

ZEROAVIA

HYDROGEN IN DEFENSE

WHITEPAPER '25





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EXECUTIVE SUMMARY

Amid a major shift in geopolitical dynamics, allied forces are seeking to bolster defense spending, more rapidly pull through innovative and disruptive technologies to adoption, and thus gain strategic advantage over adversaries. This phenomenon is creating huge opportunity for startups and scaleups with possible dual use (civilian and military) applications.¹

There has been growing interest in Hydrogen for defense in recent years, offering operational advantages across air, land and sea.

This whitepaper explores the transformative potential of hydrogen and fuel cell technologies in defense applications, highlighting their unique advantages in energy density, stealth, operational flexibility, reduced maintenance cost and tactical portability. In this paper we outline how hydrogen can support extended mission endurance, reduce logistical vulnerabilities, and enable energy independence in contested environments.

The key findings of the white paper include:

KEY FINDINGS

■ Capability Advantages

Hydrogen fuel cells offer longer range and endurance than current batteries, and with future developments of liquid hydrogen storage and high specific power fuel cells, can even emulate combustion engines. Today, they offer significantly lower thermal and acoustic signatures—ideal for stealth operations and autonomous systems. With steadily increasing demand for electric power in modern military systems, the inefficiency of diesel

generators for producing power creates more and more limitations.

■ Energy Advantages

Containerized hydrogen production systems enable in-theater and disaggregated fuel generation, reducing reliance on vulnerable and high cost supply chains and enhancing operational autonomy.

■ Platform Integration

Hydrogen-electric propulsion is being actively explored for Unmanned Aerial Vehicles (UAVs), rotorcraft, transport and intelligence, surveillance and reconnaissance (ISR) aircraft, ground vehicles, and naval vessels, with demonstrators and retrofits already underway across allied forces.

■ Dual-Use Innovation

Defense adoption of hydrogen technologies promises to accelerate and complement commercial R&D, creating synergies that support national prosperity, industrial growth, and strategic advantage.

■ Alignment with Allies

NATO, the U.S., UK, EU, and other allies are investing in hydrogen as part of broader defense modernization, recognizing its role in future-proofing military operations.

Hydrogen adoption across defense platforms and infrastructure will enhance capability, reduce costs, and strengthen national security in an increasingly complex threat environment.

To accelerate adoption, the paper recommends three key actions: increased field testing of current high-TRL hydrogen technologies, greater R&D investment in next-generation systems to

advance performance and reduce costs, and enhanced international collaboration through alliances like NATO and AUKUS to support interoperability and innovation. Ultimately, hydrogen fuel cells offer the potential for improved operational outcomes, reduced costs, and streamlined logistics in defense applications.





INTRODUCTION

Defense in a Changing World

According to the Defense Intelligence Agency 2025 Worldwide Threat Assessment, report to the U.S. House of Representatives, “in addition to traditional military modernization, developments in artificial intelligence (AI), biotechnology, quantum sciences, microelectronics, space, cyber, and unmanned systems are rapidly transforming the nature of conflict and the global threat landscape.”²

Defense challenges and threats continue to increase, for example the tensions in the Indo-Pacific and along the European Russian border create a new push for military supremacy. Terrorism remains significant and threats are bolstered by the pace of technological change.

At the same time, technological innovation is changing how militaries respond. Artificial intelligence and autonomous systems, unmanned aerial vehicles, directed energy and advanced materials are all expected to have profound effects on managing the threat landscape. In particular, autonomous and remotely operated vehicles and weapon systems, are driving a substantial change in frontline conflict, particularly notable in the Ukraine-Russia war.

The importance of strong capability in these technologies means that many nations are seeking to supercharge the innovation delivering these with schemes to get them from the lab to the frontline at quicker rates.

In April 2025, the White House issued an executive order calling for a comprehensive overhaul of the defense acquisition system to deliver state-of-the-art capabilities.³

Defense Secretary Pete Hegseth had earlier delivered a memo to the Pentagon in March instructing default rapid acquisition processes in relation to software procurement, enabling faster procurement and easier work with non-traditional defense contractors.⁴ The sentiments were echoed later in the year by Army Chief of Staff General Randy George when he declared that the Army must modernize much faster and can't keep buying "VCRs" of warfare.⁵ The U.S. Army has launched its Transformation Initiative, with agile funding designed to shift “from program-centric to capability-based portfolios, increasing timely equipment fielding and accelerate innovation cycles.”⁶

Similarly, The UK Government has launched a new UK Defence Innovation unit with a ring-fenced budget of £400m, with the express goal of delivering innovative technology into the hands of military personnel faster.⁷ The European Union's Defence Whitepaper issued in March 2025 targeted closing critical capability gaps and attracting new players and supporting investments in disruptive innovations, with priority focuses including drones, AI, quantum and electronic warfare, alongside more traditional priorities such as artillery systems and munitions.⁸

Fundamental to the deployment of many of these technological innovations are increased computing power and connectivity, driving also a massive increase in the requirement for electrical power. Existing conflicts have begun to show the limitations of batteries in delivering this electrical power in the UAV use case with drone range even determining the proximity of front lines and the size of gray zones between forces.⁹

Fuel cells, powered by hydrogen, provide substantial benefits over battery storage and combustion-driven alternators. Hydrogen is becoming increasingly relevant to allied armed forces due to its unique advantages in energy density, stealth, and operational flexibility. Notably:

■ Extended Range and Endurance in Vehicle Propulsion

Hydrogen fuel cells offer significantly longer operational times compared to traditional lithium-ion batteries, but also due to efficiency improvements can, over time, outperform range offered by existing gas turbine powered platforms.

■ Stealth Capabilities

Hydrogen systems produce lower thermal and audible signatures than combustion engines, making them ideal for stealth operations. This is especially valuable in expeditionary warfare, where remaining undetected is critical.

■ Tactical Portability

Hydrogen can be produced anywhere water is available, significantly reducing fuel supply chain challenges. The U.S. Naval Research Laboratory has developed portable hydrogen fuel cell systems like the Hydrogen Small Unit Power (H-SUP), which provide lightweight, quiet, and efficient power for Marines in the field.¹⁰ These systems reduce the logistical burden and increase the autonomy of small units.

In 2023, NATO conducted trials at France's Gergy military site, led by NATO's Energy Security Center of Excellence (ENSEC), evaluating 400W and 1,000W hydrogen fuel cells paired with advanced battery systems, showing the benefits of hydrogen fuel cells in boosting energy resilience and simplifying logistics.¹¹

■ Resilience and Capability of Increased Available Electrical Power

Hydrogen-powered vehicles can offer extra available electric power to support onboard autonomy software and GPS-independent navigation, reducing reliance on vulnerable communication links. The ability to provide plentiful onboard power efficiently opens up freedoms for new greenfield capabilities. Constraints on the design of military vehicles and their supporting systems can be stripped away opening up the possibility of major performance advantage against adversaries.

In addition, increased electrical power can enable the removal of traditional hydraulics/pneumatics, saving significant weight and fuel, while onboard liquid hydrogen storage offers the potential for cryogenic heat sink to keep sensitive instrumentation cool. Compact, rugged cryogenic coolers are already in use to cool embedded sensors, thermal imagers, and high-performance electronics in some defense applications.¹²

Hydrogen fuel cells offer significant advantages, including ...high efficiency, and quiet operation compared to traditional diesel generators. Adopting such technology for the French Armed Forces could improve operational capabilities and reduce logistical burdens associated with fuel supply.

– NATO ENSEC

A Strategic Shift Common Across Allies

As governments across the world increase spending on defense as a portion of GDP, the focus on disruptive technologies and speed to market has increased as described above. This is having substantial impact on the development of hydrogen aviation.

The U.S. Department of Defense, for example, is accelerating its investments in hydrogen aviation, mobile hydrogen generation, and defense-ready infrastructure, positioning hydrogen an important energy source for future military operations. The U.S. Army is investing in hydrogen projects through its SBIR and xTech programs, and through research taking place at the Army Energy Research & Development Center.¹³

Germany has been studying the potential benefits of hydrogen for incorporation into Leopard tanks based on stealth advantages¹⁴ and South Korea has invested in development of a new battle tank that will utilize hydrogen fuel cell propulsion.¹⁵

At NATO-level, attention is directed towards nine specific innovation priorities, of which one is new energy sources and propulsion systems for military vehicles and aircraft. According to the Strategic Concept 2022, NATO will “invest in the transition to clean energy sources and leveraging green technologies, while ensuring military effectiveness and a credible deterrence and defense posture.”¹⁶ The Alliance’s Science for Peace & Security (SPS) Program invests in research looking at development of green hydrogen, use of hydrogen in long-range drones for maritime surveillance and energy-independent camps, including creation of a ‘hydrogen highway’ in Europe.¹⁷

Further, NATO’s Science and Technology Organization hosts working groups including Hydrogen as a Fuel, Power Source & Infrastructure Challenges to NATO, as well as others looking at new propulsion technologies.



Risks of Business-as-Usual

Global armed forces are working to leverage developments around new propulsion and new energy sources in enhancing capability provision, adapting to new environments, protecting personnel and ensuring operational resilience, and delivering broader benefits to their host nations.

As well as immediate and predicted capability benefits, adopting and exploring hydrogen is of longterm strategic importance because of the risks of business-as-usual. According to the UK Ministry of Defence, the cost of energy is likely to increase over the coming decades, as governments implement carbon pricing mechanisms on fossil fuels: the MOD would be exposed to an additional cost of £2bn from carbon pricing in the 2030s to operate its current equipment, nearly a 60% increase in fuel cost when comparing the price of fuel today to 2030.¹⁸ This increase would be in addition to any increase in fuel costs due to decreasing availability of fossil fuels or other factors.”

The installation of electric assets onboard military platforms for power and propulsion remains novel territory but may offer operational and economic advantages in thermo/acoustic signatures, systems reliability and efficiency, energy security and operations in austere environments. Nevertheless, these technologies present new challenges. The poor charge/discharge rates and gravimetric properties of battery storage severely limit defense applications.¹⁹

While hydrogen and fuel cell solutions are presently underexplored in this domain, hydrogen is significantly more energetic per unit mass²⁰ than kerosene and produces only water in reaction.

The following sections will assess hydrogen and fuel cell military applications and how they can improve capability across air, land and sea, as well as improving tactical portability and independence of power and fuel provision.





From Aircraft Propulsion to Auxiliaries

The air domain is undergoing major and accelerating transformation as forces seek to leverage new technologies to counter a new array of threats.

While next generation fighter development programs have dominated headlines, developments across a vast array of other new and traditional aircraft platforms will see the number of aerial vehicles operated by militaries increase.

While hydrogen is not a propulsion solution for manned fighter aircraft on any near-term horizon, other military air applications can see enhanced capability. Mission delivery requires enhanced stealth capability and strong endurance in many areas, challenging the field performance of combustion and battery-powered vehicles. Further, while there is a dramatic rise in attritable platforms, the increased number of aerial vehicles will add significantly to the complexity and cost of managing aircraft in operation. Costs threaten to increase dramatically.

As described in the introductory section, hydrogen fuel cells are emerging as an attractive option for overcoming many of these challenges. Due to the unique weight requirements of aviation, the requirement for high-specific forms of electrical power creates an incentive to explore fuel cells against batteries.

Effective future airpower is contingent upon alternative fuels, of which hydrogen has the greatest potential for scalability, performance and economics for many UAV, transport, logistics and ISR aircraft, particularly when combined and

deployed with electric assets. The most immediate applications under consideration are propulsion and auxiliary power solutions for Unmanned Aerial Vehicles (UAV), non-fighter fixed wing platforms (such as transport, ISR and trainer aircraft) and rotorcraft, explored below.



Fuel Cell Propulsion Systems for Unmanned Aerial Vehicles/Drones

Innovations in uncrewed systems are disrupting the way wars are fought and the way in which they will be won. According to the U.S. Defense Intelligence Agency's threat review for 2025: "More advanced UxS swarms complicate the threat posed to traditional U.S. defense systems, given continued improvements in **range, payload,** and **power**. UxS technology's continued maturation and convergence with other technologies, including AI, big data, Internet of Things, and 5G telecommunications will exacerbate this threat."

With critical aspects of performance involving range, payload and power, fuel cells emerge as a key technology for achieving superiority.

Drone technologies can have an asymmetric effect on the battlefield given the deployment of cheap, attritable vehicles capable of inflicting damage on significantly more costly hardware.

2024 was seen as the year that military UAV usage saw a significant uptick. Ukraine ramped up drone production from 300,000 in 2023 to a projected 1.5 million in 2024, while Russia produced 1.4 million drones in 2024, a nearly 10x increase from previous years.²¹ Ukraine has used drones to offset Russia’s numerical superiority, with drones accounting for 70–80% of battlefield casualties in the war.²²

Their use in all theatres – Ukraine in the tens of thousands, the Middle East and the southern Red Sea – indicates the use of uncrewed systems are not only here to stay but are likely to increase as technology expands opportunities for their employment.

