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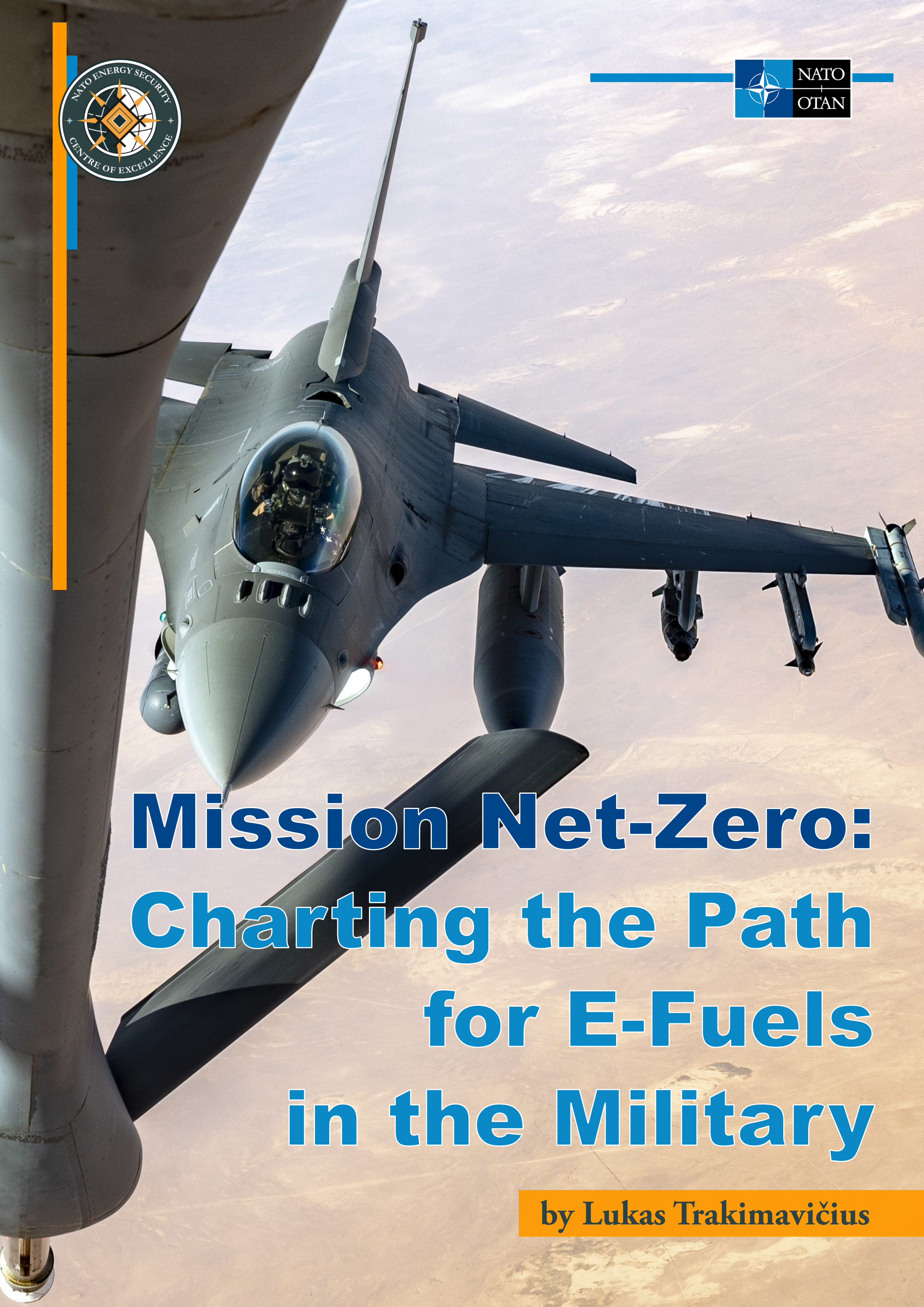

Mission Net-Zero: Charting the Path for E-Fuels in the Military

by Lukas Trakimavičius

Content

INTRODUCTION

Climate change is without a doubt one of the greatest challenges of our time. Unlike most traditional security threats, climate change respects no boundaries and affects every corner of the world. It not only impacts the environment, but also economic stability, social equity, and security across the globe. According to the world's premier body on assessing climate change, the United Nations Intergovernmental Panel on Climate Change (IPCC), humans are the main cause of driving CO_2 emissions to record levels.[1] Global temperatures are now 1.1°C above pre-industrial levels and, unless drastic actions are taken, they're likely to reach 1.5°C in the early 2030s. If that threshold is exceeded, scientists have found that climate disasters will become so extreme that people might not be able to adapt.[2] Basic components of the Earth system will be fundamentally altered. Meanwhile, heat waves, famines and infectious diseases could claim millions of additional lives by century's end.[3]

The military consequences of climate change will also be numerous, overlapping and interconnected. As sea levels will rise, military installations in low lying coastal areas will be increasingly exposed to high-tide flooding and storm surge. More powerful and frequent extreme weather events such as heavy rain, flash floods, droughts and wildfires will also call for more humanitarian assistance and disaster relief missions than ever before. Climate change will also exacerbate existing political tensions in areas exposed to heatwaves, desertification and droughts, thereby raising the risk for social unrest and large scale migration. As the polar cap melts, it will also open up new shipping routes and unearth vast quantities of natural resources, thereby fueling geopolitical tensions.

In a bid to tackle climate change, governments across the globe have pursued a number of ambitious strategies. Arguably the most important of them is the goal to reduce global carbon dioxide emissions to net-zero by 2050 and to limit the long term increase in average global temperatures to 1.5°C. So far, over 120 countries, including some of the largest polluters – the European Union, the United States and Japan – have set a net-zero target by 2050.[4] Countries like China and India have also set up net-zero targets for the years 2060 and 2070 respectively.[5] However, a colossal amount of work is needed to turn these impressive ambitions into reality, especially given the range of different circumstances among countries and their differing capacities to make the necessary changes. In fact, it would not be an exaggeration to say that this calls for nothing less than a complete transformation of how we produce, transport and consume energy.

