ENHANCING OPERATIONAL AND COST-EFFECTIVENESS: UTILITY OF "GREEN" DEFENCE TO SMALL NATION-STATES

Policy Report

March 2018

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Executive Summary

Green defence initiatives are often borne out of the desire to untether the military from exorbitant fuel requirements. In addition to being seen as cost-reducing measures, interest in green defence stems from a desire to mitigate operational risks, such as attacks on fuel convoys, that jeopardise troop safety and sometimes to increase energy independence. With these drivers in mind, this policy report comments on green defence initiatives undertaken to date, namely in the United States and Europe. The report then turns towards green technologies and identifies those with military applications. First, it looks at green technologies that have prototypes or have been deployed. — namely, camelina-derived biofuels, methanol-based fuel cells, hydrogen energy, hybrid electric drive and photovoltaic energy — and weighs the pros and cons of each for armed forces. Next, it looks at three other potentially green technology areas — pulse detonation technology, piezoelectricity, and biodegradable platforms — with lower technology readiness levels. The report concludes by looking at three ways that green technologies can affect the operational and organisational elements of forces of the future. Based on the experience of some of the bigger players discussed, it recommends that the armed forces of smaller nation-states interested in green defence avoid prioritising short-term economic arguments at the expense of long-term operational advantages.

Introduction

Since the 1950s, military weapons and related equipment have grown in numbers, steadily becoming more complex and more expensive to operate. Energy requirements for armed forces have exponentially increased, with military equipment today being fitted with more radios, computers, and associated air conditioning systems necessary for cooling. Higher energy consumption translates into higher operating and support (O&S) costs. For example, in the United States, O&S accounts for 55 per cent of the total lifecycle cost for naval aircraft.[1] In the case of smaller armed forces that do not have expensive research and development (R&D) and production costs, the share of O&S, notably including energy consumption, could easily constitute upwards of three-quarters of total lifecycle costs. This insatiable energy demand amounts to concerns about military readiness, with equipment and infrastructure being susceptible to the vagaries of energy import sources and fluctuating energy prices. Moreover, the Afghanistan conflict demonstrated the vulnerability of energy supply lines as well as the risk to human lives, with fuel convoys being easy targets for enemy attacks. As these supply problems began to translate into operational liabilities, an innovative approach to enhancing operational and cost effectiveness has emerged in the form of green defence.

In this policy report, green defence refers to the development and implementation of eco-friendly processes undertaken by armed forces to increase energy efficiency and mitigate adverse effects on the environment without negatively affecting operational readiness. This is accomplished in two broad forms: greening of facilities and greening of procurement, the latter of which will constitute the focus of this policy report.

A survey of countries actively involved in green defence measures reveals that their interest in energy efficiency exists on four levels: economic, operational, strategic and normative. With respect to the economic level, as the logistical "tail" to operate equipment has consistently grown, operating costs for platforms across the board have exploded. With widespread concerns of cost-effectiveness, green defence initiatives provide an innovative approach to, in the words of US Secretary James Mattis, "unleashing" armed forces from the tether of fuel.

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1 Daniel Burg and Paul Scharre, "The $100 Billion Question: The Cost Case for Naval Uninhibited Combat Aircraft," *Center for a New American Security* (August 2015). Accessed November 27, 2017. Available at: https://s3.amazonaws.com/files.cnas.org/documents/CNAS-Report_UAV-Lifecycle-Costs_FINAL_080715.pdf?mtime=20161220102250

Related to the economic level is the operational dimension. Over the past decade, the rise of attacks on fuel convoys has motivated armed forces to seek alternative sources to de-congest supply routes and mitigate the risks for personnel. Also, when electricity grids are vulnerable to terror attacks and natural disasters, alternative energy sources can help mitigate the risk of going off-the-grid.

Although not discussed at length here, strategic and normative motivations also play a role. From a strategic perspective, reliance on oil and gas imports blunts the strategic autonomy of a country. While higher fuel demand also translates to higher energy dependencies, green defence is not synonymous with energy security. Further, as climate change looms, public perception of governments as the main perpetrator of carbon emissions and climate change acts as a strong force to engage in military environmentalism.

To date, the strategies and initiatives undertaken by the United States, Denmark, United Kingdom, France, and Finland show that these drivers are not equally prioritised. For example, while the United States focuses on the economic and operational dimensions, Finland approaches green defence through the lens of military environmentalism. The next section expands upon the priorities and experience of each country, showing that a holistic approach to green defence — one that that acknowledges the inextricable links between at least the first three of these four levels — has not yet been achieved.