– UK Defence Drone Strategy²³

The deployment of UAV enables a low-cost, high-volume strategy, and rapid deployment and replenishment. However, airborne autonomy shifts are not limited to disposable platforms. The UK’s Autonomous Collaborative Platform and Defence Drone Strategy identify that the Remotely Piloted Aircraft System (RPAS) force, while successful in delivering tactical advantage, sees threats to existing ISR and attack operations, particularly in conflict involving peer or near-peer competitors, an increasingly plausible scenario in the current geopolitical climate.²⁴

The UK’s ACP strategy tiers potential autonomous air vehicles based on value and survivability. At the disposable end, economics will mean that gained range and payload would be undermined by the high costs of lost propulsion systems. In this arena, improvements must come from battery energy density.

The rapid development of dual-use and relatively inexpensive commercial and military technologies have democratised their employment; used both surgically and to generate mass to hold much more expensive and advanced platforms at risk.

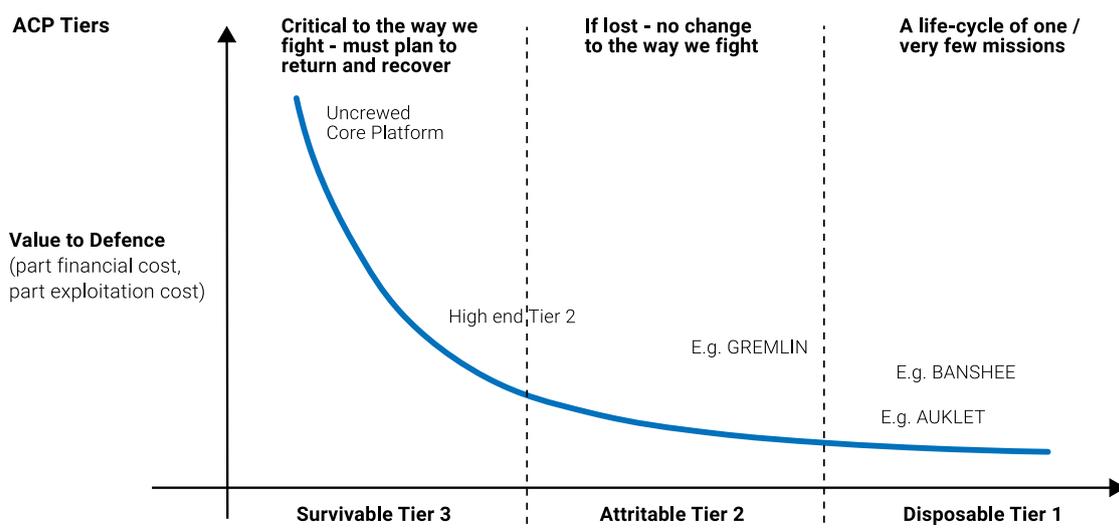


Figure 1 – RAF ACP Strategy – ACP tiers

However, above tier 2 there is substantial scope to transition from battery or combustion engine to fuel cell-electric and, on the one hand, increase range and payload, and on the other reduce detectability and cost.

Hydrogen fuel cell powered drone experimentation goes back decades in the United States, beginning with NASA's 1994 Helios prototype.²⁵ The Office of Naval Research has also invested in related research and experimentation.²⁶ More than a decade ago, researchers at the U.S. Naval Research Laboratory (NRL) flew a fuel cell powered Ion Tiger UAV for 48 hours and 1 minute in April 2025, using liquid hydrogen fuel, shattering the previous record of 26 hours and 2 minutes.²⁷

Hydrogen fuel cells offer significantly longer operational times/ranges and faster turnarounds compared to traditional battery technologies. UAVs with longer range and endurance are important for combatting anti-access, aerial denial (A2AD) strategies. Further, increased range reduces human risk in hostile environments.

Battery energy density and discharge rate presents limitations on range and power for drones, which, as discussed, are now a key determinant of battlefield superiority. Hydrogen-electric power systems offer over five times

greater Wh/kg ratios than current battery energy densities, with the prospect of over ten times higher by 2030.²⁸ Crucially, this strong power density can scale to high power delivery requirements.



Leveraging hydrogen fuel cells gives operating forces new capabilities. These include longer flight and drive ranges, less electronic signature, lower maintenance requirements, higher energy resilience, and, most importantly, reduced dependence on fuel supply chains, which are vulnerable to disruption in contested logistics environments.

– United States Defense Innovation Unit²⁹

Experiments conducted at Arkansas Tech suggest that hydrogen-powered drones can fly three to five times longer, enabling extended surveillance, reconnaissance, and strike missions without the need for frequent refueling.³⁰

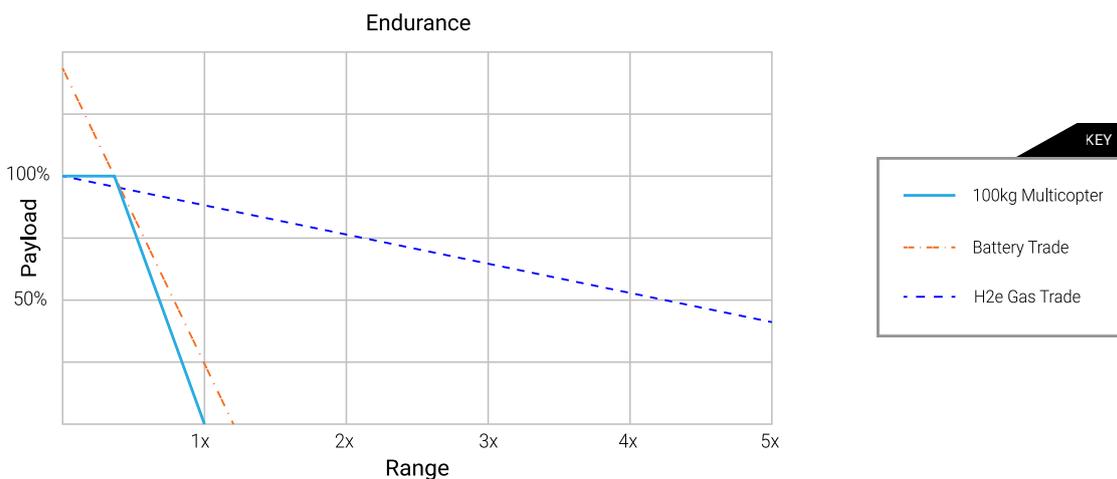


Figure 2 – Representative retrofit 100kg multirotor drone (current performance vs battery & fuel cell – ZeroAvia analysis)

For this white paper, ZeroAvia has analyzed a potential retrofit of a representative Class I(d) (small) tactical 100 kg multirotor drone with a hydrogen-electric powertrain.

The results show poor battery trade in terms of swapping payload for increased stored energy to deliver more range, for a maximum endurance of only 30 minutes. Even for a gaseous hydrogen storage fuel cell system, the heaviest hydrogen-electric solution available, the story is dramatically different, with the ability to increase the range and endurance of the system five-fold at half load. A custom designed drone for hydrogen-electric application could significantly outperform this.

In addition to weight, battery suffers from issues of cycle life, with degradation impacting operations and ultimately leading to costly replacements. In addition, the requirements for rare earth materials (cobalt, nickel and lithium), cause significant supply chain constraints and risks. Fuel cells, by contrast, rely primarily on platinum, and in small quantities.

Hydrogen fuel cells can also offer significant capability improvements compared to existing combustion-powered platforms due to improved energy efficiency (2-3 times better than

combustion equivalents according to U.S. Department of Energy) and weight of fuel (three times lower on a per unit of energy basis), either replacing the incumbent system (as a re-engining effort) or as a range extender.

According to ZeroAvia analysis, re-engining a Class III (large) high-altitude intelligence, surveillance, target acquisition and reconnaissance (ISTAR)/strike drone with a hydrogen-electric propulsion system can extend the envelope of the existing aircraft (see Figure 3). With an already impressive 40-hour endurance using gas turbine propulsion, switching to advanced fuel cell and electric propulsion, supported by liquid hydrogen fuel storage, could increase to beyond 60 hours based on the latest commercial sector literature on liquid hydrogen management system performance.

As well as retrofitting opportunities, there are several projects underway to design and build new hydrogen-electric UAVs. In France’s project RAPACE, civilian and military researchers at the Centre de Recherche de l’École de l’Air (CREA) aimed to develop a 100% French hydrogen UAV, integrating a complete hydrogen energy system.³¹ The researchers performed successful test flights in May 2023.³²

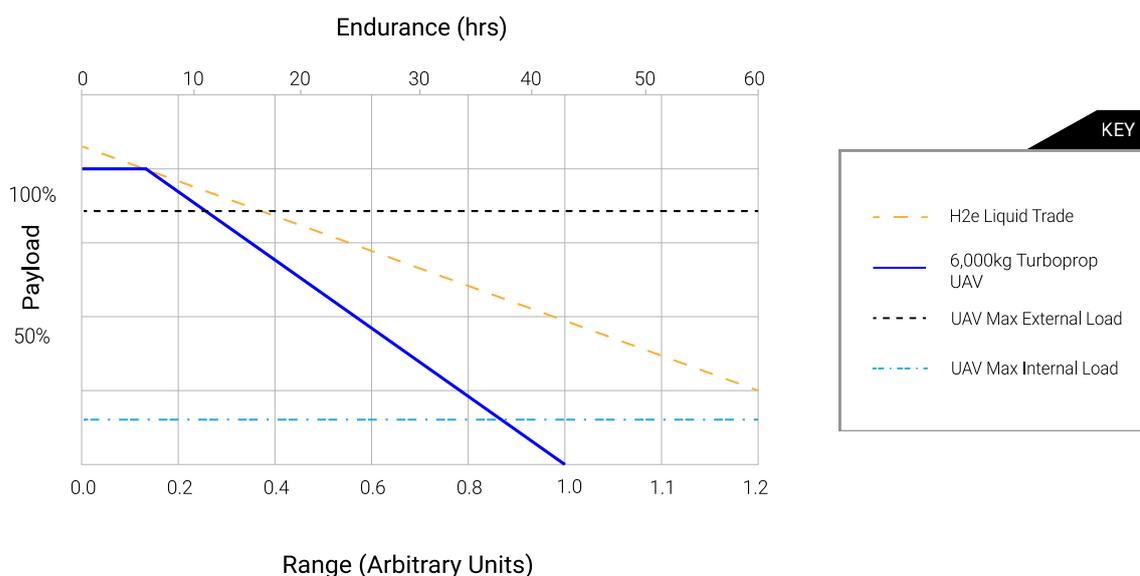


Figure 3 – Range vs payload assessment of re-engining large ISTAR/strike drone

Enhanced Stealth

Drones with internal combustion engines can today fly longer than electrified equivalents (although fuel cells and liquid hydrogen challenge that paradigm). However, combustion engine aircraft also have a high thermal/acoustic signature that makes them easy to target and intercept. That signature is much smaller in drones using hydrogen-fuel cells or batteries to power electric motors.³³

ENHANCED STEALTH

■ Reduced Temperature

Fuel cells operate at much lower temperatures than typical UAV jet engines, with exhausts three times cooler³⁴. This has a significant impact on operational safety, as well as design and maintenance, with increased component lives, and wider, more economical material options. The lower temperature would also mean substantially reduced optical distortion (heat haze) around the vehicle that can betray the presence of hardware in the air or on the ground.

■ Reduced Thermal Radiation

The quantity of IR radiation from fuel cell systems is reduced by up to 80 times as this scales strongly with temperature, therefore reducing detectability. This also minimizes weight of thermal shielding and exhaust hardware.

■ Reduced Noise

Electrical propulsion systems are also much quieter than their combustion equivalents. There is a total elimination of jet engine noise, which for some vehicles means reducing noise levels by up to 85%³⁵. With around 10 times lower air

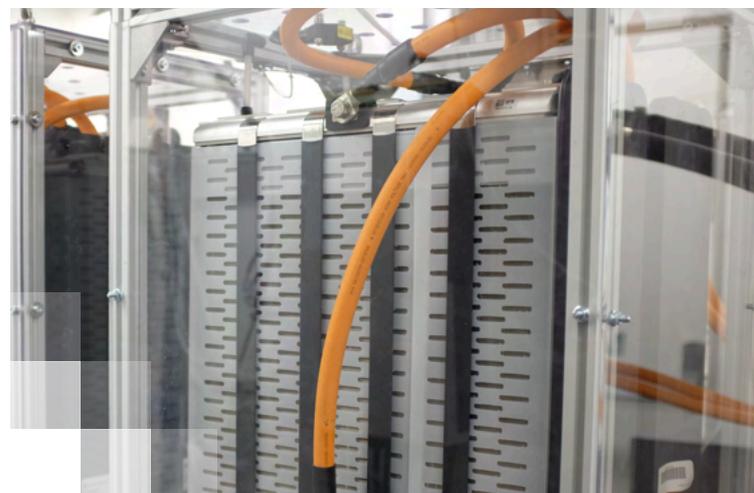
flow rates than an equivalent jet engine, hydrogen-electric powertrains would have a reduced plume size (affecting IR cross-section) and associated flow noise.