The armed forces are no exception to this growing effort of tackling climate change. While historically militaries were except from reporting their CO_2 emissions and had little appetite for having decarbonization targets, this trend is increasingly changing.[6] In recent years a growing number of militaries, including the likes of France, the United Kingdom and the United States, have announced voluntary carbon reduction goals.[7] Moreover, at the 2022 Madrid Summit, NATO announced its ambition to reduce the greenhouse gas emissions of its assets and installations by at least 45% by 2030 and reach net-zero by 2050.[8]

Moving the needle

As it usually is the case with decarbonization strategies, they are much easier said than done. This is because when it comes to the armed forces, the single greatest challenge is the substitution of fossil fuels with cleaner alternatives for operations and exercises – i.e. moving people and equipment around. Emissions from burning fossil fuels, especially in aircraft, are the main source of military emissions, varying by country and equipment type.[9] This means that even if militaries would succeed in following through such efforts like the deployment of renewable energy power generation systems, the establishment of net-zero build standards in fixed installations or the adoption of various behavioral practices that promote energy savings – it would still fail to cut emissions on a truly large scale.

There is more than one way how the military's dependence on fossil fuel use can be reduced. Arguably one of the easiest fixes is to work on increasing the energy efficiency of internal combustion engines (ICEs) that are used in military vehicles. By some estimates, it is still possible to improve the efficiency of ICEs in some vehicles by well over 20%, thereby decreasing fuel consumption by a significant margin.[I] Even greater fuel savings could be achieved by through the adoption of hybrid engines that would combine an ICE with an electric motor and a battery.[10] Such vehicles operate by switching between the ICE and the electric motor based on driving conditions and power requirements, thereby optimizing fuel efficiency, reducing the sound profile and decreasing emissions.[II]

Figure 1. A hybrid electric version of the Joint Light Tactical Vehicle by Oshkosh Defense (credit: oshkoshdefense.com)

[I] For a comprehensive discussion about the potential of ICE efficiency improvements in the armed forces, see: "Powering the U.S. Army of the Future".

[II] At least a number of militaries are currently exploring the potential of hybrid engines. The US, for example, has been since 2022 researching the prospects of using hybrid engines in vehicles like the Bradley and the Humvee, among others.

Yet another alternative is to focus on developing and deploying liquid biofuels that could be used across different army branches. In fact, in recent years there's been no shortage of such experimentation efforts. Already back in 2014 the Italian Navy successfully tested a 50:50 blend of conventional marine fuel and biofuel from vegetable oil and biomass, and saw no losses in operational capability of its ships.[11] More recently, the Swedish Armed Forces have been conducting tests on the use of biofuels on its fighter aircraft. Numerous experiments have shown that it is possible to use biofuel to power aircraft such as the Gripen by using both 50:50 kerosene-biofuel blends and 100% biofuel.[12]

Figure 2. Swedish Gripen fighter jet during its test flight on pure biofuel in 2017 (credit: saab.com)

Yet, for all their advantages, there are significant flaws with these decarbonization pathways. While gradual improvements on engine efficiency or adoption of hybrid engines can help reduce fossil fuel consumption, this would still have a fairly limited impact on the overall shift away fossil fuels. After all, vehicles would still burn fossil fuels in their ICEs, even if in smaller quantities.

Meanwhile, despite the fact that biofuels provide a reliable and immediate solution to emissions reduction, it has a serious scalability problem. Simply put, in the coming years it will be very difficult to supply enough feedstock to meet the burgeoning demand for biofuel in hard-to-abate sectors like aviation, shipping and, potentially, the armed forces.[13] In fact, estimates suggest that by the year 2027, bio jet fuel, which can be used by commercial air carriers and air forces alike, will only account for 1-2% of overall jet fuel use.[14] While in the long run it would be possible to scale up the production of biofuels, this would not come without obstacles. Major infrastructural developments would be needed to grow, handle, transport and store immense quantities of biomass that could be used to produce biofuels. On top of that, boosting the production of first generation biofuel feedstock could affect food security due to the competition for direct land use.[III] Therefore, while biofuels can and will play an important role in the decarbonization of the transportation sector and, possibly, even the armed forces, it is very unlikely that it could meet all of their fuel needs.

[III] First generation biofuels are derived from edible crops like corn, rapeseed and sugarcane, among others. Second generation biofuels use non-edible biomass like crop residues, wood and waste. Third generation biofuels mostly focus on algae to avoid competition with edible crops. However, these fuels face significant scalability and cost effectiveness challenges.

Enter e-fuels

This is where e-fuels, also known as electrofuels, could come into play. The term e-fuels refers to a category of emerging synthetic fuels that might have a significant role in the energy transition. These fuels result from the combination of "green” or "e-hydrogen," which is produced through the electrolysis of water using electricity from renewable energy sources and either CO_2 or nitrogen. Because these fuels use CO_2 that is captured either from a point source (heavy industrial emitters such as steel, cement, petrochemicals, etc.) or from the air using a process known as direct air capture (DAC), the burning of these fuels does not add to overall CO_2 emissions. Meanwhile, the nitrogen is obtained through a process called air separation, which separates atmospheric air into its primary components, typically nitrogen and oxygen.

In broad terms, there are two groups of e-fuels. The first group refers to carbon-based e-fuels like e-kerosene or e-diesel and e-methanol. These fuels can be adapted to work in existing vehicles and infrastructure with fairly minor adjustments. While they are easier to integrate into existing fuel systems than other e-fuels, there are difficulties associated with their production process. More specifically, their production costs are expected to remain very high until cheap renewable electricity and CO_2 becomes more accessible.

Meanwhile, the second category of e-fuels includes non-carbon based fuels like hydrogen and e-ammonia. The production of these fuels is relatively simpler and cheaper than the production of carbon-based fuels. However, their use poses greater challenges due to their handling complexities and the fact that they aren't compatible with existing ICEs. For these non-carbon-based fuels to become a viable option, the development of a complex transport and refuelling infrastructure, as well as progress in fuel storage and propulsion systems, is crucial. Moreover, since these fuels cannot be as seamlessly integrated as their carbon-based counterparts, their adoption is expected to be gradual, contingent on fuel availability, the renewal of vehicle fleets and the development of new fuel handling infrastructures.

[IV] Different government, private and research entities use different terms to refer to the same category of fuels. E-fuels can also sometimes called be called power-to-X (PtX), power-to-liquids (PtL) and power-to-gas (PtG) fuels. Although “green” or “e-hydrogen” is used as a feedstock to produce e-fuels, it can also be used and described as an e-fuel in its own right.