With these drivers in mind, the strategies of four countries and eight categories of green technologies have been identified in this report. A review of green defence processes, with particular emphasis on technology, will seek to answer the following question: can green defence simultaneously lower costs and enhance military readiness?

Strategies and Initiatives

An examination of green defence initiatives reveals that the countries that have thought about green defence at the strategic level are the United States, Denmark, the United Kingdom, France, and Finland. Each of these countries has interpreted green defence differently.[2] Nonetheless, they share the similarity of greening their military bases — as with various other European countries as well. With green bases in mind, this section concludes with a brief overview of renewable energies in the context of the armed forces of smaller states.

The clear leader in green defence is the United States, with each military service enacting its own strategy. The Department of Defense, responsible for 80 per cent of total US government energy usage, seeks to increase energy independence, decrease costs, and enhance troop safety. The US Navy's Great Green Fleet has received the most attention, with the US Air Force's Energy Flight Plan and Operational Energy Strategy as close seconds. The US Marines' Expeditionary Energy Strategy has produced concrete results in Afghanistan (see the photovoltaic energy section below) independent of the politicisation of green defence. Relative to the other services, the US Army's Net Zero Initiative remains relatively hypothetical — although the US Army Tank Automotive Research Development and Engineering Center (TARDEC) does invest in green technologies.

However Congressional pressure has curbed US efforts, notably disabling the Department of Defense from purchasing biofuels when petroleum is less expensive, not taking into account the greater efficiency returns that over time make green technologies more cost effective. Furthermore, the lack of a Pentagon-wide strategy on green defence has been criticised for creating "strategic cacophony" between the services,[3] which could be avoidable for smaller nation-states.

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2 *See* Daniel Fiott, "Reducing the Environmental Bootprint? Competition and Regulation in the Greening of Europe's Defense Sector," *Organization & Environment* vol. 27 issue 3 (2014): 263-278; Kristian Knus Larsen, "Unfolding Green Defence: Linking Green Technologies and Strategies to Current Security Challenges in NATO and the NATO Member States," Copenhagen University Centre for Military Studies (December 2015); Robert F. Durant, "The Greening of the US Military: Environmental Policy, National Security and Organizational Change," Georgetown University Press (Washington, D.C.: 2007).

3 Commander Daniel Orchard-Hays and Lieutenant Colonel Laura A. King, "Realize the Great Green Fleet," *United States Naval Institute Proceedings Magazine* vol. 143 issue 8 (August 2017).

Denmark, too, has incorporated a strong defence dimension into its government greening strategies, first with the Environment and Energy Strategy of 2012 and then with the second iteration of that strategy, released in 2016. The strategy has six categories of goals, which notably include committing to reduce energy consumption by 20 per cent of 2006 levels and increasing green naval technologies. Like the United States, Denmark has included in its strategy suggestions that environmental considerations could be taken up as procurement requirements in tenders. Whereas the 2012 strategy clearly sought to strike a balance between technological and behavioural changes, the 2016 iteration has shifted toward goals such as encouraging recycling, without retaining previously stated goals such as increasing renewable resources to at least 60 per cent of energy consumption. This renewed emphasis on behaviour targets the economic and normative levels of green defence, rather than maintaining a clear emphasis on the technology-centric approach.

While Denmark has moved from a technological approach to a more normative, behavioural one, the United Kingdom has moved in the opposite direction, only translating its long-held views of military environmentalism into operational benefits of green defence with its 2011 Sustainable Development Strategy (SDS). The UK Ministry of Defence accounts for half of total greenhouse gas emissions, but also makes up 39 per cent of total UK government emission reductions between 2009-2010 and 2015-2016, in part due to achieving SDS goals.[4] The UK SDS has political and operational goals to incorporate green defence by 2030, including follow-on actions such as the Sustainable Military Aviation Research Initiative (SMARTI) programme to help identify high-energy “hot spots” within the Royal Air Force.

France and Finland both look at green defence through the lens of development and environmentalism. In France, the 2010 Sustainable Development Strategy for Defence (S3D) was borne out of a desire to change energy consumption behaviour, define the armed forces as champions of environmental conservation, and draw connections between climate change and growing security threats. Its nine goals do not elaborate on the operational advantages of military greening and are laid out without concrete commitments, unlike the commitments expressed in the United States and the United Kingdom. Although S3D expired in 2013, its legacy lives on in the form of greening bases such as La Valbonne and continuing studies in Paris generally targeting ecological modernisation. Similarly, the

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[4] UK Department for Environment, Food and Rural Affairs, “Greening Government Commitments Annual Report April 2015 to March 2016” (April 2017): 10.