Fuel Cell Applicability

Fuel cell stacks can scale down to very small power outputs to support even dispensable UAVs – but then there exist challenges around redundancy, delivery voltage, minimum sizes of supporting balance of plant parts suffering scaling effects, such as turbomachinery becoming less efficient and with worse specific power.

Further, in many cases, battery performance may be good enough and more cost effective given the short lifecycle/survivability of the platform.

Based on embedded costs, sizing and operations of systems and fuel supply economies of scale, fuel cell propulsion systems are best suited to more demanding, less expendable platforms including larger, high value UAVs which are designed for survivability (for example, Tier 2 and 3 in the RAF ACP) and add value through repeated deployment and high utilization. Matching asset and engine value and technological complexity is key, and focus should be on high endurance and high utilization UAV applications to maximize benefits of switching to hydrogen fuel cells.



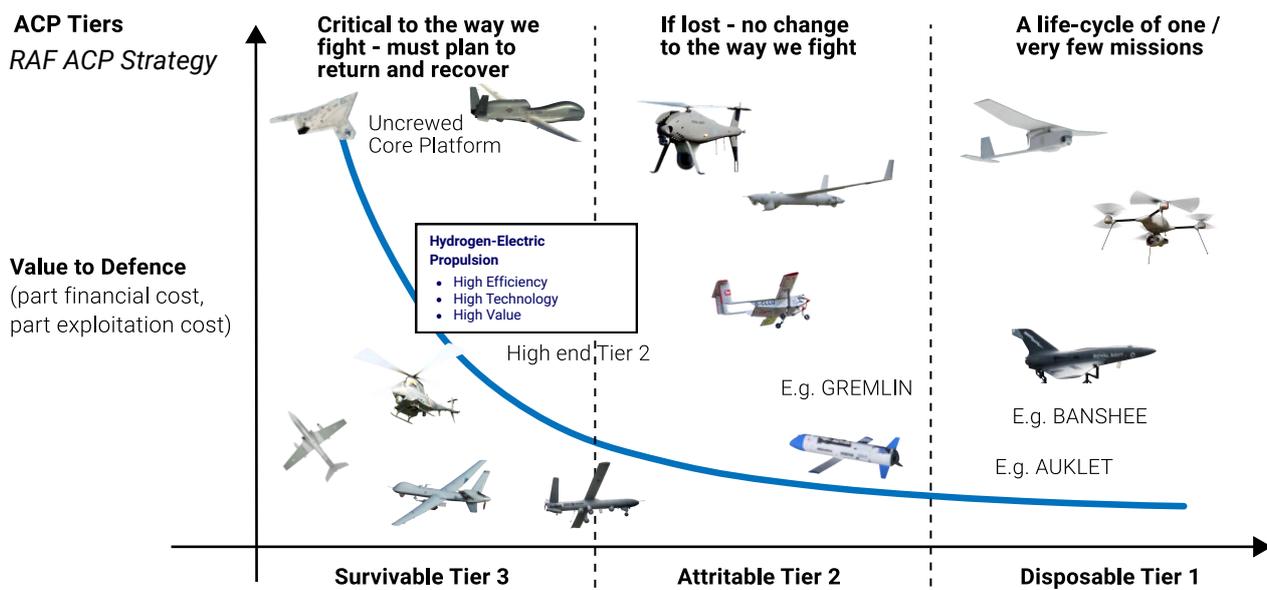


Figure 4 – RAF ACP Tiers and hydrogen fuel cell applicability

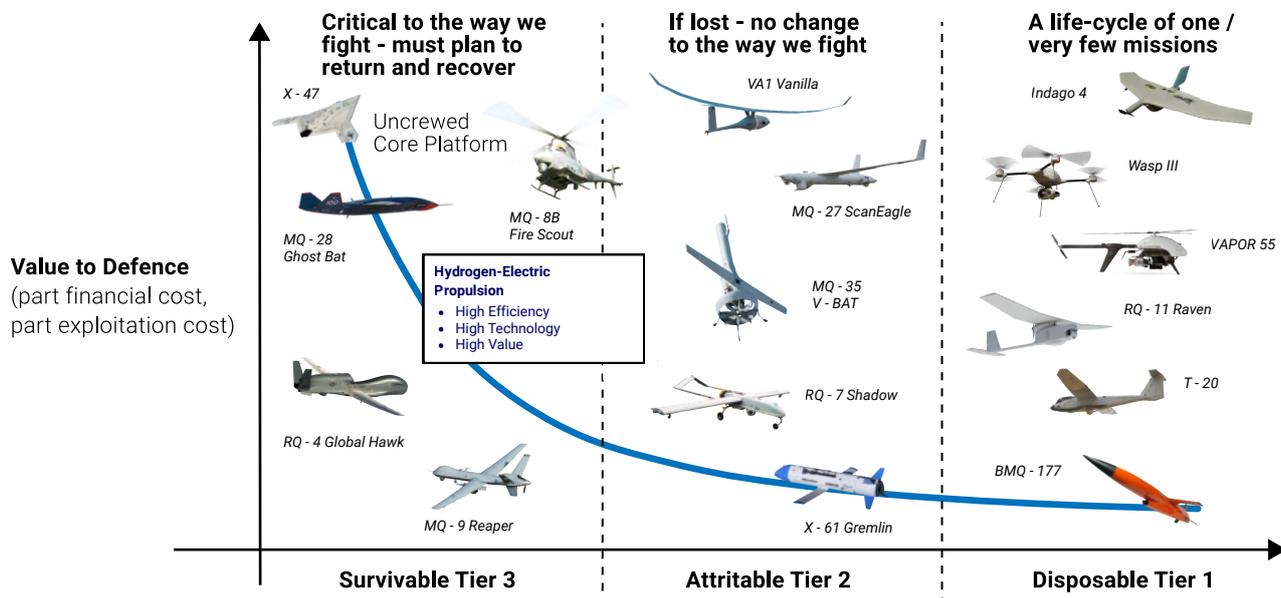


Figure 5 – U.S. UAV Platforms and hydrogen fuel cell applicability



Fuel Cells for Crewed Fixed-Wing Aircraft

Cost and supply pressures on air armed forces have been significant with fuel constituting around a quarter of total platform operating cost³⁶. The U.S. Pentagon consumes 2% of all US oil³⁷, and is the single largest consumer of liquid fuels in the world.³⁸ Operating and support costs historically constitute around 70% total aircraft lifecycle costs.³⁹

In this context, more cost effective aircraft operations and lower, stable fuel costs can be a huge advantage. Switching to hydrogen, by allowing in situ fuel production and lower vehicle maintenance costs, can provide positive cost impacts, extending beyond the UAV arena into manned aerial vehicles.

High specific thrust applications such as combat air cannot be matched electrically with current and near-term technology, while hydrogen combustion could in theory match performance (assuming development of high pressure liquid hydrogen tanks to deliver high gas flow rates required for combustion engines) and potentially

deliver some positive cost reduction, the engine efficiency and maintenance requirements would provide a less positive upside than hydrogen-electric, and required H₂ fuel volumes would be a major challenge.

However, lower costs and lower emissions can be delivered with comparable propulsion performance, increased stealth and increased resilience in transport, support and high endurance (e.g. ISTAR) aircraft using fuel cell, hydrogen-electric propulsion.

Due to the close commercial overlap, some transport and ISR aircraft are strong candidates for deploying the hydrogen-electric technologies developed initially for regional segments – noting also a plethora of dual use airframes.

ZeroAvia is working on a U.S. Department of Defense research project to study hydrogen-electric operation of Cessna Caravan aircraft. Similarly, the company has a Memorandum of Understanding with Hindustan Aeronautics Limited which owns the type certificate of the Indian Dornier 228, in use with the Indian military.

Similarly, the first hydrogen-electric engines in development and civil certification programs are designed as alternatives to engines such as the PT6. Relevant military aircraft using this and similar engines include the Beechcraft Shadow R1, Beechcraft T-6C Texan II trainer aircraft and CASA C-235/295.

Many prevalently used transport and ISR aircraft, such as the C-130 Hercules utilize 2-4 megawatt engines similar to those used by large regional turboprops such as the Dash 8 and ATR families. This category of multi-MW regional turboprop aircraft is also the target of hydrogen-electric engines with the likes of Airbus, MTU Aero Engines, ZeroAvia and Joby/H2Fly actively developing products for this segment.

With large global fleets to leverage economies of scale, the costs of transitioning to hydrogen-electric propulsion would be spread, creating quicker return on investment, alongside the reduced loss of platforms and personnel.

Bolstering Electrical Capacity

In addition to full propulsion switch, many transport, ISTAR and trainer airframes can benefit from life extension, overall cost saving, capability enhancement and reduced emissions impact by deploying fuel cell technologies for onboard power generation.

Installing a fuel cell power generation system with self-contained gaseous hydrogen fuel storage creates the possibility to increase electrical power capacity significantly with acceptable weight increases.

For example, in one popular military transport aircraft studied by ZeroAvia, replacing the auxiliary fuel tank and/or battery back-up power can deliver significant weight reduction and up to 60% extended range. Decoupling electrical power production from the main engines could also reduce maintenance cycles and costs significantly.⁴⁰

Switching Auxiliary Power Units to fuel cell power generation allows stable electrical power for engine start and all auxiliaries in flight and on ground.⁴¹ This system would enable engines-off operation of onboard systems when grounded, enabling lower detectability, greater operational autonomy, enhanced safety and lower cost of ownership.

Decoupling electrical power from main engine operation provides reduced detectability for on the ground operation thanks to lower noise and thermal signatures. Provides for more operational autonomy by removing dependence on GSE.

Fuel cell PowerPods, which combine modular fuel cells and gaseous hydrogen fuel storage in a packed drop-in solution, can also offer onboard power to support Intelligence, Surveillance and Reconnaissance (ISR) sensor suites and new power-hungry payloads such as edge compute applications. Radar systems—especially advanced ones like Active Electronically Scanned Arrays (AESA)—are power-hungry.⁴²

