exist in current technologies to include materials that become embrittled by hydrogen, the amount of energy needed, and the various processes to get usable hydrogen to the end user. Addressing the efficiency of hydrogen technologies through continued research and development to reduce losses and complexities, while increasing ease of usability, is key for widespread adoption (Miller et al., 2020).

Further development of infrastructure is necessary to store and transport hydrogen. Advancements in materials and technologies for hydrogen storage will increase the ease of transportation and drive down costs (Tashie-Lewis & Nnabuife, 2021). Building the required infrastructure takes time and is dependent upon continuous market demand and technology maturation. Reaching economies of scale will be critical for reducing costs across the entire hydrogen value chain. Building a hydrogen infrastructure, including production facilities, pipelines, and refueling stations, requires substantial upfront investments. The large infrastructure size and scope are not available today and would take major investments and resources to implement (Tashie-Lewis & Nnabuife, 2021).

Working with hydrogen presents safety concerns as it is highly flammable and has a high ignition range (Wang et al., 2023). Robust safety measures to mitigate risks during production, storage, transportation, and use of hydrogen are necessary. Continued research and development to prevent hydrogen leaks caused by embrittled materials will bolster the public views on implementing hydrogen and enhance market readiness. The ability to mitigate safety concerns is a major technical challenge that adds to the prohibitive costs of hydrogen as an energy source (Wang et al., 2023). Aligning policy for safety with infrastructure development and technology maturation can help build public trust and interest in technology to further transition and widespread adoption.

The energy limitations of hydrogen impact the public demand, and therefore the ability for widespread adoption. Experts in the private and public sectors are targeting these limitations to increase the viability of hydrogen as an energy source (Motlow, 2021). The defense market has been targeting the advancement of hydrogen technology for its ability to meet mission critical operations, while supporting global climate goals (U.S. DoD, 2022). The U.S. Department of Defense has been investing in the research and development of hydrogen technologies for the past decade and has had success in initial prototype development. Specifically, the Department of the Navy has been heavily investing in hydrogen fuel cell technology to maximize the efficiency of ground vehicles and unmanned aerial vehicles (UAVs) (Naval Research Laboratory [NRL], 2021). The diversification of the fuel supply chain is widely supported by DON and DoD leadership, which has driven the further development of hydrogen technologies (Motlow, 2021).

G. HYDROGEN EFFORTS IN THE DEPARTMENT OF DEFENSE

Hydrogen is being explored as an alternative energy source in each of the military branches. Efforts are underway to use hydrogen as a capability enabler to reduce the reliance on fossil fuels and improve operational efficiency (Vacchio, 2024). Hydrogen for defense applications has been prevalent in recent history, with the first hydrogen fuel cell diesel electric submarine being developed in 1996 by the German and Italian Navies. Advantages to hydrogen fuel cells are that they can store an immense amount of energy due to their gravimetric energy density (Vacchio, 2024).

The Department of Defense is focusing on hydrogen technologies applications in fuel cell development for power generation and transportation (Li J. et al., 2024). Fuel cells are a device that generates electricity through an electrochemical reaction, instead of combustion. They are similar to batteries, except instead of needing to be charged, they need to be refueled to continue to operate. In the case of hydrogen fuel cells, electricity is generated through a chemical reaction between hydrogen and oxygen, and the only biproducts are heat and water (Li J. et al., 2024). Hydrogen fuel cells are solid-state, meaning there are fewer moving parts, which decreases maintenance and increases reliability. The lack of moving parts in a hydrogen fuel cell also adds a layer of stealth, as electricity is generated silently (Motlow, 2021). Hydrogen fuel cells are emerging as a much more efficient alternative to current fuel cell solutions, and the added efficiency extends its range by between 50% and 80% (Li J. et al., 2024).

Fuel cells are ideal for providing portable power to support field operations. During emergencies, fuel cells can be used as a reliable backup power source (Barnett, 2025). More recently, hydrogen fuel cells are being developed for vehicle propulsion as they offer extended range capabilities and reduced noise. One aspect of hydrogen fuel cells that requires additional logistics is the hydrogen supply to the fuel cell itself. Efforts are underway with the Navy and the Marine Corps to demonstrate expeditionary hydrogen units for onsite production that can feed the fuel cell, resulting in continuous and portable power. Another defense focused expeditionary hydrogen generation system is being developed by NovaSpark Energy Corporation as shown in Figure 2 (Barnett, 2025). This mobile hydrogen fuel generation system is specifically designed for agile, long-range military deployment scenarios, addressing the DoD’s operational needs for energy resilience and logistical flexibility.

Figure 2. NovaSpark Energy Corp. Expeditionary H2 Generation System. Source: Barnett (2025).

NovaSpark's Air-to-Power technology uses renewable sources like wind and solar energy to extract water vapor from the air and produce hydrogen through electrolysis (Barnett, 2025). This solution leverages innovative green hydrogen production technologies, enabling rapid, on-site hydrogen generation to minimize logistical burdens and enhance operational security by reducing reliance on extended fuel supply chains. The initiative directly involves collaboration with critical DoD stakeholders, including the Marine Corps Expeditionary Energy Office and the Naval Information Warfare Center Pacific, underscoring its alignment with ongoing military hydrogen programs. NovaSpark's strategic partnerships emphasize a broader effort to integrate commercially derived disruptive capabilities into defense infrastructure, enhancing the DoD's ability to deploy sustainable, flexible, and secure energy solutions globally (Barnett, 2025).

1. Project BIGBANG: Hydrogen Fuel Cell for Unmanned Systems

Within the broader context of the U.S. Navy's ongoing commitment to enhancing the operational capabilities of its unmanned aerial systems, the research initiative known as Project BIGBANG was launched starting in 2019 (NAWC Wolf, Power Point slides, 2019). This project investigates the potential of hydrogen-enabled fuel cell technology as a means to significantly advance the endurance, range, and overall operational efficiency of UAV platforms. Notably, the implementation of a hydrogen fuel cell system is projected to extend the operational range of current electric UAVs by an estimated factor of four to five times that achievable with existing battery technologies, thereby enabling significantly longer-range flight capabilities. The exploration of this alternative power source is critical for bolstering the Navy's maritime surveillance and reconnaissance capabilities, and the findings of this research, as illustrated in Figure 3, contribute to the growing body of knowledge in advanced propulsion systems for military applications (NAWC Wolf, PowerPoint slides, 2019).

Figure 3. Project BIGBANG Hydrogen Fuel Cell Range Multiplier. Source: NAWC Wolf (2019).

Establishing a portable hydrogen generation system is key to maximizing the effectiveness of implementing hydrogen fuel cells. The use of hydrogen fuel cells for aviation applications is an area of Department of Defense interest (NRL, 2021). Potential benefits for integrating hydrogen technology into aviation systems include longer flight times, fast refueling, enhanced altitude performance, and reduced signatures (EASA, 2024). Aviation applications are limited by weight, which is another strong reason to further explore the use of hydrogen, as its high gravimetric energy density allows it to store a lot of energy per unit of mass. As unmanned aerial systems become more prevalent in modern day warfighting, hydrogen energy can enhance the mission capability of these systems by allowing heavier payload and operations in extreme environments (EASA, 2024).

2. Hydrogen Enabled Unmanned Aerial Vehicles

The DoD increasingly embraces UAS for their diverse operational capabilities. In parallel, the pursuit of enhanced endurance, reduced logistical footprints, and cleaner energy alternatives has driven significant interest within the DoD towards hydrogen as a potential power source for these platforms (U.S. DoD, 2022). The current efforts within the DoD to develop and prototype hydrogen-enabled UAS represent a critical step in evaluating the feasibility and benefits of integrating hydrogen fuel cell technology into military UAS (NRL, 2021).

Unmanned Aerial Systems are systematically categorized into five distinct groups (Figure 4), a classification scheme frequently employed within contexts such as the U.S. Department of Defense, primarily based on their physical attributes and performance envelopes. Group 1 encompasses the smallest UAS, typically weighing up to 20 lbs., operating below 1,200 feet Above Ground Level (AGL), and with airspeeds less than 100 knots, often utilized for close-range reconnaissance (Barnhart et al., 2012). Progressing in size and capability, Group 2 UAS range from 21 to 55 lbs., maintain operations below 3,500 feet AGL, and are limited to speeds under 250 knots, commonly serving tactical reconnaissance roles. Group 3 includes medium-sized systems weighing less than 1,320 lbs., capable of operating below 18,000 feet Mean Sea Level (MSL) at speeds less than 250 knots and are frequently employed for surveillance and target acquisition missions, often possessing runway-independent launch and recovery capabilities (Barnhart et al., 2012). The larger UAS are classified within Group 4 and Group 5, both exceeding 1,320 lbs. The distinction lies in their operating altitude: Group 4 operates below 18,000 feet MSL at any airspeed, typically comprising larger surveillance and strike platforms requiring runways, while Group 5 operates above 18,000 feet MSL at any airspeed, representing the most sophisticated, high-altitude, and often strategic reconnaissance or endurance-focused systems, also requiring runway operations (Barnhart et al., 2012). This tiered classification provides a fundamental framework for understanding the diverse capabilities and operational considerations across the spectrum of UAS.

UAS Group Classification (DoD)

Group	Max Takeoff Weight	Normal Operating Altitude	Airspeed
Group 1	0-20 lbs	Below 1,200 ft AGL	Less than 100 knots
Group 2	21-55 lbs	Below 3,500 ft AGL	Less than 250 knots
Group 3	Less than 1,320 lbs	Below 18,000 ft MSL	Less than 250 knots
Group 4	Greater than 1,320 lbs	Below 18,000 ft MSL	Any airspeed
Group 5	Greater than 1,320 lbs	Above 18,000 ft MSL	Any airspeed

Based on U.S. Department of Defense (DoD) Classification

Note: These classifications are based on the U.S. Department of Defense criteria and may vary slightly depending on the source or specific context (e.g., FAA classifications differ). AGL = Above Ground Level, MSL = Mean Sea Level.

Figure 4. Unmanned Aircraft Systems Group 1–5 Classification for Department of Defense. Source: Barnhart et al. (2012).

a. Hydrogen Enabled Unmanned Aerial Vehicles – Hybrid Tiger

The Naval Research Laboratory's has a hydrogen UAS prototype called Hybrid Tiger (NRL, 2021). This effort explores the integration of hybrid power systems for enhanced endurance. Building upon prior NRL research into alternative energy sources, Hybrid Tiger combined solar photovoltaic technology with hydrogen fuel cell systems, as seen in Figure 5. The project investigates the feasibility of achieving multi-day flight by optimizing energy management across varying operational conditions, a challenge that requires balancing the intermittent availability of solar energy with the continuous energy demands of long-duration missions (NRL, 2021).

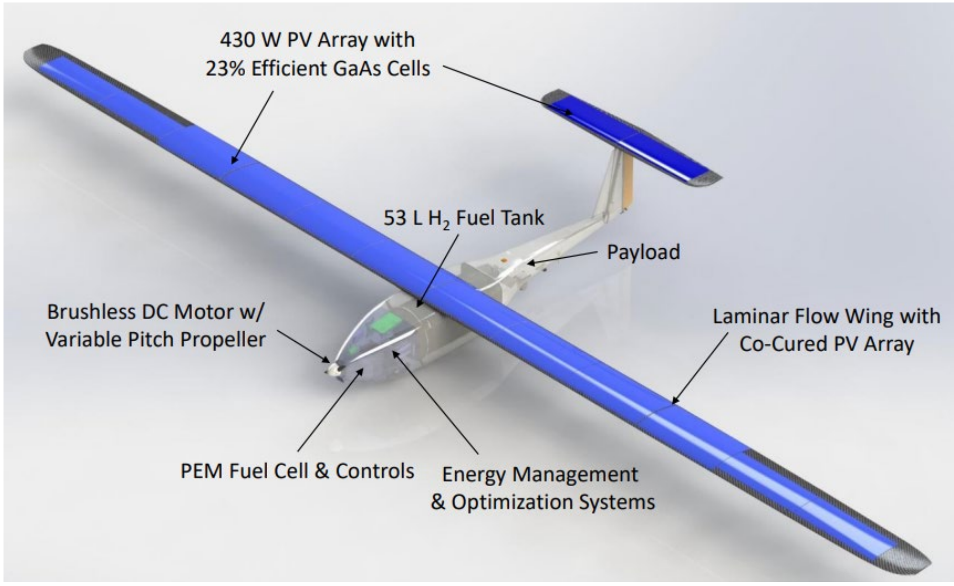

Figure 5. Naval Research Laboratory Hybrid Tiger Design. Source: Naval Research Laboratory (2021).

The core research focuses on the development of a hybrid power management system capable of transitioning between solar and hydrogen energy sources (NRL, 2021). This involves the creation of algorithms that adapt to changing environmental factors, such as weather patterns and solar irradiance, to optimize energy consumption. The project also examines the integration of high-efficiency solar panels into the UAS's wing structure and the efficiency of hydrogen fuel cell systems in long-duration flight scenarios. The data collected from these tests will provide valuable insights into the limitations and potential of hybrid power systems for extending UAS operational endurance (NRL, 2021).

b. Hydrogen Enabled Unmanned Aerial Vehicles – Stalker

Naval Research Laboratory has also been working with Lockheed Martin to utilize a hydrogen fuel cell onto their UAS, known as Stalker (Lockheed Martin, 2025). The Stalker UAS, as shown in Figure 6, is an operationally proven technology that was designed to support long-endurance reconnaissance missions to be used by special forces in contested environments. This platform aims to achieve the endurance and payload performance of a larger, more costly system, but with the flexibility of a smaller and portable UAS. The first Stalker vehicle is powered by a ruggedized solid oxide fuel cell combined with propane to reach over 8 hours of operation (Lockheed Martin, 2025). The Naval Research Laboratory has modified the design to use a hydrogen fuel cell to enhance endurance and reduce the heat signature of the platform (Hamisevicz, 2023).

Figure 6. Lockheed Martin Hydrogen Stalker Unmanned Aerial System. Source: Hamisevicz (2023).

Prototyping to support demonstrations of a hydrogen fuel cell on a Stalker platform is how the Navy is able to gather objective quality evidence that will be used to inform the use cases for this technology (Hamisevicz, 2023). The NRL is resourced to enhance the technology readiness level of hydrogen UAS through the continuous improvement of the performance of the system. The innovation of implementing a hydrogen fuel cell on an existing platform to meet the needs of DoD increases operational capability of the Fleet, while continuing to push the envelope in developing technologies (Hamisevicz, 2023).

c. Hydrogen Enabled Unmanned Aerial Vehicles – Avari Aerospace Hermes

Hydrogen fuel cell technology is increasingly considered for UAVs to achieve extended endurance and reduced emissions (Avari Aerospace, n.d.). The Avari Aerospace Hermes UAV exemplifies this trend, featuring a modular design intended for future integration of alternative energy sources. The Hermes platform addresses the challenges of hydrogen storage and fuel cell implementation through its adaptable architecture and integration with multiple safety features. This design strategy reflects a broader industry shift towards sustainable UAV operations, driven by the need for platforms capable of long-duration missions with minimal environmental impact. Hermes's design represents a key development in the transition from traditional propulsion to hydrogen-based systems within the UAV sector, as shown in Figure 7 (Avari Aerospace, n.d.).

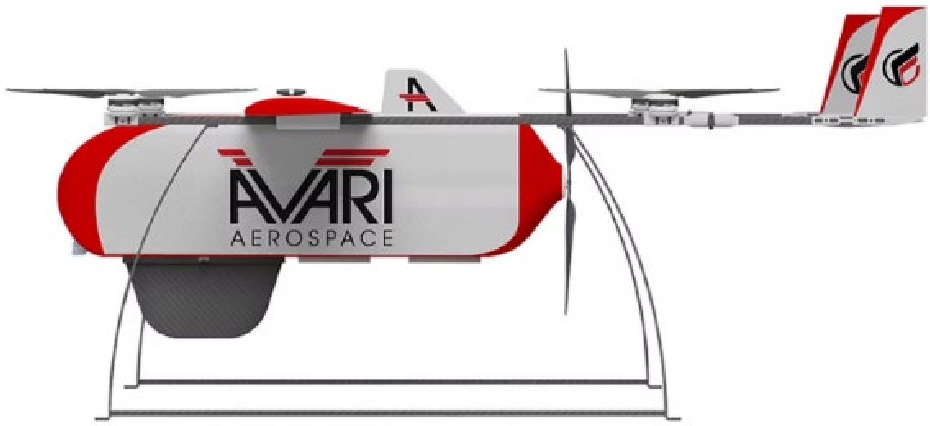

Figure 7. Avari Aerospace Hydrogen Enabled Hermes Drone. Source: Avari Aerospace (n.d.).

d. Hydrogen Enabled Unmanned Aerial Vehicles – Joby Aviation

DoD is doing internal development of hydrogen UAS systems but is closely following industry advancements and leveraging their expertise. One industry leader, Joby Aviation, is pioneering an air taxi service using electric vertical takeoff and landing aircraft (Joby Aviation, 2024). The aircraft, shown in Figure 8, is designed to provide a sustainable, quiet, and efficient transportation method for regional travel. While their core platform currently relies on battery-electric technology, Joby is also exploring the potential of hydrogen to further enhance its capabilities. A successful demonstration of the hydrogen-electric aircraft took place in 2024. Joby has partnered with the U.S. Airforce transformative vertical lift program to accelerate and transition their hydrogen battery-electric technology for DoD applications (Joby Aviation, 2024).

Figure 8. Joby's Hydrogen-Electric Technology Demonstrator Aircraft. Source: Joby Aviation (2024).

The Joby platform features a "liquid hydrogen fuel tank, which stores up to forty kilograms of liquid hydrogen, alongside a reduced mass of batteries. Hydrogen is fed into a fuel cell system to produce electricity, water, and heat. The electricity produced by the hydrogen fuel cell powers the six electric motors on the Joby aircraft, with the batteries providing additional power primarily during take-off and landing" (Joby Aviation, 2024). In 2024, Joby's hydrogen-electric technology demonstrator completed a 523-mile flight in California with no flight emissions except water. At the completion of the flight, the aircraft still had 10% of its hydrogen fuel load remaining. This type of cutting-edge technology demonstration is strongly supported by the DoD to enable energy substitution and diversification while reducing the energy demanded from platforms (Joby Aviation, 2024).

H. NAVY TRAINING AND LOGISTICS SUPPORT ACTIVITY MODEL

A core focus area to field the test case hydrogen enabled unmanned UAS would be under the existing DON TALSA and logistics aviation enablers under the Marine Wing Support Squadrons during shipboard operations. The TALSAs function as a critical component within the U.S. Navy and Marine Corps' UAS logistics framework, specifically addressing the training and sustainment of unmanned systems (Program Management Agency (PMA) 263, 2022). Navy's TALSA provides initial training, technology upgrades, and direct Depot – Intermediate level maintenance, as directed from the Naval Program Offices. The training focuses on range safety and initial system certification with practical skill development for naval operations. The current employment model for TALSAs is listed in Figure 9. The primary role of the Marine Wing Support Squadrons is to provide all essential aviation ground support requirements to a designated Aviation Combat Element of a Marine Air-Ground Task Force (PMA-263, 2022). This includes fixed-wing and rotary-wing aircraft, as well as supporting elements of the Marine Air Control Group. The test case will be focused on sustainment and fielding of Group 2 UAS to the United States Marine Corps (USMC) Rifle Platoons.

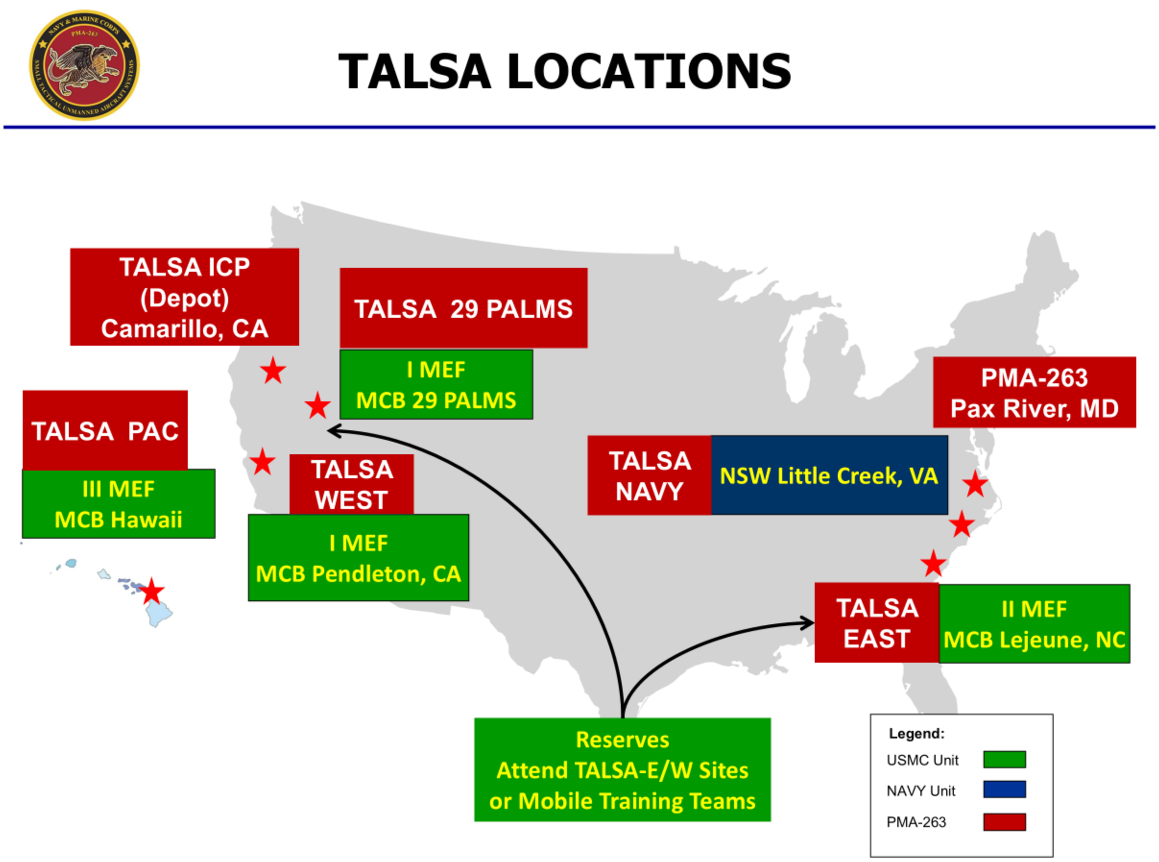

Figure 9. Training and Logistics Support Activity. Source: Program Management Activity (2022).

I. TEST CASE: MARINE CORPS' PLATOONS BACKGROUND AND DISTRIBUTION

Within the U.S. Marine Corps, the platoon serves as a foundational tactical unit, typically comprising 30–50 Marines and commanded by a lieutenant, with a platoon sergeant as the senior non-commissioned officer and second-in-command. As illustrated in a standard Marine Rifle Platoon structure (Figure 10), the platoon is organized into a headquarters element and three rifle squads, with each squad further subdivided into three fire teams of four Marines each (U.S. Marine Corps, 2019). This "rule of threes" is a common organizational principle in the Marines. The platoon functions as a crucial building block within the larger Marine Corps hierarchy, forming the primary maneuver element of a rifle company. Multiple companies, in turn, constitute a battalion, which is a key component of the ground combat element of a Marine Air-Ground Task Force (U.S. Marine Corps, 2019). Therefore, the platoon is the level at which many tactical orders are executed, playing a direct role in accomplishing the Marine Corps' mission of expeditionary warfare and crisis response by locating, closing with, and destroying the enemy by fire and maneuver, or repelling enemy assaults.

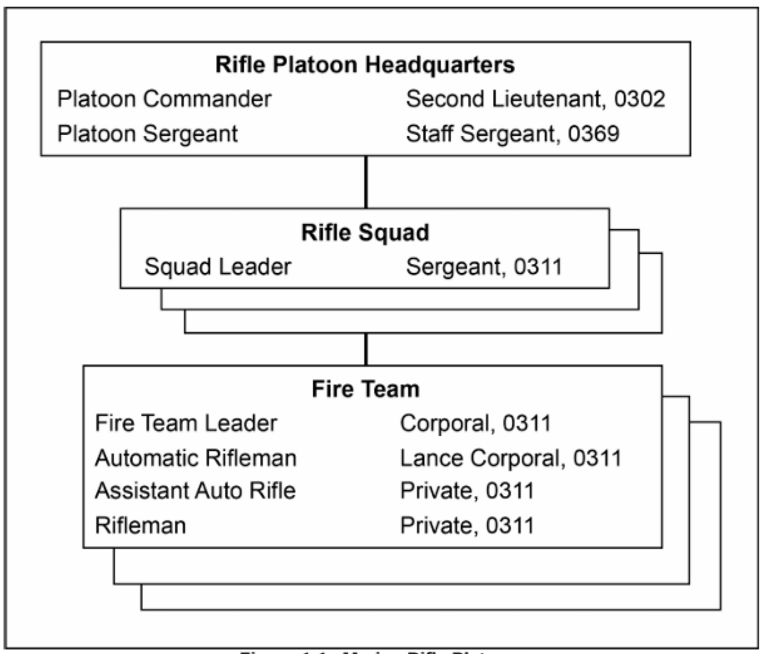

Figure 1-1. Marine Rifle Platoon.

Figure 10. Marine Rifle Platoon. Source: U.S. Marine Corps (2019).

Figure 11 illustrates the strategic disposition of the U.S. Marine Corps' major ground control element, specifically the three active-duty Marine Expeditionary Forces (I MEF, II MEF, and III MEF) and the Reserve component's 4th Marine Division (USMC, 2019). These formations collectively house the preponderance of the Corps' infantry units, serving as the foundational elements for power projection and crisis response. The geographic positioning of these forces, primarily concentrated on the East Coast (II MEF), West Coast (I MEF), and forward-deployed in the Indo-Pacific (III MEF), alongside the 4th Marine Reserves Division in the United States. Examining the existing UAS sustainment and training infrastructure at these infantry locations provides a critical lens for assessing the potential sustainment support requirements to enable the operations and sustainment of hydrogen-enabled UAS test case across the Marine Corps infantry platoons.

Figure 11. Locations for Infantry Units and Major Marine Expeditionary Forces in USMC. Source: U.S. Marine Corps (2019).

J. CHAPTER II SUMMARY

Chapter II established the foundational context for understanding the imperative driving the Department of the Navy's exploration of hydrogen fuel as a viable alternative energy source for naval aviation. The escalating global energy demands, coupled with the strategic vulnerabilities of traditional fossil fuel supply chains and the increasing impacts of climate change, necessitate a fundamental shift in military energy strategy. The Department of Defense is committed to reducing energy demand and enhancing energy resilience, recognizing hydrogen as a pivotal enabler in mitigating logistical burdens and increasing operational effectiveness in contested environments.

Chapter II detailed the current state of hydrogen technology, noting its presence primarily in prototype development and technology demonstration phases across industry, DoD, and academia. Key technical aspects of hydrogen production, such as electrolysis and its challenges, alongside diverse storage and transportation methods, were explored, revealing existing cost and technology maturation limitations. The inherent safety risks of hydrogen, including high flammability, leakage potential due to its small molecular size, and embrittlement of materials, were thoroughly examined, underscoring the critical need for robust safety protocols and advanced detection systems.

Despite these challenges, the Navy stands as a research leader within DoD, actively expanding its efforts in hydrogen fuel cell technology for mission-critical capabilities. Hydrogen fuel cell projects like BIGBANG demonstrate significant endurance gains for UAVs, while platforms such as Hybrid Tiger, Stalker, and Joby Aviation demonstrator showcase the feasibility of hydrogen-enabled UAS. Emergent capabilities like NovaSpark's expeditionary hydrogen generation system, capable of producing hydrogen from atmospheric water vapor, represent transformative opportunities to reduce logistics dependency in austere and expeditionary settings relevant to USMC platoons.

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III. LITERATURE REVIEW

Chapter III critically analyzes existing research related to the employment of hydrogen fuel within naval aviation capabilities, emphasizing programmatic considerations within the DON. It provides justification for hydrogen research and evaluates current knowledge, identifies key gaps, and provides potential sustainment pathways under a test case analysis for this research.

A. JUSTIFICATION FOR HYDROGEN RESEARCH

1. Depleting Current Global Fuel Sources

There exist multiple energy transition imperatives promoting the increased awareness and interest of hydrogen fuel as an alternative fuel source—especially in light of fossil fuel reserves projected to be significantly depleted within the next 25–30 years (Ritchie & Rosado, 2017). In 2023, the U.S. exported approximately 10.15 million barrels per day of petroleum (including crude oil and refined products), while importing around 8.53 million barrels per day (U.S. Energy Information Administration, 2024). According to current reported levels of global, proven oil reserves and present consumption rates circa 2016, there are approximately 47 years remaining until hydrocarbon-based resource exhaustion (Worldometer, n.d.). Figure 12 depicts the inverse rate of oil discovery decline as the rate of oil consumption increases that further promotes the need for alternative fuel resources (Tashie-Lewis & Nnabuife, 2021). Connecting back to Table 1 showing DON oil energy usage—there is a clear imperative to alternative fuel options with high demand and diminishing supplies.