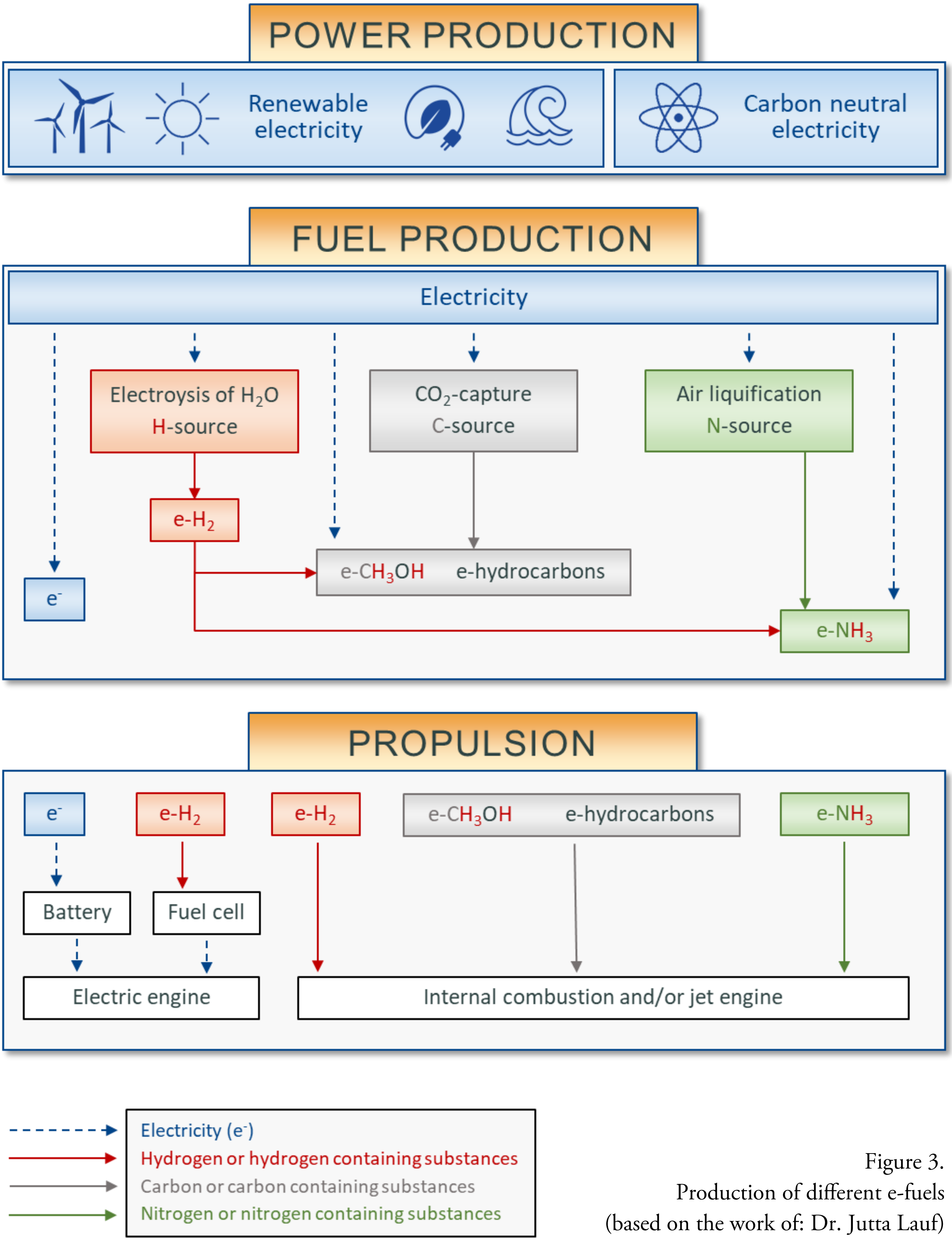

Figure 3.
Production of different e-fuels
(based on the work of: Dr. Jutta Lauf)

While the potential of e-fuels in decarbonizing transportation has in recent years received significant attention from private companies, governments and international organisations, its potential utility in reducing the carbon footprint of the armed forces received much less scrutiny. The reasons for that could be numerous, but possibly the single most important of them relates to the unique and demanding operational requirements of military vehicles. After all, it is already very difficult to predict how these fuels could facilitate the energy transition in civilian sectors like shipping, aviation and heavy duty transportation over the next 5-20 years. Yet, this pales in comparison to the challenge of anticipating how these fuels could be used to decarbonize vehicles that would be expected to perform well in battlefields and some of the most challenging of environments.

This paper intends to fill this gap. It will focus not only on comparing the production process and the properties of different e-fuels, but it will also highlight their potential utility (or lack thereof) across the main three military domains: land, sea and air. This will be done by exploring how different technological pathways square up against each other in categories such as performance, logistics, integration and safety. Granted, this admittedly rough categorization does not reflect the vast multitude of factors that logisticians and military planners need to take into consideration. This paper also does not intend to provide a comprehensive technical and economic assessment of e-fuels. Rather, the goal of this paper is to raise awareness about current technological advances in alternative fuel technologies and to contribute to the policy level debate about the need to decarbonize the armed forces.

In total, 1 alternative propulsion system (lithium-ion batteries) and 4 e-fuels (green hydrogen, e-methanol, e-ammonia and e-hydrocarbons) will be covered this paper. Lithium-ion batteries have been included in this analysis because they offer arguably the most efficient decarbonization pathway for light-duty vehicles. Green hydrogen has been chosen because it has long been perceived by governments and international organizations as possibly the single most important fuel and energy carrier of the post-fossil fuel era. Meanwhile, both e-ammonia and e-methanol have been selected because of their potential in decarbonizing the shipping industry. Ultimately, e-hydrocarbons such as e-kerosene have been included because they are widely viewed as one of the main solutions to reducing the CO_2 emissions in the aviation industry.