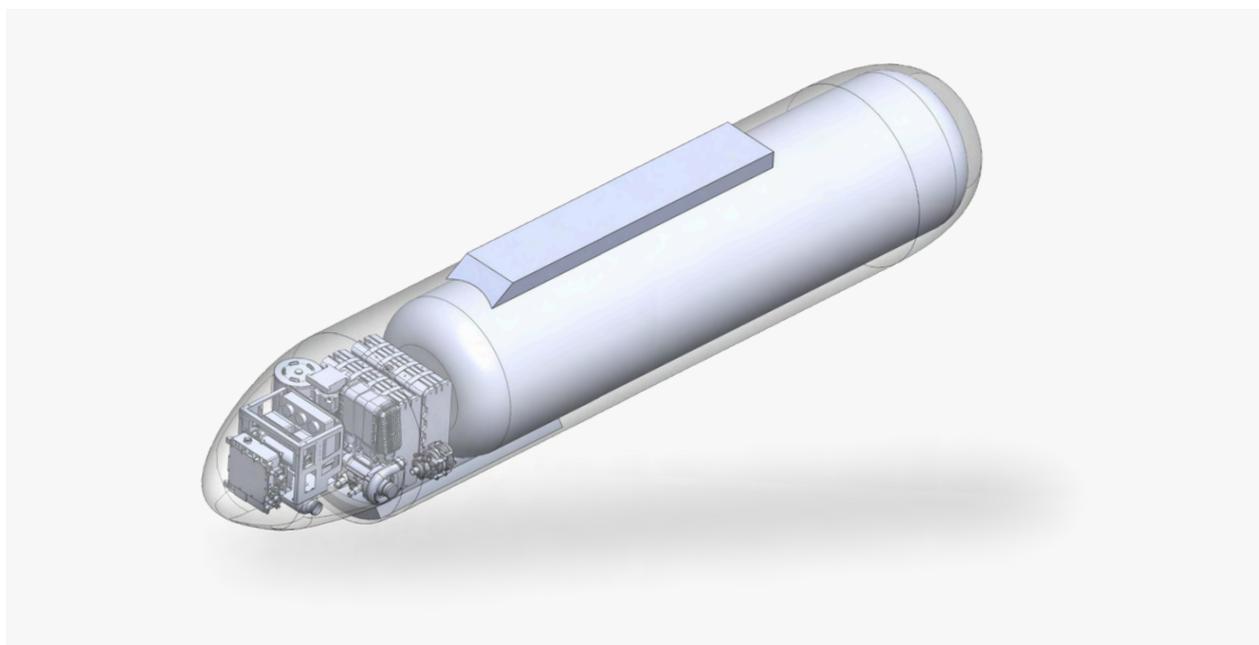


Figure 6 – ZeroAvia's PowerPod

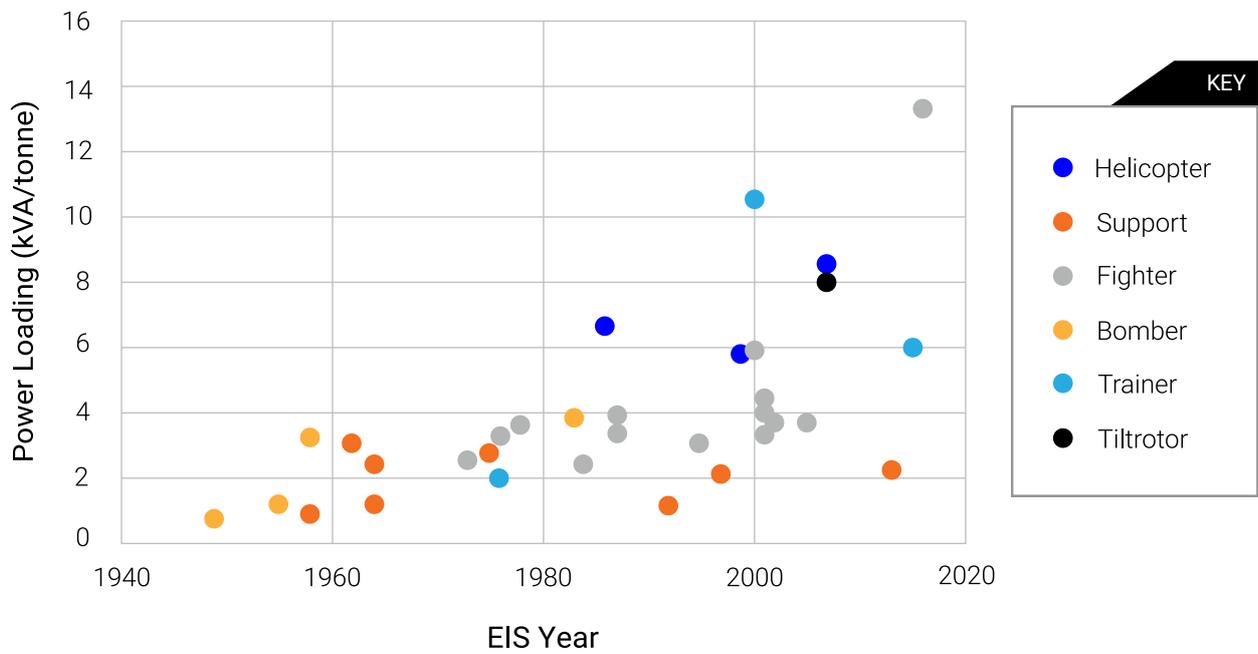
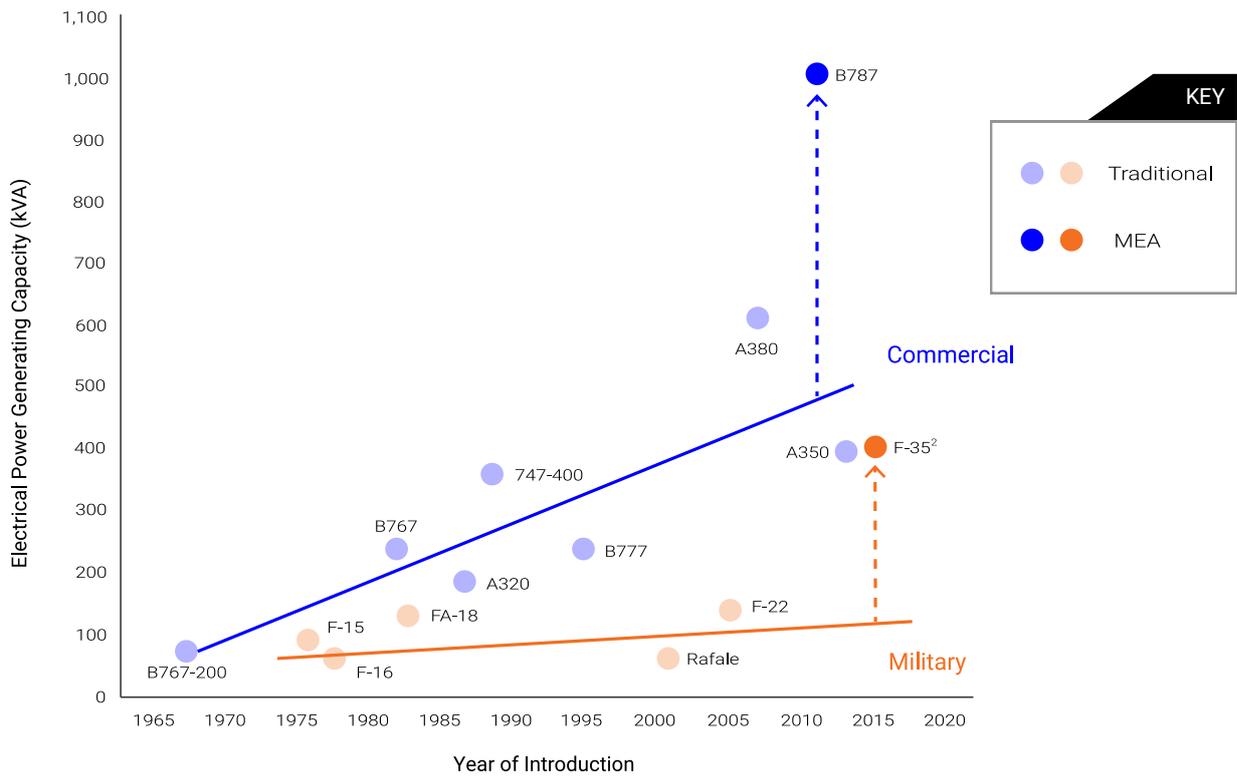


Figure 7 – Increased power loading by Military Aircraft type over time



1 Excludes APU generation capacity; 2 F-35 capacity was originally 160 kVA but has increased to 400 kVA to accommodate increasing electrification of loads

Figure 8 - Electrical power generating capacity of aircraft over time (source: Press research, Roland Berger)



Rotorcraft Propulsion Systems

Interest in fuel cell helicopter applications is growing. In late March 2025 the world's first flight of a hydrogen VTOL took place in Quebec, with a modified Robinson R44 taking off, hovering and performing maneuvers. Later this year, the company plans to transition to a liquid hydrogen system.⁴³

Piasecki Corporation and ZeroAvia have also been collaborating on the development of fuel cell rotorcraft, with support from the U.S. Department of Defense AFWERX program. With support of the Air Force's innovation arm in conjunction with the Air Force Research Laboratory (AFRL), Piasecki is collaborating with ZeroAvia to develop and implement revolutionary High Temperature Proton Exchange Membrane (HTPEM) hydrogen fuel cell technology for PA-890 and other VTOL applications.⁴⁴

The PA-890 eVTOL aircraft is expected to be the first zero-emission hydrogen-powered compound helicopter. The slowed-rotor winged helicopter is intended for use in a variety of missions including Emergency Medical Services (EMS), delivery of high-value On-Demand Logistics (ODL), On-Demand Mobility (ODM), personnel air transport, and many other commercial applications across the \$40 billion commercial light helicopter market. The PA-890 will enable significant reductions in operating cost and noise compared with today's turbine helicopters and significantly greater range than all-electric helicopters.

As part of its development program, Piasecki has already integrated an 80-kW ZeroAvia HTPEM power generation system into its two-seat Hydrogen coAXial Electric Lift (HAXEL) proof-of-concept demonstrator, with flight tests planned in the coming months.



Figure 9 – Piasecki's PA-890 hydrogen-electric helicopter design

As well as breakthrough flight testing and new, clean-sheet concepts, many utility rotorcraft are well matched to the sub-megawatt electrical powertrains that are nearest to commercial adoption. The UH-72 Lakota, of which there are nearly 500 in use with the U.S. Army, operates between 500 – 1000 kW in power.

While the MQ-8C Fire Scout deployment by the US Navy (an autonomous Bell 407) ended after just two years, a Capstone report from the Naval Postgraduate School identified liquid hydrogen fuel and a fuel cell powertrain as a preferred option to maximize operational performance: “The LH2 with fuel cell alternative had the best performance in terms of operational availability, flight hours per day, and power requirement for the [Mobile Fuel Generation System]. This project recommends further research be dedicated to the development of LH2 fuel cells as an alternative fuel/technology solution for the Navy.”⁴⁵

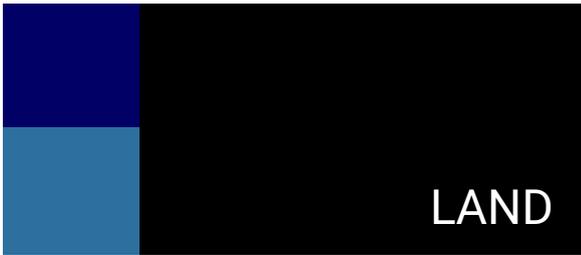
Although the MQ-8C is no longer pursued, other avenues for rotorcraft UAV conversions in the sub-MW class include the Boeing H-6U Little Bird and Korean Air KUS-VH (based on the MD 500, of which nearly 5,000 examples built) and Airbus VSR700 (based on the Guimbal Cabri G2, of which over 300 built). Rotorcraft of this configuration are much more efficient than quadcopters for long range/long endurance missions, where hydrogen-electric propulsion excels.

In the 1-4MW range, where fuel cell engine innovators are working to scale solutions for commercial segments, a further range of potential military helicopter match well, with the UH-1H Huey II, CH-47 Chinook, UH-60 Black Hawk and EH101 Merlin all operating in this power range.

Integration challenges with fuel cell propulsion systems include managing weight sensitivity (particularly regarding hover in hot and humid environments) while managing thermal management requirements when considering cooling of fuel cells at low air speeds. Further,

weight and balance impacts and aerodynamic effects of integrating new fuel systems are important areas of inquiry and rich opportunities to learn from aircraft integration projects.





Operational Value in Enhanced Power Systems

Land operations remain the backbone of military strategy, requiring more and more energy from sources that are reliable, mobile, and adaptable to diverse environments.

A consistent strategic vector in battlefield modernization aims to increase the capability of the warfighter and ground vehicle by adding and improving systems, many of which are electrically powered. This requires more electrical power to be carried in vehicles and on the soldier's person.

Land capabilities will become increasingly power hungry with the introduction of new systems such as novel weapons, active protection, and the increase in computer processing. The performance and effectiveness of new capabilities is dependent on the ability to power, charge and sustain them.

– UK Ministry of Defense⁴⁶

Additionally, as with air operations—and driven by many of the same advantages—unmanned land vehicles will play an increasing role in future engagements. For example, the British Army is actively developing uncrewed land systems as part of a broader modernization program.⁴⁷ In September 2025, the U.S. Army awarded three

startups with grants to develop self-driving infantry squad vehicles.⁴⁸ General Dynamics' TRX SHORAD is a tracked short-range air defense/anti UAS robotic vehicle, which is one of a host of new autonomous land vehicles in development across global militaries.⁴⁹

At the same time as this push for autonomy, traditional diesel-powered engines and systems, suffer from high noise and heat signatures and significant logistical challenges —particularly in contested or remote theaters where fuel convoys are high-value targets— and operational vulnerabilities.

Every liter of fuel provided to a Forward Operating Base “requires another 7 liters to get it there.” The U.S. Army estimates 1 casualty for every 24 fuel convoys in Afghanistan, with 3,000+ US soldiers or contractors killed or injured supplying fuel in Iraq and Afghanistan from 2003 to 2009. Because of these, U.K. and U.S. service branches are actively transitioning from fossil-fuel-dependent systems to electric and hybrid platforms. The global military vehicle electrification sector alone is expected to top \$1.7bn by 2030.⁵⁰



And military compounds and command centers already require significant amounts of electricity. On-site production of hydrogen can reduce the challenges and vulnerabilities associated with conventional fuels –fuel supply vulnerabilities, noise and thermal signatures, low-efficiency of combustion generators– and hydrogen production has already proven durable in austere conditions.

Hydrogen fuel cells offer a transformative alternative for land-based defense applications by delivering **silent, efficient, and low-emission power** across a range of platforms. From tactical vehicles and armored systems to portable Small Unit Power systems (SUPs) and forward operating base generators, fuel cell technology can enhance operational endurance, reduce thermal and acoustic signatures, and support energy resilience through the potential for in-theater hydrogen production.

These advantages position hydrogen fuel cells as a critical enabler for next-generation ground forces operating in dynamic, multi-domain environments.

HYDROGEN ADVANTAGES

- **Enhanced Operational Endurance**
- **Reduce Thermal and Acoustic Signatures**
- **Supports Energy Resilience**

Unmanned Systems Are Stealthier with Higher Acceptable Losses

As with aviation, uncrewed vehicles and mobile devices offer several advantages on land. These systems can operate with low signatures in hard-to-reach areas gathering surveillance, mapping

terrain, transporting soldier-support packages, moving earth and materials, and conducting kinetic strikes as needed. Some of these are Unmanned Ground Vehicles (UGVs) or Armored Robots (ARBs), while others are ground-launched aerial systems. They have been developed by the U.S., U.K., Russia, Turkiye, Israel, Ukraine, Estonia and the EU –among others– and have already entered combat service.