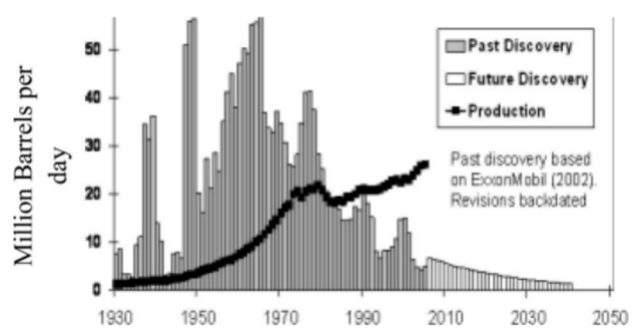

Figure 12. Rate of Oil Discovery is Falling While the Rate of Oil Consumption is Increasing. Source: Tashie-Lewis & Nnabuife (2021).

Current estimates suggest global fossil fuel reserves will face significant depletion within the next 25–30 years, further emphasizing the urgency for alternative energy adoption (Ritchie & Roser, 2017). Not only does the continued use of hydrocarbon fuels severely impact national focus on the global climate crisis, but the continued reliance upon fossil fuels is unsustainable due to diminishing reserves, volatile market prices, and dynamic geopolitical activities and relations. Continued dependency upon fossil fuels therefore goes against both national strategy and our nested National Defense Strategy (NDS). Alternatively, hydrogen fuel, with its ability to be produced from water and renewable energy sources, presents a viable long-term solution to energy security challenges (IEA, 2021). Governments worldwide must accelerate research, development, and deployment of hydrogen technologies to ensure a smooth transition away from fossil fuels.

2. Alternative Fuel Source

The increasing global demand for energy, coupled with growing environmental concerns, has spurred the exploration of alternative fuels (DOE, 2022). Hydrogen, with its potential for zero-carbon emissions, offers a promising solution as a renewable energy resource. Hydrogen presents itself as a compelling alternative fuel source for two primary reasons: its potential renewability and its substantial natural abundance. While hydrogen constitutes over 75% of the observable universe, its utility as a viable fuel hinges on its availability in diatomic molecular form (H_2) (DOE, 2022). A viable energy alternative such as hydrogen as a fuel replacement of fossil fuels could meet DoD and DON objectives by increasing energy efficiency of platforms, while reducing emissions. DoD is looking at green hydrogen to serve as an enabler for key energy resilient technologies due to its versatility. Hydrogen can act as a feedstock or fuel source for applications where there is not a green or renewable alternative source identified (DOE, 2022). Figure 13 represents various aspects of hydrogen that make it an ideal fuel resource due to its availability, versatility, and proven viability (Qyyum et al., 2021).

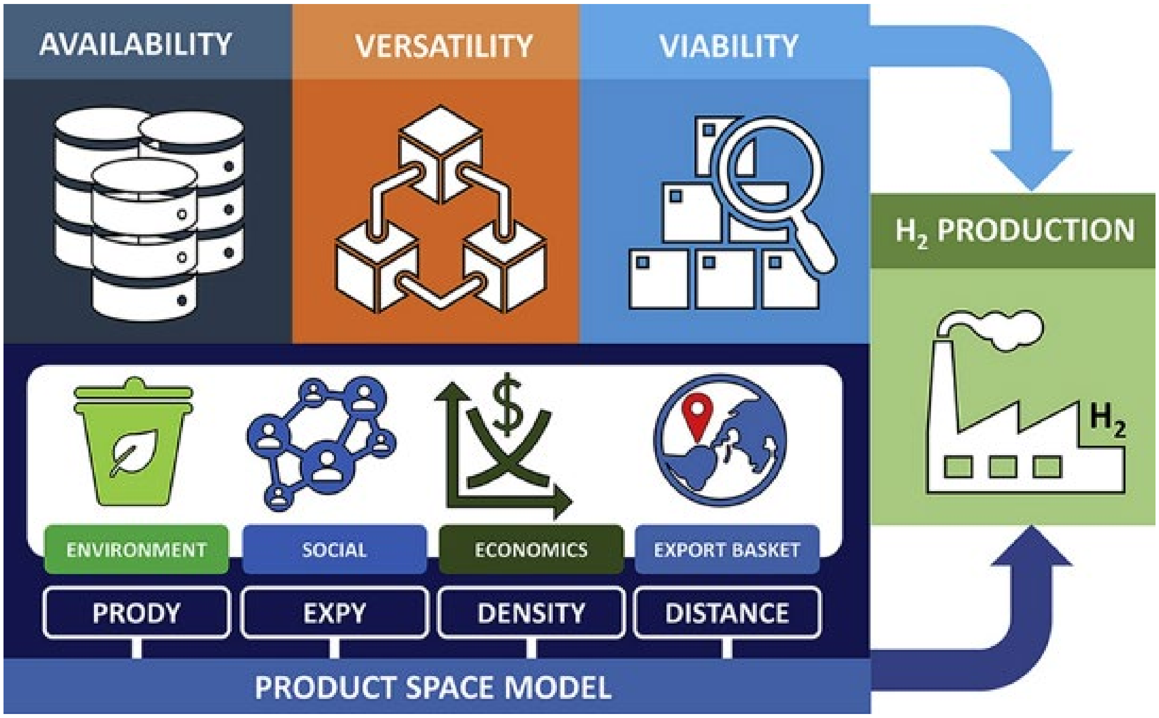

Figure 13. Availability, Versatility, and Viability of Hydrogen Fuel. Source: Qyyum et al. (2021).

Hydrogen can be produced renewably for multi-use energy storage mechanisms. Hydrogen can be used directly as feedstock or fuel, but it can also be used as an energy storage method to produce electricity (Thorson et al., 2022). As a fuel, hydrogen offers high energy density and wide flammability range for efficient combustion and engine performance. Hydrogen produced through water electrolysis using renewable electricity offers a viable solution for storing excess energy. Water serves as a significant potential reservoir of hydrogen, comprising 11.2% hydrogen by weight (Tashie-Lewis & Nnabuife, 2021). When demand exceeds supply, stored hydrogen can be converted back into electricity through fuel cells or used in other applications. Another benefit of hydrogen as an energy source is that it has a higher gravimetric energy density than fuels commonly used in the DoD, which means that it can provide more energy per unit of weight, as shown in Table 1 (Tashie-Lewis & Nnabuife, 2021). This benefit is key for applications where weight is a critical factor, such as aviation.

Table 2. Volumetric and Gravimetric Energy Densities of Common Fuels. Source: Tashie-Lewis & Nnabuife (2021).

Fuel	Gravimetric Energy Density (MJ kg^{-1})	Volumetric Energy Density (MJ L^{-1})
Hydrogen (liquid)	143	10.1
Hydrogen (compressed, 700 bar)	143	5.6
Hydrogen (ambient pressure)	143	0.0107
Methane (ambient pressure)	55.6	0.0378
Natural Gas (Liquid)	53.6	22.2
Natural Gas (Compressed, 250 bar)	53.6	9
Natural gas	53.6	0.0364
LPG propane	49.6	25.3
LPG butane	49.1	27.7
Gasoline (petrol)	46.4	34.2
Biodiesel oil	42.2	33
Diesel	45.4	34.6
Kerosene	46.4	36.7

Overall, the hydrogen market is currently projected to be a potential $2.5 trillion global economic market by 2050 (METI, 2017). While the practical challenges associated with hydrogen fuel are substantial, emergent and viable aviation technologies are actively being researched and demonstrated as feasible aviation solutions, such as Naval Research Laboratory Hybrid Tiger and Joby Air's demonstrator (Joby Aviation, 2024).

3. Department of Defense Focus into Hydrogen Sustainment

The Department of the Navy lacks a cohesive strategy and dedicated research to address the sustainment challenges in adopting hydrogen fuel. These challenges include the lack of established hydrogen infrastructure, refueling stations, storage facilities, and transportation which pose substantial barriers to operational deployment and life cycle sustainment. Current hydrogen storage limitations, specifically concerning energy density and volume requirements for military applications, necessitate advancements in storage technology to address safety, weight, and cooling considerations (Schlapbach & Zuttel, 2001). Furthermore, the integration of hydrogen systems introduces unique regulatory and safety considerations, particularly in international operational environments. Understanding the limitations and challenges of militarizing the use of hydrogen as energy in Naval aviation applications, it is necessary to provide DON with key enabling technologies necessary to meet DoD guidance.

Despite ongoing research into hydrogen as an energy source is being researched for "Naval applications in unmanned aviation vehicles, submarines, and as deployable power generation," specific technical, economic, regulatory, and logistical challenges hinder widespread adoption (Motlow, 2021). This knowledge gap impedes the development of effective guidelines, policies, and sustainment strategies for integrating Naval hydrogen-powered unmanned systems. The recent emergence of hydrogen-powered unmanned systems, such as the Joby Aviation demonstrator, Hybrid Tiger, and Avari Hermes UAS, further underscores the urgent need for a thorough review of DON sustainment methodologies. These systems, with their specialized fuel requirements, introduce novel logistical and maintenance demands, impacting personnel training, supply chain management, and overall operational readiness. This thesis aims to address the current research deficit by providing a foundational analysis of the sustainment challenges and potential solutions associated with the deployment of hydrogen-powered UAS in naval operations, thereby informing future DON sustainment strategies.

Regarding hydrogen employment concerns, the inherent flammability of hydrogen will warrant stringent safety procedures and infrastructure design considerations (Najjar, 2013). As previously discussed, advancements in leak detection, sensor technology, and improvements in storage materials are on track to meet DoD safety standards (Tae, 2021). Moreover, the infrastructure costs, while substantial, are minimal in the UAS field due to minimal footprint and deployabillity concerns in relation to the long-term benefits of a sustainable energy solution outside of current fossil fuels. The potential for modular, decentralized hydrogen production and refueling systems could significantly support the National Defense Strategy and support distributed operations required of the Warfighter (Barnhart et al., 2012). Additionally, the development of foundational regulatory frameworks and standardized safety protocols will ensure public confidence and facilitate widespread adoption. Finally, while the initial investment might be high, the potential to offset fossil fuel costs, and the need to meet future carbon emission goals, should be factored into the total cost analysis. A major limitation behind widespread utilization of hydrogen for DON aviation today are concerns over total life cycle costs and fuel safety (Tashie-Lewis &

Nnabuife, 2021). This research paper will delve into the lack of published research to support the life cycle sustainment requirements to field hydrogen as a prime energy means, specifically for DON unmanned aviation.

4. Justification Conclusion

This thesis directly addresses these identified gaps by analyzing DON's programmatic considerations specifically tailored for naval aviation systems employing hydrogen fuel. It critically evaluates product support elements, infrastructure considerations, regulatory implications, and economic viability, thereby providing comprehensive guidance for program managers overseeing systems transitioning post-rapid fielding into Operations and Sustainment phase. This research is essential to ensure effective integration of hydrogen fuel technologies within the strategic objectives and operational capabilities of naval aviation, significantly contributing to the broader goal of defense energy sustainability.

By systematically addressing these areas, the current study bridges crucial knowledge gaps, offering actionable insights essential for strategic planning, implementation, and sustainment of hydrogen-fueled naval aviation capabilities.

B. CURRENT LANDSCAPE OF HYDROGEN TECHNOLOGY IN AVIATION

The aviation sector is starting to shift away from traditional fossil fuel use to mitigate climate change, address fuel shortages, and enhance aircraft performance. Comparative analyses of energy efficiency and environmental impacts between traditional jet engines and hydrogen-powered military turbojet engines indicate that hydrogen reduces carbon footprints while enhancing propulsion efficiency (Balli & Caliskan, 2022). Solutions for full electrification and hybrid electric propulsion systems are being explored as ways to mitigate risks associated with using fossil fuels. Hydrogen fuel technology has emerged as a transformative solution within aviation due to its potential for significant environmental and operational benefits. However, there are significant barriers that could impede rapid integration into a commercial and military context (Soleymani et al., 2024).

A review of the current landscape of hydrogen technology in aviation shows that it is in the early demonstration and prototype phase and transitioning towards technology validation and pre-commercial development. Basic research and concept development has been completed through academic studies to prove theoretical feasibility. Initial concepts and system designs for fuel cells, production through electrolysis, and updated airframes have been modeled and tested (Soleymani et al., 2024). For prototype development, companies like Joby aviation are actively testing their hydrogen-powered aircraft. Integration approaches for hydrogen including hydrogen fuel cells, hydrogen combustion engines, and hybrid hydrogen systems are being tested to show proof-of-concept. These integration approaches are being tested on small UAS, large commercial aircraft, smaller regional aircraft, blimps, and other experimental aircraft (Swain, 2001).

Ongoing technology demonstrations of specific projects like Navy's Hybrid Tiger and Stalker UAS, and Joby Aviation's hydrogen-electric system are providing the objective quality evidence needed to prove performance capability. Joby Aviation's landmark 523-mile hydrogen-electric flight underscores hydrogen's capability for low carbon, extended-range aviation (Joby Aviation, 2024). These demonstrations are critical to drive investments and regulations, while building public confidence. Industry is moving forward with pilot programs as technologies are reaching maturation levels that require regulatory approvals for limited commercial use (Joby Aviation, 2024). Lagging hydrogen infrastructure development, especially at airports, will limit the ability to transition to commercialization and early market entry (EASA, 2024). Current progress in prototyping and demonstration is rapidly advancing but is dependent on the ability to scale the technology, align to regulations, and continue investment in infrastructure.

C. HYDROGEN FOR NAVAL AVIATION

Deployment of hydrogen in naval aviation applications is dependent upon the technological advancements and infrastructure improvements necessary to produce, store, and distribute hydrogen efficiently. There is an emphasis on substantial challenges associated with hydrogen production, storage, and transportation, particularly with technical, logistical, and economic hurdles that must be overcome to enable widespread use in military operations (Bhuiyan & Siddique, 2025). Significant infrastructure development is needed to facilitate large-scale hydrogen adoption, outlining the necessity of significant research and development investment in electrolysis technology, storage solutions, and distribution networks. Improving the efficiency, cost, durability, and manufacturability of technologies for hydrogen production, distribution, and end-use still requires significant investment (European Commission, 2022). This aligns with the U.S. Department of Energy's (DOE) National Clean Hydrogen Strategy, stressing similar infrastructural advancements for efficient hydrogen delivery across various platforms.

1. Generation

The Department of Defense and its allied partners are actively investing in research and development initiatives aimed at significantly advancing hydrogen generation capabilities tailored specifically for military applications (Klebanoff et al., 2021). One prominent area of development involves mobile electrolysis units, which are compact and highly transportable systems engineered specifically for rapid field deployment. These portable units provide critical operational flexibility, allowing military forces to generate hydrogen fuel directly within remote or austere environments, thereby significantly reducing the dependency on traditional logistic supply chains and enhancing mission sustainability (Klebanoff et al., 2021).

Another significant advancement is observed in hybrid renewable-hydrogen systems, which integrate hydrogen production facilities with local microgrid infrastructure powered by renewable energy sources such as solar, wind, or nuclear energy (Agarwal, 2022). These hybrid systems ensure reliable, consistent hydrogen production capabilities even in remote operational theaters, leveraging renewable resources to reduce environmental impact and enhance energy independence for military operations (Agarwal, 2022). By combining multiple energy sources, these hybrid systems offer enhanced resilience, improved operational flexibility, and lower environmental footprints compared to conventional fuel systems.

Additionally, the development of on-demand fuel production technologies represents a crucial innovation, enabling real-time generation of hydrogen fuel precisely as it is required (Miller et al., 2020). This approach significantly mitigates risks associated with long-term hydrogen storage and transportation, both of which involve complexities and vulnerabilities. Real-time generation technologies allow military units to rapidly respond to changing operational demands without maintaining large, potentially hazardous hydrogen inventories (Miller et al., 2020). The immediate availability of hydrogen fuel enhances tactical agility and reduces the logistical footprint in contested or remote areas. Information on private efforts for hydrogen generation methods is much more available and accessible compared to DoD and Navy efforts. Many DoD and Navy efforts are only able to share limited information on their efforts with the public since these efforts are ongoing.

2. Storage

Advancements in hydrogen storage technologies are being pursued rigorously, particularly focusing on solid-state and cryogenic storage methods to enhance both safety and operational efficiency (Rampai et al., 2024). Solid-state storage solutions offer improved stability, minimized risk of hydrogen leakage, and higher storage densities, making them ideal for military applications where compactness and safety are paramount. Concurrently, cryogenic storage innovations are aimed at refining insulation techniques and reducing boil-off losses, thereby maintaining operational readiness and reducing overall logistical complexities associated with hydrogen handling (Schlapbach & Zuttel, 2001). These ongoing technological advancements collectively support the strategic integration of hydrogen as a reliable and sustainable energy solution within military operations.

Storing hydrogen in austere military locations, particularly those that are remote or conflict-prone, presents several critical logistical and operational challenges. One significant constraint is space and weight limitations (Rampai et al., 2024). Compressed hydrogen gas storage typically requires large, robust tanks to withstand high pressures, posing considerable difficulties for mobile and airborne military operations due to the significant additional mass and volume. Alternatively, storing hydrogen cryogenically as a liquid reduces the required storage volume, yet this method demands extensive insulation and specialized containment structures, further complicating deployment scenarios in space-constrained environments (Rampai et al., 2024).

Another major hurdle is the substantial energy requirement associated with hydrogen liquefaction (Agarwal, 2022). Converting hydrogen gas to a liquid state is an energy-intensive process, which can be impractical for forward operating bases or remote locations lacking significant power generation capacities. The reliance on substantial and consistent power sources to sustain cryogenic storage systems could severely limit the operational feasibility and flexibility of using hydrogen as a fuel source in austere environments unless renewable or alternative energy sources can reliably support these processes (Agarwal, 2022).

Additionally, hydrogen's inherent high flammability and propensity for leaks pose significant safety and handling concerns (Schlapbach & Zuttel, 2001). Hydrogen storage systems must adhere to rigorous safety protocols and stringent handling procedures to prevent leaks, accidental ignition, or explosions. Continuous monitoring, specialized containment materials, and extremely sensitive leak detection systems are essential to ensuring the safe storage and handling of hydrogen, especially in harsh, uncontrolled environments typical of military operations (Schlapbach & Zuttel, 2001).

Establishing hydrogen storage and refueling infrastructure in austere locations introduces logistical complexities (Miller et al., 2020). Infrastructure designed for remote military operations must be exceptionally durable, modular, and mobile to ensure quick and effective deployment. Such systems must withstand extreme environmental conditions, including significant temperature fluctuations, sandstorms, humidity, and potential combat threats. The need for modular and easily transportable infrastructure solutions that can be quickly assembled or dismantled becomes paramount for sustained operational capabilities in challenging environments (Miller et al., 2020). Overcoming these challenges through ongoing research, technological innovation, and strategic planning will be essential for the effective integration of hydrogen fuel within military operations.

3. Transportation

The integration of hydrogen as a viable energy vector within the DON necessitates a rigorous analysis of its transportation logistics and safety considerations, particularly within the context of military operational environments and lack of existing infrastructure (Ustolin et al., 2022). While hydrogen offers potential efficiency gains and reduced emissions, its unique properties and the logistical complexities of military deployments present significant challenges that require careful evaluation.

As previously noted, Hydrogen's inherent flammability and potential for leakage are paramount safety concerns. Although its low ignition energy and rapid burn rate necessitate stringent safety protocols, these characteristics also offer distinct advantages compared to traditional hydrocarbon fuels. It is important to note hydrogen's rapid atmospheric dispersion due to its low density mitigates the risk of vapor cloud explosions associated with heavier fuels (Najjar, 2013). However, the colorless and odorless nature of hydrogen demands robust leak detection systems to prevent undetected accumulations, especially while in transit. The U.S. Department of Energy's Hydrogen Safety Panel guidelines provide a framework for transportation hazard analysis and mitigation. Research efforts are focused on developing advanced leak detection technologies, containment materials, and automated handling systems to minimize risks (Miller et al., 2020). Comparative studies illustrate the rapid burn and reduce radiative heat transfer of hydrogen, providing valuable data for risk assessment (Swain, 2001). Figure 14 contrasts the combustion characteristics of hydrogen and gasoline, demonstrating the former's potential for reduced structural damage in fire scenarios (Smeeks, 2022). However, the translation of these findings into large-scale military applications requires further investigation, particularly in the context of confined spaces and complex operational environments.

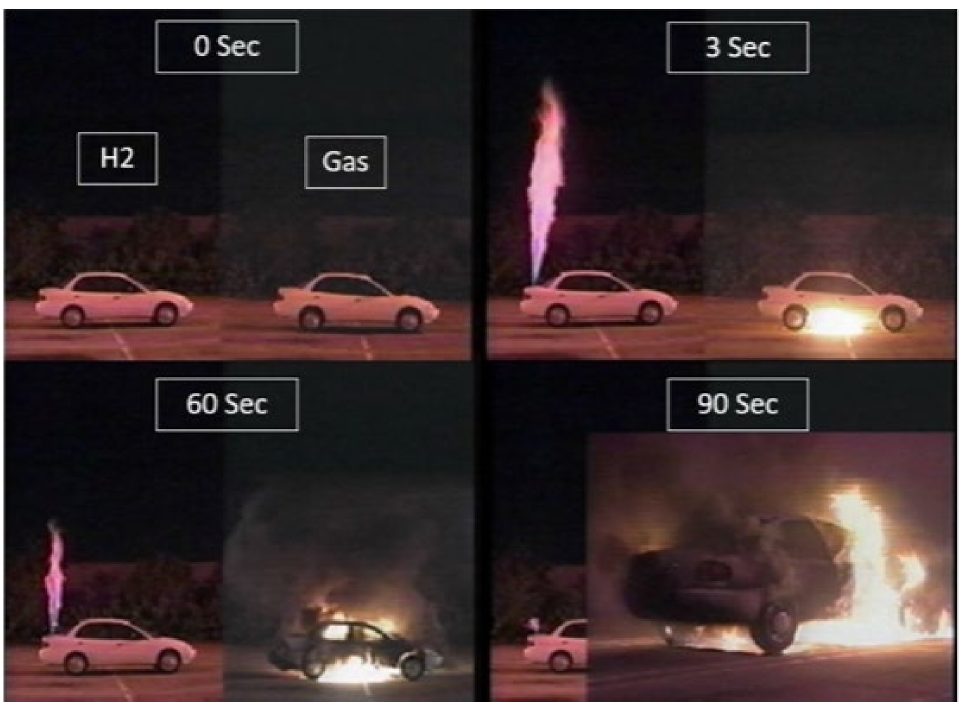

Figure 14. Hydrogen Safety Demonstration Comparing H2 and Gas Cars. Source: Swain (2001).

Transporting hydrogen to austere military locations presents substantial logistical challenges. Infrastructure limitations, including the absence of pipelines and refueling stations, necessitate the development of mobile refueling solutions (Rampai et al., 2024). The energy-intensive nature of cryogenic hydrogen transport poses further logistical complexities in off-grid environments (Klebanoff et al., 2021). However, it is crucial to recognize that hydrogen is not entirely novel to naval operations. Compressed hydrogen is currently employed onboard U.S. Navy surface vessels as a screening gas for welding processes (Smeeks, 2022). This existing utilization established a foundational, albeit introductory logistics support system, encompassing procurement, transportation, handling, and storage infrastructure. Leveraging this existing infrastructure can potentially facilitate the incremental integration of hydrogen into other naval applications.

A positive aspect of hydrogen transportation is that the DON is not alone in the transportation problem. Investment has been driven by the recognition of hydrogen's potential as a clean energy carrier, particularly in sectors difficult to electrify, such as heavy-duty transportation and industrial processes. Notable examples of research and funding include the European Union's Hydrogen Strategy, which outlines substantial funding for hydrogen infrastructure development, and private sector investments in large-scale hydrogen production and transport projects across Asia and North America (Smeeks, 2022). Current DON research efforts are focused on addressing the logistical challenges associated with hydrogen transport in military environments. Mobile hydrogen refueling units are being developed to support UAVs, aircraft, and ground vehicles in forward operating bases. Advanced storage technologies, including solid-state hydrogen storage, are being investigated to simplify transport logistics and enhance safety (Schlapbach & Zuttel, 2001). Hybrid transport approaches, combining compressed gas, liquid hydrogen, and hydrogen carriers, are being explored to optimize efficiency and flexibility (Rampai et al., 2024). This approach allows for tailored transport solutions based on specific operational requirements and environmental conditions. The development of resilient logistics networks, featuring decentralized hydrogen production and supply chains, is crucial for mitigating risks in conflict zones (Rampai et al., 2024). Non-DoD funding streams are accelerating technological advancements in hydrogen transportation, potentially creating synergistic opportunities for the DoD to leverage and adapt these emerging technologies for military applications.

a. Key Issue – Transportation Cost

Although the prohibitive costs to create hydrogen fuel is a major concern, the larger issue for the DON is how fuel supports military expeditionary capability due to the logistical challenges of fuel transportation. The additional costs of moving and protecting fuel during recent wars demonstrated increased total costs of fuel roughly 1,000 times higher than the base price of fuel itself. Marines in Afghanistan, for example, ran through approximately 800,000 gallons (19,408 barrels) of fuel a day, which must be transported or flown large distances into the country (Dumaine, 2012). Former Commandant of the Marine Corps, General James Conway, stated that, "Transporting fuel miles into Afghanistan and Iraq can raise the cost of a $1.04 gallon up to $400" (Tiron, 2009). A senior military program director estimated the fully burdened cost of fuel to be as high as $1,000 per gallon when also including the costs of equipment and personnel required to transport fuel (Tiron, 2009).

Reducing the cost of transporting hydrogen fuel and manufacturing at the point of need is a key criterion for hydrogen becoming successful long term in DON. Military services have few viable options to reduce the monetary and human costs of fuel transport: use less fuel, use regionally supplied fuel, or use a different fuel source that is transported more easily and inexpensively (Tiron, 2009). Hydrogen currently incurs higher transportation costs, but increased research and expansion of researched Mobile hydrogen refueling technology can be not only a cost driver to utilize hydrogen, but a major transportation solution for the DON (Tiron, 2009).

D. REGULATORY, SAFETY, AND STANDARDS CONSIDERATIONS

Researchers have identified critical safety considerations inherent to hydrogen fuel, emphasizing the stringent standards and regulatory frameworks required for safe adoption. Specifically, researchers underscore the importance of safety, focusing on safety concerns with hydrogen with its wide flammability range, requiring stringent handling procedures and infrastructure standards (Najjar, 2013). Various sources reinforce these considerations, asserting that robust safety measures and regulatory protocols must precede any large-scale military deployment to mitigate inherent risks associated with hydrogen handling (Tae, 2021). Moreover, the U.S. Department of Defense explicitly notes that clear regulatory frameworks and standards are pivotal for integrating hydrogen solutions within defense infrastructure, underscoring that unresolved regulatory issues could significantly delay operational deployments (U.S. DoD, 2022).

E. INTEGRATION AND INTEROPERABILITY CHALLENGES WITHIN MILITARY FRAMEWORKS

The Defense Acquisition Framework (DAU, 2024) stresses that successful integration of innovative technologies, such as hydrogen fuel, into military frameworks necessitates meticulous programmatic planning and management. These sources underline that effective interoperability with existing systems is crucial for operational viability and sustainability. The Defense Acquisition Framework states clearly, "Integration of new energy technologies requires strategic alignment with existing military operational and logistical frameworks" (DAU, 2022, pg. 24).

Examining expeditionary power solutions within constrained logistics environments emphasizes cost-effective, reliable energy solutions that are vital in the context of expeditionary military applications (Gray, 2024). One analysis suggests that hydrogen fuel could provide a sustainable, strategically advantageous solution if integration challenges, especially regarding logistics interoperability, are adequately addressed (Gray, 2024).

F. HYDROGEN SYSTEM EMPLOYMENT VIA ACQUISITION PROCESS

The introduction of a hydrogen enabled aviation platform in the Naval forces will utilize the DoD acquisition process and methodologies to be fielded and sustained. The DoD employs the Adaptative Acquisition Framework (AAF) to deliver "effective, suitable, survivable, sustainable, and affordable solutions to the end user in a timely manner" (Defense Acquisition University, 2024, pg. 5) As shown in Figure 15, the AAF provides multiple acquisition pathways to provide opportunities for the Defense Acquisitions System and Workforce to develop acquisition strategies and employ a tailorable acquisition process that matches the characteristics of the capability being acquired. A program manager will work to tailor an acquisition pathway to the hydrogen enabled platform to both meet the Fleet's capability requirements and provide necessary fielding and sustainment methodologies. Determining an acquisition pathway requires a program manager to think through Integrated Product Support aspects such as technology readiness and acquisition logistics (Defense Acquisition University, 2022).