Finnish Ministry of Defence has pursued an environmental policy since the 1960s and shares sustainable development goals with France. One priority for Finland is military environmentalism, primarily seen through measures taken by the Finnish Defence Administration to ensure that military bases respect biodiversity. While these types of initiatives are certainly relevant to green defence, they differ in that they are driven by environmental and development concerns, rather than economic and operational motivations.

One key commonality between these — and a majority of other European — nations are the attempts to reduce electricity consumption and enhance electrical efficiency in defence estates. There is also a strategic imperative: electricity reduction measures also serve to de-centralise the energy grids, rendering them less susceptible to sabotage by cyberattacks, terrorism or natural disasters. With regard to cutting costs, several other countries — and indeed multinational cooperative frameworks offered by the European Defence Agency and the North Atlantic Treaty Organisation (NATO) — have recognised the economic advantages of greening infrastructure. Another advantage is that, borrowing from lessons in the civilian domain, this can be done immediately. Indeed, as part of Singapore's whole-of-government greening initiative, Tower A of the Defence Science and Technology Agency's building complex has been lauded for receiving the Singapore Building and Construction Authority's "Green Mark" certification.[5]

[5] Benita Teo, "New DSTA Integrated Complex promotes greater inter-disciplinary teamwork," Ministry of Defence, Singapore (29 March 2016). Accessed December 9, 2017. Available at: https://www.mindef.gov.sg/imindef/resourcelibrary/cyberpioneer/topics/articles/news/2016/mar/29mar16_news.html#.WiyXA7T1XOR

Green Technologies for Today

Renewable energy sources are not covered exhaustively in this section; rather, only those with track records of military applicability have been singled out. Whereas the first five sources have prototypes, at a minimum, the last three are still in early development stages and are covered separately because, while their operational advantages are important to determining what future green militaries may look like, their low technology readiness levels provide minimal information on their cost-effectiveness.

I. Biofuels

Biofuels, which are fuels derived from organic matter, have garnered significant attention for their ability to replace or blend in with petroleum-derived fuels. The track record of militaries using biofuels is mixed, sometimes with complaints that they are too expensive. For example, the United States significantly decreased its green initiatives after a scandal of buying biofuels at four times the price of oil.[6] Nonetheless, interest in biofuels remains, particularly for camelina-derived fuels.

Various forms of organic matter are used for biofuels, with camelina-derived fuels in the lead for defence applications, particularly given their track record to meet supersonic flight requirements. A second-generation biofuel, camelina does not compete with food crops and, according to studies from the past decade, reduces carbon emissions by 50-85 per cent against petroleum jet fuel.[7]

Since 2010, successful tests have proven the utility of biofuels — derived from camelina as well as Ester and Fatty Acids (HEFA) in a variety of platforms. On Earth Day in 2010, the US Navy's "Green Hornet" test flight showed that supersonic flights of F/A-18 Super Hornet aircraft fuelled by camelina-derived biofuels was possible[8]. A year later the US Air Force

6 Noah Shachtman, "Navy's Big Biofuel Bet: 450,000 Gallons at 4 Times the Price of Oil," *Wired* (December 5, 2011). Accessed December 9, 2017. Available at: https://www.wired.com/2011/12/navy-biofuels/

7 *See* Richard H. Moore et. al., "Biofuel blending reduces particle emissions from aircraft engines at cruise conditions," *Nature* 543 (March 16, 2017): 411-415, and Sierk de Jong et. al., "Life-cycle Analysis of Greenhouse Gas Emissions from Renewable Jet Fuel Production," *Biotechnology for Biofuels* 10:64 (March 14, 2017).

8 Liz Wright, "Navy Tests Biofuel-Powered 'Green Hornet'," United States Navy (March 22, 2010). Accessed December 9, 2017. Available at: http://www.navy.mil/submit/display.asp?story_id=52768

performed a supercruise of 1.5 Mach using a 50-50 blend of similar biofuels with JP-8 jet fuel, the standard jet propellant used by the US and several other air forces. Other aircraft that have flown with biofuels include the Gripen, A-10 Warthog, MV-22B Osprey, AV-8B Harrier and MH-60S Seahawk[9].

In addition to powering aircraft, biofuel blends have also been used to power naval equipment. In 2012, the US Navy utilised biofuel blends in destroyers, a missile cruiser, and a fleet replenishment oiler in a military exercise[10]. As part of its Flotta Verde green fleet initiative, Italy, too, uses "green diesel" — second-generation biofuels from vegetable oils and tallow — to refuel offshore patrol vessels Italy has also tested submarine applications for green diesel, although there is little public information testifying to the success of these tests.