To support its efforts in the ongoing conflict with Russia, Bravel, Ukraine’s government organization that steers private investment toward military applications, has prioritized development of ground robots “to catch up with other unmanned systems”⁵¹, completing field trials of more than 70 ground robotics systems from more than 50 manufacturers. Most of the uncrewed systems matched their stated capabilities in performance, demonstrating effectiveness over distances as great as 10km.⁵²

This year we purchased several thousand ground platforms, and next year, I believe, we need tens of thousands.

– Mykhailo Fedorov, Ukraine Deputy Prime Minister⁵³



The British Army is also actively developing unmanned ground systems. The Ministry of Defense has, for example, purchased the Elta Systems REX MK II, an all-wheel drive hybrid electric powered UGV that can carry up to 1.3 tons. The vehicle operates completely autonomously or can be remotely controlled by an operator.

In 2023, the Ministry of Defense (MOD) held its first ever trial of heavy (5.5+ tons) UGVs. Example vehicles include the Elbit Robotic Autonomous Sense and Strike (ROBUST) UGV, a 6x6 all-terrain vehicle equipped with a 30 mm autonomous weapons turret, an active protection system, and a robotic arm for launching and retrieving aerial drones.

Battlefield clearing and preparation often requires ground and material moving. Movex Innovations produces a small, material-handling UGV featuring silent electric systems that operates outdoors for ground-clearing but can also function indoors for removing obstructions in an urban environment. The system can operate autonomously or as a remote-controlled platform. For UGVs, low signature and extendable range are critical features. Electrification of the vehicle or inclusion of an electric APU, powered by HFCs, achieves both.

Modern Vehicles for Modern Warfare



Electric vehicles are quiet. They have a low heat signature and incredible torque, and because they tend to be low maintenance with fewer moving parts, they have the potential to reduce logistics requirements. All [of] these attributes can help give our troops an edge on the battlefield.

– Former U.S. Deputy Secretary of Defense Kathleen Hicks⁵⁴

Traditional diesel-powered engines and systems, while proven, suffer from significant logistical challenges — particularly in contested or remote theaters where fuel convoys are high-value targets — and operational vulnerabilities. Military ground vehicles can be electrified to reduce noise and thermal signature, as discussed above, and to increase mobility via greater torque and distributed power to all axles, as in All-Wheel Drive (AWD) electric commercial vehicles. And, the fewer moving parts in an electrified vehicle operating at lower temperatures lead to lower maintenance costs and burdens.⁵⁵

Military ground vehicles also carry an increasing inventory of electric equipment, e.g. communications, hotel load, and weapons systems, that can all be operated quietly in an electric vehicle while the vehicle engine is off. This provides a significant advantage over the necessity to idle a conventional vehicle's detectable engine to provide electrical power both onboard and off. According to Col. William Arnold, U.S. Army Chief of Transportation, electric ground vehicles, "can reduce logistical burdens vulnerabilities, increase mobility, and survivability, and integrate future high-powered weapons systems on vehicles by having onboard exportable power."⁵⁶

The U.S. Army Futures Command began developing plans for Electric Combat Vehicles in 2020. For example, GM Defense's electric Infantry Squad Vehicle (eISV) uses a 66-kWh battery and Chevrolet Colorado drivetrain. In the U.K., Babcock and ElectroGenic are working in partnership to retrofit Land Rovers in project LURCHER. The U.S. Navy began electrification of the Joint Light Tactical Vehicle (JLTV) with a 2022 SBIR solicitation:

"The JLTV is currently capable of generating between 12.8-14.6 kW of electrical power and while this capability allows for future vehicle system growth, it is insufficient to support future systems.... Vehicle integrated power generation systems will be needed to power future Missile and Air Defense systems, Counter Unmanned

Arial Systems (C-UAS), and Command and Control (C2) systems without burdening the mission with standalone generators.”⁵⁷

As future-forward as the electrification of ground vehicles appears, powering those vehicles with hydrogen through fuel cell power generation systems can take that electrification a significant step further by reducing the logistical constraints of conventional fuels. Instead of recharging vehicle batteries slowly with loud, hot diesel generators that require vulnerable shipments of fuels, hydrogen offers low detectability signatures, fast refueling, and in-theater production.

One demonstration of these advantages can already be found in the U.S., where the H2Rescue fuel cell truck has been demonstrated multiple times as an emergency response vehicle that can also provide power in disaster zones. It can provide heat, water and 25kW of power for up to 72 hours (equivalent of ~15 homes) with a range of up to 180 miles (1500 miles if just driving and not being used to provide offboard power). It features an 18-tank system carrying up to 176kg H2 and is expected to conserve 1825 gallons of conventional fuel per year. An additional benefit of fuel cell support vehicles is that the sole emission is water, which can be purified for safe human consumption, supporting troops in the field. The H2Rescue is also being positioned to serve as a battlefield support vehicle.⁵⁸

Even heavy duty tracked vehicles are a potential application. Germany has been studying the potential benefits of hydrogen for incorporation into Leopard tanks based on stealth advantages.⁵⁹ The K3 tank nearing final design in South Korea has the potential to significantly increase available power for onboard fire control systems while allowing the tank itself to operate for much longer duration without refueling.

Initially powered by a hybrid diesel and hydrogen propulsion system, the K3 will be fully electric powered by hydrogen fuel cells by 2040. With a

focus on operating amid strained supply lines, the extended range and ability to produce fuel in situ are important capabilities.⁶⁰

Auxiliary Power Units (APUs) on tanks are also attractive opportunities for hydrogen fuel cell power generation. Tanks currently in use, like the Russian T-80 and the US M1 and M1A1 Abrams are powered by gas turbines. While the gas turbine provides unmatched acceleration, its fuel efficiency may be as low as 0.3 mpg depending on conditions. About 75% of the Abram’s operating hours consist of stationary time, with the gas turbine idling at less than 1% efficiency to run a 5 kW hotel load including ventilation, lights, cooling, and electronics.⁶¹

Again, the gas turbine supplying a relatively low amount of power during idling generates noise and thermal signatures and requires an unnecessary amount of conventional fuel transported at significant cost and risk. Hydrogen fuel cell APUs capable of providing this power are already in demonstration for aviation and commercially deployed in hydrogen fuel cell trucks and passenger vehicles.

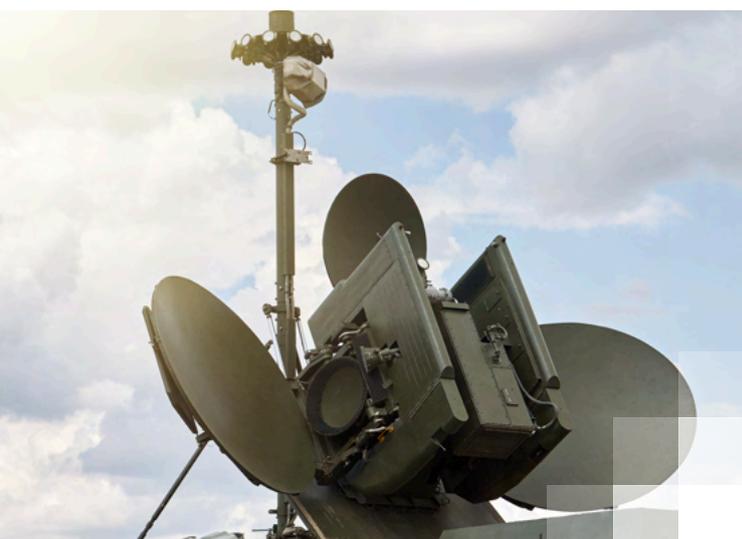


Portable Systems Require Portable Power

Soldiers operating in increasingly complex and fast-changing conditions require immediate access to situational information, communication, and more. The dismounted infantry carries smartphones and tablets; health-monitoring wearables; advanced GPS, body-mounted sensors, and real-time data sharing platforms. These technologies enable soldiers to communicate seamlessly, receive live intelligence updates, and maintain situational awareness.

In addition, today's warfighter carries electrically-powered technologies that enhance lethality like night vision and gun sights. The U.S. Army's Launched Effects project is developing a class of autonomous devices that includes ground-launched drones equipping soldiers with targeting, surveillance and strike capability.⁶²

A significant challenge to today's soldier is not only the weight of the enhanced systems and devices being carried in theater. Adding the weight of batteries to this burden increases potential soldier fatigue while reducing agility. The increase in power density (kilowatts of power per kilograms of weight) that hydrogen and fuel cells offer can provide a significant advantage.



In the U.S., Small Unit Power (H-SUP) systems are in prototype at the U.S. Naval Research Laboratory for U.S. Marine Corps expeditionary warfare operations. The H-SUP is a hydrogen fuel cell power generation system that offers greater specific energy than batteries, extends range compared to batteries, and can be refueled faster than a battery can be recharged.



This is more than a power system. It's a capability that supports distributed operations and extends mission range. That's strategic value."

– NRL Principal Investigator Kevin Cronin

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Similarly, the U.S. Army has announced a solicitation to develop a Platoon Scale Power Generator or PPG "that will allow Platoons to operate semi-independently over extended periods of time and distance during Large Scale Combat Operations. The system is targeted to provide >1.5kW of continuous power output at an energy density of 500-2000 Wh/kg and cannot exceed 55 pounds.⁶³ The goal is to minimize platoon support from higher echelon outfits, reducing the logistical burden of power generation, battery recharging, and large quantities of extra batteries. The Army is agnostic as to what energy source fuels the PPG; it is not difficult to imagine hydrogen meeting the moment.

Directed Energy for Countering Enemy UAS

Electrically powered directed-energy weapons like advanced lasers, railguns, coil guns, and electromagnetic pulses (EMPs) have grown increasingly important. The U.S. Department of War is currently developing directed energy weapons with the goal of defeating a range of threats, including drones and missiles.⁶⁴

AeroVironment has delivered to the U.S. Army Rapid Capabilities and Critical Technologies Office (RCCTO) a 20kW LOCUST Laser Weapon System (LWS) that engages targets with a high energy laser.⁶⁵ Australia's Electro Optic Systems (EOS) has produced a high-energy laser system scalable to 150kW. The "Apollo" is designed to counter drone swarm attacks and can strike 20-50 drones per minute.⁶⁶ The cost per laser strike is simply the cost of electricity, significantly reducing the considerable expense of anti-drone missiles. EOS also produces an electrically-powered "laser dazzler," a non-lethal system capable of blinding drone sensors. Earlier this year, General Atomics unveiled the development of an airborne 25 kW-class (scalable to 300kW) laser pod to equip the MQ-9B.⁶⁷

High-energy laser weapons are moving from theory to necessity. There is strong international interest in these systems, and it is increasingly clear they will play a central role in counter-drone defense.

– Dr. Andreas Schwer, EOS CEO

Directed energy weapons require substantial and reliable power⁶⁸, meaning efficient power systems are required to make them practical in the field. The Department of War plans to increase power levels of high-energy weapons

from around 150 kilowatt (kW), as is currently feasible, to around 300 kW by FY2022, 500 kW by FY2024, and 1 megawatt (MW) by FY2030.

A 1 MW capability would be required to neutralize ballistic missiles and hypersonic weapons. Deploying batteries in this context would create substantial challenges.





Endurance, Stealth and Resilience in the Most Challenging Environments

Hydrogen fuel cells represent a key enabler for improvements in naval defense operations. Their adoption will strengthen operational capabilities and reduce logistical and other vulnerabilities. Naval operations demand energy solutions that combine endurance, stealth and resilience in some of the most challenging environments. Conventional propulsion systems, heavily dependent on fossil fuels, create vulnerabilities due to detectability that can compromise mission success.

Hydrogen fuel cells offer a compelling alternative by delivering quiet, efficient, and low-emission power for a wide range of maritime platforms. Their ability to reduce acoustic and thermal signatures enhances stealth for subsea and surface vessels, while modular designs enable distributed power generation for propulsion and onboard systems.

Beyond propulsion, hydrogen systems can provide shore or hotel power for docked or anchored vessels, support unmanned maritime systems, power advanced sensors and weapons, and integrate with more portable energy sources to strengthen resilience. These capabilities align with global naval priorities for operational flexibility, cost containment, and reduced reliance on vulnerable fuel supply chains—positioning hydrogen fuel cells as a cornerstone of future maritime warfare.

The 2019 U.S. “Naval Power and Energy Systems Technology Development Roadmap” provided a strategy for the service to modernize its power

and energy systems to meet the changing nature of naval warfare. The document opens by stating, “Ensuring maritime superiority requires a ready and capable fleet, and fundamental to fleet capability is the electric power behind the fleet.”⁶⁹

Maritime drones are an increasing focus of U.S. military funding with \$185 million funded for large, unmanned surface vehicles (USVs); \$1.1 billion for medium USVs through reconciliation; plus \$137.2 million for small USVs. All of these amounts represent a considerable boost over previous spending. The Department of Defense budget request for core USV technology development is lower for FY26 than FY25, indicating the core tech stack of USVs have reached some degree of maturity.



Surface and Subsea Crewed Maritime Vessels

Despite the U.S. Navy having opened its Electric Ships Office in 2007, legacy power systems operating on conventional fuels largely propel its vessels, particularly in open waters.⁷⁰ For electric power and in-theater quieter propulsion, diesel generators are common and can be

positioned in noise-insulating chambers. These power systems, however, are not equipped to sustain the quick ramp-up and ramp-down of advanced mission systems. Advanced controls and alternative energy storage are required to avoid generator thermal and mechanical stress and detectability.