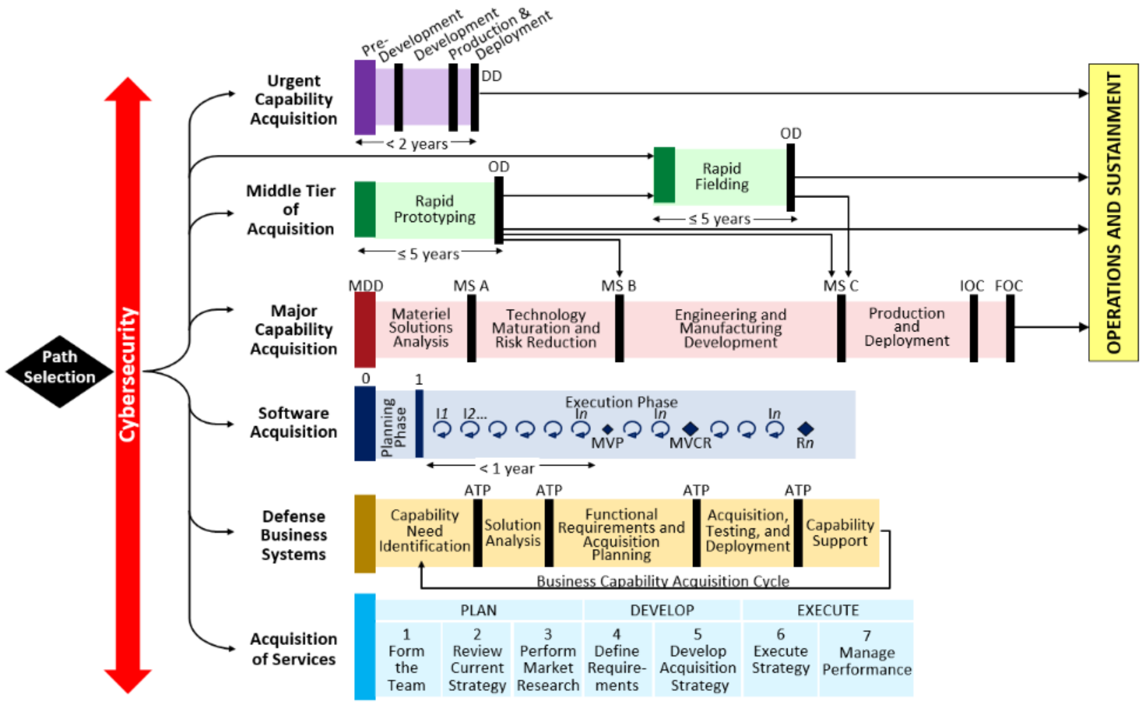

Figure 15. Adaptive Acquisition Framework Pathways. Source: Defense Acquisition University (2024).

Within the U.S. DoD's Middle Tier of Acquisition framework, the Rapid Fielding pathway serves as a streamlined mechanism designed to expedite the delivery of capabilities to the warfighter (Defense Acquisition University, 2024). Distinct from the Rapid Prototyping approach, Rapid Fielding focuses specifically on the rapid acquisition and deployment of proven technologies or existing capabilities to address urgent operational requirements. The primary objective of this pathway is to field a functional capability within a compressed timeframe, typically targeting deployment within six months of the requirement's validation. This is achieved through a significantly streamlined process that minimizes extensive documentation, reviews, and testing, emphasizing only the essential verification necessary to ensure safety and basic operational effectiveness in the intended environment (Defense Acquisition University, 2024). By prioritizing the leverage of mature technology and bypassing the longer cycles of traditional acquisition, MTA Rapid Fielding enables the direct transition to production and deployment, thereby enhancing responsiveness and ensuring warfighters are equipped with needed capabilities swiftly to maintain a tactical advantage. (Defense Acquisition University, 2024). The reviews at the end of the research phase, PM and PSMs ensure that programmatic risks related to technology development, engineering, integration, and sustainment are accounted for and have the necessary mitigation strategies to transition into Operations and Sustainment phase (Department of Defense, 2021). Understanding and mitigating the risk with innovative technologies requires a program manager to understand the life cycle technology readiness levels (TRLs) and manufacturing readiness levels (MRLs) and shown in Figure 16 (Plexus, n.d.).

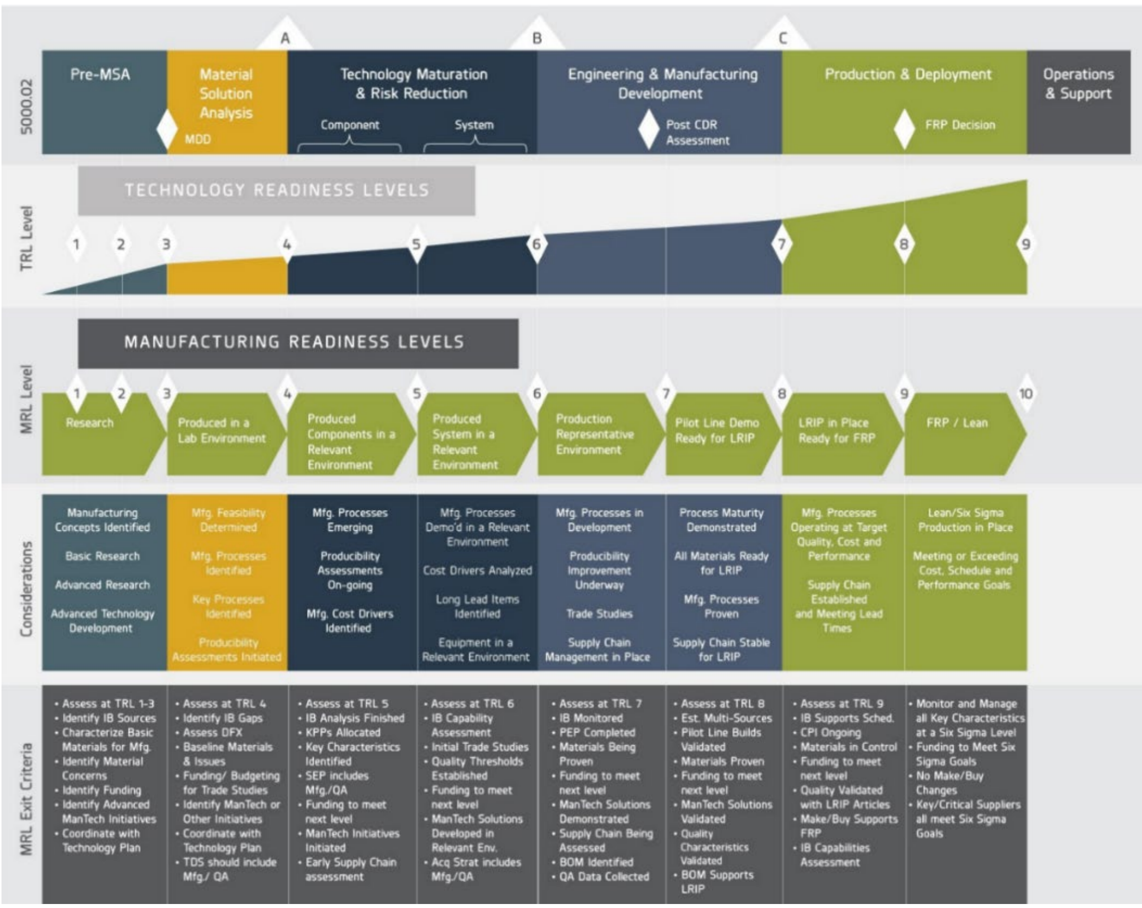

Figure 16. Technology Readiness Levels and Manufacturing Readiness Levels. Source: Plexus (n.d.).

Determining where specific technology falls in terms of technological readiness and manufacturability are crucial elements for the later parts of the acquisition process like sustainment and maintenance (Plexus, n.d.). A holistic view of the life cycle of a technology is rooted in the acquisition process, with TRLs and MRLs being extremely important measures that allow program managers to develop and sustain that technology.

G. LIFE CYCLE SUSTAINMENT PLAN

Life-cycle sustainment in DoD acquisitions involves the early planning, development, implementation, and management of a comprehensive, affordable, effective performance driven logistics support strategy. Sustainment planning plays a key role during all phases of the life cycle as illustrated in Figure 17 (Defense Acquisition University, 2022).

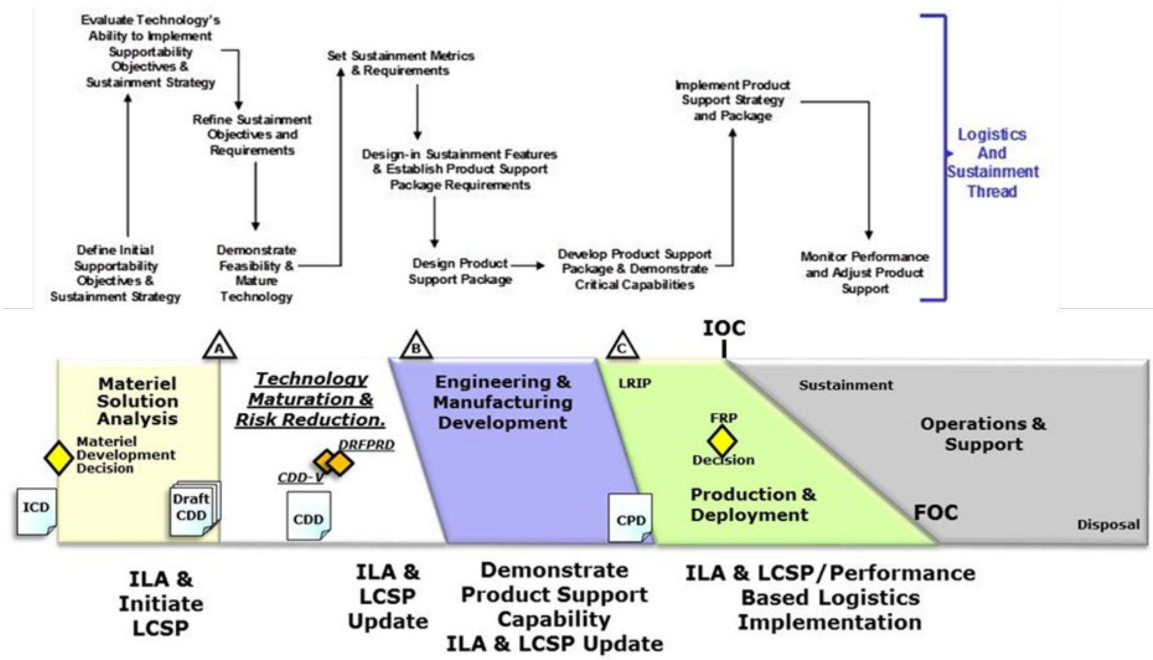

Figure 17. Sustainment Thread in the Defense Acquisition Management System. Source: Defense Acquisition University (2024).

The compilation of the sustainment plan is formulated into the LCSP. The LCSP is a critical element in ensuring the long-term viability and effectiveness of complex acquisition systems. A primary focus is placed on the integration of supportability and sustainability considerations early in the design process, aiming to acquire systems with inherent ease of maintenance and reduced environmental impact (Defense Acquisition University, (2024). The LCSP also necessitates the development and implementation of affordable, reliable, and effective support strategies and systems precisely tailored to user requirements, with the overarching goal of optimizing materiel availability. Integral to this is the establishment of appropriate support metrics to rigorously validate and verify the system engineering design and continuously measure the performance of the support strategy and underlying supply chain. Furthermore, the LCSP emphasizes providing users with effective and suitable systems while simultaneously minimizing the logistics footprint, thereby reducing the resources (manpower, materiel, or facilities) required for deployment, sustainment, and movement (Defense Acquisition University, 2024). The research also examines the development of more integrated and streamlined acquisition and statutorily compliant logistics support processes, alongside mechanisms for facilitating iterative technology enhancements throughout the system's life cycle to maintain relevance and performance.

The LCSP is an iterative plan through the acquisition process to support the Operations and Sustainment phase in DoD program management. The LCSP is supported by the analysis of the IPS as detailed in Figure 18. The 12 IPS support the Life Cycle Sustainment Management, Technical Management, and Infrastructure Management of a DoD system (DAU, 2022). The IPS framework comprises twelve key elements essential for planning, developing, acquiring, and sustaining a system throughout its entire life cycle, from initial concept to disposal. These elements collectively ensure that a system is affordable, ready, and sustainable in the hands of the warfighter. They encompass all aspects necessary for system supportability, including product support management, design interface, sustaining engineering, supply support, maintenance planning and management, packaging, handling, storage, and transportation, support equipment, technical data, training and training support, manpower and personnel, facilities and infrastructure, and information technology systems support (Defense Acquisition University, 2022). Effective integration and management of these elements are critical for minimizing life cycle costs, maximizing operational availability, and ensuring the long-term success of defense acquisition programs.

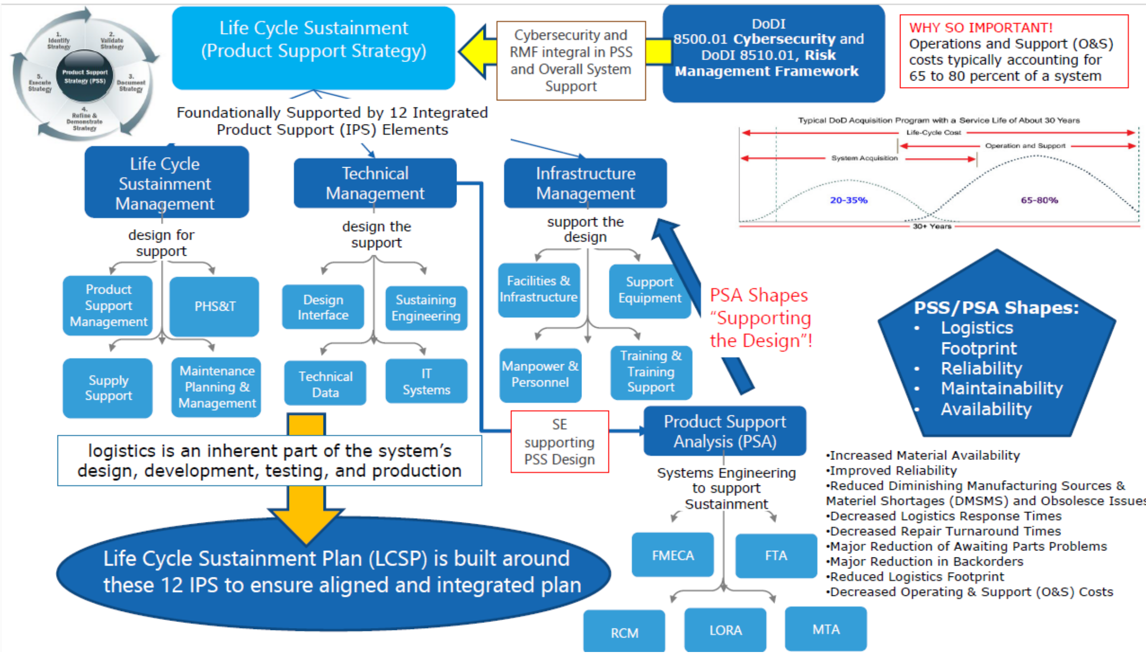

Figure 18. Life Cycle Sustainment Plan within Department of Defense Product Support Strategy. Source: Defense Acquisition University (2022).

The goal is to ensure sustainment considerations that are integrated into all planning, management, implementation, and oversight activities in coordination with the acquisition, development, production, fielding, support, and disposal of a system across its life cycle. This comprehensive approach (focused around the 12 IPS) ensures the system remains effective, affordable, and supportable throughout its operational life. This begins with active participation in the design process, influencing the development of a system that is inherently supportable and sustainable from the ground up. This proactive involvement aims to minimize future logistical burdens and maximize operational availability.

H. ECONOMIC AND STRATEGIC IMPLICATIONS

A critical analysis of the economic implications of adopting alternative fuel vehicles provides essential insights into cost-benefit analyses pertinent to hydrogen adoption within the military (Vacchio, 2024). U.S. Navy policy underscores that transitioning to hydrogen aligns strategically with broader national defense guidance and sustainability goals outlined by Department of Defense Operational Energy Goals (USD(A&S), 2023). Navy policy explicitly states, "hydrogen technologies offer a viable path to achieving substantial reductions in operational greenhouse gas emissions" (U.S. Department of the Navy, 2022, pg. 1).

However, research cautions that Pentagon fuel use, deeply interwoven with operational strategy, presents complex challenges when transitioning to alternative fuels such as hydrogen (Crawford, 2019). Crawford highlights the need for comprehensive economic and operational evaluations, stating, "transitioning fuel sources in the military environment requires detailed analysis to mitigate potential disruptions to operational readiness" (Crawford, 2019).

I. LACK OF SUSTAINMENT RESEARCH AND DATA FOR HYDROGEN IN DEFENSE AVIATION

Despite extensive research, significant gaps persist in hydrogen technology development, along with insight into naval aviation applications. The Navy has unique operational, logistical, and tactical requirements for aviation that are classified. Public information that highlights naval efforts for hydrogen fuel integration is exceedingly high level and provides limited data for analysis. Detailed information exists, but at a classified distribution level. Generic studies on hydrogen for aviation applications do not capture the unique military use cases that are required to understand the full logistical picture of integrating hydrogen. Detailed evaluations of long-term sustainment strategies that are tailored to hydrogen-specific supply chains are sparse in existing literature.

Hydrogen technology advancements for generation, production, and storage are well documented by private industry. Although there is limited documentation for DoD's hydrogen technology, the military is generally risk-adverse and often follows industry's path for technological expansion. A research gap exists in the bridging of the commercial product into a militarized setting. It is likely that hydrogen technology for naval aviation will be procured from commercial vendors and then hardened to meet military specifications. Hardening processes can be deduced from the analysis of various use cases, but there is no research documenting this process.

The acquisition process is well defined in the DoD, but research does not address the integration challenges for existing naval systems. Current acquisition strategies for hydrogen systems in the Navy are not public information. There is not a clear transition path for hydrogen technologies in the Navy. Programmatic and strategic acquisition processes post-rapid fielding in a Middle Tier of Acquisitions are not defined in current literature. This is likely due to the novelty of hydrogen technology and the focus on initial maturation. It can be assumed that near-term future research will focus on technology integration and scalability, but it is unlikely that public information detailing military integration will be available.

1. Production Challenges

A critical consideration in employing hydrogen fuel within military applications, especially naval aviation, involves efficient and sustainable production and minimizing logistical footprints to effectively support military sustainment needs (IEA, 2021). Generating hydrogen directly within austere environments, often characterized by remote or limited-resource scenarios, provides distinct strategic advantages to the DON. By enabling localized hydrogen production, the Navy can significantly mitigate logistical vulnerabilities associated with fuel transportation, thus enhancing overall operational resilience and readiness.

One primary logistical challenge in hydrogen production is energy availability (IEA, 2021). Hydrogen generation through electrolysis demands substantial electrical power, a resource often scarce or unreliable in austere operational settings. To address this limitation, deploying renewable energy sources such as portable solar photovoltaic arrays or compact wind turbines presents a viable solution (IEA, 2021). These renewable systems not only provide a sustainable energy source but also significantly reduce dependency on external fuel supply lines, thereby increasing operational autonomy and reducing vulnerability.

Additionally, hydrogen production via electrolysis requires a consistent and reliable water supply, which poses a significant logistical challenge in arid, desert-like, or maritime operational environments where water availability may be severely constrained. To overcome this limitation, innovative water-harvesting methods, such as atmospheric water generation technology, can be employed (Tang et al., 2023). Atmospheric water generators utilize ambient humidity to produce potable water directly from the air, offering a self-contained, sustainable water solution that can significantly expand the Navy's operational capabilities in diverse and challenging environments.

Hydrogen's highly volatile nature necessitates specialized containment systems and rigorous safety protocols for storage and transportation, adding complexity and risk to traditional logistical chains. Consequently, establishing localized, on-site hydrogen generation capabilities diminishes the requirement for long-range transportation, greatly enhancing operational security and reducing the overall logistical footprint (Klebanoff et al., 2021). This strategy minimizes vulnerabilities to supply line disruptions and adversarial threats, bolstering the Navy's ability to sustain continuous operations with minimal external support.

2. Integration Challenges

Effectively integrating hydrogen as a viable and sustainable fuel source within military operations involves addressing several complex technical and logistical challenges. To overcome these, ongoing research and targeted technological advancements are critically important. One of the primary areas of research is the development of next-generation storage materials (Agarwal, 2022). These include high-capacity metal hydrides and porous carbon-based materials designed specifically for solid-state hydrogen storage. Utilizing these advanced materials has the potential to significantly enhance both safety and energy density, making them particularly suited to military environments where operational efficiency, compactness, and risk mitigation are essential (Agarwal, 2022).

Another innovative research direction is on-demand hydrogen production technologies. These solutions enable real-time hydrogen generation directly at the operational site, thus substantially minimizing the challenges posed by long-term hydrogen storage (Rampai et al., 2024). By generating hydrogen as needed, on-site production greatly reduces associated logistical complexities, such as prolonged storage safety concerns and significant infrastructure demands. On-demand systems can provide heightened operational agility and responsiveness, vital for sustaining military readiness in dynamic and resource-limited environments (Rampai et al., 2024).

Additionally, exploring hybrid storage solutions is emerging as a valuable strategy to overcome sustainment challenges. Hybrid storage involves strategically combining different hydrogen storage methodologies—such as compressed gas, cryogenic liquid, and solid-state storage—to achieve optimized balance in safety, efficiency, and spatial considerations for military applications. These integrated storage systems can effectively mitigate the individual limitations of each storage type by leveraging their complementary advantages.

Consequently, hybrid solutions provide a versatile and robust framework capable of supporting diverse and demanding operational scenarios (Miller et al., 2020).

A critical and overarching sustainment challenge involves the substantial financial and logistical commitments required to develop comprehensive hydrogen infrastructure. The establishment of widespread hydrogen production facilities, robust pipeline networks, and strategically located refueling stations necessitates significant upfront investment and resource allocation. Currently, the scale and costs associated with developing such hydrogen infrastructure are considerable. Nonetheless, historical precedents from other renewable technologies offer insightful parallels; notably, the cost of solar photovoltaic (PV) modules has decreased by approximately 99% since 1980 due to continuous innovation and scaling economies. A similar trajectory for hydrogen technologies is plausible, provided sustained investment, policy support, and technological advancements continue to drive down costs and improve efficiencies (Tashie-Lewis & Nnabuife, 2021). Through sustained research, development, and strategic implementation, these targeted approaches hold significant potential to effectively overcome hydrogen sustainment challenges, enabling the successful integration of hydrogen as a primary energy source within naval aviation and broader military contexts.

3. Structural Challenges

Hydrogen production in austere military locations necessitates robust and durable infrastructure and specialized equipment capable of withstanding harsh environmental conditions. Field-deployable, ruggedized hydrogen generation units must be developed to endure the extremes of temperature, humidity, and other environmental stress commonly encountered in naval expeditionary operations (Miller et al., 2020). Mobile, modular production systems tailored specifically for military applications ensure rapid deployment, efficient scalability, and maintenance simplicity, thereby enabling effective sustainment of operations in remote or hostile regions.

The production, storage, and transportation of hydrogen inherently involve energy losses, impacting the overall efficiency and effectiveness of its deployment as a fuel source. Addressing these losses is essential for maximizing the strategic value of hydrogen fuel within naval aviation sustainment. Ongoing research and technological advancements are critical to enhancing the efficiency of hydrogen conversion, reducing energy losses during storage, and improving the reliability of transition processes between storage and operational use. Continued advancements in materials science, storage solutions, and energy conversion technologies will directly contribute to overcoming these logistical challenges, enabling hydrogen to become a practical and strategic fuel alternative for the Department of the Navy.

J. SUMMARY OF LITERATURE REVIEW

The literature shows a strong understanding of hydrogen technologies and potential use cases for operational and environmental benefits. The research points to a global, and more specifically a DoD demand, to increase energy efficiency through the adoption of sustainable technologies, such as hydrogen-based fuel sources. Hydrogen for naval aviation and maritime applications is not a novel concept, but there is a clear gap with transitioning these technologies from their various stages of development into sustained operational capabilities. Various hydrogen-enabled UAS platforms have high TRL and MRL. However, these unmanned systems focus on rapid acquisition and deployment without clear, documented planning to logistically support long-term sustainment. Research and analysis are needed to fill this gap in the understanding of hydrogen enabled unmanned systems acquisition logistics aspects. Despite its potential as a clean and high-energy-density fuel, hydrogen has yet to achieve widespread adoption within the DoD aviation sector due to these significant sustainment concerns. While research and development efforts continue, several key factors hinder hydrogen's transition from a promising technology to a widespread practice. This research analysis explores these impediments, focusing on sustainment methodologies to enable hydrogen for Naval Aviation.

IV. METHODOLOGY

Chapter IV outlines the organizational context of this paper and details the methodology employed to conduct the research and arrive at the presented findings and analysis on hydrogen employment during the Operations and Sustainment phase of a UAS Group 2 system. It describes the structured approach taken to investigate the established research questions, including the specific methods used for data collection and analysis. This chapter provides the reader with a clear understanding of the research design and how the conclusions and recommendations were derived.

A. HOW WAS THE DATA ACCESSED

DON is currently exploring the adoption of hydrogen fuel as a primary energy source for naval aviation. Hydrogen is an alternative energy source that can be used to help address global energy demands and align with DoD energy policies. However, hydrogen utilization in military applications remains limited, lacking a clear sustainment framework for implementation, standardization, and supportability. This research explores the critical challenges and opportunities associated with this transition, focusing on the Operations and Sustainment phase of the acquisition life cycle.

The data is focused on input from open-source documentation, outreach to industry partners, the Defense Innovation Unit (DIU), and UAS employment program offices, specifically Navy and Marine Corps small tactical unmanned aircraft systems program office (PMA-263). By examining the IPS elements of this test case study – the research team identifies specific challenges related to hydrogen storage, fuel cell technology, infrastructure development, and logistics. It assesses the qualitative and quantitative benefits and risks of hydrogen fuel, considering factors such as environmental impact, energy security, and operational performance.

B. DESCRIPTION OF ORGANIZATION

The research utilizes case study examples of viable Group 2 UAS hydrogen enabled unmanned system to generate a baseline IPS overview and considerations discussion to support the test case fielding to 216 Marine Corps Infantry Companies. This employment parameter matches what the current U.S. Marines employ their existing Group 2 UAS. The hydrogen-enabled case studies and research data introduce the technical, logistical, and regulatory sustainment hurdles that must be overcome to successfully integrate hydrogen-powered aircraft into naval operations.

This research provides avenues for collaboration with industry, academia, and international partners to improve and standardize hydrogen employment regulations and safety protocols. By addressing these challenges and creating a baseline IPS overview for program managers, our hydrogen case study can serve as a starting point for future hydrogen enabled employment and sustainment. The research will contribute to a possible sustainable and efficient energy infrastructure for naval aviation, reducing reliance on fossil fuels, and mitigating environmental impacts.

Our research aims to deliver critical sustainment insights into the viability of hydrogen fuel from technical, economic, and logistical perspectives. By doing so, we will inform strategic decision-making, guide development of impactful policies and technologies, and enable DON to take a leading role in hydrogen fuel adoption. Ultimately, this work will ensure the continued operational excellence of the Navy's aviation forces while positioning the DON at the forefront of this emerging technology.

V. FINDINGS AND ANALYSIS

Chapter V presents a detailed findings and analysis of the critical sustainment challenges and potential pathways for the successful integration and employment of example test case – hydrogen-fueled Group 2 unmanned aircraft systems across 216 U.S. Marine Corps Infantry Platoons alongside NovaSpark Energy's mobile atmospheric hydrogen generation system. The findings are structured around the Integrated Product Support elements within the Life Cycle Sustainment Plan, examining the key considerations and regulatory impacts, key areas of concern, and opportunities presented by hydrogen fuel in distributed land and sea operational environments. The analysis incorporates the complex regulatory landscape and DON limitations for sustainment that will govern the life cycle sustainability of hydrogen technology, from acquisition through disposal.

A. FINDINGS

1. Product Support Management

a. Key Considerations and Regulatory Impacts:

This research examines the complex landscape of standards, certification, and safety organizations that significantly influence the adoption and sustainment of novel energy technologies, specifically hydrogen fuel, within the DON. For the establishment of product support management, it is critical to understand the coordinating agencies and partnerships organizations to leverage product support and required standards and guidelines. Key among these organizations are the Occupational Safety and Health Administration (OSHA), which establishes and enforces workplace safety standards, including those pertaining to hazardous materials like hydrogen; the EPA, responsible for regulating the environmental impacts of energy production and use, including air and water quality related to hydrogen generation; the DOT, which governs the safe transportation of hazardous materials, including compressed and liquid hydrogen; and the National Fire Protection Association (NFPA), a consensus standards organization that develops codes and standards related to fire safety, including comprehensive guidelines for hydrogen technologies under NFPA 2 hydrogen subsection (National Fire Protection Association [NFPA], 2025). Understanding the roles and regulatory frameworks of these organizations is crucial for navigating the technical, logistical, and safety challenges inherent in integrating hydrogen fuel into naval aviation capabilities and ensuring compliance throughout the system's life cycle.

Effective product support management for hydrogen-fueled UAS necessitates an overarching strategy that meticulously integrates all IPS elements. This strategy must align with the DoD Operational Energy Strategy and actively leverage federal initiatives for funding opportunities that foster innovation and cost-sharing. A critical PSM function will be the proactive anticipation and adaptation to the evolving regulatory landscape, encompassing energy policies, environmental standards, and emerging reporting requirements for DoD acquisitions. Furthermore, life cycle cost management is intrinsically linked to regulatory compliance, encompassing permitting fees, procurement of specialized safety equipment mandated by the OSHA and NFPA, development of specialized training programs, and potentially ongoing environmental monitoring (NFPA, 2025).