Table 1. Properties of different fuels[15]

E-fuel	Volumetric energy density [MJ/l]	State of transportation	Flashpoint [°C]
(E-)Hydrogen	0.0108 (at atm) 3.12 (at 350 bar) 8.5 (liquid)	Gas (compressed 20°C at 300 – 700 bar), in containers and pipelines. Liquid (-240°C, 13 bar), in containers (ships)	-231
(E-)Ammonia	12.8 (liquid)	Gas in containers (20 °C, compressed) Liquid in pipelines (1 bar, -33°C or 10 bar 20°C)	132
(E-)Methanol	15	Liquid	11
E-kerosene (JP8/Jet A)	~40	Liquid	38
E-Diesel	~41	Liquid	~60
Marine oil	~36	Liquid	~60

LITHIUM-ION BATTERIES

Developed during the 1970s, lithium-ion cells offer remarkable power in compact and lightweight forms, surpassing the lead-acid and nickel-cadmium units that previously held sway in the rechargeable battery market. Pioneering the rise of portable electronics, lithium-ion batteries have emerged as the dominant force in electric vehicles and many other applications.[16]

All batteries operate on a common principle. They store electrical energy in chemical form, where chemical reactions between positive and negative electrodes produce electrons that flow through an external circuit, generating electricity. The term "lithium-ion" refers to an entire battery category, specifying the type of ions transferred between anode and cathode, rather than the specific materials constituting the electrodes. Anodes typically feature graphite and dictate the battery's charging speed, while cathodes, constructed from a range of materials, primarily influence the battery's cost and energy storage capacity.[17] Within the electric vehicle sector, two prominent cathode chemistries vie for supremacy: NMC, employing lithium, nickel, manganese, and cobalt in varying proportions, and LFP, comprised of lithium, and iron phosphate.[18]

Yet, despite the differences between the two most popular lithium-ion battery types that are used by most automotive original equipment manufacturers (OEMs), the following section will not differentiate between them. Instead, it will focus on the general electrification potential of the armed forces using lithium-ion batteries. This is because despite the differences in their energy densities, charge rates and costs, in the context of military mobility NMCs and LFPs still perform fairly similarly.[V]

Performance

Battery electric vehicles (BEVs) already provide a reliable solution for reducing CO2 emissions of light-duty vehicles. However, their operational utility in a military context is fairly limited, primarily due to weight constraints.

For BEVs to substantially reduce the carbon footprint of the armed forces, they must be capable of decarbonizing not only non-tactical vehicles, but also the heavy equipment such as tanks and combat vehicles.[VI] However, the current generation of batteries would fail to accomplish this task because of the great weight of these vehicles. For example, armoured vehicles and main battle tanks can weigh anywhere between 20-70 tons. A significant portion of this weight comes from the armour plating and the ammunition that they carry. By contrast, a BEV like a Tesla S

[V] Given the higher power density, which could ensure a greater driving range, NMCs would probably provide the better technological pathway for military mobility. However, the advantage of LFPs is that they cost less to produce, boast a superior lifespan (more recharge cycles), and are safer than NMCs.

[VI] Various militaries worldwide are currently experimenting with or have already adopted all-electric support and non-combat vehicles. These include items such as e-bikes, passenger cars, vans, and light-duty trucks. However, due to the different operational requirements, these direct electrification efforts are unlikely to meet equal success when it comes to combat vehicles.

model weighs around 2 tons with the 70-kWh battery accounting for roughly a quarter of its weight, making it easily the heaviest component of the vehicle.[19] By some estimates, about 60% to 75% of a battery's total weight comes from the cells and the materials they contain, while the remaining 25% to 40% is made up of the battery's metal casing, cables, and thermal and battery management systems.[20] If an existing armored vehicle or main battle tank were to be electrified using the same power density battery cells as those in the Tesla S model, it can be reasonably assumed that these 20-70-ton military vehicles might need to carry anywhere between 5 to 17 tons of lithium-ion batteries on board. It goes beyond saying that the sheer added weight of these batteries would severely limit the operational capabilities of these vehicles.[VII]

Admittedly, one could argue that there may be no need to replace existing models of armored vehicles or main battle tanks with their electric counterparts. As technologies evolve, so do the battlefield requirements for different military systems. In the future, 70-ton battle tanks may become obsolete if other vehicles, or a combination thereof, can perform the same functions. However, current military conflicts, such as Russia's war against Ukraine, suggest that the primacy of the main battle tank remains undisputed. As long as this is the case, it is important to consider the challenges of reducing the CO_2 footprint of even the largest and heaviest equipment that militaries operate.