Both civilian and military circles are actively investing research and development (R&D) funds into other forms of biodiesel and biofuels, as well as into measures to increase the efficiency of all biomasses.

Synthetic kerosene can be blended with petroleum fuels for lower carbon emissions,[11] as was explored with test flights of a US Air Force B-52 bomber using Syntroleum in 2006. However, synthetic fuels are expensive to produce and maintain and are also time-consuming to produce in large quantities. As such, their utility to the armed forces is more limited than other biomass alternatives — which could potentially include Jatropha in the future owing to the fact that it is easy to grow and has a high oil yield. Separately, third-generation algae-derived biofuels are recognised as the most promising for their prevalence and high efficiency levels — but they are not a viable solution, given the massive capital investments they require.

For all biomasses, a technical challenge to overcome is increasing the level of hydrogen to match the combustion performance of traditional aviation fuels and JP-8. R&D is needed to adjust the composition of biomasses to make them more efficient, but, equally importantly, to also make them "cleaner". The higher hydrogen balance in traditional aviation fuels results in lower carbon emissions, which is not yet matched in biomasses. Indeed, biofuels pose an issue in this regard: "green" does not necessarily equate to "clean".

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[9] Knus Larsen, "Unfolding Green Defence": 15.

[10] Ibid.

[11] Delanie Lamprecht, "Fischer-Tropsch Fuel for Use by the US Military as Battlefield-Use Fuel of the Future," *Energy and Fuels* vol. 21 (2007): 1448-1453.

This reality is brought further to light when taking other greenhouse gases into account. The oxygen from biofuels can cause harmful increases in nitrous oxide that cancel out any reductions in carbon emissions. Even worse, nitrous oxide is graded to have 295-298 times the global warming potential of carbon dioxide.[12] As such, the cost of biofuels is only one consideration: the disproportionately high nitrous oxide emissions also puts into question the very "green" nature of biofuel utilisation when assessing the environmental impact.

Figure 1: Advantages and disadvantages of biofuels

Pros	Cons
• Tests yield no changes in performance in comparison to petroleum-derived fuels • 50-85% reduction of carbon emissions in comparison to petroleum-derived fuels per test flight	• Not guaranteed to be less expensive than fossil fuels • Mixed reviews on environmental impact owing to hydrogen imbalance and nitrous oxide release offsetting lower carbon emissions • Higher maintenance costs and potentially corrosive effects with rubber • Continued dependency on import sources, given land constraints in small nation-states for dedicated biofuel facilities • Unintended downstream consequences of diverting land from food production to biofuel production

II. Methanol-based fuel cells

Fuel cells, which convert "[the] energy of chemical reactions into electrical energy without combustion and with virtually no pollution", are used to both generate and store energy.[13] The most important proton exchange membrane

[12] "Understanding Global Warming Potentials," United States Environmental Protection Agency (2017). Accessed December 20, 2017. Available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[13] Anna Welch Crull, "Direct Methanol Fuel Cells," *Altenergy.com* (October 1, 2006). Accessed September 1, 2017. Available at: http://www.altenergymag.com/content.php?issue_number=06.10.01&article=dmfc

fuel cells (PEMFCs), a type of fuel cell developed primarily to power vehicles, that have military application are direct methanol fuel cells. Over the past decade, military applications of methanol fuel cells have gained traction with customers including the US Army and US Air Force, as well as the German and Belgian armed forces. An alternative power source, these plug-and-play solutions allow warfighters to utilise off-grid and recharge remotely high-energy gear such as radios, GPS devices, remote and mobile surveillance systems, satellite equipment, and rugged computers.[14]

Of particular note is the fact that methanol-based fuel cells have proven to actually increase —not just maintain — operational effectiveness by increasing the mobility of "dismounted warriors". The operational advantage comes in the form of unburdening warfighters from carrying heavy equipment, and using fuel cell storage technologies in forward operating bases. Methanol-based fuel cells developed by companies such as Protonex, UltraCell, and SFC Energy weigh as little as 4 kg, replacing the need for batteries, chargers, and specialised equipment that on average weigh more than 20 kg. Furthermore, they are reported to entail significant decreases in energy consumption for multi-day missions — all the while lowering acoustic, visible, and thermal signatures[15]. The German company Siemens has used fuel cells in its air-independent propulsion system for German Type 212 Howaldtswerke-Deutsche Werft submarines, which may offer similar advantages in the naval domain.