As a cornerstone of IPS, product support management ensures the system's logistics and sustainment elements are strategically managed across the life cycle of a capability. For the integration of hydrogen fuel systems such as NovaSpark's mobile atmospheric hydrogen generators, early coordination with agencies like Naval Sea Systems Command (NAVSEA) and Naval Air Systems Command (NAVAIR) is essential. This ensures that key engineering considerations, such as MIL-STD-882 (System Safety) compliance, interoperability with legacy aviation platforms, and adherence to explosive safety protocols, are addressed before full system deployment. Additionally, the involvement of the Defense Logistics Agency (DLA) provides an enterprise-level approach for leveraging existing logistics channels while enabling novel energy technologies to meet mission-specific needs.

Furthermore, regulatory alignment is critical given the unique risks and material requirements associated with hydrogen fuel systems. Compliance with Federal Acquisition Regulation, Title 49 Code of Federal Regulations (CFR) (pertaining to hazardous materials), and Department of Defense Instruction (DoDI) 5000.91 on product support management is imperative for planning life cycle affordability, materiel readiness, and supportability. The evolving nature of clean energy initiatives across the DON places added emphasis on programmatic oversight to ensure overarching policies are upheld in all stages of acquisition and fielding.

b. Land and Sea Obstacles for 216 Platoons

A significant obstacle for the Product Support team is the current hydrogen policy vacuum – there is an absence of established, comprehensive DoD and USMC-specific policies, clearly defined responsibilities, and mature doctrine for the tactical sustainment of hydrogen-fueled UAS. We know how to store, transfer, and manage hydrogen in laboratory type environments, but hydrogen applications for maritime and expeditionary operations are still minimal. The good news, as mentioned in Chapter III, is that emergent capabilities are making it through the research and development phase such as expeditionary hydrogen generation (NovaSpark), hydrogen fuel cell systems (BIGBANG), and capable aviation systems (Joby and Hybrid Tiger). To field to 216 USMC Platoons – the distributed management complexity of overseeing a novel and hazardous fuel source across numerous geographically dispersed platoons, operating in diverse and austere land and sea environments, presents substantial command, control, and logistical oversight challenges. Achieving standardization and interoperability in safety protocols, operational procedures, and equipment (e.g., UAS-to-fueler interfaces, hydrogen generation to storage connections) across all units will be exceedingly difficult without clear, top-down guidance and rigorous configuration management.

A key aspect of product support management is the assignment of program oversight and support. Data-driven sustainment should be a core principle, achieved by implementing a robust data collection and analysis system. This system would track hydrogen consumption rates, UAS and fuel cell performance metrics, maintenance actions, safety incidents, and regulatory compliance data from all 216 platoons. Such data will be invaluable for enabling predictive maintenance, optimizing supply chain efficiency, refining safety protocols, and informing future system upgrades, reflecting the focus on sustainment performance monitoring. The existing unmanned Group 2 systems management under PMA-263 would be a viable solution, but there would still need to be one or two dedicated personnel to manage the emergent hydrogen systems and interact with the Fleet. Additionally, the life cycle tracking for hydrogen-specific components, such as fuel cells with finite operational hours, high-pressure tanks requiring periodic inspection and recertification demands a robust and detailed tracking mechanism not currently in place for USMC electric battery UAVs at this scale.

Deploying NovaSpark hydrogen generators across distributed land- and sea-based platoons presents unique organizational and logistical challenges. Chief among these is ensuring compatibility with existing aviation and vehicle fueling infrastructure, many of which are designed for naval jet fuel (JP-5) and other traditional fuels. The absence of hydrogen-compatible refueling equipment in forward operating bases, shipboard flight decks, and expeditionary logistics systems requires significant upfront investment in equipment modification or retrofit.

Additionally, the program office must contend with limitations in trained personnel and a lack of standardized maintenance protocols for hydrogen-based systems. Given the novelty of this technology within Marine Corps and Navy aviation support communities, PSMs must forecast personnel growth and ensure alignment with institutional training commands to prevent degradation in field operations (Defense Acquisition University, 2022). Budgeting becomes a constraint, particularly if hydrogen generation technology is not yet reflected in the DoD document that outlines military resource allocation, known as the Program Objective Memorandum (POM) process.

c. Solutions and Mitigation Strategies

To address the product support management concerns, the establishment of dedicated governance is paramount. This could take the form of a USMC hydrogen fuel integrated product team (IPT), or the assignment of a dedicated PSM chartered with authority and responsibility for developing, implementing, and overseeing the comprehensive hydrogen UAS sustainment strategy. As previously mentioned, the ideal solution would be to coordinate additional personnel at the existing management structure in the Navy (PMA-263), but this would still require an adaptive LCSP framework that accounts for hydrogen-fueled Group 2 UAS. This LCSP must include distinct modules addressing the unique requirements of land-based and sea-based operations and thoroughly integrate all relevant regulations.

A phased hydrogen fuel system implementation and learning approach is recommended, commencing with a smaller, representative subset of platoons under specific operating conditions. This allows for the identification and resolution of unforeseen sustainment issues in controlled settings before committing to full-scale deployment, with lessons learned iteratively updating the LCSP and training programs. This iterative approach is consistent with the LCSP being an evolving document. Lastly, cross-service collaboration with other DoD components actively exploring hydrogen technologies will be crucial to leverage lessons learned, share best practices, avoid redundant efforts, and potentially develop joint standards, training curricula, or procurement strategies, thereby enhancing overall DoD efficiency in hydrogen adoption.

Mitigating these concerns requires a phased and scalable implementation plan grounded in the Navy's product support business case analysis methodology. Establishing a dedicated concept of operations (CONOPS) for hydrogen, post-Milestone B, will allow for deliberate planning and alignment with broader strategic energy resilience goals. This should include collaboration with the DON Office of Energy Infrastructure (DON-EI), Naval Facilities Engineering Command (NAVFAC), and the Office of the Chief of Naval Operations (OPNAV N4) to synchronize sustainment and facilities investment planning.

Moreover, the DON can capitalize on existing rapid acquisition authorities, such as Other Transaction Agreements (OTAs), the DIU, and Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) programs, to reduce fielding timeframes and increase investment in operator-focused logistics. NovaSpark's modular hydrogen production capabilities offer the flexibility to deploy incrementally, reducing risk while enabling real-time feedback to PSMs. When coupled with predictive analytics and Digital Twin modeling, these solutions can offer a high-resolution view of system readiness, performance, and cost, ultimately enhancing the PSM's ability to execute their statutory responsibilities under 10 U.S. Code §2339a (Defense Acquisition University, 2022).

2. Design Interface

a. Key Considerations and Regulatory Impacts

The design interface, a critical component of supportability analysis, between the hydrogen fuel system and the Group 2 UAS platform is critically influenced by airworthiness and operational safety regulations. UAS platform selection or modification must align with DoD airworthiness directives and consider operational aspects covered by FAA regulations for UAS, even though military aircraft have specific exemptions.

The chosen hydrogen storage method (i.e., high-pressure compressed gas, typically 350–700 bar for UAS, versus future liquid hydrogen) profoundly impacts platform design parameters such as weight and balance, structural integrity, center of gravity, and the integration of requisite safety systems as outlined in NFPA 2 for onboard systems, including hazard zone delineation and pressure relief. Additionally, onboard hydrogen systems must incorporate robust safety features including, but not limited to, hydrogen-specific leak detectors, calibrated pressure relief valves, emergency shutdown mechanisms, and adequate ventilation pathways, all adhering to the stringent requirements of OSHA §1910.103 and NFPA 2 (NFPA, 2025). The DoD transportation of explosive and hazardous materials is already a key concern and tracked sustainment issue area due to current reliance on lithium batteries for most UAS under Title 49 CFR, Part 172.101 hazardous materials table managed by the Department of Transportation. Material selection for fuel tanks, fuel lines, valves, and seals is paramount, necessitating careful consideration of hydrogen embrittlement phenomena, long-term material compatibility depending on operational environment, and performance across varied environmental conditions (temperature, humidity, vibration).

The integration of hydrogen fuel systems into the DON aviation and ground platforms presents complex interface challenges. NovaSpark's mobile atmospheric hydrogen generators must align with airworthiness, material compatibility, and fueling safety requirements dictated by NAVAIR and NAVSEA protocols. One primary consideration is the safe interface between NovaSpark systems and existing aircraft refueling and storage infrastructures, which were designed primarily for JP-5 or JP-8 fuels (standard naval aviation fuels). Compliance with military standards and aircraft-specific operating and training procedures are essential to avoid system incompatibility or operational risks.

From a system design perspective, adopting hydrogen fuel requires structural and systems engineering assessments, particularly for the integration of cryogenic or high-pressure gaseous storage tanks aboard naval vessels and aircraft carriers. Design interfaces must also account for hydrogen embrittlement in metal piping and valves, thermal protection systems, and explosion-proof components, particularly on flight decks and in confined shipboard environments.

b. Land and Sea Obstacles for 216 Platoons

One of the most pressing challenges is achieving form, fit, and function compatibility with existing air and ground systems. Most forward-deployed platforms do not currently possess the infrastructure necessary to support hydrogen storage, handling, or fueling interfaces. For example, existing fueling couplings, flight deck fueling operations, and support vehicles are not universally equipped to handle high-pressure hydrogen connections, thereby necessitating design modifications and the introduction of specialized hydrogen-compatible connectors.

A primary concern is ensuring the inherent safety and maintainability of the selected Group 2 UAS platforms when powered by hydrogen. These systems must be designed or retrofitted to be intrinsically safe for hydrogen operation and maintainable by platoon-level technicians, who will have limited specialized hydrogen training, in austere expeditionary settings (both land-based and shipboard). This relates to design analysis and Failure Mode, Effects, and Criticality Analysis (FMECA). The principle of modularity and field serviceability is critical; designs must facilitate the rapid replacement of key hydrogen system components, such as fuel cell stacks, hydrogen tanks, or integrated sensor suites, at the platoon level with minimal specialized tools and under challenging field conditions. A key concern is the Ground Support Equipment (GSE) footprint associated with hydrogen (e.g., mobile fuelers, diagnostic tools, purging equipment) must be minimized in terms of size, weight, and power (SWaP) requirements to align with USMC expeditionary concepts that emphasize agility and reduced logistical tails.

For sea-based operations, maritime environment survivability is a significant hurdle, requiring enhanced corrosion resistance for all hydrogen system components and GSE exposed to saltwater spray, high humidity, and the constant motion and vibration experienced aboard naval vessels. The DoD has stringent shock trials and testing requirements for the inclusion of any equipment used during shipboard operations. Additionally, ensuring safe venting of hydrogen (which is lighter than air and highly buoyant) in the often confined and complex ventilation systems of ships is a critical design challenge.

Furthermore, there is apparent concern around safely integrating workable solutions like the NovaSpark systems within austere and mobile environments where SWaP constraints are paramount. This is especially true for UAVs and expeditionary aviation assets, which operate in remote environments without extensive ground support equipment. Ground troops and aviation ordnance personnel may lack the detailed engineering knowledge to manually interface with high-pressure hydrogen systems, increasing the likelihood of misconfigurations or safety incidents unless interface design is intuitive and error resistant.

c. Solutions and Mitigation Strategies

Future acquisitions could prioritize “designed-for-hydrogen” platforms rather than relying solely on retrofitting existing airframes. Such platforms would incorporate integrated safety systems, optimized hydrogen storage configurations, and simplified maintenance interfaces from the outset. For any existing platforms considered for hydrogen retrofitting, rigorous engineering safety reviews and airworthiness assessments are non-negotiable for the DoD and program offices. This proactive approach aligns with influencing design for sustainment. For instance, the NRL’s research and testing on platforms like the Hybrid Tiger and modifying the Stalker UAS demonstrates existing efforts to integrate hydrogen into UAS designs, providing valuable lessons for future platforms specifically architected for hydrogen. The recent work performed by NovaSpark in the pacific demonstrates that reverse engineering UAVs to interface with emergent hydrogen fuel generation sources is possible.

Human systems integration analysis must be conducted throughout the design, development, and testing phases. This ensures that all hydrogen-related tasks, such as handling cylinders, connecting fuelers, performing pre/post-flight checks, emergency procedures, can be performed safely and efficiently by Marines, potentially wearing standard combat gear, in diverse and demanding operational conditions. Existing human factors data from handling other compressed gases or hazardous materials within the USMC can inform this process. Additionally, the development and mandating of standardized fueling interfaces—including nozzle types, operating pressures (350–700 bar), and data communication protocols for “smart” fueling—for all Group 2 UAS and associated fueling equipment is essential. This ensures interoperability across the 216 platoons, prevents vendors’ lock-in, and leverages existing standardization efforts within the broader hydrogen industry.

The utilization of advanced materials and manufacturing techniques should be pursued when accounting for design interface for the hydrogen enabled Group 2 UAS. This includes high-strength, lightweight composite materials for fuel tanks and advanced corrosion-resistant alloys or coatings for components exposed to marine environments (NFPA, 2025). Additive manufacturing, an area of increasing DoD investment, could also be explored for on-demand, in-field production of certain non-critical spare parts or custom fittings, reducing reliance on traditional supply chains.

Finally, for sea-based operations, dedicated shipboard integration kits and procedures must be developed in collaboration with NAVSEA and NAVAIR. These kits would address safe stowage, handling pathways, ventilation requirements potentially requiring modifications to ship systems based on NFPA 2 and UFC guidelines, hazard zone management, and robust securing mechanisms for hydrogen UAS and support equipment against ship motion and vibration. Supportability trades would be essential in evaluating these solutions, drawing on existing Navy experience with handling other flammable gases or hazardous materials aboard ships.

To overcome these integration challenges, the DON should employ an incremental system integration approach aligned with SECNAVINST 5000.2 series requirements. This includes establishing an interface control document for NovaSpark components that define mechanical, electrical, software, and safety boundaries with host systems. Using digital modeling and simulation tools, such as model-based systems engineering and digital twin environments, can accelerate interface validation while reducing physical prototyping costs.

Additionally, design modifications to support modular, plug-and-play integration—such as quick-disconnect fueling hoses, intermodal mounting platforms, and containerized power modules—can drastically improve field usability. Collaboration with DON and DoD programs will ensure interface solutions adhere to survivability and damage tolerance standards. Integrating feedback from pilot programs, such as those executed through DIU, into evolving design interfaces will help validate and refine interoperability standards across naval aviation and ground systems.

3. Sustaining Engineering

a. Key Considerations and Regulatory Impacts

Sustaining engineering within the context of integrating hydrogen fuel into Department of the Navy aviation systems, particularly for USMC operations, is fundamentally about ensuring that these complex systems remain safe, reliable, and effective over their entire operational life. This requires careful consideration of numerous technical, logistical, and regulatory factors. A critical aspect of sustaining engineering for hydrogen involves navigating a detailed web of applicable regulations and proactively planning for technological advancements. A significant regulatory area is the potential applicability of OSHA standard 29 CFR 1910.119, which governs process safety management for highly hazardous chemicals. This standard becomes particularly relevant if hydrogen generation or storage activities at operational sites, such as expeditionary bases or aboard ships, could involve quantities exceeding specific regulatory thresholds.

Compliance with process safety management necessitates rigorous processes, including conducting comprehensive process hazard analyses (PHAs) – a systematic review to identify potential hazards and safeguards associated with a process – developing detailed operating procedures, implementing robust mechanical integrity programs to ensure equipment reliability, and establishing comprehensive emergency action plans. Beyond process safety management, system safety programs, a core responsibility of SE, must meticulously integrate standards from various authoritative bodies throughout the system's life cycle, from initial design through disposal. This includes adhering to the National Fire Protection Association (NFPA) 2 (Hydrogen Technologies Code), which provides fundamental requirements for the safe production, storage, and use of hydrogen, and OSHA §1910.103, specifically addressing the handling and storage of gaseous hydrogen. Relevant Unified Facilities Criteria (UFCs), such as UFC 3–430-08 for compressed gas systems, provide essential design and construction guidelines for infrastructure supporting hydrogen operations (NFPA, 2025). Adherence to these and other applicable guidelines and standards is not merely a compliance exercise; it is foundational to ensuring the overall system airworthiness and operational suitability. Airworthiness, as defined by DoD and USMC policies like MIL-HDBK-516, confirms that an aircraft system is safe for flight under specified operating conditions. Operational suitability ensures the system can perform its mission effectively in its intended environment.

For Group 2 unmanned aircraft systems utilizing hydrogen fuel, demonstrating both airworthiness and suitability requires proving the safety and performance of the integrated hydrogen power system within the demanding operational profiles of the USMC. SE establishes a forward-looking strategy for technological refreshment and upgrades. Recognizing the rapid pace of innovation in hydrogen fuel cell technology, advanced hydrogen storage methods (like cryo-compressed or solid-state storage), and the associated evolution of regulations and standards, a proactive SE plan is vital. This foresight ensures the system can incorporate future improvements to enhance performance, reduce cost, and improve safety, thereby maintaining system relevance and preventing premature obsolescence.

Finally, a critical aspect of sustaining engineering involves planning for the responsible end-of-life management of hydrogen-specific components, such as fuel cells and high-pressure storage tanks. This engineering must ensure compliance with environmental regulations, notably the Resource Conservation and Recovery Act (RCRA) for managing hazardous waste, and adhere to specific DoD demilitarization requirements, ensuring that retired components are handled safely and securely.

Sustaining Engineering for hydrogen-enabled platforms such as NovaSpark's mobile atmospheric hydrogen generators involves continuous assessment and improvement of design, safety, reliability, and maintainability throughout the system life cycle. The Department of the Navy must incorporate standards such as MIL-HDBK-502A (Product Support Analysis) and DoDI 4151.22 to ensure proactive life cycle management and system modernization. Given the unique operating characteristics of hydrogen fuel, such as low ignition energy and the potential for material degradation due to hydrogen embrittlement, ongoing engineering assessments are essential for platform safety and readiness.

Additionally, the integration of NovaSpark systems into naval aviation and expeditionary environments mandates compliance with DoD, OSHA, and EPA regulations governing hazardous materials and energy systems. For instance, sustained usage of lithium-ion batteries and potassium hydroxide electrolyte requires oversight under Title 49 CFR

(Hazardous Materials Transportation) and adherence to NFPA codes on flammable gas storage (NFPA, 2025). The implementation of predictive and reliability-centered maintenance frameworks will be essential in meeting these regulatory expectations while extending the useful life of critical subsystems.

b. Land and Sea Obstacles for 216 Platoons

Operational environments in which 216 platoons operate—ranging from maritime to remote land-based theaters—pose substantial challenges to sustaining hydrogen generation systems. Environmental factors such as temperature extremes, saltwater exposure, sand and dust, and fluctuating power availability can accelerate system wear and reduce component lifespan. These variables demand robust environmental qualification and the hardening of NovaSpark systems beyond standard commercial tolerances. Further, because hydrogen fuel systems represent an emerging technology within naval aviation and ground logistics, there is often limited historical maintenance data or failure mode experience to guide sustainment planning. Maintenance personnel may be unfamiliar with unique degradation modes such as hydrogen embrittlement, electrolyte leakage, or degradation of membrane separation units. Without extensive technical data packages (TDPs) and modular component design, field-level troubleshooting becomes inefficient, reducing operational availability and increasing life-cycle costs.

For the USMC's 216 platoons, operating in diverse and often austere land and sea environments, the integration of hydrogen fuel presents several significant Sustaining Engineering challenges. A primary obstacle lies in the inherent complexity required to integrate what are often disparate hydrogen subsystems into a single, cohesive, reliable, and safe operational system suitable for widespread expeditionary use. These subsystems might include distinct types of on-site hydrogen generators (each with unique inputs and outputs), diverse storage solutions (from standard high-pressure cylinders used with current Group 2 UAS to potentially novel storage methods), mobile fueling apparatus, and the UAS platform itself incorporating the fuel cell. Managing the numerous physical interfaces (connections for fuel and power), electrical interfaces (power conditioning and distribution), and data interfaces (monitoring system status, fuel levels, diagnostics) between components from potentially multiple vendors presents a substantial engineering hurdle to achieving seamless operation.

Ensuring consistent system performance and safety across the extreme environmental conditions encountered globally by USMC platoons poses another substantial engineering challenge. Unlike traditional fossil fuels or simple battery systems, hydrogen systems can be particularly sensitive to factors such as extreme temperatures (affecting fuel cell efficiency and material integrity), high humidity (impacting fuel cell membranes), dust (potentially clogging filters or damaging components), and corrosive saltwater exposure (degrading materials and electrical connections). Sustaining reliable operation in these varied and harsh environments requires meticulous engineering to harden components and design systems resilient to such stresses. The current lack of established interoperability and standardization across the nascent hydrogen technology landscape further complicates sustainment for distributed platoons. This includes a deficit in standardized fueling component interfaces (preventing easy interchangeability between different fuelers and UAS), common data exchange protocols between system elements (hindering integrated monitoring and diagnostics), and universal diagnostic tools capable of interfacing with components from multiple vendors. This lack of standardization impedes seamless operations, complicated troubleshooting, and increases the logistical burden of supplying compatible spare parts and support equipment to numerous dispersed units.

Finally, managing system-level safety becomes significantly more complex when considering the cumulative risk associated with multiple hydrogen systems operating in proximity within a constrained platoon footprint. Unlike operations with less volatile energy sources, the presence of multiple potential leak points and ignition sources in a confined land base or aboard a naval vessel with limited dispersion options and potentially shared ventilation systems increases the overall risk profile. Sustaining engineering must address how the operation and potential failure modes of individual hydrogen systems interact within this shared environment to ensure collective safety, requiring careful consideration of layout, ventilation, and emergency response procedures.

c. Solutions and Mitigation Strategies

Addressing the Sustaining Engineering challenges associated with hydrogen fuel in USMC aviation requires a multi-faceted approach grounded in established engineering practices and forward-thinking technology strategies. A foundational solution is the implementation of robust Systems Safety Engineering throughout the entire life cycle of the hydrogen-fueled UAS systems. This discipline, guided by standards such as MIL-STD-882E (System Safety), is a structured process to identify, assess, and mitigate hazards. It involves conducting thorough analyses at different stages: Preliminary Hazard Analyses (PHA) during early concept development to identify potential major hazards; subsystem hazard analyses to examine risks within specific components like the fuel cell or storage tank; system hazard analyses to evaluate hazards arising from the interaction of subsystems; and OSHA to assess risks during planned missions, maintenance, and handling. These analyses must specifically address the unique safety considerations of both land and sea deployment environments and integrate requirements from key standards like NFPA 2 and OSHA.

The establishment of a robust configuration management (CM) program, as outlined in standards like MIL-HDBK-61 (Configuration Management Guidebook), is essential. Configuration management is the process of tracking and controlling changes to a system's design, documentation, and performance over its life cycle. For hydrogen-related hardware (e.g., tanks, fuel cells, generators), software (e.g., control systems, diagnostics), and technical documentation, a rigorous CM program ensures consistency, traceability, and control over system baselines across all 216 platoons. This is crucial for ensuring that all units operate with the correct, validated equipment and procedures, simplifying maintenance, and managing upgrades effectively.

Extensive environmental and operational testing (DT/OT) of the fully integrated hydrogen UAS systems in realistic USMC operational environments is critical. Development testing verifies system performance against design specifications, while operational testing assesses its suitability in the hands of typical users in anticipated environments. This testing must include dedicated shipboard trials to evaluate performance and safety in the unique maritime environment (e.g., motion, saltwater spray, confined spaces) and operations in extreme climatic conditions (e.g., desert heat, arctic cold, high humidity) to identify and mitigate performance degradation or safety issues before widespread deployment.

Advocating for and prioritizing open system architecture (OSA) principles in the design of hydrogen systems, their interfaces, and associated software is a key strategy to overcome standardization and interoperability challenges. An OSA, structures a system with well-defined, published interfaces between components. This approach facilitates technology insertion for future upgrades, improves interoperability between components from different vendors, reducing reliance on single-source suppliers, and ultimately reduces long-term sustainment costs by enabling competition and flexibility in maintenance and upgrades.

Performing detailed FMECA on critical hydrogen components and subsystems is a valuable preventative measure. FMECA is a systematic process to identify potential failure modes within a system, determine the effects of these failures, and assess their criticality. Performing FMECA allows engineers to proactively identify potential weaknesses in the design and implement preventative design features, select more robust components, or develop targeted maintenance strategies (e.g., predictive maintenance based on potential failure modes) to enhance overall system reliability and safety, minimizing unexpected failures in the field.

To enhance the sustainability of possible hydrogen generation solutions, like the NovaSpark systems, the Navy should adopt a life cycle sustainment model that emphasizes modularity, field replaceability, and predictive analytics. Engineering resilience can be built into the system design by incorporating hot-swappable components, corrosion-resistant materials, and automated diagnostics. NovaSpark's integration with condition-based maintenance (CBM+) principles and embedded sensors can enable predictive fault detection, minimizing unplanned downtime and maximizing system uptime.

The development of digital twins for NovaSpark units will allow PSMs to simulate operational conditions, identify failure points, and iterate engineering upgrades more effectively. Establishing a collaborative feedback loop between the engineering support team, field operators, and depot-level maintainers will help refine technical manuals and maintenance allocation charts, ensuring continuous improvement. The use of DIU's initiatives and other pilot deployments as testbeds for sustainment best practices will also generate valuable lessons learned to inform full fleet integration.

4. Supply Support

a. Key Considerations and Regulatory Impacts:

The supply support strategy for hydrogen fuel is fundamentally shaped by the choice of fuel source and its associated regulatory framework. On-site electrolysis, for instance, is governed by EPA 40 CFR concerning water usage (requiring potential permits for water withdrawal from local sources, especially in water-scarce regions) and National Pollutant Discharge Elimination System permits if any wastewater is discharged. Additionally, local and state environmental and safety permits will be necessary for establishing and operating production facilities, including adherence to NFPA 2 for facility design and safety systems (NFPA, 2025). Conversely, procuring hydrogen from external suppliers necessitates strict adherence to DOT 49 CFR Parts 100–185 for transportation and requires thorough supplier vetting to ensure their compliance with DOT (e.g., cylinder qualifications, vehicle placarding), OSHA (e.g., safe handling procedures, worker training), and international quality standards such as ISO 14687 for hydrogen fuel purity or SAE J2719 for fuel cell vehicle applications. Supplier certifications (e.g., ISO 9001 for quality management systems) and robust audit processes are critical for ensuring a reliable and safe supply.

Establishing a resilient supply chain involves navigating a complex web of federal, state, and local regulations pertaining to the transport (UN 1049 for compressed hydrogen, requiring specific packaging and labeling) and storage of hazardous materials across various nodes, from production site to the end-user platoon. Rigorous fuel quality control protocols, adhering to established military (e.g., future MIL-PRF specifications) or industry standards, must be implemented, potentially involving field-level sampling and analysis capabilities to prevent fuel cell contamination. Leveraging potential regulatory incentives, such as federal or state tax credits and grants (e.g., via DOE hydrogen hub initiatives or DoD's operational energy funding streams), could promote the development of sustainable and cost-effective hydrogen production and distribution infrastructure, impacting the overall affordability of supply support.

Supply Support being a critical component of the 12 IPS Elements, ensures all necessary spares, tools, and consumables are available and delivered efficiently to sustain operational readiness. The introduction of NovaSpark's mobile atmospheric hydrogen generation systems represents a transformative shift in how fuel is generated and supplied, effectively decentralizing energy logistics and reducing dependency on bulk fuel transportation. This aligns closely with emerging DoD energy resilience and contested logistics strategies, such as those outlined in the 2022 NDS and the Naval Operational Energy Framework. However, employing hydrogen generation systems introduces new classes of supply, particularly compressed hydrogen gas, lithium-ion energy storage modules, and potassium hydroxide electrolyte; each are governed by specialized storage and transport requirements. Compliance with Title 49 CFR for hazardous materials, MIL-STD-2073-1 for packaging, and DLA's cataloging and provisioning processes must be ensured to facilitate integration into the Navy's supply support architecture. Accurate provisioning data, including National Stock Numbers (NSNs) for NovaSpark's modular components, must be developed in conjunction with Item Unique Identification (IUID) registration to ensure traceability and accountability across the logistics enterprise.

b. Land and Sea Obstacles for 216 Platoons

The foremost challenge is the "last tactical mile" logistics – the immense difficulty of reliably and safely supplying hydrogen (whether generated on-site further up the echelon or procured externally) to 216 highly mobile and geographically dispersed USMC platoons. This is particularly acute in contested or austere expeditionary environments where traditional supply lines for POL (Petroleum, Oils, and Lubricants) are already strained and vulnerable. Platoons operating in expeditionary and maritime environments face significant logistical constraints when managing fuel supply, especially in contested or denied areas. Traditional supply lines for JP-5 or diesel fuel are highly vulnerable to interdiction, and the reliance on centralized bulk fuel distribution increases operational risk. The shift to hydrogen production decentralizes energy provisioning but introduces new complexities, such as the need for specialized refueling connectors, spares for electrolysis and filtration subsystems, and hazardous material shipping containers. On-site generation limitations are significant: for land operations, this includes water scarcity in arid regions (requiring robust AWH or purification systems), the substantial and continuous power demand for electrolysis units (which could strain tactical generators or necessitate dedicated renewable energy sources like deployable solar arrays), and the physical footprint, weight, and mobility constraints of current generation systems relative to platoon lift capabilities.