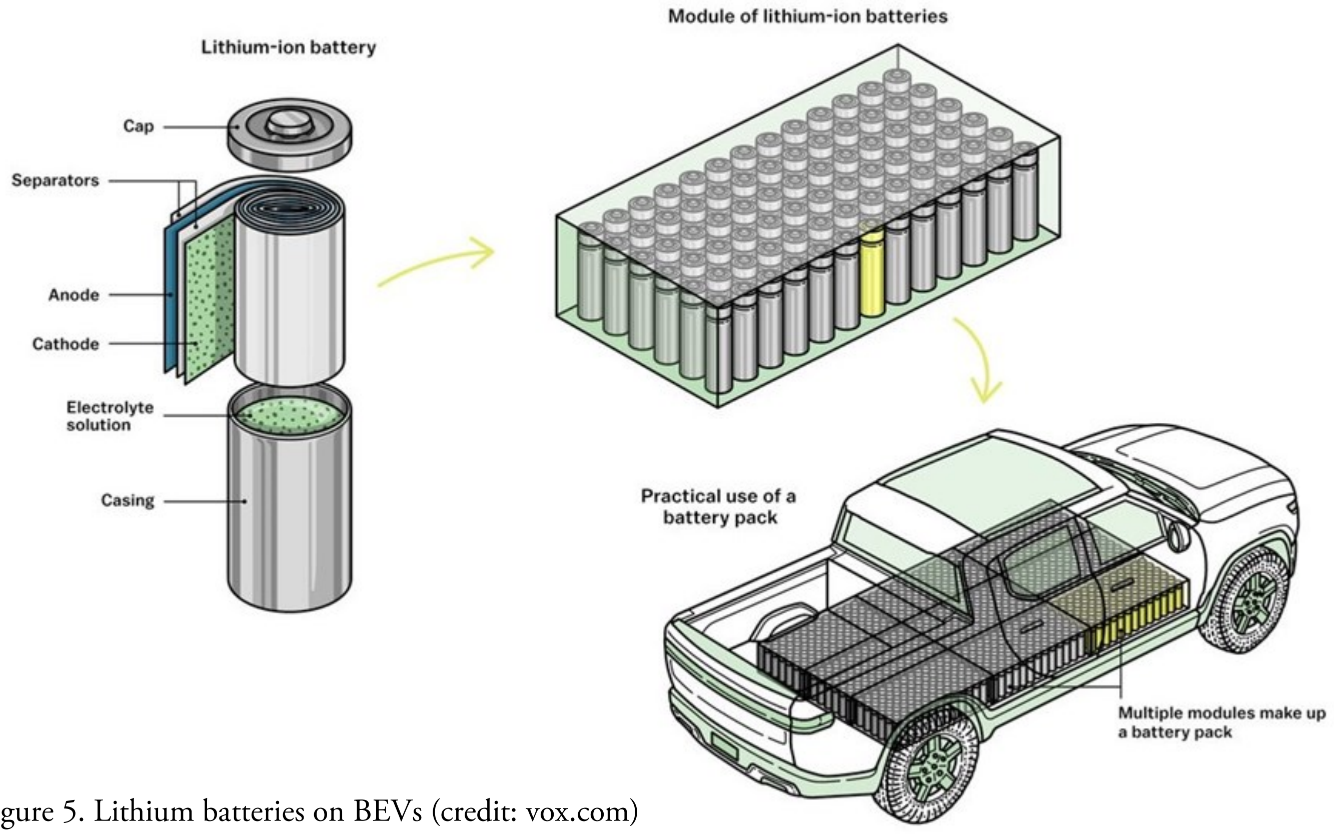

Figure 5. Lithium batteries on BEVs (credit: vox.com)

[VII] It is important to note that as battery chemistries improve and their overall power densities increase the current rule of thumb that up to a quarter of a BEVs weight comes from the battery might become less relevant. However, given that battery densities are unlikely to ever rival the power densities of liquid fossil fuels, it is extremely unlikely that some of the heaviest vehicles that are currently used by the militaries would ever become electrified.

The added weight would also make the electrification of military trucks very unlikely. This is because it would significantly reduce the amount of cargo a single truck is able to deliver, thereby increasing the need for more trucks during resupply missions. In practice, this could have fatal consequences as it would expose a greater number of troops to roadside bombs and enemy attacks. In fact, estimates suggest that between 2001 and 2010, over 18,000 American troops were killed in Iraq and Afghanistan during land transport missions alone.[21] In Afghanistan this may have equaled to nearly one casualty for every 24 fuel resupply missions.[22]

Range would also be an issue for battery-powered military trucks. In 2023, the Swedish multinational car manufacturer Volvo has released its newest FL Electric truck — one of the most advanced battery-powered medium-duty trucks in the market, which boasts a maximum driving range of around 450 kilometers.[23] These trucks are designed for urban distribution and have a load capacity of 5.5 tons.[24] While the drive range of the FL Electric truck is more than enough for civilian needs, it would likely struggle to meet the military's needs. This is not solely due to the fact that the FL Electric truck lacks personnel protection features (whose hypothetical addition would undoubtedly increase its overall weight and even further decrease the operational range), but also because many military trucks are typically capable of covering distances of well over 500 km.[VIII]

Again, if at some point in the future battlefield requirements change and shorter range military trucks would be able to do the job, then trucks like the FL Electric could definitely see greater utility on the battlefield. But until operational requirements change, it is important to be clear-eyed about the pros and cons of replacing current military truck fleets with their electric counterparts.

Figure 6. Volvo FL electric truck (credit: electrive.com)

[VIII] BEVs also suffer from battery capacity degradation. This is primarily caused by charge cycles. As the battery goes through charge cycles — discharged while driving and charged back up while plugged in — it slowly loses its energy storage capacity, and, in turn, its maximum driving range.

Meanwhile, when considering the navies, the prospects for direct electrification are even more discouraging. This is because navies maintain fleets warships that have very specific operational requirements and are much times bigger than even the heaviest of combat vehicles such as the 70-ton M1 Abrams tank. Based on their load out, Horizon-class destroyers weigh around 7,000 tons, Brandenburg-class frigates about 4,000 tons, and Sandown-class minehunters approximately 600 tons. Therefore, from a practical perspective, it would be unwise to focus on electrifying these warships, as the sheer weight of the extra batteries would significantly reduce their operational capabilities. In addition, factors such as the risk of running out of fuel (or, more accurately, electricity) in the middle of the ocean and the difficulty of obtaining sufficient electricity and charging these (presumably) gigantic batteries clearly undermine the prospects of naval electrification.

Ultimately, the potential for electrifying the air force is equally slim. Despite ongoing advances in battery storage technology, it is impossible for existing batteries to meet the operational requirements of most military aircraft. Generally speaking, fighter jets need to reach supersonic speeds and large transport aircraft needs to be able to carry loads of over 100 tons for thousands of kilometers. Yet, due to various technical limitations, none of this is achievable with batteries and electric engines. Only high-density fuels such as kerosene and ICEs can provide the right weight and the right thrust for such aircraft.

Granted, a growing number of companies are currently working on battery-powered aircraft, which might revolutionize flying. For instance, Pyka, a US-based startup is developing a small cargo unmanned aerial vehicle (UAV) called "Pelican Cargo".[25] The designers expect it to be able to carry loads of up to 181 kg at distances of over 300 km and maintain a cruise speed of over 100 km/h. Meanwhile, Eviation, an Israeli-US start up, is working on a battery-powered plane that could be either used for cargo transportation or regional travel purposes.[26] Going under the name of "Alice" the aircraft is expected to be able to transport a payload of around 1100 kg, have a maximum range of some 180 km and fly at speeds of over 450 km/h. Although both of these airplanes are designed for civilian purposes, it is not inconceivable that at some point in the future similar designs could be adopted for niche applications by the air forces.

Figure 7. Pyka's Pelican Cargo UAV (credit: flypyka.com)

Logistics

Viewed purely from an operational perspective, BEVs would present considerable logistical hurdles and provide minimal advantages compared to fossil fuels. There are at least two reasons for it.