The low signatures also make PEMFCs attractive for unmanned aerial vehicles (UAVs). In May 2017, one year after delivering a prototype, Protonex Technology Corporation completed test flights of the Boeing Insitu ScanEagle UAV using PEMFCs and a high-pressure hydrogen fuel tank. The Singapore company Horizon Energy Systems is recognised internationally for developing alternative fuel cells for micro-UAVs, with its accolades including tripling the duration that a civilian South Korean UAV could stay airborne[16].

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14 Janadhanan Pillai Narayana Das, "Fuel Cell Technologies for Defence Applications" in *Energy Engineering*, ed. K.V. Raghavan and P. Ghosh (Springer Nature Singapore Pte Ltd, Singapore: 2017): 9-18.

15 Ryan J. Umstattd, "Future Energy Efficiency Improvements within the US Department of Defense: Incentives and Barriers," *Energy Policy* vol. 37 (2009): 2873.

16 "Bluebird Unveils 10 hours Endurance Civilian UAV, Powered by Horizon," *Horizon Energy Systems* (January 2014). Accessed December 9, 2017. Available at: https://www.hus.sg/copy-of-news

Figure 2: Advantages and disadvantages of methanol-based fuel cells

Pros	Cons
• Compatibility with current equipment (e.g., “drop-in” replacements) • Ability to blend direct and reformed methanol fuel cells with gasoline • 80% weight reduction of kits for soldiers • Increased mobility of warfighters owing to off-grid power solution • Demonstrated use for range of electrical and electronic devices, as well as platform-level with UAVs and submarine propulsion systems • Low acoustic, visible and thermal signatures • Quicker turnaround between missions owing to faster recharge than batteries	• Increasing methanol prices, particularly in Asia (although projections show 2016 as trough) • Methanol production unlikely in Singapore • China by and large the global price setter, with large production facilities and half of global consumption • Higher toxicity and higher flammability, as well as lower density than other alternative fuels such as ethanol • “Methanol crossover” making PEMFCs less efficient owing to fuel permeating through electrolyte membrane

III. Hydrogen fuel cells

Owing to its prevalence and high efficiency rates, pure hydrogen energy is another alternative source that armed forces have considered for cutting energy costs — particularly for electricity — and reducing carbon emissions. Similar to methanol-based fuel cells, its silence is an attractive feature for military users. Although the density of hydrogen makes it far more efficient than other types of fuel cells, hydrogen as an energy carrier is prohibitively expensive to generate, store, and transport. Generating hydrogen energy requires more fossil fuels than it does to simply use the fossil fuels in equipment and on bases. The inherent need to use fossil fuels for hydrogen energy puts into question its status as an “alternative” energy source. Nonetheless, interest from the armed forces has been sustained for nearly two decades — and recently renewed, with an army-grade, electric pickup truck being designed by TARDEC and General Electric.

In Japan, Mitsubishi Heavy Industries and the Japan Agency for Maritime Earth Science and Technology (JAMSTEC) have teamed up to work on fuel cell-powered autonomous/unmanned underwater vehicles (AUVs/UUVs) since

1998, putting out prototypes of both the Urashima and Second Generation Long Cruising AUV. Both of these prototypes use hydrogen energy; the latter has fewer hydrogen leakage issues.[17] Because fuel cells store reactants on the outside of their structure and have lower acoustic signatures than batteries, PEMFCs significantly reduce the weight and detectability of vehicles.[18] Germany and France also have put forth UUV prototypes, and the United States and China have produced designs for hydrogen-powered UUVs.

UAVs with hydrogen fuel cells vary greatly in size. At the small end of the spectrum is the Ion Tiger UAV, which set an endurance record of 48 hours and 1 minute for small electric UAVs in April 2013. The Ion Tiger uses hydrogen tanks which compress 21 more times the amount of energy than batteries do.[19] Further, its quieter, more efficient engine enables it to stay airborne for longer and also has freed up weight to carry 6 lb (2.7 kg) payloads. On the heavier end is Boeing and Aurora Flight Science's High Altitude, Long Loiter (HALL) platform, which is intended to carry payloads over 1,000 lb (454 kg) and, thanks to hydrogen power, can still fly for over 100 hours.[20] These differences also speak to the range in mission types for which hydrogen fuel cells would be applicable if some of the technological disadvantages are eventually overcome.

Figure 3: Advantages and disadvantages of hydrogen fuel cells

Pros	Cons
• Abundance of hydrogen supply in theory and ability to create from renewable sources • Creation of water as by-product simplifies military logistics	• Prohibitively high production costs • Limited transportation and distribution options; few filling stations and inadequate storage systems • Higher risk of explosion than combustion engine alternatives

17 Alejandro Mendez, Teresa J. Leo and Miguel A. Herreros, "Fuel Cell Power Systems for Autonomous Underwater Vehicles: State of the Art," *International Conference on Energies* 1 (March 18, 2014).