For sea operations, severe space and weight limitations aboard ships, the availability of sufficient high-purity potable water (creating competition with the ship's essential needs for drinking water and other systems), and ensuring the safe operation and venting of hydrogen generation equipment in a dynamic maritime environment pose major hurdles. Procured hydrogen limitations include the sparse availability of certified, military-grade hydrogen suppliers near potential global deployment areas (especially for high-purity, fuel-cell grade hydrogen), the inherent security risks of transporting a highly flammable hazardous material through potentially contested land or sea routes, the cost volatility of commercially procured hydrogen, and the challenge of maintaining stringent fuel purity standards throughout a complex, multi-modal supply chain. Finally, ensuring the timely availability of hydrogen-specific spares and consumables—such as fuel cell stacks (which have limited lifespans), high-pressure tanks and valves requiring periodic recertification, specialized sensors (for leaks, pressure, temperature), electrolyzer membranes or catalysts, and purification cartridges—for 216 platoons operating globally will require a sophisticated and responsive provisioning and inventory management system, potentially more complex than for existing UAS components.

Another critical concern is maintaining readiness and availability of high-demand components such as hydrogen membrane stacks, lithium batteries, and KOH canisters. These items may be subject to limited vendor availability, long lead times, or classified handling procedures. Supply chain bottlenecks, whether caused by regulatory constraints or industrial base limitations, can reduce mission effectiveness. Additionally, many current Navy logistics systems are not yet optimized for real-time visibility or sustainment of emerging energy technologies, creating gaps in inventory forecasting and resupply timeliness.

c. Solutions and Mitigation Strategies

A hybrid and distributed supply model offer the most resilient and operationally relevant pathway. This would involve developing and fielding modular, scalable, and highly mobile expeditionary hydrogen generation units (e.g., leveraging existing efforts like NovaSpark's atmospheric water harvesting for land, or advanced, compact water purification systems for sea-based generation from seawater, as mentioned in the attached document) that could be organic to battalion or regimental echelons, capable of supporting multiple platoons. This decentralized generation capability would be complemented by establishing regional "hydrogen hubs" at key USMC bases or major logistics nodes (e.g., existing DLA Energy supply points) for the bulk storage of procured hydrogen (meeting ISO 14687 and SAE J2719 standards) and as forward operating sites for larger, more efficient generation capabilities. A "milk-run" concept, utilizing specialized and DOT-certified transport assets (potentially including autonomous ground vehicles in the future), could then be employed for delivering compressed hydrogen cylinders or generation system consumables (like replacement membranes or water purification elements) to forward-deployed platoons. Equipping platoons with advanced storage solutions is critical; this includes lightweight, high-capacity, and robust hydrogen storage cylinders (e.g., DOT-compliant Type IV or V composite tanks, offering significant weight savings over steel) or exploring the maturation and fielding of solid-state hydrogen storage technologies (metal hydrides, adsorbents) that offer potentially greater safety, lower pressure, and reduced storage footprint, aligning with research by organizations like the DOE.

Continued investment in Research and Development for smaller, potentially man-portable or vehicle-integrated "point-of-need" hydrogen generation systems could provide solutions for extreme remote operations or special forces applications, perhaps using novel methods like chemical hydrogen generation from stable precursors (e.g., ammonia cracking, sodium borohydride hydrolysis), building on existing research in portable power. An integrated spares management strategy must be developed. This strategy should be based on reliability data derived from rigorous testing (DT/OT) and early fielding experiences, leveraging advanced analytical tools like Reliability Centered Maintenance (RCM) for demand forecasting, and potentially incorporating additive manufacturing for on-demand production of certain non-critical or long-lead-time parts. For on-site electrolysis, particularly in water-scarce land environments, investment in highly efficient automatic water harvesting (AWH) systems is crucial. For shipboard or coastal generation, development and fielding of compact, energy-efficient reverse osmosis and desalination units specifically designed for integration with hydrogen electrolyzers would be a key enabler, potentially leveraging existing Navy expertise in shipboard water purification.

To overcome these challenges, the Navy and Marine Corps can modernize its supply support strategy by integrating NovaSpark's technology into a distributed logistics architecture. Onsite hydrogen production from ambient water vapor allows for fuel independence, eliminating the need for bulk fuel convoys and associated risks. The NovaSpark H2GO system's modularity allows logistics planners to scale deployments based on mission requirements, reducing the burden on centralized depots.

To strengthen sustainment, the Navy and Marine Corps should work with NAVSUP and DLA to provision NovaSpark's components within standard supply catalogs, establishing replenishment levels and reorder points in key theaters. This includes the development of PM-managed Readiness Spares Packages (RSPs) for hydrogen generator units and mobile refueling assets. Additionally, integration of IoT-enabled supply tracking and AI-powered forecasting models can optimize inventory levels, predict demand spikes, and reduce waste. Partnerships with DIU, small business innovators, and global logistics integrators can also enhance surge capability and diversify the supply base, improving resilience in future contingency operations.

5. Maintenance Planning and Management

a. Key Considerations and Regulatory Impacts

Effective Maintenance Planning and Management for hydrogen fuel systems supporting DON aviation systems are foundational to ensuring operational readiness, reliability, and, critically, safety. The intricate nature of these systems, involving hydrogen as a unique high pressure and flammable gas, necessitates strict adherence to a complex framework of regulations and industry standards applicable to both shipboard and shore-based environments. The upkeep of the entire hydrogen infrastructure, encompassing storage tanks, dispensing equipment, and associated piping networks, is heavily regulated. Specific compliance is mandated under key regulations such as OSHA §1910.103, which provides general safety standards for the handling and storage of hydrogen. Relevant UFCs, such as UFC 3–430-08 for compressed gas systems, dictate design, construction, and maintenance requirements for facilities handling high-pressure gases. Additionally, the comprehensive National Fire Protection Association (NFPA) 2 (Hydrogen Technologies Code) provides detailed guidelines spanning production, storage, dispensing, and use, including specific requirements for inspection and maintenance activities (NFPA, 2025). These regulations collectively dictate precise inspection frequencies, often specifying the scope of examinations required, such as internal and external inspections for hydrogen fuel cells.

Beyond equipment inspections, these standards also establish stringent personnel qualification standards, ensuring that only professionally trained and certified individuals perform maintenance on hydrogen systems. This is paramount given the inherent risks involved. The development of clearly defined step-by-step maintenance procedures is essential for all critical components. This includes detailed instructions for tasks involving fuel cells (which may require specialized handling), high-pressure tanks, valves (which control hydrogen flow), sensors (for monitoring pressure, flow, and leaks), leak detection systems (vital safety components), and emergency shutdown mechanisms. These procedures must not only align with manufacturer recommendations but also satisfy overarching regulatory requirements, ensuring that maintenance activities are conducted safely and effectively. This meticulous, proactive approach to maintenance planning forms a cornerstone for ensuring the overall system reliability and safety throughout the operational life cycle of the hydrogen-enabled Group 2 UAS.

Maintenance Planning and Management is foundational to ensure that hydrogen-enabled systems like NovaSpark's mobile generators achieve operational availability and life cycle affordability. For post-Milestone B systems, the PM must develop a comprehensive maintenance concept that is aligned with DoDI 5000.91 and tailored for fielded units operating in complex and contested environments. This includes not only the definition of Organizational, Intermediate, and Depot (O-I-D) -level responsibilities, but also the standardization of Preventive Maintenance Checks and Services (PMCS) schedules and procedures.

Hydrogen systems present unique maintenance challenges requiring adherence to specific safety and handling protocols. Maintenance plans must incorporate MIL-STD-3001 for technical manual development, comply with the National Fire Protection Association

(NFPA) standards for flammable gases, and meet OSHA guidelines for servicing high-voltage lithium-ion batteries and corrosive electrolyte systems (NFPA, 2025). Regular hydrostatic testing of compressed hydrogen tanks, visual inspection for corrosion and stress fractures, and electrolyte level checks must be included in maintenance planning. Furthermore, maintenance strategy must account for both platform sustainability and personnel safety, particularly given the risks of hydrogen embrittlement and gas leakage.

b. Land and Sea Obstacles for 216 Platoons

For the USMC's dispersed 216 platoons, implementing effective maintenance for complex hydrogen systems presents several significant obstacles rooted in logistics, personnel readiness, and environmental factors. A primary concern is the anticipated low skill density regarding the maintenance of complex hydrogen fuel cell systems and the handling of high-pressure gas components at the tactical level (platoon or larger company level). Existing Military Occupational Specialties (MOSs) may not encompass the highly specialized knowledge and hands-on experience required for diagnosing issues within advanced fuel cell stacks or safely handling components rated for pressures up to 700 bar (approximately 10,000 psi). Bridging this skill gap requires significant investment in training and potentially the development of new MOSs or certifications. The diagnostic complexity associated with advanced fuel cell systems poses another challenge. Pinpointing the root cause of a performance issue within a fuel cell or identifying minute, but dangerous, high-pressure hydrogen leaks in noisy, austere field conditions is significantly more difficult than troubleshooting traditional systems.

This difficulty is compounded by the likelihood of having only limited Specialized Tools and Test Equipment (STE) available at the platoon level. Furthermore, hydrogen systems often require STE unique to their technology (e.g., specific leak detectors, high-pressure fittings, specialized purges), adding to the platoon's logistical burden in terms of transporting, calibrating, and maintaining the STE itself in challenging environments. The maritime environment introduces a unique layer of complexity and concern for maintenance. Saltwater exposure and high humidity accelerate corrosion of metallic components, potentially compromising the integrity of piping, valves, and structural elements. Ultraviolet (UV) radiation and saltwater can also degrade elastomeric seals and gaskets, which are critical for maintaining the integrity of high-pressure connections and preventing leaks. The increased salinity and humidity aboard ships also increases the likelihood of electrical system issues (e.g., short circuits, corrosion of contacts), which can affect the performance and safety of hydrogen system controls and sensors.

These environmental factors not only complicate maintenance tasks but can also significantly reduce the lifespan of components compared to land-based operations. Finally, ensuring safety during all maintenance activities is paramount and presents specific challenges for both land and sea operations. Working with high-pressure hydrogen requires rigorous procedures to prevent leaks and ignition. This includes developing and strictly enforcing procedures for safe handling of components, purging (the process of removing residual hydrogen from a system or component, often by flushing with an inert gas like nitrogen), inerting (filling a system or component with an inert gas to remove or dilute hydrogen below flammable levels before maintenance), and the safe replacement of high-pressure hydrogen components like tanks. The potential presence of hazardous materials within fuel cell stacks (e.g., catalysts) also necessitates specific handling and disposal protocols during maintenance.

Small units operating in expeditionary maritime and land-based domains are often constrained by limited access to trained maintenance personnel, specialized tools, and repair parts. These constraints are exacerbated when maintaining advanced systems such as NovaSpark's hydrogen generators, which differ markedly from conventional fuel systems. Technicians may be unfamiliar with the diagnostic requirements of electrochemical stacks or the degradation profiles of lithium-ion modules, and the absence of codified Navy maintenance doctrine for hydrogen systems creates further ambiguity.

Another challenge lies in the environmental sensitivity of hydrogen systems. Inconsistent temperatures, humidity, and the presence of saltwater or dust can accelerate component degradation, especially for membrane separation units, fuel cell enclosures, and electronic control modules. Without embedded condition monitoring systems or predictive diagnostics, field operators may be unable to detect impending failure states, leading to unplanned downtime and reduced mission readiness. Moreover, the logistical delay in acquiring replacement parts, particularly those sourced through small business or international suppliers, could disrupt unit maintenance cycles.

c. *Solutions and Mitigation Strategies*

To effectively address the Maintenance Planning and Management concerns for hydrogen-enabled UAS within the USMC, several strategic solutions can be implemented. An optimized maintenance concept, leveraging an echeloned approach, offers a viable pathway for supporting these systems across both land and sea environments. This structure typically divides maintenance responsibilities based on complexity and required resources:

- **Organizational (Platoon-level):** Focuses on tasks executable by system operators with minimal specialized training. This includes daily pre- and post-use checks, visual inspections for obvious leaks or damage, routine and safe fueling operations following established procedures, replacement of simple filters, and potentially minor component swaps involving quick-disconnect fittings or easily accessible sensors. These tasks would be guided by simplified Interactive Electronic Technical Manuals (IETMs) – digital technical publications allowing interactive access to procedures – and basic toolkits provided at the platoon level.
- **Depot-level or Contractor Logistics Support:** Is reserved for intermediate & major repair activities requiring highly specialized equipment and expertise, such as major overhaul of fuel cells, mandatory recertification of high-pressure tanks after specific periods or events, and repair of complex electronic control modules or specialized ground support equipment. Leveraging existing capabilities, such as those provided by TALSA support contractors already familiar with aviation systems, could manage this highest echelon of support.

The implementation of Condition-Based Maintenance Plus (CBM+) strategies present a significant opportunity for optimizing maintenance schedules. CBM+ utilizes data gathered from embedded sensors, health monitoring systems, and operational usage to predict potential failures before they occur. By continuously monitoring the actual condition of components, maintenance can be scheduled only when needed, rather than strictly adhering to fixed intervals. This approach minimizes unnecessary interventions, reduces maintenance costs, and increases system availability for both ship and shore-based systems.

To support field units operating with limited organic expertise, establishing robust remote maintenance support capabilities is crucial. This includes developing user-friendly, fault-isolation troubleshooting guides integrated within IETMs and establishing reliable "reach-back" support mechanisms, allowing platoon-level maintainers to consult with experts at higher echelons or engineering support centers for guidance on complex issues. Given the corrosive nature of the maritime environment, a specific Corrosion Prevention and Control (CPC) Program tailored for hydrogen systems operating at sea must be implemented. This program would encompass careful material selection during design (prioritizing corrosion-resistant alloys), application of protective coatings, and establishment of regular wash-down procedures using fresh water to minimize the impact of saltwater exposure on system components, thereby preserving integrity and extending component lifespans. Finally, emphasizing modular design for repair is a key strategy to minimize operational downtime and reduce the need for extensive field repairs requiring highly specialized skills for both land and sea deployments. This involves designing critical components as Line Replaceable Units (LRUs) – modules that can be quickly and easily swapped out at the organizational or intermediate level – or Shop Replaceable Assemblies (SRAs) – components requiring slightly more complex procedures or tools but still replaceable at the intermediate level. This design philosophy allows a faulty component to be replaced with a spare in the field, quickly returning the system to operational status, while the faulty module is sent to a higher echelon or depot for repair.

A key opportunity to enhance maintenance effectiveness lies in the adoption of predictive maintenance enabled by NovaSpark's real-time system telemetry. These hydrogen units can be outfitted with diagnostic sensors that monitor pressure, temperature, humidity, and electrolyte quality, feeding data back to centralized dashboards that leverage AI for fault prediction. Aligning this capability with the Navy's Digital Maintenance Environment and Naval Operational Business Logistics Enterprise (NOBLE) systems would enable a unified view of asset health across the enterprise.

Additionally, the Navy can mitigate supportability risk by implementing a two-tiered maintenance approach: field-level replacement of Line Replaceable Units (LRUs) and depot-level refurbishment of critical subsystems. Field maintainers can be equipped with modular toolkits and ruggedized diagnostic tablets pre-loaded with IETMs compliant with S1000D standards. As part of initial fielding, Maintenance Training Teams (MTTs) can be deployed in coordination with the Fleet Readiness Centers (FRCs) to establish core competencies among maintainers and support the development of long-term training pipelines.

Incorporating NovaSpark systems into existing IPS databases such as DON's Naval Visibility and Management of Operating and Support Costs (VAMOSC) and Maintenance Engineering Requirements and Improvement Tool (MERIT) will further enhance planning, tracking, and resource allocation across the maintenance life cycle.

6. Packaging, Handling, Storage, and Transportation

a. Key Considerations and Regulatory Impacts

Packaging, Handling, Storage, and Transportation (PHS&T) for hydrogen is arguably one of the most complex IPS elements due to its hazardous nature and the stringent regulatory environment. The Department of Transportation's (DOT) 49 CFR Parts 100–185, known as the Hazardous Materials Regulations (HMR), provides an overarching framework for all modes of hydrogen transport in the U.S (DOT, 2024). Specifically, Part 172 (Hazardous Materials Table) designates "UN 1049, Hydrogen, compressed" as a Class 2.1 Flammable Gas, which mandates specific labeling (e.g., flammable gas placards), shipping documentation, and emergency response information requirements (DOT, 2024, pg. 121). Part 173 (Shippers—General Requirements for Shipments and Packaging) further details authorized packaging, including cylinder specifications (such as DOT 3AA, 3AAX, or various special permits for composite cylinders), along with requirements for pressure testing and valve protection. Transportation by specific modes is subject to additional regulation: Part 174 for rail, Part 175 for air (with significant restrictions on flammable gases), Part 176 for vessel transport (requiring specific stowage and segregation), and Part 177 for public highway transport (detailing driver qualifications and vehicle placarding). The chosen method of hydrogen storage, whether high-pressure compressed gas (common for current Group 2 UAS applications) or future liquid hydrogen, profoundly impacts PHS&T requirements. Liquid hydrogen, being a cryogenic fluid, falls under more extensive regulations within 49 CFR Part 173, Subpart G, which necessitates specialized cryogenic tankers and handling procedures (DOT, 2024).

For storage, NFPA 2 (Hydrogen Technologies Code) is a comprehensive consensus standard widely adopted by jurisdictions and referenced by OSHA (NFPA, 2025). This standard dictates requirements for storage quantities (both indoor and outdoor), minimum separation distances from exposures (such as buildings, property lines, other flammable materials, and ignition sources), the design of storage facilities (including specifications for ventilation and electrical classification as per NFPA 70, the National Electrical Code), and the delineation of hazard classification zones. UFC 3–430-08 (Compressed Air and Gas Systems) provides specific criteria for the design and construction of compressed gas storage and distribution systems on military installations, directly applicable to fixed or semi-permanent hydrogen storage. Additionally, OSHA 29 CFR 1910.103 (Hydrogen) specifies detailed requirements for gaseous hydrogen system storage locations (e.g., separate buildings, outdoors, or special rooms), design parameters for containers and piping, and operational safety procedures. Collectively, these regulations aim to mitigate the substantial risks associated with hydrogen's flammability, wide explosive range, and potential for leaks.

The introduction of hydrogen fuel systems to naval aviation and expeditionary operations necessitates a new set of critical considerations for PHS&T. These operations must ensure strict compliance with the Department of Transportation's Hazardous Materials Regulations (49 CFR Parts 100–185), the Defense Transportation Regulation (DTR Part II, Chapter 204), and the U.S. Navy's Explosives Safety Manual (OPNAVINST 8020.14). Systems like NovaSpark's mobile atmospheric hydrogen generators, for example, incorporate compressed hydrogen gas stored in DOT-UN certified tanks, lithium-ion batteries, and potassium hydroxide (KOH) electrolyte, all of which are classified as hazardous materials. Consequently, these components must be packaged, labeled, and transported under strict guidelines. Each component must be secured in accordance with DoD's UFC 4–010-06 for hazardous material storage and accompanied by applicable Material Safety Data Sheets (MSDS). For instance, lithium-ion battery packs are subject to Class 9 hazardous material regulations and must be packaged to prevent short circuits and accidental activation. Compressed hydrogen tanks require periodic hydrostatic testing and feature safety relief valves, while KOH electrolytes must be stored in corrosion-resistant containers with appropriate limited quantity markings. These regulations directly impact how units package equipment for movement by land, air, or sea, often requiring specific placards, segregated compartments, and the involvement of trained HAZMAT personnel.

b. Land and Sea Obstacles for 216 Platoons

A paramount concern is achieving safe and compliant transport of high-pressure hydrogen cylinders (potentially hundreds required to sustain 216 platoons over an operational period) to and with deployed platoons across all relevant modes: ground vehicles (Humvees, JLTVs, larger trucks), tactical aircraft (V-22, C-130, CH-53 – with strict adherence to Part 175 quantity limits and packaging), and naval vessels and landing craft (adhering to Part 176 stowage and segregation). This includes ensuring proper blocking, bracing, valve protection, and segregation from incompatible materials like oxidizers. Establishing expeditionary storage limitations that meet NFPA 2 separation distances and UFC criteria in constrained forward operating sites or within the extremely limited and shared spaces aboard naval vessels presents a major logistical and safety engineering challenge. The safe handling of hydrogen in austere conditions—manual and mechanical handling of heavy, high-pressure cylinders by Marines in harsh weather, uneven terrain, low light conditions, or under the duress of combat operations—must minimize risks of drops, impacts, valve damage, or uncontrolled releases.

The weight and volumetric cube of current compressed hydrogen cylinders (even advanced composites) and their associated transport and storage racks significantly impact the mobility and logistical footprint of expeditionary USMC units, potentially conflicting with concepts like distributed maritime operations (DMO) and expeditionary advanced base operations (EABO) that prioritize agility. Ensuring the security of stored hydrogen, a flammable and potentially high-value (or high-risk if captured) commodity, in forward or less secure areas from enemy action, sabotage, or pilferage is a critical concern. Shipboard specifics amplify these challenges: ensuring adequate and often forced ventilation to prevent accumulation of leaked hydrogen (which is lighter than air and can collect in overheads), safely managing pressure relief device discharges (directing them overboard away from personnel and ignition sources), ensuring compatibility with existing shipboard fire suppression systems (e.g., Halon or water mist may not be optimal for hydrogen fires), securely stowing cylinders against severe ship motion (pitch, roll, heave, shock), and establishing clearly defined and safe transfer routes from pier-to-ship and within the ship for refueling operations.

Expeditionary units often operate with constrained logistics infrastructure, which poses a significant challenge for the compliant storage and safe transportation of hydrogen systems. Standard field supply chains are not yet optimized for handling hydrogen gas or corrosive electrolytes, nor are most tactical or strategic lift platforms configured with proper containment solutions or monitoring systems to safely transport high-pressure gas tanks. This increases the risk of damage during movement and potential safety incidents during offloading or staging operations.

There is also the issue of training. Handling compressed hydrogen requires personnel to be familiar with flammability thresholds, leak detection procedures, and the use of non-sparking tools. A gap in HAZMAT certification among operators and logisticians raises concerns about improper handling or the inadvertent mixing of incompatible substances. Additionally, remote storage locations in austere environments often lack climate control, which can degrade battery performance or alter the behavior of pressurized systems and electrolytes over time, introducing risks during system activation.

c. Solutions and Mitigation Strategies

The development and fielding of standardized expeditionary PHS&T kits is a crucial pathway. These kits would comprise certified (to DOT, International Air Transport Association (IATA) for air, International Maritime Dangerous Goods (IMDG) Code for sea) hydrogen transport modules (e.g., multi-cylinder packs or "quads") and storage racks specifically designed for compatibility with USMC tactical vehicles, aircraft cargo bays and external lift, and naval vessel tie-down points. These kits should incorporate integrated safety features such as pressure relief manifolds, grounding points, robust impact protection, and quick-release tie-downs, drawing on existing best practices for transporting other hazardous gases. Lightweight cylinder prioritization, mandating the use of the lightest available certified high-pressure composite cylinders (e.g., Type IV or V, which can offer up to 70% weight reduction over steel Type I cylinders), will significantly reduce manual handling burdens and improve overall transport efficiency. This leverages existing commercial technology already compliant with DOT regulations. Aggressive pursuit and field-testing of advanced hydrogen storage Research and Development, particularly solid-state hydrogen storage materials (metal hydrides, chemical hydrides, adsorbents) or conformable tanks, could offer game-changing improvements in volumetric efficiency, lower operating pressures, and enhanced intrinsic safety for PHS&T, aligning with ongoing DOE and DoD research efforts aimed at overcoming these traditional storage barriers.

For field deployment, mobile, modular storage units could be developed. These could be small, containerized, or palletized units that meet NFPA 2 and UFC requirements for temporary field storage, potentially offering some level of ballistic protection and controlled environmental conditions (e.g., forced ventilation, integrated leak detection). Such units could be designed for easy transport by USMC logistical assets. A critical pathway for sea-based operations is the development of shipboard-specific PHS&T doctrine and certified equipment in close collaboration with NAVSEA and NAVAIR. This must address designated, approved storage locations (considering ventilation requirements of NFPA 2, proximity to ignition sources, and structural integrity of decks), specialized handling equipment (e.g., certified hoists, non-sparking trolleys), clear procedures for pier-to-ship and intra-ship transfers (potentially using dedicated routes), and integration with shipboard damage control and emergency response protocols, including specific training for ship's company (NFPA, 2025). Exploring "Just-in-Time" (JIT) delivery concepts for hydrogen to forward units, where feasible through secure and reliable transport (potentially leveraging unmanned logistics systems in the future), could minimize the quantity of hydrogen stored on-site at the platoon level, thereby reducing the hazard footprint. However, this JIT approach increases the frequency of transport and reliance on the supply chain, requiring careful trade-off analysis. Finally, integrated leak detection and emergency stop systems must be incorporated into all storage and transport configurations, with clear visual and audible alarms and pre-defined emergency response protocols (ERPs) that are regularly drilled by personnel, ensuring rapid response to any PHS&T incidents.

To mitigate these risks, the Department of the Navy should standardize PHS&T procedures for hydrogen fuel systems by developing tailored Technical Manuals (TMs) and SOPs that align with DoD 4500.9-R and NAVSUP P-805 guidelines for special handling materials. The use of ruggedized, modular transport containers with integrated shock absorption and leak detection sensors would provide added safety for hydrogen tanks and battery modules during movement. These containers should meet ATA 300 standards for military air transport and be certified for intermodal movement across maritime, air, and ground systems.

Personnel readiness can be improved by embedding HAZMAT handling certifications into formal training pipelines for all supply and logistics billets associated with hydrogen-enabled platforms. The Navy should also establish forward-deployed HAZMAT response kits and issue shipboard and airfield compatibility guidance through NAVSEA and NAVFAC channels. Additionally, NovaSpark platforms can be upgraded to include self-monitoring logistics readiness indicators and QR-coded IETMs for rapid scanning and inventory verification during embarkation. These capabilities, when combined with DLA's wide-area workflow (WAWF) and IUID tracking, would significantly improve the traceability and accountability of hydrogen-related materials across the global logistics architecture.

7. Technical Data

a. Key Considerations and Regulatory Impacts

The availability of comprehensive, accurate, and readily accessible technical data is not merely a convenience but a critical enabler for the safe and effective operation, maintenance, and sustainment of hydrogen fuel systems integrated into Department of the Navy (DON) unmanned aircraft systems. This includes technical manuals, maintenance procedures, safety information, and performance specifications for the UAS, fueling equipment, and all associated support equipment and safety systems. These technical publications must adhere to stringent military standards for content, style, and format, such as MIL-STD-38784 for general technical manual preparation or the international S1000D specification, which provides a framework for creating modular, data-driven IETMs. Crucially, these technical manuals must meticulously integrate and clearly delineate procedures based on applicable regulatory requirements from various authoritative bodies. This includes detailed instructions derived from OSHA §1910.103 (Hydrogen) concerning safe handling and storage, NFPA 2 (Hydrogen Technologies Code) for comprehensive safety guidelines throughout the hydrogen system life cycle, and relevant UFCs for facility-related procedures. This integration ensures that maintenance and operational tasks are not only technically correct but also compliant with mandatory safety standards.

A significant consideration, particularly when incorporating Commercial-Off-The-Shelf (COTS) or modified COTS hydrogen components (such as fuel cells, high-pressure tanks, valves, and sensors), is securing appropriate data rights, often referred to as Government Purpose Rights (GPR). GPR allows the government to use, modify, reproduce, release, or disclose technical data within the government and by government contractors for government purposes. Obtaining these rights for maintenance, repair, and overhaul procedures is critical to fostering long-term organic supportability by enabling military personnel or authorized depots/contractors to perform necessary upkeep without exclusive reliance on the original manufacturer. This aligns directly with the DoD's overarching Intellectual Property (IP) Strategy, which emphasizes acquiring necessary IP rights to ensure competition and reduce life cycle costs, as further underscored by requirements within standard LCSP outlines. Furthermore, all relevant personnel—operators, maintainers, safety officers, and logisticians—must have ready access to and a working understanding of the applicable regulatory codes and standards themselves (from bodies like OSHA, NFPA, DOT) for transport, UFCs, International Organization for Standardization (ISO), and Society of Automotive Engineers (SAE)). These documents, while extensive, provide the foundational safety and technical principles governing hydrogen systems.