The Royal Navy pioneered implementation of electric propulsion with its Type 23 Duke Class frigates, multi-role warships built by Swan Hunter and BAE Systems and powered by a combination of gas turbines, electric motors, and diesel-electric auxiliaries.⁷¹ The typical operating profile for destroyers includes a significant amount of time at low speed when electric propulsion can meet the vessel's power requirement while reducing fuel burn.⁷²

GE Vernova is one provider offering a fully integrated electric power and propulsion system (IFEP). The company cites the ability to locate motors around a vessel as one more advantage, "to help maximize available space and separation for improved survivability," an advantage that gas turbines cannot offer.⁷³ The USS Zumwalt is the first Navy vessel deploying this system. The Zumwalt carries a pair of advanced induction motors to power the ship's systems.⁷⁴

Whether electric power is used solely for on-board power to reduce reliance on expensive fuel subject to transport vulnerabilities or are used for propulsion as well, thereby entirely eliminating reliance on those fuels, deploying fuel cells makes vessels more independent and able to operate in the field for longer. In either case, hydrogen fuel cells reduce risk over conventional fuels while offering greater endurance and faster refueling than batteries.

The U.S. Defense Innovation Unit recently awarded a contract to prototype an Expeditionary Hydrogen On Ship & Shore system (EHOSS). Under EHOSS, Pratt Miller will create a solution "designed to generate, store, and distribute hydrogen both aboard ship and ashore, creating a tactical 'micro hydrogen supply chain.'"⁷⁵ The prospects are bright as Pratt Miller Chief

Engineer Christopher Archambo noted, "We've done multiple fuel cell variants, side-by-side comparisons, and thermal acoustic inventory testing. We took thermal acoustic data even at a demonstration," which verified the lower signatures.⁷⁶



Hydrogen fuel cell technologies offer a pathway to reduced logistical risk and greater operational flexibility, especially in environments where conventional fuel delivery is constrained or compromised.

– Andrew Higier DIU Energy Portfolio Director⁷⁷

For submarines, the two primary propulsion options are nuclear and diesel-electric, both of which rely on heat to produce electricity which then turns the propeller(s). Of these, diesel-electric systems are more vulnerable because their range between surfacing events is more limited due to the diesel's oxygen requirement. An Air-Independent Propulsion system (AIP) is now included on modern submarines, allowing them to remain subsurface while in a threat-heavy operational area. AIPs are essentially fuel cells, generating electricity from chemical reactions.⁷⁸ To date, these systems have been limited because of the volume of hydrogen required. However, the use of high-temperature fuel cells (HTPEM) operating at greater efficiency could help overcome this constraint.

In addition to frontline strike vessels, electric power and propulsion can reduce conventional fuel demand added by common transport vessels. In any vessel where space is at a premium, high power is required, and low signatures provide a protective advantage, fuel cells offer a viable alternative.

Unmanned and Autonomous Surface and Subsea Drones

Over the past two decades, the deployment of maritime drones, equipped with sensors and strike capabilities, has increased, offering a cost-effective alternative to traditional naval forces. Whether in Yemen or Ukraine, these small, autonomous or remotely controlled Unmanned Surface Vessels (USVs), Unmanned Underwater Vessels (UUVs), and Autonomous Underwater Vessels (AUVs) have demonstrated their effectiveness and challenged the norms of naval warfare. Maritime drones can perform missions from surveillance and inspection to mine-laying and missile launching. They are more agile and less expensive than larger vessels, and they engender less risk to naval lives.⁷⁹

More and more, these drones are seen as cost-effective and life-saving alternatives for smaller nations countering large-vessel navies, whether for Europe defending Russian submarine forays or Taiwan guarding against incursion in the Strait of Taiwan.

Since 2024, the U.S. Navy has operated at least three simultaneous efforts to study the integration of uncrewed systems. In the Europe-Africa theater, Task Force 66 (TF66) has essentially deconstructed the typical destroyer (DDG) mission and distributed smaller mission sets to commercially available maritime drones. The leader of TF66, Rear Adm. Michael Mattis said, "We think that with 20 USVs of different, heterogeneous types, we could deconstruct a mission that a DDG could do. And we think we could do it at a cost point of essentially 1/30 of what a DDG would cost."⁸⁰

The war in Ukraine has created a laboratory for maritime drones. Ukraine's drone success in the Black Sea has pioneered "the tactical use of commercially-derived USVs for offensive operations against a conventionally superior naval force." The combined impact of the MAGURA V5, Sea Baby, and others has included

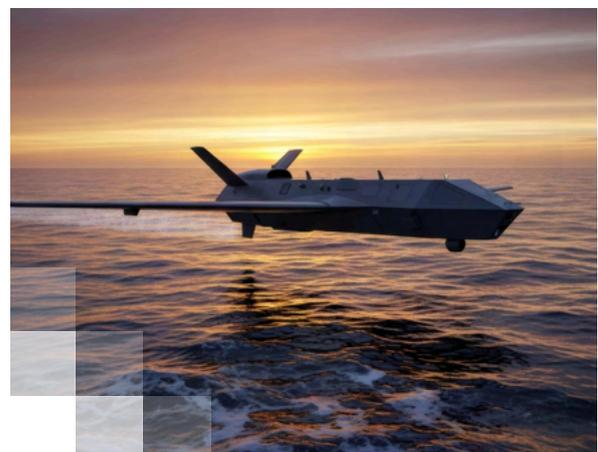
damage to Russian Navy vessels and to infrastructure at the port of Sevastopol.⁸¹

While these Ukrainian USVs have been powered by combustion engines, they can be powered by electric motors for greater stealth. Using hydrogen fuel cells instead of batteries can provide extended range, and for those USVs not on suicide missions, fuel cells can be refueled faster upon return than battery recharging.

PROTECTING AGAINST THREATS TO CRITICAL INFRASTRUCTURE

According to a report published by the UK's Joint Committee on National Security Strategy, the country's internet system relies almost entirely on subsea telecommunications cables to connect to the outside world. The trend towards critical amounts of data being concentrated in new high-capacity cables will create a small set of high-value targets.

The report notes that amid the deterioration in international stability, the chances of attacks that cause national disruption are high, and therefore calls for a new integrated monitoring and alert systems to improve early warning and vessel interception.⁸²



Surface Drones

Surface drones, or USVs, are autonomous or remotely operated vessels operating on the water's surface. Electric propulsion can provide quiet operation, low maintenance, fast acceleration, and modular power systems. And, as with electrification of land warfare technologies, every drop of conventional fuel displaced by electric power saves lives and vessels potentially lost in fuel convoys.

In addition to Ukraine, USVs have been deployed effectively by the Houthis to target commercial and military vessels in the Red Sea and by cartels transporting drugs undetected in the Caribbean Sea.⁸³

In 2021, Leidos delivered its first autonomous vessel, the Seahawk, to the U.S. Navy. Seahawk built on the company's experience developing its Sea Hunter prototype under DARPA's Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) program. The 135-foot vessel (a medium displacement USV) features a trimaran hull, is powered by twin diesel engines, carries 14,000 gallons of fuel, and can operate continuously for months.⁸⁴ Four years later, Leidos debuted its Sea Archer, a 37-foot speeder that can move at 40 nautical miles per hour, travel 1,500 miles on a diesel refuel, and carry 2,000 pounds of payload.⁸⁵ Both vessels burn conventional fuel, generating heat and noise.

The U.S. Navy recently announced requirements for its Modular Attack Surface Craft unmanned program. These will be medium and large attritable USVs capable of firing containerized weapons systems. The smallest will carry a 20-foot shipping container while the largest will accommodate four 40-foot containers.⁸⁶ The MASC program is again working with conventional fuels.

Texas-based startup Saronic Technologies has garnered several contracts to build small USVs for the U.S. Navy. Its 6 products range from the swarmable 6-foot Spyglass and 14-foot Cutlass to the 150-foot Marauder.⁸⁷



In the UK, the Pioneer class of USVs in development by ACUA Ocean "feature a hybrid-electric powertrain and are being built ready to receive either a gaseous hydrogen or a low-emission diesel powertrain."⁸⁸

In all of the above vessels, hydrogen-electric propulsion can reduce detectability and improve survivability. For the most disposable among them, battery electrification could be the most cost-effective pathway, but for the least attritable, hydrogen fuel cells can offer extended range, rapid refueling, and the ability to produce fuel in-situ.

Underwater Drones

Subsea drones can be used for lethal strikes, mine countermeasures, surveillance, infrastructure inspection (e.g. vessel hulls, undersea cables, and pipelines). Electric propulsion is essential for low acoustic signatures and long-duration missions. Some are suggesting the UUV can and should replace the conventionally crewed naval submarine and aircraft carrier.^{89 90}

The Orca, an extra-large UUV, is the U.S. Navy's largest unmanned subsurface vessel,⁹¹ stretching to the size of a semi-truck and capable of laying mines, surveillance, and

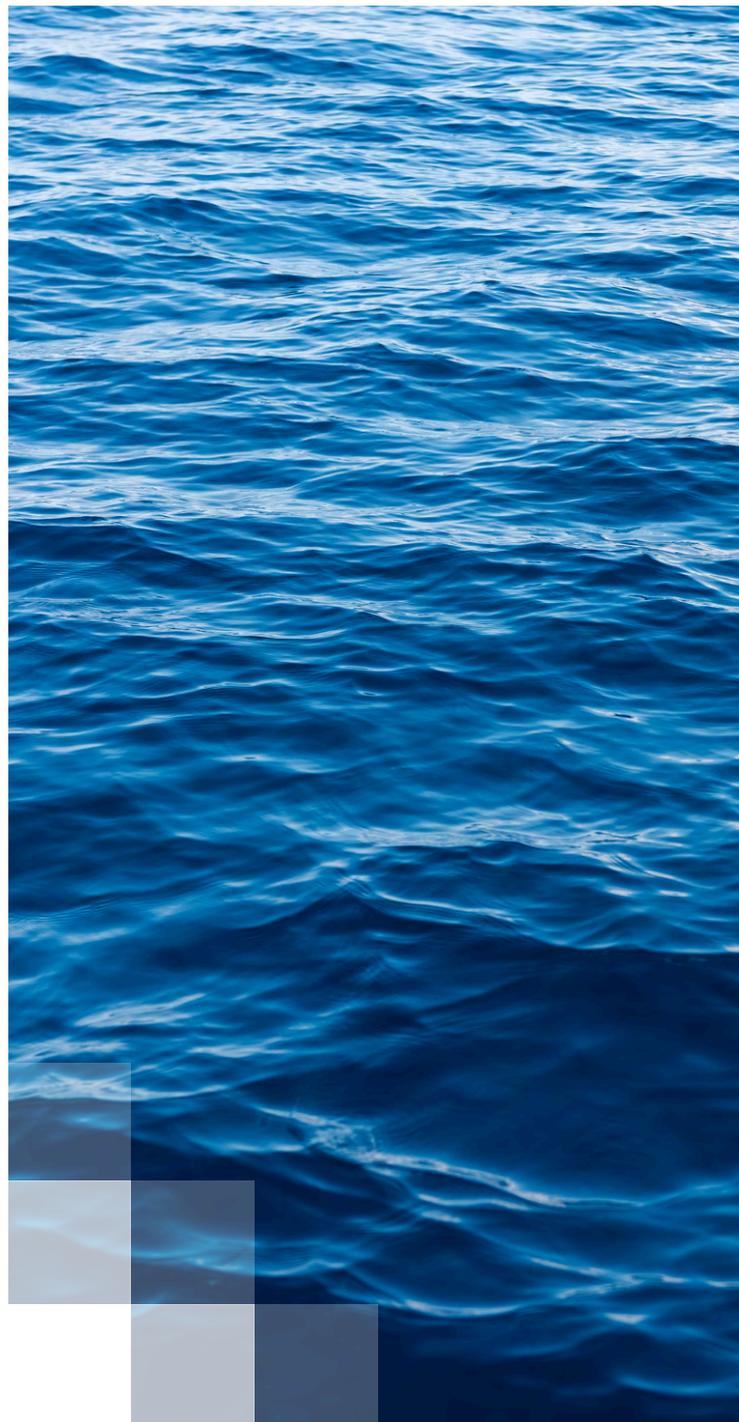
conducting strikes.⁹² The Boeing Company based its design on their Echo Voyager prototype XLUUV with hybrid diesel-electric propulsion and modular payloads for long-range missions.⁹³

On the smaller side, Leidos has developed the Sea Dart, a UUV that comes in a diameter of either 6 or 9 inches and can be used for mine detection, surveillance, sensing, and mapping. Its battery-powered electric propulsion system gives it a low heat and low acoustic signature.⁹⁴

One platform that is already trying to leverage the advantages of a hydrogen fuel cell electric power generation system is the U.S. Navy's Sabretooth AUV. Developed by Hibbard Inshore based on a Saab AUV, this uses a Subsea Supercharger fuel cell from Teledyne Energy Systems to improve the battery range of autonomous operations from its current 20km at a depth of 1,200m.⁹⁵

Undersea drones like the Sabretooth AUV will face challenges transitioning to hydrogen fuel cells. Operating within a sealed container means dealing with gas purging, condensation, and corrosion. While all of these can be managed, as the Sabretooth is demonstrating, surface drones are a simpler hydrogen fuel-cell application.