First, BEVs would require considerable amounts of carbon-neutral electricity. Even very compact civilian BEV models like the Nissan Leaf, which has a 40-kWh battery, weighs about 1.6 tons, and has a driving range of up to 243 kilometers, consume substantial amounts of power.[27] In fact, fully charging such a small battery would require around 32 standard 250-watt solar panels operating during a sunny day. Meanwhile, if similar batteries were installed on military trucks or combat vehicles, these vehicles would consume much more electricity. In a purely hypothetical scenario, consider a 70-ton electric Abrams M1 tank that relies on the same battery chemistry as a Nissan Leaf. If we assume that the tank's battery capacity is proportional to its weight, the tank would need to have a 1,750-kWh battery on board. To fully charge this battery in a single day, it would require the energy produced by over 1,400 solar panels operating under sunny conditions.[IX] Therefore, a military formation with 100 electric Abrams M1 tanks (excluding other types of equipment or vehicles for simplicity's sake) would need a colossal total of 140,000 solar panels to recharge them. These solar panels alone would take up an area of 230,400 m², equivalent to about 32 football fields.[X]

Granted, these back-of-the-envelope calculations should not be regarded as anything more than an extremely rudimentary attempt at illustrating the power needs of military BEVs. After all, they do not reflect the multitude of factors involved in different battery designs and chemistries. They also do not take into account the engineering solutions that would necessarily have to be implemented when redesigning existing vehicles for electrification. Furthermore, they do not consider the multitude of factors that go into solar power generation, storage, and distribution systems. However, the goal of this exercise is to point out that sourcing enough carbon-neutral electricity would be next to impossible if a fleet of military BEVs were dispatched to a geographically remote area. At this point, no combination of deployable carbon-neutral energy solutions could realistically generate this much power.[XI]

Second, there would also be an issue with charging all of these vehicles. Depending on factors like battery size and charging station capacity, it could take a very long time to fully charge a military BEV. For instance, a civilian 4.5-ton Hummer EV that has a 210-kWh battery pack can fully recharge its batteries using a standard 240V charger in under 24 hours.[28] However, for

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[IX] 1) 70 tons/1.6 tons x 40-kWh = 1,750-kWh; 2) assuming there are about 5 peak sunlight hours in a day, we have: 5 h/day x 250 W = 1250 Wh = 1.25 kWh of energy generated by one solar panel in a day 3) to charge a 1,750-kWh battery in a single day, we would need: 1,750 kWh/1.25 kWh/day = 1,400 solar panels.

[X] 1) 144,000 panels × 1.6 m²/panel = 230,400 m²; 2) assuming we use FIFA recommended football fields that are 105 meters in length and 68 meters in width and a have a total area of 7,140 m². 230,400 m²/7,140 m² = 32.25 football fields

[XI] It is also unclear if the so-called micro modular nuclear reactors, like the ones that the US is developing could provide enough power for a fully electrified brigade combat team or even larger military formations. This is because these micro reactors are expected to generate between 1-5 MW of electricity – fraction of the total needs of a hypothetical fully electrified combat vehicle fleet.

obvious weight and battery size reasons, it would take much longer than that to recharge an electric M1 Abrams tank replacement. By contrast, the refueling of a standard M1 Abrams tank using regular jet fuel takes less than 10 minutes.[29] While the deployment of more powerful chargers (800-volt DC fast charging, etc.) would help reduce the recharging times of heavy vehicles by a significant margin, this would still be much slower than what liquid fuels could offer.[30]

Ease of integration

It would be a tough challenge for military planners to integrate a large fleet of BEVs. For starters, existing vehicles equipped with ICEs would need to be entirely replaced with hypothetical battery-powered counterparts. This implies a potentially premature retirement of a significant amount of equipment that could still be put to good use. Furthermore, the current fossil fuel handling system would largely need to be abandoned in favor of establishing an entirely new electricity-based charging infrastructure. This shift would entail significant costs and inefficiencies due to stranded equipment and major infrastructural changes. Personnel responsible for the logistics would also have to undergo specialized training. While the armed forces could partially benefit from the civilian charging infrastructure, this would only marginally alleviate the costs of overhauling the entire military fuel handling system.

The introduction of a substantial fleet of military electric vehicles would also strain the existing power grid infrastructure. Simultaneously charging dozens or hundreds of vehicles using energy-intensive power chargers could result in heightened electricity demand during peak hours, possibly leading to grid instability or overload. Without substantial parallel investments in expanded grid capacity, effectively managing a large fleet of military BEVs would be exceedingly challenging.

Safety

While BEVs are considered safe for regular driving scenarios, there could be significant challenges when deploying them in battlefield conditions. Despite recent advances in energy storage technology, batteries still carry a notable risk of fire and explosion.[XII] In fact, in recent years there have been several high-profile instances of battery failures and thermal runaways in devices like cell phones, tablet computers, and even vehicles.[31] While in the civilian domain some of these risks can be mitigated through enhanced design, handling, and quality control, in a military setting this would be a much more challenging task. Hence, it would likely be too risky to deploy vehicles to situations where their batteries could be vulnerable to penetration or destruction by projectiles or explosives.[XIII]

[XII] There's a reason most airlines do not allow passengers to take lithium-ion batteries in their checked luggage. Uncontrollable battery thermal increases can be caused either by internal defects or when they age, leading to the growth of dendrites — tiny, conductive, branch-like structures that can short-circuit the battery and generate heat.

[XIII] It is well documented that if battery packs of EVs go into thermal runaway and the vehicle bursts into flames, these fires are very difficult to extinguish. This is primarily because of the large amount of energy that is released when a lithium-ion battery short circuits.

HYDROGEN

Hydrogen, the lightest and most abundant element in the universe, holds the promise of becoming a key player in the energy transition due to its high energy content and minimal environmental impact. It is a versatile fuel that can be produced from various sources, including water and natural gas.

The transition to green hydrogen production is a critical step in achieving carbon neutrality. Green hydrogen — as opposed to grey or blue hydrogen, which originate from coal and natural gas respectively — is produced through a process known as electrolysis. For hydrogen to be considered green it has to rely on renewable sources of energy such as solar, wind or hydro to power a device called an electrolyser. An electrolyser consists of a conductive electrode stack separated by a membrane to which a high voltage current is applied. This results in an electric current in the water, which causes water to break down into its components: hydrogen and oxygen.

Hydrogen serves as a good energy carrier capable of decarbonizing the transportation sector via two technological pathways: hydrogen internal combustion engines (HICEs) and fuel cell electric vehicles (FCEVs), more commonly known as hydrogen fuel cells. While both routes have their own pros and cons, FCEVs are currently seen as the superior alternative. For starters, FCEVs offer higher energy conversion efficiencies compared to HICEs. Fuel cells directly convert hydrogen's chemical energy into electrical energy through an electrochemical reaction, whereas ICEs rely on hydrogen combustion to drive pistons and generate mechanical energy. For context, FCEVs can achieve a conversion efficiency of around 60%, while HICEs typically trail behind at 25-30%, allowing fuel cells to use much more of hydrogen's overall energy.[32]

Furthermore, FCEVs produce no CO_2 emissions and generate only water vapour as a by-product. In contrast, HICEs emit pollutants during combustion, including nitrogen oxides (NOx), which contribute to smog and acid rain formation. Therefore, given the clear advantages of FCEVs over HICEs, the hydrogen section of this paper will exclusively focus on FCEVs.