Establishing a system for effectively distributing and regularly updating these documents to dispersed units, potentially through a centralized digital library accessible via military networks, is essential for maintaining awareness and compliance. Finally, implementing robust consumption tracking and data collection capabilities for hydrogen-fueled UAS systems is essential. This data encompasses hydrogen usage rates, system performance metrics, and component health indicators, and serves multiple critical purposes. It is vital for logistical optimization (accurately forecasting and informing supply demands), enabling predictive maintenance (analyzing operational data to anticipate component wear and schedule maintenance proactively), and is increasingly relevant for potential future environmental regulatory reporting requirements. Depending on the hydrogen generation method (e.g., using reformers or electrolysis powered by non-renewable sources), operations could potentially fall under reporting mandates related to emissions or energy usage directives from federal or DoD initiatives, aligning with environmental compliance considerations such as those under the purview of the EPA and the CAA.

Technical data is a foundational element in the sustainment and life cycle management of defense systems, especially emerging technologies like NovaSpark's hydrogen generators. Effective technical data support includes the creation, validation, configuration control, and provisioning of engineering drawings, maintenance manuals, parts lists, and software documentation. These materials must be structured according to MIL-STD-31000B (Technical Data Packages), DoDI 5010.44 (Intellectual Property Management), and the S1000D standard for IETMs, which ensures interoperability across platforms and logistics systems.

Given the complexity of hydrogen systems, technical data must encompass detailed procedures for safe handling of compressed hydrogen gas, maintenance of electrolyzer stacks, battery system management, and emergency response protocols. Each component within the NovaSpark platform, hydrogen tanks, lithium-ion batteries, KOH reservoirs, must be accompanied by MSDS, exploded diagrams, and troubleshooting flowcharts. Furthermore, adherence to cybersecurity standards for data access and distribution (e.g., RMF NIST SP 800-171) is essential to prevent compromise of system controls or technical vulnerabilities, particularly as digital twins and remote diagnostics become integral to field support (NIST, 2024).

b. Land and Sea Obstacles for 216 Platoons

For the USMC's 216 platoons, operating across diverse land and sea environments, ensuring the effectiveness of technical data encounters significant practical obstacles. A primary challenge is guaranteeing the accessibility and usability of technical data in demanding field conditions. These platoons often operate in disconnected or limited-bandwidth environments, whether inland or aboard naval vessels, where traditional online access is unreliable or impossible. Each platoon must have immediate access to the correct, up-to-date technical data, including critical safety information, emergency procedures tailored for hydrogen incidents, and necessary Safety Data Sheets (SDS) for hydrogen (which provide comprehensive information on hazards and safe handling), in a format that is easily navigable and understandable even under the stress of an emergency. One of the most significant concerns in supporting small, expeditionary units is ensuring the availability of up-to-date and accessible technical documentation in environments with limited bandwidth or digital connectivity. Units deployed to austere locations may lack real-time access to updated manuals, firmware updates, or revised safety procedures, resulting in operational risks and maintenance errors. Paper-based manuals may quickly become outdated or lost, while digital files require hardened, secure, and ruggedized devices for field access.

Maintaining strict configuration management of technical data across such a large and geographically dispersed fleet of UAS and support equipment presents a significant logistical and technical challenge. This includes ensuring that the correct versions of technical manuals, software for diagnostic tools, and firmware for system components are deployed and maintained consistently across all units. Achieving this requires disciplined processes, potentially leveraging automated tools for distribution and verification, to prevent discrepancies that could lead to incorrect procedures, diagnostic errors, or system malfunctions.

Protecting the integrity and security of sensitive technical data is also a key concern. Data related to military-specific modifications, performance characteristics, operational employment tactics, or detailed system schematics could be valuable targets for adversaries. Ensuring this information is protected from unauthorized access, modification, or exfiltration while still being readily accessible to authorized personnel in the field requires robust cybersecurity measures integrated into the data distribution and access systems. The format and language of technical data must be carefully tailored for USMC operators and maintainers, who possess varying levels of technical expertise. Complex engineering documentation, while necessary for depot-level repairs, must be translated into clear, concise, and immediately actionable procedures for field use. This requires incorporating appropriate visual aids, such as clear diagrams, detailed illustrations, and instructional videos, to minimize the potential for misinterpretation and reduce the likelihood of errors during critical operational or maintenance tasks in stressful environments.

Moreover, the absence of structured technical data repositories, such as those managed through Navy Data Environment (NDE) or Joint Computer-Aided Acquisition and Logistics Support (JCALS), may hinder knowledge transfer to new operators or units rotating into theater. Technical data that is contractor-owned or proprietary, and not delivered in a Government Purpose Rights format, also impedes organic sustainment and may lead to vendor lock-in. This is particularly problematic for small-business innovations like NovaSpark, where data rights and delivery formats must be clearly defined early in the acquisition life cycle.

Solutions and Mitigation Strategies

Addressing the technical data challenges for hydrogen-enabled UAS involves strategically leveraging established technical data tracking technologies and data management processes. The development and fielding of IETMs specifically designed for hydrogen UAS, fueling systems, and all associated support equipment represents a key pathway forward. These IETMs should aim for higher levels of interactivity, ideally Class IV or V, meaning they are fully interactive and potentially integrated with system diagnostics, allowing maintenance personnel to troubleshoot more effectively. They must be accessible on ruggedized, platoon-organic tablets or devices (such as the Marine Air-Ground Tablet (MAGTAB) or similar systems already in use) and designed for robust offline functionality, ensuring access even without network connectivity. Effective IETMs should incorporate features that enhance safety and usability. This includes embedded safety warnings linked to specific procedural steps, interactive 3D schematics allowing users to visualize components and assemblies, guided fault isolation trees to assist in diagnosing problems, video demonstrations of critical or complex procedures, and direct digital links to relevant SDS and emergency protocols. These features improve comprehension, reduce training time, and minimize errors.

A critical component of the solution is establishing a centralized digital library and a reliable field update mechanism. This library, potentially hosted on existing DoD portals like the Joint Technical Data Integration (JTDI) system or housed in a dedicated USMC Hydrogen Knowledge Center, would serve as the single authoritative repository for all approved technical data, applicable regulations, relevant industry standards, accumulated lessons learned, and safety alerts. Robust procedures for disseminating updates and revisions to field units are essential, including solutions for low-bandwidth or disconnected environments, such as utilizing delta updates (sending only the changes) or secure physical media transfer as a backup.

Ensuring hydrogen UAS and support systems have robust data logging and analytics integration is also crucial for enriching the technical data ecosystem. These systems should automatically collect detailed operational parameters (such as pressures, temperatures, hydrogen flow rates, fuel cell voltage and current), record fuel consumption, log fault codes, and document maintenance events. This data should be securely transmitted where connectivity allows or periodically downloaded and integrated into a centralized sustainment system (like the Global Combat Support System-Marine Corps (GCSS-MC) or a dedicated platform). Analyzing this data supports real-time performance monitoring, enables precise consumption analysis for improved supply chain planning, facilitates Prognostics and Health Management (PHM) for critical components like fuel cells and tanks by identifying trends indicating potential failure, and aids in the identification of safety trends across the fleet. Promoting the use of standardized data formats for technical publications (such as S1000D for IETMs) and operational data logging (using common data dictionaries and schemas) is a vital step. This standardization improves interoperability between different systems and software, reduces life cycle data management costs, and facilitates easier integration with existing enterprise logistics and maintenance systems.

Finally, ensuring all hydrogen equipment is clearly and durably labeled is a fundamental safety and maintenance requirement. Labels must comply with relevant standards such as ANSI Z535.4 and ISO 3864 for safety signs and labels and be consistent with OSHA 29 CFR 1910.145 specifications for accident prevention signs and tags, and NFPA 704 marking requirements for storage areas (NFPA, 2025). These labels must clearly display appropriate warnings, critical operating instructions, pressure ratings, inspection and recertification dates for tanks, and emergency contact information, providing essential information to personnel in the field.

To ensure effective technical data support, the Navy should require delivery of a complete and validated Technical Data Package (TDP) from NovaSpark at Milestone C, structured according to MIL-STD-31000B and integrated into existing Product Life cycle Management (PLM) systems such as Windchill or Teamcenter. The use of S1000D-compliant IETMs with embedded interactive features, such as clickable schematics, QR codes for reordering parts, and 3D maintenance animations, will enhance the usability and training value of technical data in field conditions.

Additionally, equipping forward units with encrypted, ruggedized tablets that contain offline versions of critical documentation will ensure uninterrupted access to procedures and safety references. These devices should synchronize with central databases (example being the USMC LOGWAY system), enabling periodic updates and configuration management. Contractually, program managers must assert Government Purpose Rights or negotiate Special License Rights to guarantee long-term government access to NovaSpark's data. Where feasible, the use of open architecture standards and XML-based data structures will further facilitate data reuse, interoperability, and integration into future hydrogen-based naval systems.

8. Manpower and Personnel

a. Key Considerations and Regulatory Impacts

The introduction of hydrogen fuel systems into DON UAS' necessitates a careful evaluation of manpower and personnel requirements for both ship and shore operations, heavily influenced by safety and technical skill regulations. OSHA regulations, particularly 29 CFR 1910.103 (Hydrogen) and 1910.1200 (Hazard Communication), mandate specific training, qualifications, and safe work practices for personnel handling hazardous materials like hydrogen. National Fire Protection Association (NFPA) 2 and other industry standards, such as those from the American Society of Mechanical Engineers (ASME) for pressure vessel inspection personnel qualifications, recommend competency levels and often imply certification requirements for personnel involved in the design, installation, operation, inspection, and maintenance of hydrogen systems. Furthermore, specific DoD and USMC regulations governing fuel handling (e.g., MCO P11240.106B for Fuels Management), operation of complex technical equipment, and performance of specialized maintenance tasks require adaptation, or new directives must be created to address the unique aspects of hydrogen. The LCSP framework emphasizes identifying the organization responsible for product support, including government program office staffing and IPTs, which inherently include determining the right personnel structure to support hydrogen-enabled systems.

The Manpower and Personnel element focuses on ensuring that the right quantity and quality of military and civilian personnel are available, trained, and equipped to operate, maintain, and support a system. For a novel capability like NovaSpark's hydrogen generation platforms, this requires a reexamination of current billets and workforce structures under the Navy's Total Force strategy. Regulatory guidance such as OPNAVINST 1000.16, MCO 5311.1E, and DoDI 5000.66 should inform the planning and development of hydrogen-focused personnel requirements.

NovaSpark systems introduce new operational roles that intersect electrical engineering, energy systems, safety compliance, and environmental hazard management. These roles may not be covered by traditional Navy NECs or Marine MOS codes, thereby necessitating the creation or modification of personnel designators. Additionally, workforce planning must incorporate personnel health and safety considerations per OSHA 29 CFR 1910 Subpart H and NAVOSH Program elements, as the handling of hydrogen, lithium batteries, and potassium hydroxide involves unique occupational risks.

b. Land and Sea Obstacles for 216 Platoons

A critical concern is the skill availability and already 'spread-thin' manpower demands within the USMC. Fielding hydrogen systems to 216 platoons will demand a significant training investment for Marines possessing specialized skills in hydrogen system operation (including fueling protocols for high-pressure gas for both land and sea-based systems), maintenance (troubleshooting fuel cells, managing high-pressure gas systems, potentially operating electrolyzers), and safety oversight. Existing Military Occupational Specialties (MOSs) for UAS operators and maintainers (e.g., 7314 – 7316 for Group 1–3 UAS) or ground support equipment technicians (e.g., 1161 Utilities, 1341 Engineer Equipment Mechanic) may not adequately cover these unique and safety-critical hydrogen-specific requirements, potentially leading to significant skill gaps at the platoon level. There is likely insufficient demand and justification to establish dedicated career progression paths and advancement opportunities specifically for hydrogen systems specialists within the USMC structure, although current UAS training schoolhouses must account for hydrogen training. This requires a review of the Tables of Organization (T/O) to adequately support hydrogen UAS operations without over-burdening existing structures or creating an unsustainable personnel footprint – a complex force structure decision impacting both ship and shore detachments.

The workload and cross-training implications for existing platoon personnel must be carefully assessed; determining whether to increase schoolhouse time, create On-The-Job (OTJ) training solutions dedicated to building up hydrogen specialists, or cross-train existing MOSs involves trade-offs in terms of depth of expertise, training time investment, billet efficiency, and operational flexibility. Finally, there is a clear potential need for dedicated Hydrogen Safety Officers or Non-Commissioned Officers (NCOs) at appropriate command echelons (company, battalion) to ensure rigorous compliance with the myriads of safety regulations and to effectively manage the unique risks associated with widespread hydrogen use in tactical environments, including the confined and dynamic conditions aboard naval vessels.

Small, expeditionary units operate in dispersed and resource-constrained environments, which complicates the assignment of specialized technical personnel. Currently, there is no dedicated hydrogen systems technician classification within the Navy or Marine Corps enlisted force structure. This gap could result in over-reliance on contractor support or lead to under-qualified personnel attempting to manage high-risk systems. The lack of tailored NECs and MOS for hydrogen-specific maintenance, repair, and safety monitoring also complicates readiness reporting and workforce tracking within systems like Total Force Manpower Management System (TFMMS).

Another concern is the potential impact on unit manning levels. Introducing innovative technologies without adjusting manpower documents or revising workload estimates may inadvertently overburden existing billets. For example, if a hydrogen generator requires daily electrolyte checks and monthly membrane replacements, but no dedicated personnel are assigned for these tasks, it can create cascading effects across unit readiness. Additionally, without built-in incentives or clear advancement pathways, the Navy and Marine Corps may struggle to recruit or retain skilled personnel to fill these emerging technical roles.

c. Possible Solutions and Mitigation Strategies (Opportunities)

A formal analysis for New MOS and Additional Skill Identifier (ASI) Development, following established Marine Corps force structure review processes, could be conducted to objectively determine if the complexity, safety criticality, and unique skill sets required for hydrogen systems warrant the creation of a new MOS. However, the demands of manpower will likely lead to the conclusion that developing an ASI appended to existing relevant MOSs (e.g., a "Hydrogen Systems Technician" ASI for select 73XX UAS Maintainers, 1161 Utilities Marines, or 1341 Engineer Equipment Mechanics) would be a more efficient and realistic approach for integrating hydrogen expertise into the force structure for both ship and shore billets. A key pathway involves curriculum integration, incorporating hydrogen-specific training modules into existing relevant MOS-producing schools. For example, Group 2 UAS operator and maintainer courses would need to include comprehensive modules on hydrogen fuel cell operation, flight line and shipboard flight deck safety procedures specific to hydrogen, and basic troubleshooting. Aviation support equipment technician courses could cover the maintenance of hydrogen fueling equipment tailored for both land and maritime use, while Utilities Marine or Engineer Equipment Mechanic courses could address the operation and maintenance of hydrogen generation and storage systems in diverse environments. A detailed Manpower Requirements Analysis (MRA), using established DoD and USMC methodologies, is essential to accurately determine the optimal number, skill level (e.g., E-3 through E-7), and appropriate placement of hydrogen-qualified personnel needed to effectively and safely support 216 platoons across diverse land and sea deployment scenarios.

The MRA must inform any T/O changes and training pipeline throughput requirements. To attract and retain qualified individuals, targeted recruitment initiatives highlighting the innovative technology aspect of hydrogen systems, and potentially offering skill-based incentives (e.g., Special Duty Assignment Pay, re-enlistment bonuses for certified hydrogen technicians, or advanced schooling opportunities), could be explored. Contractor logistics support (CLS) augmentation may serve as a viable initial or interim support solution, particularly for initial fielding support, complex depot-level repairs on fuel cells, or surge support while organic USMC capabilities are fully developed and matured. However, any reliance on CLS must be carefully balanced against the USMC's core need for organic expeditionary capability and the security implications of deploying contractors in forward or contested environments, including those at sea. Lastly, specific Safety Officer and NCO training and certification awareness in Naval Safety School's curricula should be developed and implemented, potentially as an additional qualification for existing unit safety personnel.

These individuals would be responsible for overseeing local hydrogen safety programs, conducting unit-level sustainment training on safety procedures for both land and shipboard operations, and leading initial emergency response efforts, ensuring compliance with OSHA, NFPA, and USMC-specific safety directives.

To bridge these gaps, both the Navy and Marine Corps should work with Bureau of Naval Personnel (BUPERS), Marine Corps Manpower & Reserve Affairs (M&RA), and Training and Education Command (TECOM) to establish new NEC and MOS codes that reflect hydrogen system competencies. These could be modeled after existing billets in aviation ground support, ordnance handling, or energy systems management, with specialty tracks developed in partnership with NovaSpark and other clean energy OEMs. Manpower requirements should be integrated into Table of Organization and Equipment (TO&E) updates and reflected in Capability Development Documents (CDDs) to support resourcing.

The use of embedded training pipelines, combining classroom instruction, mobile training teams, and augmented reality simulation, can shorten the qualification timeline for these roles. Personnel assignment policies should also consider collocating hydrogen-qualified personnel with expeditionary units most likely to operate NovaSpark systems, thereby preserving operational continuity and improving sustainment capacity. Long term, the establishment of a "Hydrogen Energy Systems" career field or concentration could align with broader DON energy initiatives and support the professionalization of this emerging technical specialty.

9. Training and Training Support

a. Key Considerations and Regulatory Impacts

Establishing a robust training and training support infrastructure is paramount for the safe and effective integration of hydrogen-fueled UAS within the DON. Hydrogen, being a highly energetic and potentially hazardous substance, necessitates that all personnel who interact with it, directly or indirectly, receive specific and thorough training. Several key regulations mandate or strongly imply the need for comprehensive training. OSHA 29 CFR 1910.1200, the Hazard Communication Standard, requires employers to train employees on the hazards of chemicals they may encounter, including hydrogen, and how to access and understand information like Safety Data Sheets (SDS), which detail a chemical's properties, hazards, and safety precautions. OSHA 29 CFR 1910.103, specifically addressing hydrogen, further underscores the need for documented training on safe operating procedures, equipment specifics, and emergency responses for personnel involved with hydrogen systems. The National Fire Protection Association (NFPA) 2 (Hydrogen Technologies Code) provides extensive, detailed guidance on personnel qualifications and competency requirements across various roles—from system designers to operators and emergency responders (NFPA, 2025).

Adherence to these NFPA recommendations should heavily inform the development of USMC training programs that are based out of the existing TALSA schoolhouse (and then expanded to other deployable units) to ensure a high standard of proficiency. Existing DoD and USMC training directives concerning fuel handling (such as MCO P11240.106B for Fuels Management), hazardous materials (HAZMAT) management, and operational safety must be carefully reviewed and adapted. New, hydrogen-specific training standards and curricula will likely need to be created and formally published to ensure a standardized and consistent level of knowledge and proficiency across the entire force, applicable whether operating on land or within the confines of a maritime vessel. This standardized approach is vital for ensuring predictable performance and safety outcomes regardless of the operating environment. The LCSP framework explicitly requires programs to detail their approach to training and training support as a core product support element. This ensures that the necessary skills required to operate and sustain the system are developed, maintained, and available throughout the system's entire life cycle, thereby meeting stated operational requirements.

Effective training is essential for safe and sustainable operation of hydrogen fuel systems across the Department of the Navy. NovaSpark's mobile atmospheric hydrogen generators introduce specialized safety, operational, and maintenance requirements that go beyond the scope of traditional fuel systems training. In accordance with SECNAVINST 1500.41, DoDI 1322.26, and NAVMC 1553.1, training programs must be tailored to the unique characteristics of hydrogen as a fuel source—particularly its flammability, low ignition energy, and potential for embrittlement of containment materials.

Training must encompass both operator and maintainer perspectives and include a blend of formal instruction, on-the-job training (OJT), and simulated environments. Personnel must be taught how to handle and store compressed hydrogen, manage lithium-ion battery charging cycles, detect leaks, and respond to emergencies such as rapid depressurization or electrolyte spills. Moreover, training programs must be validated by NAVAIR and Naval Education and Training Command (NETC) to ensure integration into the broader training enterprise and alignment with aviation and ground support certification standards.

b. Land and Sea Obstacles for 216 Platoons

Delivering effective training and training support for hydrogen-fueled UAS to the USMC's 216 platoons presents logistical and instructional obstacles. A primary challenge is the scalability and standardization of training across a large, geographically dispersed USMC force across the globe. Developing and consistently delivering high-quality, effective training on hydrogen safety, system operation, and maintenance to potentially thousands of Marines (216 systems x 2 operators per system minimum = 432 students annually) across numerous separate platoons, often operating in disconnected locations globally, will be a challenge. This requires not only significant effort in curriculum development but also necessitates a sufficient base of qualified instructors and readily accessible training resources distributed across various regions and commands. Providing access to realistic training environments and the necessary support equipment is another major challenge. Effective learning goes beyond classroom instruction and requires immersive, hands-on practical exercises. This means providing training with actual or high-fidelity simulated hydrogen fueling equipment, the UAS platforms themselves, and the correct personal protective equipment (PPE) required for handling hydrogen.

Creating safe training environments that accurately replicate expeditionary land-based conditions (including varied terrain, climatic extremes, and austere settings) alongside the unique constraints and higher risks of shipboard operations (such as confined spaces, vessel motion, and limited ventilation options where hydrogen can accumulate) will be particularly difficult, resource-intensive, and potentially costly to establish and maintain. Establishing and managing a robust and auditable system for initial certification and subsequent periodic re-certification and proficiency training for all personnel who handle or maintain hydrogen systems is critical but challenging. This system must meticulously track individual qualifications, training completion dates, and required recurrences to ensure that skills remain current and high-level safety standards are consistently met across the entire force, spanning active duty and reserve components.

Specialized emergency response training is essential and poses unique instructional challenges. Marines must be prepared to effectively and safely respond to hydrogen-specific emergencies, such as leaks, which behave differently than other fuels due to hydrogen's buoyancy and wide flammability range. They also need training on hydrogen fires, which are nearly invisible in daylight, requiring specialized detection methods and firefighting techniques. Training must also cover responses to high-pressure incidents, such as cylinder ruptures, and must specifically address these scenarios within diverse operational environments, including the particularly challenging confined spaces aboard ships where hydrogen can rapidly accumulate to explosive concentrations if a leak occurs.

Finally, the overall cost and resources required for developing training support materials—including curriculum design by subject matter experts, procurement or development of advanced training aids and simulators, the establishment of dedicated training facilities or the deployment of Mobile Training Teams (MTTs), and the initial qualification, ongoing certification, and sustainment of a sufficient cadre of competent instructors—represent a significant upfront and recurring investment for both land and sea-based training scenarios.

The deployment of hydrogen generation systems to austere environments with expeditionary personnel presents unique training challenges, primarily due to their dispersed nature and the limited availability of hydrogen-qualified instructors. These platoons may be deployed across maritime vessels, expeditionary airfields, or austere forward operating bases, where access to traditional classroom instruction or simulation centers is minimal. This can lead to inconsistent training quality and potential safety risks, especially for new join personnel or rotating units unfamiliar with hydrogen system hazards.

Additionally, there is no existing training infrastructure or standardized courseware within the Navy or Marine Corps focused exclusively on hydrogen technologies. As a result, unit-level training may rely heavily on OEM-provided materials, which vary in quality and are often geared toward commercial applications. This lack of institutionalized curricula hinders the development of long-term expertise and prevents integration of hydrogen systems into capstone exercises or readiness assessments. Furthermore, a lack of real-world training scenarios involving hydrogen refueling, emergency leak response, and autonomous system integration limits the preparedness of operators in dynamic environments.

c. Solutions and Mitigation Strategies

To effectively address the training and support challenges for hydrogen-enabled UAS, a strategic approach focusing on tailored instruction and leveraging appropriate technologies is essential. A tiered and role-based training curriculum offers a viable pathway. This approach structures training content to ensure personnel receive instruction commensurate with their specific duties and responsibilities in both ship and shore environments, avoiding unnecessary training burden while ensuring critical knowledge is gained:

- **Tier 1 (General Awareness):** A concise, mandatory module covering fundamental hydrogen properties, associated hazards (like flammability, the risk of asphyxiation in confined spaces, high pressure, and potential cryogenic hazards if liquid hydrogen is considered), and general safety precautions. This is designed for all personnel who may operate in proximity to hydrogen systems or be present during fueling.
- **Tier 2 (Operator):** Detailed, hands-on training for designated UAS operators and fueling crews focusing on the specific Group 2 UAS hydrogen systems they will use. This covers normal operating procedures, routine system checks, recognizing abnormal conditions, and immediate action emergency procedures. Training involves practical exercises using actual fueling equipment and UAS mock-ups or ground-operable trainers, integrating hydrogen employment into existing UAS operator qualification pipelines.
- **Tier 3 (Maintainer):** Provides in-depth technical training for specialized maintenance personnel. This covers advanced troubleshooting, diagnostics, repair, and replacement of hydrogen system components, including the critical safety procedures for safe purging (removing hydrogen) and inerting (filling with inert gas) before handling components.
- **Tier 4 (Safety and Emergency Response – Instructor level):** Offers advanced, scenario-based training for unit safety personnel and designated first responders. This focuses on hydrogen incident command, hazard assessment, specialized firefighting techniques, and coordinating with higher-level emergency services, specifically incorporating scenarios relevant to diverse environments, including the complexities of shipboard incidents.

A blended learning approach, combining various instructional methods, can significantly enhance engagement and accessibility. This involves using interactive computer-based training (CBT) or web-based training (WBT) for foundational knowledge, regulatory requirements, and procedural steps, combined with essential hands-on practical exercises using actual or high-fidelity simulated equipment for skill development. Advanced training aids and simulators are key here, allowing for realistic practice of operating and maintenance procedures, including emergency responses, without the inherent risks and logistical complexities of using live hydrogen for all training events.

Leveraging existing infrastructure and establishing dedicated support mechanisms can improve training delivery. Consideration should be given to establishing specialized training centers for hydrogen systems, potentially co-located with existing USMC aviation, engineering, or logistics schools to utilize existing facilities and instructor expertise. This approach can facilitate training distribution by using established training locations across different Marine Expeditionary Forces (MEFs). Integrating hydrogen training into the existing Navy TALSA model is a key opportunity. TALSAs currently provide initial UAS training and technology updates; their personnel can develop and deliver hydrogen-specific modules within the established UAS training infrastructure at various Navy sites, ensuring standardized training delivery across the Fleet for both active duty and Reserve Marines. Additionally, deploying Mobile Training Teams (MTTs), equipped with portable training aids, part-task trainers (simulators for specific tasks), and simulators, can provide on-site initial certification and sustainment training directly to units at their home stations or during pre-deployment phases. This is particularly valuable for reaching dispersed reserve units and those operating from various deployed sites.

However, practical shipboard training will require different considerations, potentially involving dedicated ship-specific training teams or facilities. Integrating hydrogen UAS operation and sustainment scenarios into regular collective training events is vital. From platoon-level drills to larger Marine Expeditionary Unit (MEU) and Marine Air-Ground Task Force exercises, incorporating hydrogen systems allows units to practice command and control, logistical support flows (including fuel resupply), and coordinated emergency response in a realistic, combined arms context. Finally, developing and implementing a robust “Train the Trainer” program is crucial for building internal capability and ensuring long-term training sustainability. This program certifies qualified USMC personnel to become instructors, reducing reliance on external contractors for delivering basic and intermediate training. This organic capacity allows for faster adaptation of training content based on fleet feedback, evolving Tactics, Techniques, and Procedures (TTPs), and changes in equipment or regulations. To ensure consistency and quality across all training deliveries, standardized training packages must be developed and maintained under strict configuration control. These packages should include detailed curricula, student guides, instructor manuals, clear performance evaluation criteria, and certified training aids.

To address these shortfalls, the DON should develop a dedicated training curriculum for hydrogen fuel systems in collaboration with NovaSpark and aligned with the Navy's Ready Relevant Learning (RRL) initiative. This curriculum should include tiered learning modules, basic, intermediate, and advanced, and incorporate simulations of hazardous scenarios using virtual and augmented reality (VR/AR) platforms. For example, VR-based training can allow personnel to practice emergency shutoff procedures, membrane replacements, or leak detection drills without exposing them to real-world risks.

Mobile Training Teams (MTTs) can be deployed during the initial fielding phase to establish unit proficiency and to collect feedback for iterative improvements to training content. Additionally, the development of IETMs and digital job aids, hosted on ruggedized tablets or accessed via secure online portals, can provide on-demand reference material for field operators. Incorporating hydrogen system operations into Aviation Maintenance Training Continuum System (AMTCS), Expeditionary Warfare Training Group courses, and the Marine Corps Integrated Training and Education Plan (ITEP) will ensure that hydrogen competencies become a core element of readiness assessments and Fleet Marine Force capabilities.

10. Information Technology Systems Continuous Support

a. Key Considerations and Regulatory Impacts

The successful integration of hydrogen fuel systems into Group 2 unmanned aircraft systems for expeditionary and shipboard operations introduces specific requirements for Information Technology (IT) systems continuous support. This support must rigorously address software integrity, cybersecurity, and compliance with relevant regulations and standards. The software that controls critical functions—such as UAS flight parameters, the intricate management of hydrogen fuel (including monitoring crucial parameters like tank pressure and temperature, hydrogen flow rates, fuel cell stack voltage and current, and system state-of-health), and embedded diagnostic systems—must demonstrate extremely high levels of reliability and fault tolerance. For aviation systems, ensuring this reliability often requires adherence to rigorous software safety standards like DO-178C, "Software Considerations in Airborne Systems and Equipment Certification." This widely recognized standard provides detailed guidelines for the processes involved in developing and verifying software used in airborne systems to ensure it performs its intended function safely and reliably. Tailored military equivalents or adaptations of such standards are likely necessary for critical IT functions within these hydrogen-enabled systems.