18 Janadhanan Pillai Narayana Das, "Fuel Cell Technologies for Defence Applications": 14.

19 Andrew Tarantola, "This Liquid Hydrogen UAV Just Flew For Two Days Straight," *Gizmodo* (May 14, 2013). Accessed September 10, 2017. Available at http://gizmodo.com/this-liquid-hydrogen-uav-just-flew-for-two-days-straigh-504876691

20 "Aurora plans two versions of Orion long-loiter UAV," *FlightGlobal* (July 20, 2007). Accessed December 9, 2017. Available at: https://www.flightglobal.com/news/articles/aurora-plans-two-versions-of-orion-long-loiter-uav-215584/

IV. Hybrid electric vehicles

A more viable green technology than hydrogen fuel cells is hybrid electric drive for vehicles that are battery-powered and use gasoline engines when the batteries run out. In comparison to two-speed gas engines, electrical power offered by hybrid electric drive (HED) uses less energy when operating at low speeds. Generally speaking, vehicles powered by single engines are known to be more efficient than HED, but militaries nonetheless have experienced anecdotal success with HED, largely depending on domain, speed, and acceleration. In the naval domain, both the United Kingdom and United States have retrofitted destroyers with HED propulsion, with the US Seventh Fleet destroyers estimated to achieve 16 per cent efficiency gains[21]. In the naval domain, HED has greatest utility in the case of vessels that operate at low speeds. Currently, most vessels have to expend large amounts of fuel to operate regardless of speed, whereas the use of HED in slower vessels could free up precious fuel for high-speed craft.

Efficiency gains have been proven to be twice as high for HED in the land and aerial domains. In developing its HED ground combat vehicle, BAE Systems found that the HED battery packs enabled fast acceleration, high torque, and hill-climbing abilities — exceeding performance requirements offered by the internal combustion engine.[22]

In the air domain, HEDs offer the added advantage of significant thrust. One example is the hybrid turbine-electric Excalibur UAV, which travels at 530 mph (853 kph) — twice as fast as helicopters — with the ability to accelerate more than 300 knots in the air.[23] The US Defense Advanced Research Projects Agency (DARPA) is currently looking into how constant-volume combustion hybrid engines from the "Vulcan" turbojet could be used for surface vessels.

Regardless of domain, a pitfall for militaries considering the adoption of HEDs is that the high voltage in batteries renders them dangerous, with users having been electrocuted in some cases.

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21 "$32.7 million to General Atomics for DDG-51 Propulsion System Prototype," *Defense Industry Daily* (July 12, 2009). Accessed August 28, 2017. Available at http://www.defenseindustrydaily.com/327M-to-General-Atomics-for-DDG-51-Propulsion-System-Prototype-05598/

22 Dave Ahearn, "GCT Program Overview," *Ground Combat Technology* 3:4 (August 2012): 6.

23 Eric Hagerman, "The Present and Future of Unmanned Drone Aircraft: An Illustrated Field Guide," *Popular Science* (February 24, 2010). Accessed September 4, 2017. Available at: http://www.popsci.com/technology/article/2010-02/field-guide-flying-robots

Figure 4: Advantages and disadvantages of hybrid electric vehicles

Pros	Cons
• Efficiency gains achieved when operating at low speeds in naval domain • Faster acceleration in aerial domain	• Charging at stations not as fast as fuel cells, elongating mission turnaround time • Depending on speed, single-engine-powered vehicles may be more efficient • High voltage increases risk of electrocution for users

V. Photovoltaic energy

To date, photovoltaic, or solar, fuel cells have been utilised by militaries to reduce energy consumption and extend the time on station for disaggregated units, as was best demonstrated by the US Marine Corps' use of solar technologies in Afghanistan's Helmand province in 2010. Using the Ground Renewable Expeditionary Energy System (GREENS), the ZeroBase Generator, and the Solar Portable Alternative Communication Energy System (SPACES), the Marines were able to cut fuel usage by 90 per cent.[24]

In Europe, the United Kingdom has been a leader in developing solar-powered air conditioning systems for troop tents[25]. On the other side of the Atlantic, the US Army has retrofitted trailers to transform them into Hybrid Energy ITV Trailer (HEIT) Tactical Quiet Generators, with photovoltaic energy simplifying the entire expeditionary logistics supply chain. Reducing the expensive logistical tail of military operations is a key motive for such efforts, but the surge in the exploitation of photovoltaic energy over the past five years stems also from the operational advantages of lowering detectability and enhanced safety of troops.