[XIV] A low carbon alternative to green hydrogen can come in the form of pink hydrogen. Like green hydrogen, its process incorporates electrolysis, but it uses electricity sourced from nuclear power plants as opposed to renewables.

[XV] Currently, there are three main electrolyzer technologies: alkaline, Polymer Electrolyte Membrane (PEM), and Solid Oxide. The latter is still in the development stage, while the alkaline technology is mature, and PEM is in a fairly early phase of commercialization. All of them have advantages and disadvantages in terms of cost, efficiency, flexibility and scalability.

[XVI] Fuel cells can also be powered by other energy carriers such as methanol and ammonia. However, across most publications the term FCEV usually refers to hydrogen fuel cells. Therefore, across this paper, the term FCEV will exclusively refer to fuel cells that are powered by hydrogen.

[XVII] In principle, the environmental impact of HICEs can be mitigated through after-treatment methods similar to those used for diesel engines. However, this would come at an additional cost.

[XVIII] In recent years a number of OEMs, including the likes of BMW and Mazda have experimented with the idea of using pure or blended hydrogen in ICE's. However, most of those projects have been eventually abandoned due to the difficulties of commercializing this technology. Toyota is one of the last major OEMs that is still actively working on a hydrogen ICE.

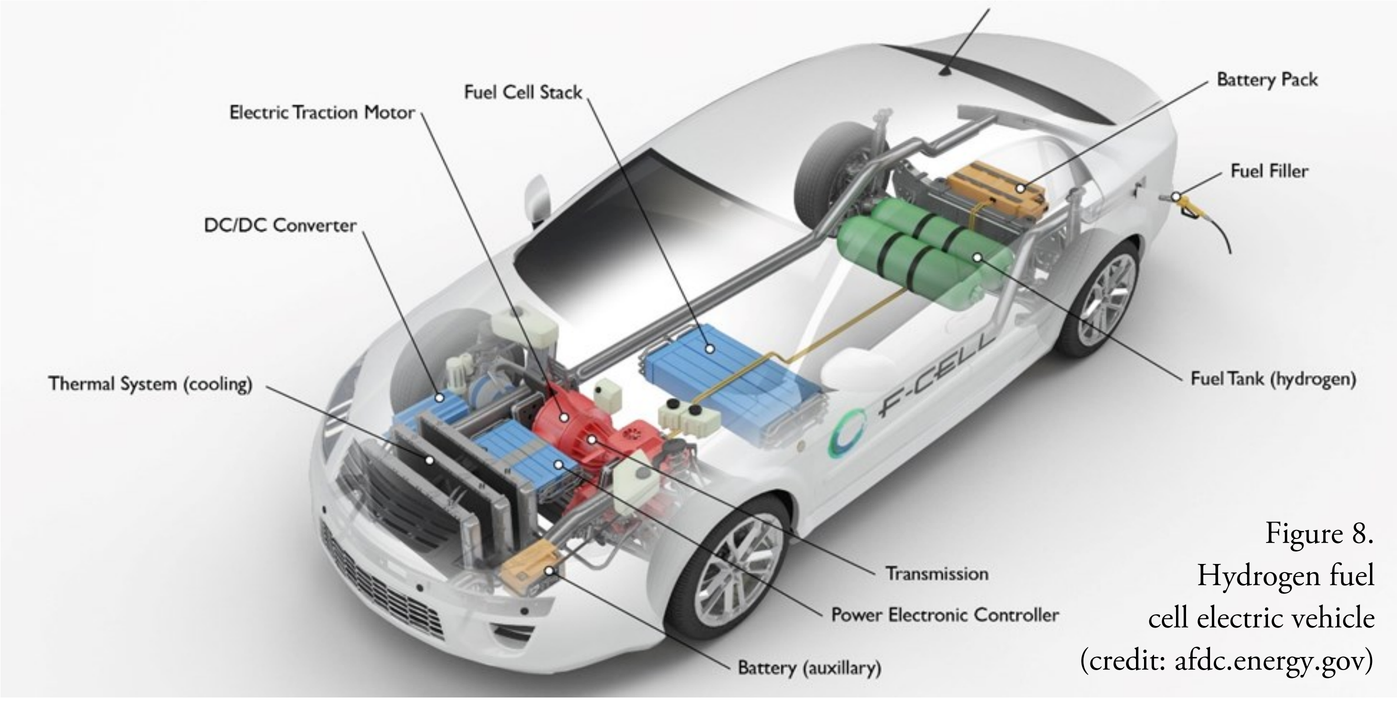

Figure 8.
Hydrogen fuel
cell electric vehicle
(credit: afdc.energy.gov)

Performance

FCEVs would be a generally much better alternative for combat vehicles and military trucks than BEVs for several reasons. Hydrogen fuel cells have roughly four times the power density of batteries.[33] Their fuel tanks, while still bulkier than traditional liquid fuel tanks, are also lighter and more compact than batteries. Thus, in relative terms, combat vehicles powered by fuel cells would face a smaller disadvantage compared to their gas-guzzling counterparts, while military trucks could travel longer distances and haul more cargo, compared to BEVs.

In addition, hydrogen fuel cells handle temperature fluctuations better than batteries. For instance, the performance of some lithium-ion batteries can decline by approximately 50% at temperatures of -20°C and around 40% at -10°C.[34] If temperatures rise to 40°C, their efficiency also diminishes by about 20%. In contrast, when exposed to sub-zero temperatures, hydrogen fuel cells only experience a reduction in efficiency of around 20%, while in hot climates, their efficiency deteriorates far less than those of lithium-ion batteries.[35]

Similarly to BEVs, the prospects of using FCEVs on warships are not great. Despite their superior power density to batteries, they would still fall short of meeting the military's operational requirements. Large ships shifting from heavy fuel to hydrogen would need much larger fuel tanks — about four times their current size.[36] As result, hydrogen-powered warships would have reduced operational utility, leading to shorter travel distances, smaller crews, and less power projection capabilities.[XIX]

While the potential of hydrogen fuel cells on surface vessels is very limited, they might have better success on certain types of submarines. This is because fuel cells offer very low noise levels, as