A critical consideration is the cybersecurity posture of all networked hydrogen system components. This includes the UAS data links, the ground control stations (GCS) used to operate aircraft, control systems for fueling equipment, and any backend platforms used for data analysis and sustainment monitoring. These systems require robust protection from unauthorized access (preventing breaches), manipulation (such as altering sensor data to hide a leak or triggering valves without authorization), or denial-of-service attacks that could disrupt operations. Such cyber incidents could potentially lead to catastrophic safety failures or compromise the mission. Ensuring this protection aligns directly with DoD Instruction 8500.01 (Cybersecurity) and necessitates the implementation of the Risk Management Framework (RMF), a structured process for integrating cybersecurity and risk management into the system development life cycle.

Electrical installations associated with IT components in hydrogen systems, particularly computer control panels, sensors, and interface devices located in potentially hazardous areas where hydrogen gas may be present, must comply with specific safety standards. National Fire Protection Association (NFPA) 70 (National Electrical Code) provides essential requirements for electrical wiring and equipment. Specifically, articles within NFPA 70 addressing "hazardous locations" (areas where flammable gases, vapors, or dust may be present) provide guidelines for designing and installing electrical systems to prevent ignition from electrical sources like sparks or overheating, a critical safety measure in hydrogen environments (NFPA, 2025). Finally, standardized data logging protocols and formats are necessary for consistently capturing critical operational parameters (like temperatures, pressures, and power output), fuel consumption rates, records of maintenance events, and activations of safety systems (like leak detectors or emergency shutdowns). This collected data is vital for multiple purposes: informing logistics planning for hydrogen resupply, supporting Prognostics and Health Management (PHM) to predict component failures, and potentially for demonstrating regulatory compliance or providing essential evidence during incident investigations.

Continuous IT support is vital for the monitoring, diagnostics, predictive maintenance, and cyber protection of NovaSpark's hydrogen generation systems. These systems rely on embedded sensors, telemetry interfaces, and digital control units to optimize performance and ensure safety. As such, IT system design and sustainment must align with DoD cybersecurity and system assurance requirements including the RMF under DoDI 8510.01, and the Cybersecurity Maturity Model Certification (CMMC) protocols for defense contractors. System software and firmware must be compatible with Navy and Marine Corps enterprise networks and meet National Institute of Standards and Technology (NIST) SP 800–53 security controls for federal information systems.

NovaSpark units also support data integration with centralized maintenance and logistics platforms, such as the Naval Operational Business Logistics Enterprise (NOBLE), Condition-Based Maintenance Plus (CBM+), and the Defense Logistics Management Standards (DLMS). These systems require continuous IT support to ensure that critical system health indicators, failure mode analysis, and parts consumption data are transmitted accurately and securely for fleet-wide readiness reporting. Failure to maintain consistent IT connectivity could impair decision-making related to life cycle sustainment and safety incident response.

b. Land and Sea Obstacles for 216 Platoons

For the USMC's 216 platoons operating in diverse and often challenging land and sea environments, ensuring continuous IT system support for integrated hydrogen fuel systems presents several key obstacles. A primary concern lies in guaranteeing the reliability and security of the software and firmware that manages the complex hydrogen fuel cell systems, monitors high-pressure storage tanks, controls fueling operations, and interfaces with UAS flight control systems. These IT systems must function flawlessly and remain resilient against both accidental issues (such as software defects or glitches) and deliberate cyber threats in dynamic and often contested tactical environments where adversaries may attempt to exploit vulnerabilities. The lack of consistent data exchange standards between different hydrogen system components—which may include UAS platforms, fueling units, on-site hydrogen generation systems, and diagnostic tools potentially sourced from various manufacturers—creates a significant obstacle. Without standardized protocols for how these components communicate and share data, integrated operations become difficult, efficient data analysis across the entire system is hindered, and streamlined support for dispersed units becomes challenging, potentially resulting in a fleet of incompatible systems requiring unique and costly support solutions for each variation. Managing software updates and security patches for IT systems deployed across a large and geographically dispersed fleet poses a substantial logistical and technical challenge. Platoons often operate in environments with limited or intermittent network connectivity, such as remote expeditionary locations or aboard naval vessels far from shore infrastructure. Delivering timely and secure updates under these conditions requires innovative solutions that go beyond typical network-dependent methods.

The effective management and analysis of the potentially large volumes of data generated by hydrogen systems is crucial for understanding system health, optimizing performance, and planning logistics. Continuous sensor readings, performance logs, and fault codes accumulate rapidly. This necessitates capabilities for secure data transfer from field units (where connectivity is available), robust on-board or at-site data storage to capture information during disconnected operations, and centralized analysis platforms capable of processing this data to support fleet-wide PHM (predicting when components might need maintenance), optimizing logistical planning based on actual consumption, and identifying safety or performance trends across systems operating in diverse conditions. Finally, ensuring sufficient and reliable network connectivity for fundamental functions like UAS command and control (C2) data links and the downlink of sensor data becomes even more critical if the monitoring and control of hydrogen systems adds to the existing data load. This is particularly challenging in operational environments where communication interference or electronic jamming is likely, potentially disrupting the flow of vital operational and safety-related data.

IT systems supporting expeditionary units are typically challenged by limitations in bandwidth, cybersecurity infrastructure, and digital device sustainment in harsh and austere environments. NovaSpark's hydrogen generation units may rely on satellite or intermittent terrestrial communication networks, making data transmission to higher headquarters inconsistent. This can disrupt real-time diagnostics, delay predictive maintenance alerts, and inhibit timely reporting of potentially hazardous system conditions.

Additionally, the lack of IT-trained personnel at the platoon level can hinder proper setup and management of the control software and system interfaces. If configuration files, software patches, or encryption keys are not managed correctly, it could result in system malfunctions or vulnerabilities. There is also the risk of cyber exploitation, particularly if NovaSpark systems are interfaced with unclassified tactical networks or accessed through non-secure devices in field environments. Without zero-trust architecture principles or endpoint protection software, even a localized breach could compromise system functionality or expose operational data.

c. Solutions and Mitigation Strategies

Addressing the IT system continuous support challenges requires a strategic approach focused on integrating security, promoting standardization, and leveraging data effectively. A foundational solution is adopting a "security-by-design" approach for all IT resources supporting hydrogen-enabled UAS. This means cybersecurity measures are not added as an afterthought but are integrated from the initial design phase and maintained throughout the entire system life cycle. Key measures include robust user authentication (ensuring only authorized personnel can access systems), end-to-end data encryption for both stored data and data transmitted between components (protecting sensitive information), implementing intrusion detection and prevention systems tailored for the unique characteristics of embedded systems, incorporating secure boot processes to ensure that only authorized and untampered software is loaded, and conducting regular security assessments and testing to identify and mitigate vulnerabilities.

All these efforts must align with current DoD cybersecurity directives and the RMF processes. The USMC should actively advocate for and prioritize the use of OSA and standardized data protocols for hydrogen system software and interfaces. An OSA, which uses well-defined, published interfaces between components, along with standardized data formats (potentially leveraging existing military standards for UAS C2 or adopting emerging industry standards for hydrogen system data), significantly enhances compatibility and simplifies the integration of components from different vendors. This not only facilitates the incorporation of technological upgrades but also reduces life cycle costs by promoting competition and making sustainment less dependent on a single vendor.

Developing secure and efficient mechanisms for remote software updates is essential for supporting a dispersed fleet. This includes creating solutions specifically designed for deploying updates in environments with limited or intermittent connectivity. Potential methods include using secure data transfer devices, employing "store-and-forward" techniques via available tactical networks where data is stored and forwarded when connectivity is available, or utilizing secure physical media transfer as a backup method for critical updates. All update processes must include strong data integrity checks to ensure that the software received is complete and untampered.

Establishing a centralized data analytics platform is a powerful solution for managing and leveraging the data generated by the fleet. This platform, which could be integrated with existing USMC maintenance and logistics information systems or leverage secure cloud-based solutions, would be responsible for collecting, processing, and analyzing hydrogen system data from all deployed units. Leveraging advanced analytics, such as Artificial Intelligence (AI) and Machine Learning (ML) algorithms, this platform can provide valuable insights for advanced system health monitoring, automatically detecting anomalies that may indicate impending issues, optimizing fuel consumption based on operational patterns, and predicting maintenance needs for critical components, thereby supporting operations on land and at sea. Ensuring that all field-deployed control systems, diagnostic tools, and operator interface devices utilize ruggedized and secure hardware is fundamental. This hardware must be designed to withstand the harsh physical environments encountered during expeditionary and shipboard deployments (e.g., vibration, temperature extremes, moisture, dust) and be physically secured to prevent unauthorized access or tampering that could compromise system integrity or safety.

Finally, maintaining close coordination regarding radio frequencies is essential to ensure adequate and protected communications are allocated. Sufficient bandwidth and secure channels are needed not only for UAS C2 and the downlink of sensor data but also for any data links associated with hydrogen system monitoring and control. This is particularly important in operational areas where electronic interference or jamming is likely, requiring careful frequency planning and potentially redundant communication pathways to ensure critical IT functions remain supported during operations on both land and at sea.

To strengthen IT systems support, NovaSpark platforms should be integrated with secure edge computing solutions that enable localized processing, analytics, and storage, reducing dependency on continuous connectivity. Units can be equipped with hardened, preconfigured network modules, capable of operating in disconnected, intermittent, and limited (DIL) bandwidth environments, to buffer and forward operational data once secure links become available. These modules should support automated system health reporting, encrypted data transmission, and seamless integration with enterprise logistics and maintenance systems.

Further, each NovaSpark unit should be equipped with a cybersecurity baseline aligned with DoD zero-trust architecture initiatives, including multi-factor authentication, behavioral monitoring, and endpoint detection and response (EDR). Navy Cyber Defense Operations Command (NCDOC) should validate all firmware and interface protocols before fielding, and periodic cyber assessments should be embedded into unit sustainment evaluations.

Training IT support personnel on hydrogen system-specific digital interfaces, as well as issuing standard operating procedures for software updates, secure file transfer, and incident response, will enhance operational resilience. In the long term, NovaSpark systems can be tied into the Naval Digital Platform ecosystem, leveraging AI, digital twins, and machine learning, to provide comprehensive IT-enabled life cycle visibility, enhancing safety, logistics, and mission assurance in forward-deployed environments.

11. Support Equipment

a. Key Considerations and Regulatory Impacts

The Support Equipment (SE) strategy for hydrogen-enabled Group 2 UAS must ensure safe, effective, and sustainable operations and maintenance across all echelons and operational environments. This encompasses all equipment required to launch, recover, fuel, troubleshoot, service, and transport the UAS and its hydrogen subsystems. Key considerations include the development of a comprehensive Support Equipment Management Plan detailing acquisition, fielding, sustainment, and disposal. SE selection and design must prioritize interoperability and standardization to the maximum extent possible, not only among the 216 platoons but also with potential joint or coalition partners. Regulatory impacts are significant; SE used for handling or maintaining hydrogen systems must comply with OSHA standards (e.g., 29 CFR 1910 Subpart S – Electrical, for powered SE; 29 CFR 1910.242 for hand and portable powered tools and equipment) for worker safety. Calibration equipment must adhere to standards traceable to NIST. SE used in potentially hazardous locations where hydrogen could be present must meet NFPA 70 (National Electrical Code) for electrical classification (e.g., Class I, Division 1 or 2). The overall SE footprint, including SWaP, must be minimized to align with USMC expeditionary doctrine, and all SE must be integrated into the overall system safety program (MIL-STD-882E).

SE encompasses all tools, test sets, calibration devices, and auxiliary gear necessary to operate, maintain, and sustain a system throughout its life cycle. In the context of NovaSpark’s hydrogen generation systems, this includes fueling connectors, electrolyte refill kits, lithium battery diagnostic tools, portable gas leak detectors, and portable fire suppression systems specifically rated for hydrogen environments. SE planning must be aligned with MIL-STD-1364 for logistics support analysis, and acquisition programs must ensure SE is provisioned in accordance with the Naval Supply Systems Command (NAVSUP) policies and the Support Equipment Resources Management Information System (SERMIS).

Moreover, since NovaSpark’s systems will interface with both legacy and emerging platforms, compatibility across operational units must be addressed early. Support equipment should be designed to meet Navy and Marine Corps Ground Support Equipment (GSE) standards and must account for expeditionary requirements; this means tools and devices must be modular, lightweight, and deployable. All SE must also conform to applicable safety regulations, such as NFPA hydrogen hazard mitigation codes, and be accompanied by proper calibration protocols to maintain compliance with NAVAIR's Metrology and Calibration (METCAL) Program guidance.

b. Land and Sea Obstacles for 216 Platoons

A primary obstacle is the potential proliferation of unique and specialized SE for hydrogen systems, including but not limited to: mobile hydrogen fuelers and dispensers (potentially integrated "hydrogen in a box" fueling skids), high-purity hydrogen transfer lines and connectors, specialized leak detection equipment, purging and inerting kits, diagnostic tools specific to fuel cell stacks and Balance of Plant (BoP) components (which may be proprietary to system providers like NovaSpark or others), high-pressure cylinder handling equipment, and potentially specialized fire suppression equipment. One of the most significant obstacles for expeditionary units is the fieldability and availability of appropriate SE. In many expeditionary and forward-operating environments, space and transport weight are at a premium, making it difficult to accommodate large or delicate diagnostic and support tools. Moreover, the availability of replacement parts and consumables for hydrogen-specific equipment, such as compressed gas fitting seals, specialized gauges, or digital analyzers, can be inconsistent, especially in conflict zones or maritime regions without established supply hubs.

The logistical burden of transporting, calibrating, maintaining, and powering this diverse range of SE to support 216 geographically dispersed platoons, particularly in austere land environments (dust, extreme temperatures, rough terrain) and corrosive and dynamic sea-based conditions (saltwater, shock, vibration), is substantial. The durability and reliability of sensitive diagnostic or electronic SE in these harsh environments is a significant concern. Furthermore, the training requirement for Marines to safely operate, maintain, and calibrate this new suite of SE will be considerable. Limited space for SE storage, operation, and maintenance, especially aboard naval vessels or within constrained expeditionary advanced base (EAB) footprints, poses a significant challenge. The cost of acquiring, fielding, and sustaining this specialized hydrogen SE across the entire force also represents a major investment.

Another key concern is the SE training gap. Personnel must be familiar not only with the operation of GSE, such as NovaSpark's hydrogen systems, but also with the unique calibration requirements of all their supporting equipment. For example, improper use of a hydrogen gas detector or battery analyzer could result in false safety assessments, leading to potential mission compromise. Inconsistent SE provisioning across units and rotations may also create a disparity in capability, especially when moving between CONUS and OCONUS environments or between shipboard and land-based operations.

c. Solutions and Mitigation Strategies

A key strategy is to prioritize the development and acquisition of common, multi-use SE wherever feasible, minimizing the number of unique items. SE should be designed with modularity, ruggedness (meeting MIL-STD-810 environmental standards), and lightweight characteristics, specifically for expeditionary use. This includes exploring compact, mobile fueling solutions that could be considered a form of "hydrogen in a box" for point-of-need refueling. Investing in advanced Built-In Test (BIT) and Built-In Diagnostics (BID) capabilities within the UAS and its hydrogen subsystems can significantly reduce the reliance on complex external diagnostic SE at the platoon level. Consideration should be given to establishing consolidated SE pools or specialized Mobile Maintenance Teams (MMTs) at battalion or regimental echelons to manage and deploy high-value or less frequently used SE.

Where appropriate, leveraging Commercial-Off-The-Shelf (COTS) SE, including potentially innovative solutions from companies like NovaSpark or other emergent technology providers offering specialized diagnostic tools or compact support systems, with necessary militarization or ruggedization, can reduce development costs and timelines. Clear, illustrated maintenance procedures for all SE, integrated into IETMs, along with robust calibration schedules and support mechanisms, are essential. Exploring advanced diagnostic technologies, such as AI-driven fault prediction or remote diagnostics, could simplify troubleshooting tasks and reduce the complexity of STE required at the forward edge. Collaborative efforts with other DoD services and allied nations also exploring hydrogen technologies, potentially engaging with industry partners like NovaSpark who are working on integrated hydrogen ecosystems, should be pursued to identify opportunities for common SE development, procurement, and sustainment strategies.

To address these challenges pertaining to GSE, the Navy should procure standardized SE kits tailored to assets, such as the NovaSpark platform, and certified for operational environments under MIL-STD-810H. These kits should include ruggedized tools and embedded diagnostics compatible with Navy Common Support Equipment (CSE) platforms. By integrating modular and multi-use tools, such as combination gas detectors, wireless data loggers, and tablet-based calibration software, the Navy and Marine Corps can reduce the overall logistics burden while maintaining performance assurance.

Field maintainers should be issued SE that interface directly with IETMs, leveraging QR code scanning or NFC-based identification to automatically access diagnostics or procedural walk-throughs. Moreover, implementation of Predictive Maintenance (PdM) enabled by NovaSpark's telemetry can be supported by portable analytics devices, offering plug-and-play capabilities in environments with limited connectivity.

Lastly, aligning SE provisioning with NSN assignment and DLA's National Cataloging System will facilitate smoother requisitioning and life cycle tracking. Coordinating with NAVSEA, MARCORLOGCOM, and FRCs (Fleet Readiness Centers) will ensure a cross-service approach to SE development and sustainment, critical for interoperable hydrogen capabilities across joint and coalition operations.

12. Facilities and Infrastructure

a. Key Considerations and Regulatory Impacts

The successful fielding and sustainment of hydrogen-enabled aviation systems necessitates a comprehensive assessment and development of supporting facilities and infrastructure. This encompasses requirements across all operational, maintenance, storage, and training sites, including both permanent installations (such as home stations and depots) and temporary or expeditionary locations. A detailed Facilities Management Plan, which should be a critical component integrated into the LCSP, is essential to outline the requirements and strategy for developing, modifying, and maintaining the necessary physical infrastructure throughout the system's life cycle. All facility design, construction, and modification activities must strictly comply with relevant UFCs, which are tri-service standards for planning, design, construction, sustainment, restoration, and modernization. Key applicable UFCs include UFC 3–430-08 (Compressed Air and Gas Systems), providing standards for systems handling high-pressure gases like hydrogen; UFC 4–211-01 (Aircraft Maintenance Hangars), which will govern spaces where hydrogen-fueled UAS maintenance occurs; and UFC 1–200-01 (DoD Building Code), establishing overall structural and safety requirements for military construction. Critically, NFPA 2 (Hydrogen Technologies Code) is paramount and will govern the design and operation of any area where hydrogen is generated, stored, handled, or used. This comprehensive standard dictates specific requirements for crucial safety elements such as ventilation (to prevent hydrogen accumulation), separation distances between hydrogen systems and other facilities or ignition sources, hazard classification zones (defining areas with potential hydrogen presence), and necessary safety systems (like leak detection and emergency shutdown). Furthermore, NFPA 70 (National Electrical Code) must be strictly applied for all electrical installations within these potentially hazardous locations to ensure that electrical equipment and wiring do not become ignition sources.

Worker safety within these facilities is also a paramount consideration, guided by various OSHA regulations. This includes adherence to 29 CFR 1910.103 for the general safe handling and storage of hydrogen, as well as standards within OSHA Subpart E for emergency egress and fire protection, and Subpart J for general environmental controls like adequate ventilation in work areas. Environmental considerations, guided by regulations from the EPA and state or local authorities, will significantly impact the siting of facilities, the process for obtaining necessary construction and operating permits, requirements related to water usage (particularly for electrolysis-based hydrogen generation), regulations regarding wastewater discharge (potentially requiring National Pollutant Discharge Elimination System (NPDES) permits), and standards for air emissions from any generation processes or support equipment. Finally, ensuring the physical security of facilities, particularly those storing quantities of hydrogen or sensitive UAS technology, must meet stringent DoD physical security standards outlined in documents such as UFC 4–010-01.

Facilities and infrastructure planning are essential for ensuring the safe and sustainable deployment of hydrogen-based systems like NovaSpark's mobile atmospheric hydrogen generators. These systems require designated areas for hydrogen fuel production, safe storage, refueling, maintenance, and hazard containment; each are governed by rigorous safety and engineering standards. Key regulatory frameworks include UFC 3–410-04N (Industrial Ventilation), UFC 3–460-01 (Design: Petroleum Fuel Facilities), OSHA 1910 Subpart H (Hazardous Materials), and NFPA 2 (Hydrogen Technologies Code). These standards dictate separation distances, ventilation requirements, leak detection protocols, and construction material specifications to mitigate risks associated with flammable gases and corrosive chemicals.

Importantly, new infrastructure must be compatible with existing expeditionary platforms and naval installations without requiring extensive or permanent modification. Facilities that support hydrogen fuel must also enable interoperability with legacy systems and ensure compliance with energy resilience objectives articulated in the Navy Energy Security Framework and the DoD Climate Adaptation Plan. Considerations for stormwater management, emergency power supply, environmental permitting, and integration into base command energy monitoring systems are also critical during planning and construction phases.

b. Land and Sea Obstacles for 216 Platoons

For the USMC's 216 platoons, operating in diverse land and sea environments, a significant obstacle is the widespread lack of dedicated, compliant facilities and infrastructure designed specifically for hydrogen UAS operations, maintenance, and, particularly, bulk hydrogen storage and on-site generation at most existing USMC bases and envisioned expeditionary sites. The infrastructure currently in place is largely not configured to safely handle the unique properties of hydrogen, such as its flammability, wide explosive range, and tendency to leak easily. The cost and lead time associated with new construction or undertaking major modifications to existing structures (such as hangars, workshops, or storage bunkers) to meet stringent hydrogen safety codes are substantial challenges. Requirements mandated by NFPA 2, such as maintaining specific separation distances between hydrogen infrastructure and other buildings or activities, designing specialized ventilation systems to prevent hydrogen accumulation in enclosed spaces, and installing explosion-proof electrical fittings in hazardous zones, can necessitate extensive and costly retrofitting or entirely new buildings, requiring significant budget allocation and planning lead times.

Establishing safe and compliant hydrogen storage and handling areas, even when leveraging emergent modular or "hydrogen in a box" generation and storage systems, within the extremely constrained footprints of forward operating bases, expeditionary advanced bases (EABs), or aboard naval vessels presents a major engineering and logistical challenge. The limited available space makes it difficult to meet the required separation distances and safely integrate the necessary equipment and safety systems without compromising other critical operational functions or safety margins within the confined area. Meeting the utility demands required for hydrogen operations, especially the significant electrical power needed for electrolysis units (which split water into hydrogen and oxygen), even for containerized or modular systems, will strain the often-limited power generation capabilities of existing expeditionary infrastructure. Electrolysis requires a consistent supply of high-purity water, which, while technologies like those developed by NovaSpark utilize atmospheric water harvesting, still presents a logistical challenge to ensure sufficient volume and purity in all operating environments.

Ensuring the resilience of hydrogen-related infrastructure against harsh environmental conditions (corrosion, temperature extremes) and potential adversary threats (physical attack, cyber intrusion affecting facility controls) is critical and adds complexity to facility design and protection. The complexity of navigating environmental impact assessments and obtaining necessary permits from federal, state, and local authorities for establishing new hydrogen facilities or deploying mobile generation units can lead to significant administrative delays before operations can commence. For sea-based operations, there are specific challenges related to finding adequate, safe, and certified locations for hydrogen storage and generation equipment aboard naval vessels that meet stringent naval safety requirements, including considerations for how these systems might be integrated into existing shipboard power and ventilation systems.

Forces frequently operate from expeditionary and maritime platforms that lack the purpose-built infrastructure needed to safely manage hydrogen production and distribution. Many forward operating bases, amphibious ships, and airfields have limited capacity for segregated hazardous materials storage, leak containment zones, or vehicle refueling stations compliant with hydrogen safety codes. The mobile nature of these expeditionary units, paired with unpredictable operating environments, exacerbates the challenge of deploying fixed infrastructure or relying on conventional construction timelines.

Another concern is the logistical and administrative burden associated with establishing hydrogen-compatible facilities in foreign countries or in joint operational environments. Status of Forces Agreements (SOFAs), host-nation environmental regulations, and differing construction standards may limit or delay deployment of NovaSpark systems. Furthermore, existing facility engineers and civil affairs planners may lack the technical expertise to design or evaluate hydrogen infrastructure projects, particularly in contexts where mission timelines do not permit detailed site surveys or environmental assessments.

c. Solutions and Mitigation Strategies

To overcome the facilities and infrastructure challenges, a key pathway is prioritizing the development and fielding of modular, containerized, and rapidly deployable facility solutions for expeditionary hydrogen support. These "hydrogen in a box" concepts, which might be offered by innovative companies such as NovaSpark or other emergent technology providers, can provide compliant and self-contained environments for hydrogen generation, storage, and fueling directly in austere settings without relying on extensive fixed infrastructure. Thorough site surveys and detailed infrastructure assessments must be conducted at all planned home station and potential deployment locations. This is crucial to identify the specific requirements and constraints for both potential fixed base upgrades and the effective deployment of modular solutions, ensuring that the chosen approach meets safety and operational needs for each unique site.

Developing standardized facility designs and updating UFCs specifically for USMC hydrogen UAS operations is essential. These updated standards should explicitly accommodate the requirements and unique characteristics of these new expeditionary hydrogen systems, providing clear guidance for planning and construction across the force. Integrating renewable energy sources, such as deployable solar arrays or wind turbines, directly with these modular "hydrogen in a box" generation units and other support facilities presents a significant opportunity. This can substantially reduce the logistical burden and vulnerability associated with transporting conventional generator fuel to remote locations and enhance overall energy resilience at the tactical edge.

For shipboard integration, close collaboration with naval engineering commands, NAVSEA and NAVAIR, is essential to develop certified installation designs and procedures for integrating modular hydrogen systems aboard vessels, identifying approved storage and operational locations, and engineering necessary modifications to ship systems to ensure safety and compatibility. Leveraging existing USMC expeditionary infrastructure capabilities, such as expeditionary power generation and water purification units already in the inventory and adapting or integrating them with emergent hydrogen support systems should be explored to maximize efficiency and reduce the need for entirely novel support systems.

Implementing strict environmental management plans for all facilities, including deployable units, is critical. These plans must address sustainable water sourcing strategies, proper waste disposal procedures, and continuous monitoring to ensure compliance with all applicable environmental regulations. Utilizing advanced modeling and simulation tools offers an opportunity to optimize the placement and layout of these modular hydrogen support systems within constrained operational areas for maximum safety (e.g., optimizing separation distances), workflow efficiency, and minimal physical footprint. Finally, a phased approach to facility development is recommended. This would involve prioritizing the fielding of robust, rapidly deployable expeditionary solutions like those being tested by NovaSpark and other providers to support initial operational capabilities, while concurrently planning for and executing more permanent infrastructure upgrades at key strategic locations to support long-term sustainment and expanded operations.

DON should adopt a modular, scalable approach to GSE hydrogen infrastructure deployment as well. NovaSpark's self-contained, containerized hydrogen generation units offer a sturdy foundation for this strategy. These "hydrogen-in-a-box" systems can be deployed rapidly to new locations, require minimal site preparation, and are designed to comply with international HAZMAT shipping and setup regulations. These units can be transported by air, land, or sea and set up within hours, enabling commanders to generate fuel at the point of need and drastically reducing reliance on vulnerable fuel supply lines.

In parallel, DON should invest in facility design templates and standard deployment packages for hydrogen infrastructure, modeled on the Expeditionary Energy Office's scalable microgrid and fuel node kits. These templates can be incorporated into the Naval Facilities Engineering Systems Command (NAVFAC) standard designs and used as a baseline for field planners. Pre-approval of infrastructure designs and material lists under Environmental Impact Statements (EIS) and Record of Decision (ROD) frameworks will also accelerate fielding in both CONUS and OCONUS locations.

Lastly, the DON should leverage public-private partnerships, technology demonstrations through the DIU, and Energy-as-a-Service contracts to expand hydrogen infrastructure without incurring large capital investment. Aligning infrastructure modernization with Naval Installation Energy Plans (IEPs), mission resilience initiatives, and clean energy mandates will create synergies that support both operational and environmental objectives, ensuring that NovaSpark's technology becomes a core enabler of future force mobility.

B. RECOMMENDATIONS GOING FORWARD

The integration of hydrogen fuel into the USMC's Group 2 UAS fleet offers transformative potential for enhancing operational endurance, reducing acoustic and thermal signatures, and aligning with broader DoD strategic energy objectives. However, this research underscores that realizing these benefits for a force of 216 platoons operating in demanding, distributed land and sea environments necessitates a comprehensive and meticulously planned approach to overcome significant sustainment challenges. The complex regulatory landscape, particularly concerning the safe handling, storage, and transportation of hydrogen, coupled with the logistical intricacies of supplying this novel fuel to expeditionary units, stands as a primary hurdle. The unique safety considerations inherent to hydrogen demand the cultivation of an unwavering safety culture, supported by rigorous and specialized training for all personnel involved. Sea-based operations, with their inherent spatial and environmental constraints, further amplify these sustainment complexities.