More generally, fuel cell use undersea is not common owing to the lack of available oxygen. However, a new research project is developing a fuel cell "equipped with gills" that can harvest oxygen from water, combining with stored hydrogen to fuel the reaction in the fuel cell.⁹⁶



HYDROGEN FUEL PRODUCTION

Delivering Energy Independence

Fuel logistics is one of the most vulnerable and expensive elements of military operations. According to data from 2009, in Afghanistan the U.S. military was using as much as twenty-two gallons of fuel per day, per deployed soldier⁹⁷, 22 times higher than during World War II.⁹⁸

The U.S. Defense Logistics Agency spent over \$12 billion on energy and related operation costs in 2024, more than one quarter of its overall budget.⁹⁹ However, this is the tip of the iceberg, as the cost of fuel acquisition is dwarfed by the costs of getting it to where it needs to be. In some places analysts have estimated the fully burdened cost of fuel might even be as high as \$1,000 per gallon.¹⁰⁰ Assessments show that U.S. Defense Logistics' fully burdened cost of fuel is between five and 200 times the acquisition cost to deliver in-theatre.^{101 102}

NATO estimated that 3,000 U.S. troops were killed or wounded from 2003 to 2007 by attacks on water and fuel convoys in Iraq and Afghanistan, according to the RAND Corporation.¹⁰³

Fuel Production at the Battlefield Edge

According to a report by the Modern War Institute at West Point, armed forces “can increase lethality by replacing petroleum-based fuels with hydrogen.”¹⁰⁴

One of the chief advantages that the fuel can provide is in reducing fuel logistics complexity, saving dollars and lives, by producing fuel in-theatre. Delivering energy independence equates to operational advantage in contested, remote, or

or infrastructure-poor environments, and as such, Government defense organizations are exploring how new energy supply chains can aid in this endeavor.¹⁰⁵

As well as the ability to reduce the attack surface and reduce costs by simplifying fuel logistics, containerized hydrogen production enables several additional benefits. Systems already in the field are containerized, ruggedized and quickly deployable, and are also scalable, with modular designs that can scale from powering a drone team to full FOB microgrid. Furthermore, these units can be used as distributed systems, meaning lower risk of single-point failure (improving redundancy) and the removal of a single focal point of attack.

Systems that are being deployed are designed to align with NATO MIL-STD packaging and handling standards and can be slotted into current containerized logistics or deployed as standalone systems.

Further, using hydrogen fuel cell generators for electrical power provision includes many of the same benefits of vehicle fuel cells. Fewer moving parts in the system mean reduced wear and tear and lower maintenance costs when compared with combustion generators. Power generation is similarly near silent and with low heat signature.



Key Developments and Uses of Containerized Hydrogen Production

As part of a Defense Innovation Unit project, the first Hydrogen at the Tactical Edge of Contested Logistics (HyTEC) prototype systems have recently been delivered to Marine Corps units on Marine Corps Base Hawaii (MCBH) and Marine Corps Air Station (MCAS) Yuma for operator testing and evaluation.¹⁰⁶

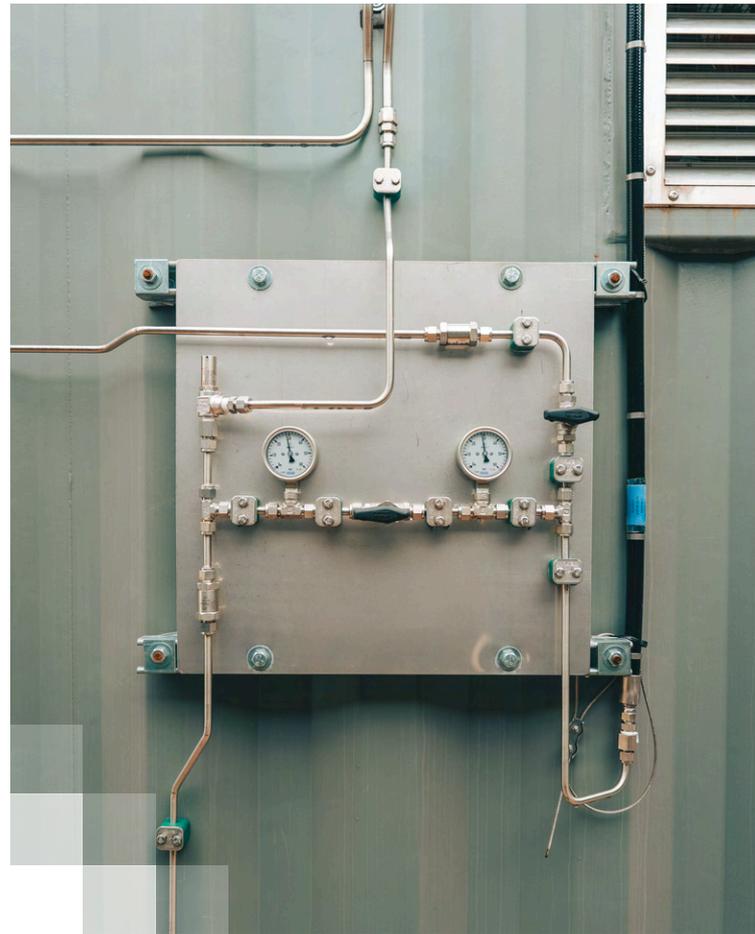
This deployment followed contracts awarded by DIU to Zepher Flight Labs and Nova Spark Energy to prototype hydrogen generation trailers that can produce hydrogen from water in austere environments.¹⁰⁷

Hydrogen can be generated and used at the tactical edge of the battlefield, whereas petroleum fuels have to be extracted, refined, stored, and transported long distances.

– Modern War Institute at West Point

But the capabilities in containerized hydrogen fuel production are not limited to tactically portable solar arrays and electrolyzer units on land. A new project announced in July 2025 by DIU will see the delivery of an Expeditionary Hydrogen On Ship & Shore (EHOSS) solution. The effort is designed to generate, store, and distribute hydrogen both aboard ship and ashore, creating a tactical “micro hydrogen supply chain” using commercial- off-the-shelf components (COTS) including data acquisition and remote monitoring capability.¹⁰⁸ The system is designed for Designed for UAV refueling, autonomous vehicle recharge, or remote base power, and capable of producing 20kg of fuel cell grade H2 per day.

In the UK, the RAF recently hydrogen-powered



off-grid energy systems at RAF Leeming, Devonport and Merville Barracks, working with UK hydrogen fuel cell generator specialist GeoPura.¹⁰⁹ The trials which ran from 2023 generated enough electricity for around 120,000 miles of travel. The Hydrogen Power Units were able to operate independent of the grid, showing potential for energy independence in theater.

In France, NATO conducted trials at the Gergy military site, led by NATO's Energy Security Center of Excellence (ENSEC), evaluating 400W and 1,000W hydrogen fuel cells paired with advanced battery systems to support a variety of energy needs in the field. The trials showed the benefits of hydrogen fuel cells in boosting energy resilience and simplifying logistics.¹¹⁰

The European Defence Agency's Fuel Cell for Soldier Systems (FUSS) project completed its first phase in April 2023, with the intent of designing a soldier-sized fuel cell system to deliver portable power in the field. Based on the

recommendations provided in the first phase, a Research and Technology (R&T) demonstrator of fuel cell for soldier systems will be developed and tested in relevant environments in the following phase of the project.¹¹¹

Meanwhile, the Slovenian military is setting up a network of self-sufficient energy hubs in Slovenia for defense (bases and barracks) and civilian needs (disasters and other crisis situations) as part of project RESHUB. The hubs are producing energy and storing that in the form of hydrogen, before deploying it in fuel cells for the production of electricity and heat when needed, as well as using the fuel for hydrogen vehicle refueling.¹¹²

FUNDAMENTAL DRIVERS ADVANCING POTENTIAL FOR ELECTROLYTIC HYDROGEN PRODUCTION AT FOBS

■ Renewable Energy Efficiency Improvements

Significant advances in the capabilities and cost profile of portable renewables make containerized solutions ever more practical and impactful in the field. Photovoltaic cell efficiency shows continued and consistent improvement over more than 50 years (see Figure 9¹¹³), approaching 50% efficiency for multi-junction cells.

Driven by the virtuous circle of demand driving scale, scale driving down cost, lower cost driving further demand, PV cell cost is falling precipitously.¹¹⁴ Polysilicon production capacity is a key determinant of whether the rate of costs falling can be maintained. China alone has facilities capable of 7m tons a year in the pipeline, enough to produce an annual 3.5TW of solar panels.

The skewing of the supply chain to China over recent decades (now at 40% of global market share¹¹⁵) creates supply chain security concerns. However, non-China module production capacity is expected to reach 276 GW, a 17% increase from 2023, driven primarily by the U.S., India and Europe.¹¹⁶

■ Electrolyzer Costs Falling and Performance Improving

At the time of writing, green hydrogen market dynamics are seeing slower progress than anticipated to large scale production projects, putting the brakes on declining costs.

However, longer term projections suggest that both PEM and Alkaline electrolyzer costs will fall precipitously over the next few years. According to analysis by a 2023 academic paper, the total Alkaline and PEM stack costs reduce from a range of 242–388 €/kW and 384–1071 €/kW in 2020 to 52–79 €/kW and 63–234 €/kW in 2030 respectively.¹¹⁷

Beyond the Single Fuel Concept

One identified challenge is the longstanding single fuel concept (SFC) practiced by the United States military and NATO. The aim of the concept is to maximize equipment interoperability through the use of a single fuel, namely F-34, on the battlefield for land based military aircraft, vehicles and equipment.¹¹⁸

Recognition is becoming more widespread of the need for a more flexible approach to the Single Fuel Concept. The UK Defence Operational Energy Strategy notes that “the current NATO single fuel recommendation has resulted in reduced efficiency of some platforms not designed for its use, lower performance in certain conditions and a mixed application of relevant environmental standards for fuels.”¹¹⁹

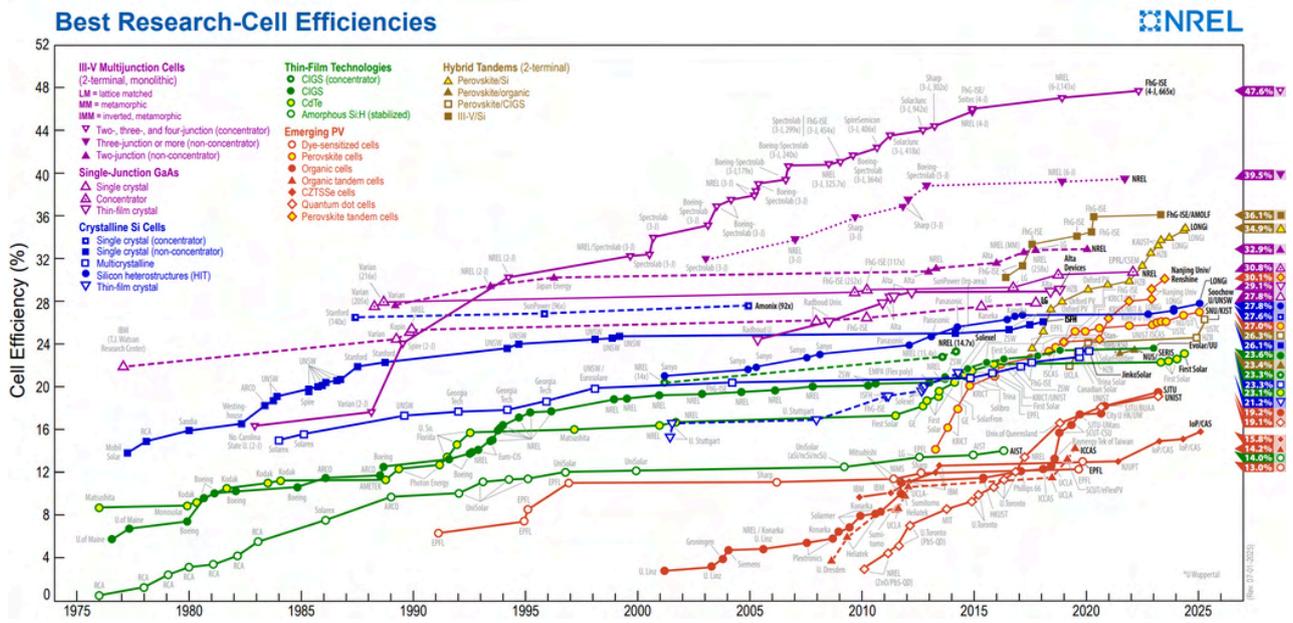


Figure 9 - Best Research-Cell Efficiencies (NREL)

NATO is transitioning its Single Fuel Concept from a reliance on a single fossil fuel to a more sustainable Operational Energy Concept that incorporates renewable energy sources, energy efficiency, and alternative fuels to adapt to climate change and ensure future energy security and military effectiveness.