With its ability to enhance the endurance of unmanned vehicles, photovoltaic energy is now used to power a variety of unmanned vehicles, foremost among them the QinetiQ/Airbus Zephyr[26] and the Boeing Vulture

[24] Lisa Daniel, "Marines Prove Energy Efficiencies in Afghanistan," US Department of Defense (May 5, 2011). Accessed December 9, 2017. Available at: http://archive.defense.gov/news/newsarticle.aspx?id=63841

[25] Fiott, "Reducing the Environmental Bootprint," 10.

[26] Rob Goodier, "Solar Plane Aims for New Record: 3 Months Aloft Without Pilot or Fuel," *Popular Mechanics* (July 7, 2010). Accessed December 9, 2017. Available at: http://www.popularmechanics.com/flight/drones/how-to/a5914/solar-plane-zephyr-uav-record/

II.[27] With solar cells installed on top of their wings and rechargeable lithium-ion batteries inside, these unmanned vehicles are capable of flying for weeks or maybe even months — and, depending on the altitude, can also overcome cloud cover issues, which are endemic in tropical climates.

Figure 5: Advantages and disadvantages of photovoltaic energy

Pros	Cons
• Reduced power demand in bases, particularly forward-operating and expeditionary bases • Longer time on station for disaggregated units • Proven applicability for unmanned vehicles • 90% fuel use reductions, as proven in Helmand province • Market forces significantly cutting costs • Off-grid energy storage capable of maintaining electricity for months in case of electricity grid disruption	• Minimal mission flexibility owing to weather constraints, particularly given significant cloud cover in Southeast Asia. • Space-based solar alternative prohibitively expensive • Track record from desert conditions could mean benefits are overstated for other environments • Potential security risks to military drills, military frequencies/ communications, and surveillance technologies

[27] Rebecca Boyle, "Boeing Wins Bid to Build Vulture, the Solar Spyplane That Stays Aloft for Five Years," *Popular Science* (September 18, 2010). Accessed December 9, 2017. Available at: https://www.popsci.com/technology/article/2010-09/boeing-wins-bid-build-solar-plane-flies-five-years-end

Green Technologies for Tomorrow

In addition to the technology areas reviewed above, other technologies could classify as "green" in the future, should they overcome significant technical and cost challenges. Three such technologies are introduced below.

I. Pulse detonation engines

Still in development, pulse detonation engines aim to produce thrust through near-constant volume combustion and constant pressure combustion. This constancy renders them more efficient than turbojets and turbofans: if able to compress quickly and add heat constantly instead of in bursts, pulse detonation engines would be able to achieve a higher thermodynamic efficiency and could also replace moving parts that take up too much weight in engines currently used today. In comparison to Brayton cycle thermodynamics operations, pulse detonation technologies are 25-35 per cent more efficient, with projections of reaching 55 per cent greater efficiency by 2030. Pulse detonation research currently focuses on turbojets and cruise missile systems, with some already considering eventual UAV applications in the distant future.[28]

II. Piezoelectricity

Piezoelectricity is the process that describes electricity generation from motion. In the military domain, research is currently focused on how to generate electric energy from the mechanical energy generated by warfighters and land vehicles. As R&D for "exoskeleton" armour expands, piezoelectricity-generated boot steps and other motions could be fully maximised. In 2009, TARDEC added piezoelectric sensors onto armour to measure how much energy would be generated by the impact of bullets and also to relay real-time information about the enemy's weaponry and location.[29] Capturing the energy is a technical challenge, but, if harnessed in the future, then piezoelectricity could also be utilised to power electrical devices and provide operational advantages similar to those described in the methanol-based fuel cells section.

[28] Omari D Buckley et. al., "An Integrated Command and Control Architecture Concept for Unmanned Systems in the Year of 2030," US Naval Postgraduate School (June 2010): 89.

[29] Clay Dillow, "Smart Armor Knows Its Own Strength, As Well As The Enemy's," *Popular Science* (November 26, 2009). Accessed December 9, 2017. Available at: https://www.popsci.com/technology/article/2009-11/smart-armor-knows-how-its-own-strength-and-enemy

III. Biodegradable platforms

DARPA is also researching biodegradable platforms as another futuristic technology area. With a focus on synthetic biology, DARPA's Inbound, Controlled, Air-Releasable, Unrecoverable Systems (ICARUS) programme was launched in 2015, building upon previous research on vanishing materials dating back two years[30]. One example of how such materials would be used is having aerial delivery vehicles that, having completed their tasks, disappear into thin air without polluting the environment and without having to return to their original launch sites.[31] Similar to other futuristic technologies, the early research and technology (R&T) stages give few signals about the eventual cost-effectiveness of such materials.