Successfully navigating these obstacles requires more than technological advancement; it demands a holistic, system-thinking approach to product support, as embodied in an adaptive LCSP. This plan must be data-driven, informed by continuous learning, and underpinned by strong leadership commitment and dedicated resources. Key pathways to success include: establishing clear governance and policy for tactical hydrogen use; prioritizing inherently safe and expeditionary-focused designs; investing in advanced, lightweight storage and mobile generation technologies; developing standardized interfaces and open architectures; implementing multi-echelon maintenance concepts supported by CBM+; creating specialized career paths and immersive training programs; and fostering a resilient, hybrid supply chain. Through concerted effort across all IPS elements, proactive engagement with the regulatory environment, and sustained collaboration within the DoD and with industry partners, the USMC can effectively integrate hydrogen fuel, thereby enhancing the operational capabilities of its future force while contributing to a resilient and sustainable energy posture.

1. Technical Pathway: Advancing Hydrogen Fuel Adoption

Consolidation and integration with existing naval aircraft and fueling infrastructure, as well as current hydrogen-enabled aviation platforms' programs is paramount to an overall smooth transition into hydrogen-enabled aviation. Departments, such as DIU, MIU, and Program Management Offices, need to collaborate so that sustainment is professionally researched, funded, and emplaced to enable successful hydrogen solutions in support of multiple DoD programs. Further integration with NAVSEA and NAVAIR to develop hydrogen storage and handling protocols for naval aviation to meet, and refine, safety and certification alignment efforts is also key to smooth transition and optimum logistical support during those efforts.

This early-on integration would help companies such as NovaSpark to ensure mobile hydrogen generation units meet MIL-STD-882, NAVSEA lithium battery safety (if applicable), and aviation-specific explosion mitigation requirements.

With centralized management and leadership through DLA, the DoD could leverage technologies and information from the subject matter expertise of multiple companies, without concern from smaller companies being lost in the programmatic competition from larger corporations, or their proprietary data being infringed upon. As an example, NovaSpark's mobile and modular hydrogen generation system with its atmospheric water extraction for distributed hydrogen production is designed to reduce logistics dependency on centralized refueling depots. This in no way directly impacts existent platform contracts by Lockheed or Northrop Grumman but enables both companies' efforts and competitive advantage in contract attainment. By focusing on the logistical support contract first, these companies could then refine their designs with a more refined mission, based upon the expected logistical support web in the expeditionary environment. Furthermore, by this method, we might limit the number of platform variants, thus streamline production and reduce financial cost to the DoD and taxpayer.

2. Approval Pathway: Regulatory and Policy Acceleration

Engage DON Hydrogen Working Group and the DON-EI to work with companies such as NovaSpark and advocate for fast-tracked approvals for hydrogen technology integration. Simultaneously, work with FAA, DoD, and DOE to align mobile hydrogen generation with aviation fueling regulations. Develop a DON Hydrogen CONOPS post-Milestone B that integrates with current naval aviation readiness frameworks. Highlight the ease of NovaSpark atmospheric hydrogen generation adoption as a warfighting resiliency strategy to reduce reliance on petroleum-based supply chains in conflict zones.

3. Logistics and Sustainment Pathway

a. Distributed Hydrogen Production in Tactical Environments

The implementation of distributed hydrogen production through NovaSpark's advanced hydrogen generation systems offers a transformative approach to logistical and sustainment pathways in tactical military environments. Deploying NovaSpark units directly on aircraft carriers, destroyers, and forward operating bases ensures on-demand hydrogen production, significantly reducing the logistics tail associated with conventional fuel transportation. These units, leveraging atmospheric hydrogen generation technology, produce hydrogen fuel directly from water vapor in the air, thus minimizing or completely removing the need for traditional diesel fuel resupply operations. The impact of this capability on military operations is substantial, enabling extended platform endurance, lower logistical footprints, and enhanced operational autonomy.

To complement these decentralized hydrogen generation capabilities, the development of mobile ship-based and airborne hydrogen refueling infrastructure using specialized fueling pods is underway. The mobile fueling pods facilitate rapid refueling operations and can be adapted to meet the dynamic operational demands of carrier flight decks and UA deployments. NovaSpark hydrogen delivery systems are engineered to integrate seamlessly into existing naval aviation and UAV logistical frameworks, enhancing refueling efficiency and safety under combat or austere conditions.

The NovaSpark systems have undergone comprehensive evaluations to ensure compliance with rigorous DoD, OSHA, EPA, and DOT standards. Key hazardous components of the platform, including compressed hydrogen gas, lithium-ion batteries, and potassium hydroxide (KOH) electrolyte, have been meticulously assessed and regulated for safe handling, storage, and transport. These materials are governed by stringent federal guidelines, requiring periodic inspection, specialized packaging, clearly marked labeling, and secured transportation procedures as stipulated under Title 49 of the CFR.

For tactical environments, operational guidance is firmly aligned with DoD UFC and OSHA guidelines, emphasizing safe operational practices, robust maintenance schedules, and comprehensive personnel training. Moreover, the DLA provides clear directives for handling, transporting, and disposing of hazardous materials, significantly streamlining compliance and operational readiness.

NovaSpark's innovative platform, thus, not only revolutionizes fuel supply chains but also ensures adherence to comprehensive safety and regulatory standards, thereby reinforcing strategic, operational, and logistical advantages for military applications in contested logistics environments.

b. Hydrogen Storage and Distribution

The logistics and sustainment pathway for hydrogen storage and distribution within the NovaSpark initiative leverages advanced, lightweight, high-density hydrogen storage solutions. Central to this approach is the integration of NovaSpark's innovative atmospheric hydrogen generators, which uniquely generate hydrogen fuel directly from atmospheric water vapor, thereby significantly reducing the traditional logistical complexities associated with transporting diesel or other fuel sources. These patent-pending, mobile generators eliminate the challenges associated with transporting hydrogen by producing it on-site and providing immediate fuel availability for a variety of applications, including military drones, generators, vehicles, and tactical balloons.

NovaSpark's H2GO system exemplifies the expeditionary capabilities required for agile military operations, being easily transportable and deployable to diverse and resource-limited environments such as disaster zones, military forward-operating bases, and temporary shelters. To support operational efficiency and adaptability, mobile hydrogen refueling vehicles and autonomous drone-based fueling systems are also implemented, enhancing distribution flexibility and reducing personnel exposure to risk in potentially hazardous environments.

NovaSpark adheres strictly to DOT and DoD guidelines regarding the transport of hazardous materials, ensuring compliance with federal safety standards. Specifically, compressed hydrogen gas utilized within the NovaSpark system is securely contained in DOT-UN certified tanks designed for safe and stable transportation. These tanks undergo periodic hydrostatic testing and visual inspections, maintaining operational readiness and safety compliance.

For air transport scenarios, adherence to DOT regulations necessitates emptying compressed hydrogen gas tanks prior to transportation, aligning with safety protocols for hazardous materials management. The accompanying lithium-ion batteries used for power storage within these systems are carefully managed under strict packaging, labeling, and transportation requirements as outlined in Title 49 of the Code of Federal Regulations. NovaSpark's integration of lithium batteries follows guidelines ensuring these are transported safely, packaged to prevent accidental activation, short-circuits, and potential damage.

Additionally, the NovaSpark platform incorporates rigorous safety and environmental protocols for potassium hydroxide (KOH) solutions used within the electrolyzer systems, ensuring secure packaging and clear labeling for air, road, and rail transport. Packaging solutions designed to resist alkalis and stringent testing procedures such as leak-proofness, impact, vibration, and hydrostatic pressure testing guarantee the safe transportation and operational readiness of the KOH solutions.

Collectively, these comprehensive hydrogen storage and distribution strategies, combined with stringent adherence to DOT and DoD safety regulations, position

NovaSpark's technology as a robust solution for sustainable and efficient military logistics, significantly reducing the logistics tail, enhancing operational agility, and improving mission resilience.

c. Enhanced Supply Chain Resilience

To significantly enhance supply chain resilience, NovaSpark's innovative technologies are employed, specifically their mobile hydrogen generation capability. By leveraging NovaSpark's advanced mobile atmospheric hydrogen generation systems, dependence on global hydrogen transportation logistics is markedly reduced. These atmospheric hydrogen generators uniquely extract hydrogen fuel directly from ambient water vapor, eliminating traditional logistic burdens associated with hydrogen fuel distribution and reducing operational risks inherent to supply chain disruptions. NovaSpark's patented mobile systems integrate atmospheric water harvesting with hydrogen production, enabling onsite generation of energy and fuel, thus significantly streamlining supply logistics in remote, austere, and contested environments.

To further bolster resilience, NovaSpark's atmospheric hydrogen production infrastructure is strategically installed to facilitate scalable deployments across various operational landscapes, from forward operating bases to disaster response zones. The composability and adaptability of these generators offer flexible solutions suitable for both military and commercial sectors. By producing hydrogen onsite and on-demand, NovaSpark's infrastructure reduces operational reliance on long logistics tails traditionally required for fuel resupply, enhancing reliability and scaling ease while ensuring continuous energy availability.

These advanced hydrogen generation systems provide additional operational advantages, such as longer platform endurance, lower operational signatures, and reduced maintenance demands, compared to traditional diesel-dependent solutions. Coupled with GPS tracking and real-time status updates, NovaSpark solutions offer unprecedented supply chain transparency and operational agility, facilitating rapid deployment and recovery cycles. The utilization of NovaSpark's technology ensures a resilient, responsive, and sustainable supply chain capability, particularly in environments with contested logistics, thereby significantly enhancing operational readiness and sustainability.

4. Strategic Implementation

a. NovaSpark Dual-Use Applications in Military and Civilian Aviation

To strategically implement NovaSpark's hydrogen generation technology for dual use in both military and civilian aviation sectors, the initiative will leverage collaboration with DIU's Expeditionary Hydrogen Operations for Sustainable Systems (EHOSS) program. This partnership facilitates the accelerated integration of NovaSpark's atmospheric hydrogen generation system into military applications, especially within naval aviation, by capitalizing on DIU's established processes for transitioning commercial innovations into defense operations. Concurrently, achieving FAA approval is essential for positioning NovaSpark technology within the commercial aviation sector, allowing for a seamless transition and adoption across multiple operational contexts.

NovaSpark will strategically position its hydrogen generation systems as naval-centric energy solutions tailored explicitly for maritime and airborne platforms. This alignment with naval operations leverages the system's capability to provide decentralized, onsite, and on-demand hydrogen production, significantly enhancing operational flexibility and reducing dependency on extensive fuel logistics infrastructures. Such capability is particularly beneficial for naval forces operating in remote, contested, or austere environments where traditional fuel supply chains are vulnerable or infeasible.

On the civilian side, NovaSpark's atmospheric hydrogen technology addresses critical market needs for sustainable aviation fuel solutions, supporting the transition towards zero-emission aviation. The dual-use strategy will capitalize on the modularity and scalability of NovaSpark systems, which can be adapted for varied commercial aviation applications ranging from unmanned aerial vehicles to regional air mobility and urban air mobility. This adaptability ensures NovaSpark's broad market appeal and operational relevance, positioning it as a critical enabler of green aviation initiatives aligned with global sustainability targets.

To ensure effective implementation, NovaSpark will pursue a phased approach. The initial phase, which is one to three years, will focus on integrating mobile hydrogen generation units at select military bases, forward-operating sites, and initial commercial airfields. Mid-term efforts, which are three to seven years, will expand the network of NovaSpark-enabled hydrogen refueling hubs, establishing interoperability and standardizing procedures across military and civilian aviation platforms. In the long term, seven to 10 years, the objective will be comprehensive integration within global aviation logistics and operations, supported by robust training programs, infrastructure enhancements, and continuous regulatory alignment.

Ultimately, NovaSpark's dual-use application will not only advance military operational effectiveness and resilience but also significantly contribute to the commercial aviation industry's sustainable growth, fostering broader adoption of hydrogen fuel technologies across both sectors.

b. Warfighter Training and Doctrine Development

A comprehensive Warfighter Training and Doctrine Development initiative is crucial for the successful integration of NovaSpark's hydrogen technology into naval aviation and ground operations. Initially, the development of robust training programs for naval aviators, maintenance personnel, and ground crews will focus heavily on hydrogen safety, proper fueling procedures, and ongoing maintenance protocols. Given hydrogen's distinct safety and handling requirements due to its high flammability and potential for material embrittlement, targeted education will prioritize leak detection, emergency response, and fuel cell maintenance to ensure safe operational environments.

Integrating hydrogen fuel usage into the Naval Aviation Training and Operating Procedures Standardization (NATOPS) will represent a critical milestone. This integration ensures consistent and standardized procedures across all naval aviation platforms. Updating NATOPS manuals to include hydrogen fuel protocols will encompass guidelines for handling, storage, and emergency scenarios, leveraging insights from NovaSpark's mobile hydrogen generation units deployed in varied operational contexts including aircraft carriers and expeditionary airfields.

Moreover, advanced training will involve realistic scenario-based exercises incorporating NovaSpark's on-site hydrogen generation systems, enhancing operational readiness and personnel proficiency. Virtual and augmented reality training solutions will also be employed to simulate complex fueling and emergency response scenarios, significantly boosting warfighter preparedness without the risks inherent in live exercises.

NovaSpark's advanced technology, including atmospheric hydrogen extraction and onsite hydrogen generation, will be central to developing scalable and adaptable training scenarios, reflecting real-world operational conditions in contested or austere environments.

Long-term doctrine development will require close coordination within the Department of Defense to include the DIU, NAVAIR, and NAVSEA. This coordination will establish comprehensive certification standards and regulations for hydrogen fuel use, storage, and transport across naval aviation and maritime platforms. These efforts will dovetail with existing DOT, OSHA, and EPA standards, ensuring compliance and alignment with broader federal guidelines and DoD-specific operational requirements. The collaborative development of these standards and procedures will ensure the seamless integration of hydrogen technology, positioning NovaSpark as an integral component of the Navy's transition toward enhanced operational resilience and sustainability.

c. Funding and Acquisition Pathways

The strategic implementation of these pathways will be crucial to accelerating NovaSpark's integration within naval aviation and enhancing operational readiness. Initial funding will be strategically pursued through the SBIR program, DIU, and leveraging OTAs. These funding sources provide flexible, rapid procurement mechanisms that align with NovaSpark's innovative technology profile and support early-stage prototyping, operational testing, and rapid scalability.

Securing SBIR funds will enable initial proof-of-concept demonstrations, such as the Pacific Operation Science & Technology Field Experimentation (POST-FX) Conference and facilitate iterative development cycles critical for technology maturation. Collaboration with DIU will be prioritized, leveraging their mandate to expedite the incorporation of commercial technologies into defense applications, thereby reinforcing NovaSpark's alignment with DoD's innovation priorities in renewable energy generation and contested logistics. OTA frameworks will be instrumental for rapid prototyping and accelerated acquisition processes, reducing bureaucratic hurdles and fostering agile integration into existing naval operations.

To sustain long-term implementation and ensure full-scale deployment across the naval fleet, NovaSpark will actively explore inclusion within the Navy and Marine Corps'

POM cycle. This inclusion is critical for providing stable, predictable funding streams and integration into Navy budgeting cycles, allowing systematic scaling of NovaSpark's technology. Inclusion in the POM cycle will be strategically aligned with broader Navy operational energy objectives, emphasizing energy resilience, operational autonomy, and compliance with clean energy directives, thus securing buy-in from key stakeholders across the DON and DoD.

VI. SUMMARY AND CONCLUSIONS

The concluding chapter of this paper provides a comprehensive synthesis of the research. It commences with a concise summary of the principal findings presented in the preceding chapters. Following this summary, concluding remarks are offered, integrating the study's key contributions and broader implications. Finally, the chapter identifies and recommends specific avenues for future research, proposing directions for continued investigation building upon the foundation established by this work.

A. SUMMARY

As the previous Secretary of the Navy, Honorable Ray Mabus stated, "Since the 1850s, the Navy has moved from sail power to coal to oil to nuclear. And every time we changed, plenty of people said the new energy source was too expensive, too hard, and too unproven. But every time, we made a better Navy" (Lyle, 2012). This research examined the complex programmatic considerations for integrating hydrogen fuel into DON aviation capabilities, specifically focusing on the sustainment challenges and opportunities for a rapid fielding of Group 2 UAS to 216 USMC platoons operating in diverse land and sea environments.

Drawing upon an analysis framed by the twelve IPS elements, key findings consistently highlighted significant technical, regulatory, logistical, and personnel hurdles impacting the sustainment of hydrogen-powered UAS in this specific operational context. Challenges were particularly pronounced in areas such as establishing comprehensive hydrogen sustainment doctrine and policy, streamlining complex regulatory approval pathways across multiple agencies, overcoming the lack of dedicated, compliant facilities and infrastructure, addressing low skill density and diagnostic complexity within maintenance personnel at the tactical edge, ensuring accessibility and security of technical data in disconnected environments, managing the substantial PHS&T complexities of a hazardous fuel to dispersed units, and developing scalable, standardized training programs. The maritime environment consistently amplified these concerns due to factors like corrosion, confined spaces, and unique safety requirements.

Despite these significant obstacles, the research also identified promising solutions and mitigation strategies. These included leveraging modular and expeditionary technologies for generation and infrastructure, allowing for rapid technology insertion and prioritizing OSAs for interoperability, implementing echeloned and Condition-Based Maintenance Plus (CBM+) strategies, developing tailored, multi-tiered training curricula utilizing blended learning approaches, and establishing a robust data collection and analysis framework to inform sustainment decisions. The potential for localized, on-site hydrogen generation using technologies capable of extracting water from the atmosphere or seawater emerged as a transformative opportunity to reduce the logistical tail and enhance energy resilience in contested logistics environments. Early and continuous integration of product support considerations throughout the system life cycle will be essential for ensuring the operational effectiveness and affordability of future hydrogen-powered military aircraft.

B. CONCLUSIONS TO RESEARCH OBJECTIVES AND QUESTIONS

1. Research Objective One Summation

Understand the product support limitations of hydrogen technology for energy in an emergent unmanned aviation use case (operations and sustainment within the next two to three years), in terms of logistics policy, sustainment aspects, and technical feasibility.

Based on the findings of this research, it can be concluded that while the technological maturation of hydrogen-enabled UAS prototypes demonstrates the feasibility of this alternative energy source for naval aviation, the absence of a defined, comprehensive sustainment framework presents the primary barrier to widespread implementation. Successfully transitioning hydrogen fuel beyond limited prototyping into sustained operational capability for a distributed force like the USMC 216 platoons is fundamentally an issue of sustainment readiness, requiring deliberate planning across all facets of product support.

The analysis confirms that accelerating the transition to hydrogen fuel necessitates a proactive and integrated strategy that simultaneously addresses technical advancements, regulatory clarity, and logistical innovation. The study concludes that a detailed IPS analysis provides a necessary roadmap for program managers and product support managers to identify specific challenges and develop tailored solutions for hydrogen systems in operational environments. Key contributions of this research include highlighting the specific sustainment challenges within each IPS element in the unique context of hydrogen fuel for expeditionary and maritime UAS operations and identifying potential mitigation strategies grounded in existing or emergent technologies and processes.

The broader implications of this study are significant for DON's energy strategy and operational capability. It concludes that embracing hydrogen fuel, particularly with expeditionary generation capabilities, offers a viable pathway to enhance energy resilience, reduce reliance on vulnerable fossil fuel supply chains in contested environments, and potentially improve the operational performance (e.g., endurance, signature) of unmanned systems. However, realizing this potential requires dedicated leadership focus, sustained investment in infrastructure and training, and aggressive pursuit of regulatory and standardization solutions in parallel with technology development. The transition is not solely a technical problem but a complex socio-technical and logistical challenge that demands a holistic, enterprise-wide approach to product support from the earliest stages of acquisition.

2. Research Objective Two Summation

Consider an emergent, unmanned aviation-specific system as a case study for hydrogen energy solutions to be a program manager's LCSP primer (via the twelve sustainment IPS elements) to highlight key challenges and solutions to enable future aviation hydrogen enabled systems.

By utilizing a Group 2 UAS rapid fielding case study, this research served as an LCSP primer for program managers. The analysis across the twelve IPS elements (as detailed in Chapter V) highlighted specific challenges and provided actionable solutions for hydrogen-enabled systems. Key challenges included:

- **Product Support Management:** Absence of comprehensive DoD/USMC hydrogen sustainment policies and distributed management complexities.
- **Design Interface:** Ensuring intrinsic safety, maintainability, and form/fit/function compatibility with existing air/ground systems, particularly in maritime environments.

- **Sustaining Engineering:** Complex integration of disparate hydrogen subsystems, environmental sensitivities, and lack of standardization/ interoperability.
- **Supply Support:** “Last tactical mile” logistics, on-site generation limitations, availability of military-grade suppliers, and managing hydrogen-specific consumables.
- **Maintenance Planning and Management:** Low skill density, diagnostic complexities with limited tools, and unique maritime environmental impacts on components.
- **Packaging, Handling, Storage, and Transportation:** Safe transport of high-pressure cylinders, establishing expeditionary storage limitations, and managing weight/volume constraints.
- **Technical Data:** Accessibility/usability in disconnected environments, configuration management for dispersed fleets, and tailoring complex data for tactical users.
- **Manpower and Personnel:** Skill availability, lack of dedicated MOS/NECs, and workload implications for existing personnel.
- **Training and Training Support:** Scalability/standardization, access to realistic training environments, and specialized emergency response training for unique hydrogen hazards.
- **Information Technology Systems Continuous Support:** Reliability/security of software/firmware, lack of data exchange standards, and managing updates in disconnected environments.
- **Support Equipment:** Proliferation of unique/specialized equipment, logistical burden of transport/calibration, and limited space for SE storage.
- **Facilities and Infrastructure:** Lack of dedicated compliant facilities, prohibitive cost/lead time for modifications, and utility demands (power, water) in austere/constrained environments.

3. Primary Research Question Response

How can DON accelerate transition to hydrogen fuel as a primary energy source for unmanned naval aviation operations in the Operations and Sustainment phase of acquisitions while mitigating current technical, regulatory, and logistics barriers?

The DON can accelerate the transition to hydrogen fuel by implementing a multifaceted, integrated strategy. Technically, this involves prioritizing “Designed-for-Hydrogen” platforms, investing in modular/expeditionary generation units capable of atmospheric water harvesting, pursuing advanced lightweight and high-density storage solutions (e.g., solid-state), and employing rigorous System Safety Engineering from early design through disposal. Regulatory barriers can be mitigated by establishing clear, streamlined approval pathways within the DoD, engaging proactively with federal agencies for military-specific standards, and developing comprehensive, hydrogen-specific doctrine to standardize procedures across land and sea operations. Logistical challenges are best addressed through a hybrid, distributed supply model that leverages on-site generation, develops standardized PHS&T solution, and employs advanced data analytics for predictive maintenance and supply chain optimization. Strategic investments in research, development, test, and evaluation (RDT&E) focused on these expeditionary solutions, coupled with fostering industry-DoD partnerships, are critical to maturing the necessary technologies and reducing costs.

4. Secondary Research Question Response

What specific Integrated Product Support elements require unique consideration and adaptation to facilitate successful transition to hydrogen fuel within unmanned naval aviation?

All twelve IPS elements require unique consideration and adaptation for hydrogen fuel integration. Specifically:

- **Product Support Management:** Requires new governance (e.g., IPT, dedicated PSMs), adaptive LCSP frameworks, and data-driven sustainment systems for novel hazardous fuel.
- **Design Interface:** Demands intrinsic safety, modularity for field serviceability, standardized fueling interfaces, and advanced materials resistant to hydrogen embrittlement and marine corrosion.
- **Sustaining Engineering:** Necessitates continuous assessment for unique degradation modes (embrittlement, electrolyte leakage), robust configuration management, and extensive environmental/operational testing in extreme conditions.
- **Supply Support:** Requires "last tactical mile" solutions, managing new classes of hazardous materials (hydrogen, KOH, Li-ion), and sophisticated provisioning for specialized spares.
- **Maintenance Planning and Management:** Calls for tiered maintenance concepts, specialized diagnostic tools, and tailored Corrosion Prevention and Control (CPC) programs for maritime environments.
- **Packaging, Handling, Storage, and Transportation:** Demands certified transport modules, lightweight cylinders, mobile storage units, and shipboard-specific doctrine for hazardous material movement and stowage.

- **Technical Data:** Requires updated IETMs with embedded safety features for offline use, centralized digital libraries, and robust data logging for predictive maintenance for emergent hydrogen technology unique safety requirements.
- **Manpower and Personnel:** Focus on just-in-time training that requires the development of new skill identifiers – Aviation Skills Identifier (ASIs), comprehensive Manpower Requirements Analysis (MRA), and targeted recruitment/retention strategies for hydrogen specialists.
- **Training and Training Support:** Requires tiered, role-based curricula, blended learning approaches, specialized emergency response training, and the establishment of dedicated hydrogen training centers or mobile teams.
- **Information Technology (IT) Systems Continuous Support:** Mandates "security-by-design," OSAs for interoperability, secure remote software updates, and centralized data analytics platforms for fleet health monitoring.
- **Support Equipment:** Requires common, multi-use, ruggedized SE; integration of Built-In Test/Diagnostics (BIT/BID); and advanced diagnostic technologies like AI-driven fault prediction to reduce the safety risks of hydrogen fuel.
- **Facilities and Infrastructure:** Necessitates modular/containerized deployable solutions ("hydrogen in a box"), standardized facility designs, and integration with renewable energy sources, while navigating complex environmental permitting.

5. Department of the Navy Coordination with Industry, Academia, and International Partners

How can the DON collaborate with industry, academia, and international partners to develop standardized regulations and safety protocols to enable unmanned naval aviation hydrogen fuel applications?

DON can foster collaboration through several avenues that involve industry, academia, and international partners, focused on existing hydrogen standardization bodies for clarity of safe hydrogen utilization, as discussed:

- **Industry Partnerships:** Leverage existing rapid acquisition authorities (e.g., OTAs, DIU, SBIR)/STTR programs) to engage commercial innovators like NovaSpark for technology maturation and integration. Joint research and development efforts and pilot programs can demonstrate military applications and lead to shared infrastructure utilization.
- **Academia Engagement:** Collaborate with academic institutions for fundamental research into advanced hydrogen technologies (e.g., new storage materials, efficient generation methods), safety modeling, and environmental impact assessments. This can also support curriculum development for specialized training needs within the military.

- **International Partners:** Engage with international allies (e.g., EU, Japan, Australia, China) who have national hydrogen strategies and are developing their own regulatory frameworks and infrastructure. This collaboration can inform U.S. regulatory development, accelerate research, and shape global trade in hydrogen technologies, potentially leading to joint standards and procurement strategies. Specific examples like EASA's focus on hydrogen in aviation provide direct opportunities for alignment.
- **Standardization Bodies:** Proactively engage with federal agencies (DOT, EPA, OSHA) and consensus standards organizations (NFPA, ISO, SAE) to clarify applicability of civilian regulations to military systems and jointly develop military-specific standards or equivalencies where appropriate. This includes establishing standardized fueling interfaces, data exchange protocols, and cybersecurity baselines.

C. AREAS FOR FURTHER RESEARCH

Addressing these critical challenges—specifically the volumetric storage constraints and the reliance on fossil fuel-based production methods—demands substantial research and development investment. Overcoming these obstacles is paramount to achieving the widespread implementation of hydrogen as a viable, affordable, efficient, and safe energy carrier. Future research must prioritize the development of advanced storage technologies, such as novel materials for high-density hydrogen storage, and the exploration of sustainable hydrogen production pathways, including electrolysis powered by renewable energy sources, biomass gasification, and advanced thermochemical cycles. These advancements are crucial for realizing the full potential of hydrogen as a key component of a future sustainable energy economy.

1. Detailed Cost-Benefit and Affordability Analysis

While this research identified cost as a concern, a comprehensive, scenario-based cost-benefit analysis comparing the total life cycle cost of hydrogen-fueled UAS sustainment (including infrastructure, training, maintenance, and fuel production/delivery) against traditional fossil fuel or battery-electric systems for the USMC 216 platoon model is needed. This should account for the fully burdened cost of fuel in contested logistics environments. The fidelity of the research is to establish a foundational cost assessment to be able to submit funding requests to initiate and start the initial hydrogen sustainment program.

2. Material Compatibility and Performance in Maritime Environments

In-depth, long-term studies are required to assess the degradation of hydrogen system components (tanks, seals, fuel cells, catalysts, balance of plant) when exposed to the specific corrosive, thermal, and mechanical stresses of operational maritime environments. This research would inform material selection, maintenance schedules, and design modifications for sea-based systems.

3. Development of Hydrogen Generation and Fueling Concepts Standards

Further research and experimentation are needed to develop and validate standardized CONOPS and Tactics, Techniques, and Procedures (TTPs) for tactical hydrogen generation and fueling at the platoon and company level in diverse expeditionary settings (including ship-to-shore and shipboard). This should evaluate the effectiveness and feasibility of emergent technologies like atmospheric water harvesting and modular generation units in realistic operational scenarios.

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