As can be seen above, experimentation with new energy sources is increasing, driving forward a more flexible approach to fuels, while seeking to maximize interoperability.





Defense and Commercial R&D and Adoption Impacts

In the aftermath of the Cold War, private organizations began to shoulder the majority of national R&D burden, often with direction and support from government innovation schemes, driving a dynamic innovation engine that served both the economy and the broader national interest.¹²⁰

While there are countless examples of the Cold War era model of defense innovation later adopted to huge economic and societal benefit via commercialization, civilian-first innovation can leverage access to larger and more diverse markets to expand use cases, ultimately driving greater potential in defense also.¹²¹

It is not a new concept to engage private innovators in developing for the defense sector – from Department of Defense Small Business Innovation Research Awards to programs like AFWERX, DIU, DIANA in NATO, DSTL in the UK or the European Defence Accelerator. However, the changing threat landscape and pace of technological change has heightened sensitivity, with many initiatives to speed up cross-pollination of dual use technologies. Commercial sectors, driven in large part by sustainability considerations, have advanced fuel cell technologies. However, capability benefits identified in the previous sections see armed force research, development and deployment beginning to seek to adapt these technologies.

The deployment of well-developed, high TRL technologies such as low temperature PEM fuel cells, PEM and other variants of electrolyzer, in new defense applications has the potential to advance the civilian applications.

Hydrogen-electric UAV deployments will further understanding of civilian drone applications such as emergency response, agriculture, aerial surveyance and logistics. Rotorcraft adoption in military contexts can equally support new requirements for increased payload in the emergency medical space, alongside the need for cleaner operation.¹²²

Innovation crossover that can enhance defense capability while supporting overall national prosperity, health and wellbeing has clear strategic benefits in outperforming adversaries. Current focus in many European economies on coupling economic growth and industrial advantage with upscaling military capability is of note.

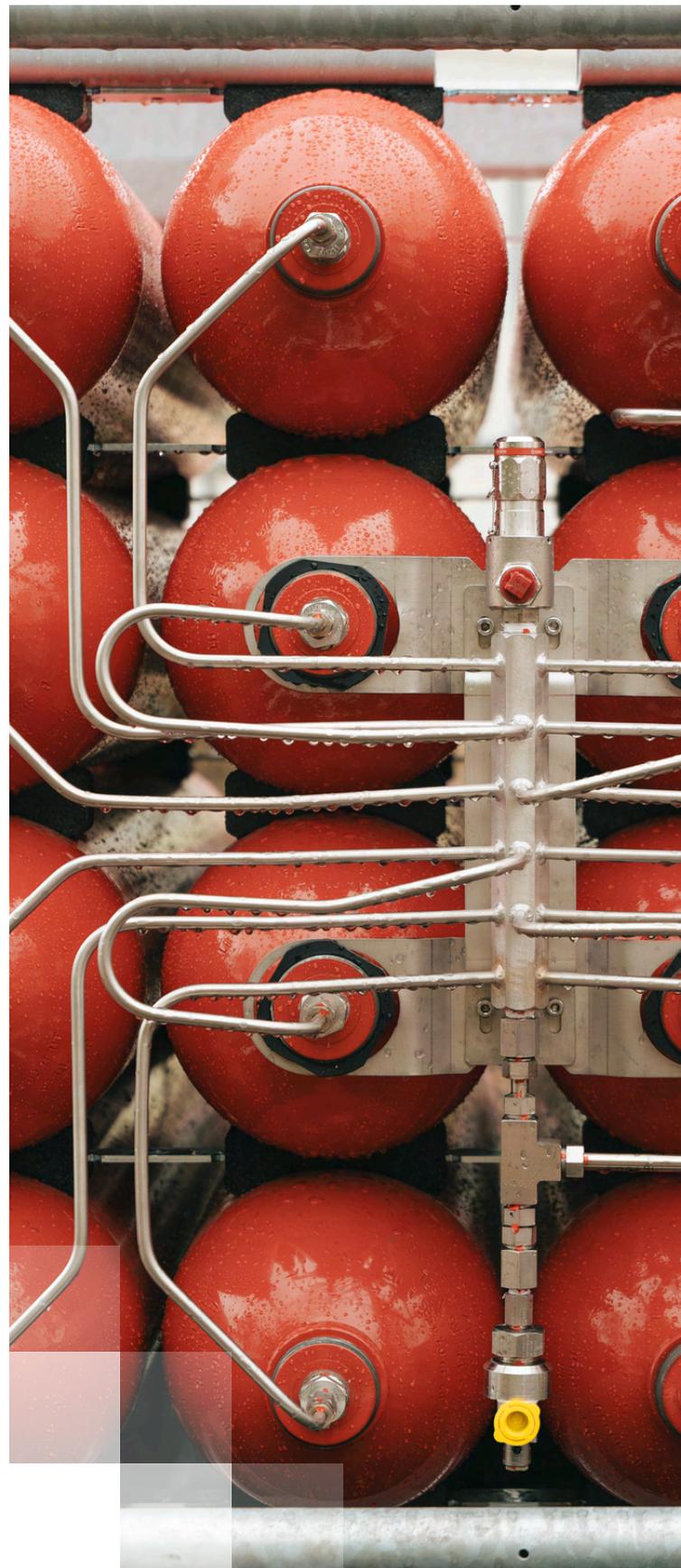
In September 2025, the UK Government published its Defence Industrial Strategy, three months on from the publication of the overall Industrial Strategy. The Defence Industrial Strategy identifies dual use technologies as “an area of significant growth opportunity for the UK.”¹²³ The strategy looks to accelerate, wherever possible, development and adoption of dual-use technology to drive economic growth, tasking UK Defence Innovation to define and communicate areas of dual-use priority for strategic and growth advantage, with the goal of steering supportive policy and encouraging investment.

In January 2024 the European Commission published a plan on how it will support research and development involving technologies with dual-use potential.¹²⁴ The EU’s European Defence Readiness 2030 whitepaper, published in March 2025, makes clear the importance of developing transport and mobility infrastructure with clear dual-use applications, underscoring the opportunity for applicable mobility technologies to serve a large market. The European Investment Bank intends to introduce changes to further widen the scope of its defense-related funding, and double its annual investment to €2bn, to help crowd-in additional private capital.

The total addressable market for hydrogen fuel cell systems across defense and commercial segments, across aviation, automotive, maritime and power applications, is vast, with enormous advanced manufacturing potential for nations that harness this development. Growth Market Reports predicts a \$51.7 billion market for hydrogen fuel cells by 2033, driven by transport, stationary power and defense use cases.¹²⁵

The traditional industrial base will need a larger ecosystem and the innovation of startups and nontraditional companies to innovate at pace and bring disruptive technologies to the frontline. Startup companies can help bring new technologies which provide operational and tactical advantage to fruition more quickly. According to the National Bureau of Economic Research, “startups have more incentive than incumbent firms to engage in potentially disruptive R&D because large, established firms have more to lose from the discovery of new technologies that replace traditional ways of doing things.”¹²⁶

Where startups can access dual-use markets, they can have better odds of securing funding, thus enabling R&D breakthroughs to reach later stage TRL, and ultimately into the field. According to a report by Crunchbase, dual-use tech scaleups now make up 27% of the total scaleup population in NATO countries, attracting large amounts of capital.¹²⁷



CONCLUSION

This whitepaper has documented some of the advantages of hydrogen fuel cells in air, land and sea domains, and also in power generation in the field and at FOBs. We have examined multiple projects across the world that display promising results and potential, and can accelerate adoption in day-to-day operations.

Hydrogen fuel cell offer unique advantages in energy density while meeting growing electrical demands, stealth, operational flexibility, and tactical portability.

There are three strategic areas of development that governments and ministries of defense must address to maximize the potential for hydrogen and fuel cells in the defense arena:

1.

Expansion of Field Testing

Platforms using today's technology (at high TRL due to commercial application) need greater field testing in forward operating environments. While we have documented a plethora of promising defense sector R&D and small-scale trials, there are only a handful of deployments noted. Defense departments are at different scales of maturity in assessing where fuel cells can be deployed across vehicles and operations. Those that are more mature must begin deployments and expand field testing in the identified areas at pace. Procurement programs need to work with the industrial base to ramp up manufacture and stress test the supply chain, alongside gleaning insights in field performance for optimizations.

2.

Increased R&D Focus in Defense, Commercial and Dual Use Funding Schemes

Market-ready fuel cell technologies have many of the operational advantages described in this paper and are ready to be integrated and deployed today. With increased field testing, further optimizations can be achieved in short order. Case studies show the use of liquid hydrogen, on-going improvements in storage technologies and moving to next generation, lighter weight fuel cells (such as HTPEM), promise significant additional capability enhancement.

Next generation technologies require increased R&D investment from defense organizations to advance TRL maturity and ensure defense requirements are embedded in the innovation process. Technology roadmaps for liquid hydrogen management systems and advanced high specific- power fuel cells offer the prospect of low thermal and noise signature vehicles that can outperform the range of combustion equivalents and significantly reduce costs. Commercial roadmaps will deliver this technology maturity over decades, but defense co-investment will significantly accelerate that end state, providing military performance and commercial export advantage to nation states that engage in both arenas. Hydrogen technologies must be treated as a strategic capability across government-supported R&D programs to deliver lockstep, dual use advances, with defense programs particularly supporting next generation developments and adopting current state of the art at pace.

In addition, many innovative startups, unencumbered with large legacy programs and with a clear "pure play" focus, are able to move at high velocity through R&D and have the potential to make step-change progress as opposed to incremental. However, primes have the capacity

to industrialize these new technologies at scale. Defense innovation units and similar entities should launch R&D programs specifically designed to bring established primes together with innovative SMEs, so that new technology can be trialed more rapidly, routes to market established and scaled production achieved in shorter time frames.

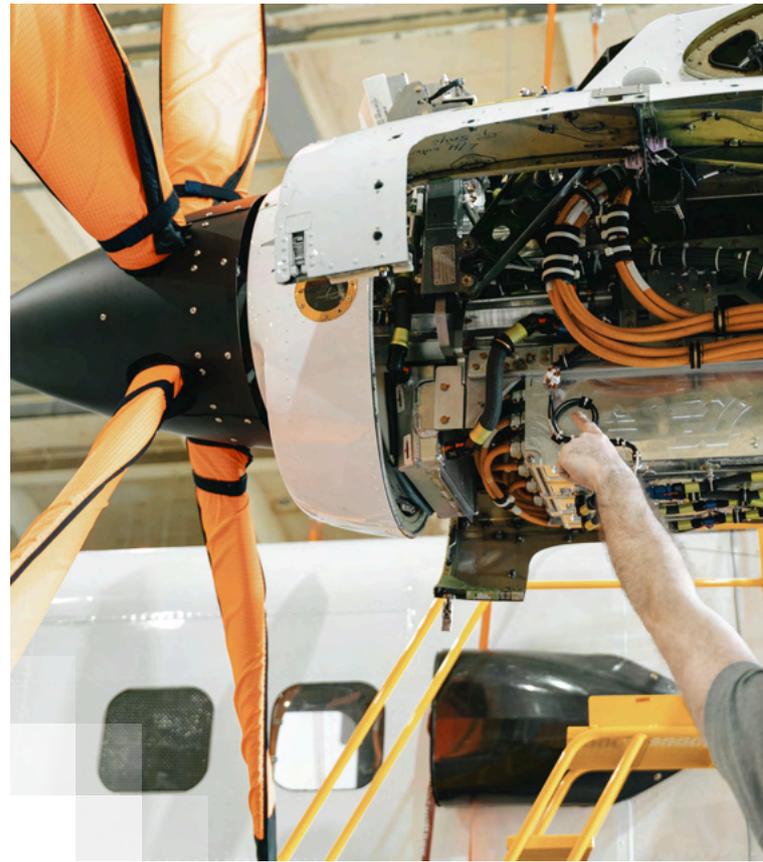
3.

Increased Collaboration Among Allies

Establishment of further global collaboration amongst Allies to jointly develop capability in hydrogen technologies. NATO DIANA can be an important vehicle for fostering cross-Alliance collaboration between civilian, military and academic players, but other approaches are likely needed. As the paper has identified, increased defense spending commitments have been accompanied with a desire to get innovation to the front line quicker. This urgency will bolster the development of hydrogen technologies, but the efficacy of this investment can be greatly enhanced by collaboration across allies. Defense sector leaders advancing hydrogen technology R&D and deployment must be proactive in seeking out forums for knowledge-sharing with peers.

Collaboration can also help enable the gradual establishment of a flexible fuel concept that maximizes interoperability, while allowing adoption of new fuels that can lower costs and enhance operations.

At different levels, the defense sector can play both the roll of fast follower and of advanced technology accelerator in hydrogen fuel cell technology. The ultimate opportunity is increased operational success, reduced vehicle attrition, reduced costs and simplified logistics, and this opportunity must be seized.





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