30 "Vanishing Acts: A Call for Disappearing Delivery Vehicles," US Defense Advanced Projects Research Agency (October 9, 2015). Accessed December 9, 2017. Available at: https://www.darpa.mil/news-events/2015-10-09

31 Ivan Amato and Troy Olsson, "Episode 11: The Thin-Air Specialist," US Defense Advanced Projects Research Agency (July 13, 2017). Accessed December 9, 2017. Available at: https://www.blubrry.com/voices_from_darpa/25217980/episode-11-the-thin-air-specialist/

Conclusion

While the motivations to engage in green defence largely revolve around cost reductions, the processes — in particular, the development of green technologies — thus far tend towards securing operational advantages. Of the technology areas highlighted, most of the tangible technology areas of today boast concrete augmentation of military readiness levels. Nevertheless, budget constraints dictate that economic affordability will always take precedence over operational advantages.

The operational advantages offered by green technologies can be summarised in three categories that will help to define the future battlefield. First are portable technologies for the warfighter, including wearable solar cells and methanol fuel cells to reduce the weight and increase the power duration of equipment used in military missions. Next is the ability to generate, distribute, and store power more efficiently and with lower signatures, as is particularly relevant for forward operating bases. Similar to portable technologies, distributed power allows disaggregated units to operate for longer in the field. Lastly, alternative energy sources could become a force multiplier for unmanned systems, with some prospective green technologies offering higher torque and higher thrust and almost all extending flight times.

In each of these categories, the applicability to smaller armed forces is clear. By emphasising smaller platforms with more dual-use components, including unmanned vehicles, they can be made available to a greater number of users. Distributed power systems also make it more difficult for guerrilla fighters or terrorists to target centralised systems with reverberating impact on wider forces or populations at large. If fuel cells become more widely adopted, their lower signatures could also serve to “emancipate” relatively stealthy features to the advantage of armed forces unable to procure or operate the more expensive and sophisticated stealth platforms.

Even with the operational advantages of green technologies now coming to light, questions of affordability remain valid. One hindrance to further green technology adoption is the tendency to treat alternative energy sources as direct substitute goods — which can be used as one-for-one replacements serving the same purpose — for fossil fuels. The US Navy’s experience shows that it is reductive to compare commodity prices against alternative energy sources. Although US green defence initiatives are most advanced on strategic, technological, and operational levels, they are also most vulnerable to politicisation, which overemphasises fluctuating commodity prices at the expense of a more strategic view. A direct comparison of biofuel to petroleum prices, as done in the United States, fails to take into account the costs of equipment such as batteries and rechargeable systems that fuel cells could render redundant.

Even if the sunk costs are higher for green technology utilisation, the assumption is that they achieve a higher return-on-investment more quickly — as can already be seen in the civilian realm with solar panels, which are expensive to install, but are able to reduce electricity bills over the long run. When applied to the military realm, the operational advantages should be seen in a similar light: even if fuel cells are more expensive to procure than batteries and chargers, it is the extra-economic benefits of aiding readiness and sustainability that make them less expensive in the long-run.

Another reason that the economic perspective on green defence technologies shows promise for smaller armed forces is that militaries can reap the benefits of commercial technologies whose prices are driven down by market forces. To follow with the example of solar panels, increased demand has attracted more producers to the market as they can achieve economies of scale, and this development in turn has forced prices down. As a “green revolution” becomes more prevalent in the civilian domain, it is likely that several of the technologies reviewed here will become more affordable.

Not all green technologies offer a good balance of economic and strategic advantages for expansive use. For example, algae biofuels and hydrogen fuel cells are expected to remain prohibitively expensive. And, some renewable energy sources will garner less interest owing to natural and geographic limitations, for example, the applications of photovoltaic energy may be more interesting above the clouds than on land outside of desert conditions. What is more, certain “green” technologies may not be as “clean” as purported, notably when taking into consideration the hydrogen imbalance and nitrous oxide production in biofuels. The environmental impact is a crucial consideration and should not be taken for granted in green defence matters. Nonetheless, the crux of green defence, i.e., its rationale and reality, lies in cost effectiveness and enhanced readiness. Green defence technologies, whose operational and environmental considerations render them more complex than classic substitute goods, do not offer a one-size-fits-all solution to armed forces: their diversity in size, form, price, and utility means they can find applicability for armed forces of any size.

About the Author

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