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[XIX] Hydrogen fuel cells might make some sense on small auxiliary ships, which are not designed or expected to engage in combat duties or venture beyond the port area. However, given the relatively low CO_2 emissions of such vessels, the introduction of such a step would do fairly little to address the navy's carbon footprint.

almost no sound is produced by the electrochemical reaction.[37] The only components in the engine room that could contribute to a sound signature are the compressors and pumps for fuel, water, and cooling. Although purely hydrogen-powered submarines do not exist, some navies already employ hybrid diesel-hydrogen fuel cell propulsion systems. For instance, the German-built Type 212A submarine, operational since 2005, employs a fuel cell to provide an alternative power source when submerged.[38] The fuel cell significantly extends its underwater endurance and enhances the reputation of this model as one the quietest submarines in the world.[39]

Figure 9. Type 212A submarine (credit: bundeswehr.de)

By contrast, when it comes to cleaning up the air force, hydrogen does not seem particularly promising. The reasons closely mirror those of batteries: the relatively poor power density of hydrogen would pose a significant weight challenge for military aircraft, while electric engines would unlikely be able to produce enough thrust to meet the air force's needs.

Granted, several companies including Airbus and Universal Hydrogen are currently working on hydrogen-powered aircraft. Airbus aims to test its ZEROe concept aircraft, designed to accommodate up to 100 passengers by approximately 2026.[40] Universal Hydrogen, on the other hand, has already conducted a debut test flight of its modified De Havilland Canada Dash 8 aircraft in early 2023, showcasing the potential of hydrogen as a fuel for short-distance passenger planes.[41] Yet, despite these and other attempts to bring hydrogen to the skies, the unique speed, range, maneuverability or airlift requirements of military aircraft make it near impossible that hydrogen-powered fighter jets like the F-22 or cargo planes like the Airbus A400M would take flight anytime soon, if at all.

Figure 10. Universal Hydrogen's first Dash 8 hydrogen-electric flight in 2023 (credit: aviationweek.com)

Logistics

In comparison to lithium-ion batteries, hydrogen fuel cells offer a notable advantage in refueling times. This is because hydrogen tanks can be refilled almost as quickly as regular diesel tanks. For example, the refilling of a hydrogen tank on a mid-sized Toyota Mirai sedan takes no more than 5 minutes.[42]

Unfortunately, this is where the strengths of hydrogen end and its drawbacks become apparent. In addition to need to cut CO2 emissions, one of the other reasons why the military is interested in alternative propulsion systems lies in the need to decrease the logistical burden and vulnerability of supply lines during out-of-area missions. However, rather than improving the situation, FCEVs might exacerbate this problem. A recent study commissioned by the US Department of Defence determined that, compared to conventional jet fuel, due to lower power density, four to seven times as many hydrogen-powered trucks (depending on whether it is compressed or liquefied) would be required to transport an equivalent energy amount to the battlefield.[43]

Furthermore, handling hydrogen is notably more complex than hydrocarbon fuels. Hydrogen storage presents a challenge as it requires costlier and specially constructed fuel tanks that can prevent hydrogen molecules from leaking. Regular fuel tanks cannot be used for this task because direct exposure to hydrogen can lead to the fracturing and embrittlement of many metals.[44]

Also, long distance hydrogen transportation is impossible without either compression or liquefaction. Choosing the latter, which is more space-efficient, requires a substantial amount of energy to cool it to -253°C and keep it in a liquid state. Based on existing liquefaction technologies, this process consumes more than 30% of the energy content of hydrogen and is also very costly.[45]

Finally, the transportation of liquid hydrogen via cargo ship is difficult due to factors like boil off and sloshing. Boil off occurs during transportation when liquefied hydrogen evaporates into gas due to heat transfer, leading to hydrogen loss and potential pressure build up in tanks.[XX] Meanwhile, sloshing happens due to the acceleration or deceleration of the vessel. This can pose a significant challenge to the tank's integrity, as the movement of liquid hydrogen can lead to pressure fluctuations, structural stresses, and fatigue over time.[46] While both of these issues can be minimized through additional investments and design tweaks, transporting hydrogen by ship is likely to remain a complex task for many years to come.

Ease of integration

The potential introduction of hydrogen fuel cells would present significant challenges to the armed forces. Just as it would be the case with lithium-ion batteries, it would be impossible to retrofit existing military vehicles in a way that they could accommodate hydrogen fuel cells. As a result, certain vehicles might require premature retirement and scrapping. Given that many

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[XX] Boil-off associated with the transportation of liquid hydrogen can consume around 1%-3% of the hydrogen content per day.

military vehicles are built to last for 30 years or more, the effort of replacing them with hydrogen fuel cell-powered alternatives would be both costly and inefficient.

Furthermore, to enable the widespread integration of hydrogen fuel cells an entirely new set of refueling infrastructure would need to be established across all three military domains: air, land, and sea. This costly and monumental task would require the commissioning of new vessels capable of transporting hydrogen, personnel training, as well as developing pipelines, storage tanks, and all associated components. According to some estimates, hydrogen pipelines can be up to 50% more expensive than natural gas pipelines and a single liquid hydrogen refueling station may cost anywhere between $3 and $20 million, depending on its refueling capacity.[47]

Granted, the challenge of high capital costs might be justified if the armed forces were to completely transition away from hydrocarbon fuels and fully adopt hydrogen on all its vehicles. However, given the low probability of such an event, it is much more likely that militaries would need to develop and maintain multiple parallel refueling systems. In practical terms, this means that logisticians would have to not only establish new hydrogen refueling infrastructure, but also keep portions of the existing hydrocarbon handling infrastructure. It goes beyond saying that this would lead to extremely high capital and operational costs.

Safety

Hydrogen, though difficult to handle, is not as hazardous as commonly believed. Its lightweight nature causes quick dispersion into non-flammable concentrations upon release.[48] Consequently, a hydrogen leak at a refueling station is unlikely to lead to a Hindenburg-type explosion and might even be less dangerous than gasoline. It is also important to note that hydrogen fires emit less ambient heat compared to gasoline fires due to its higher heat of combustion and non-thermal radiation emissions.[49] Therefore, a hydrogen fire could be less harmful to people and the immediate surroundings.

However, these attributes don't necessarily guarantee safety of liquid hydrogen for military use. First, a notable risk remains that a tank containing liquefied hydrogen could be compromised by a projectile, potentially causing an explosion. Although tests suggest that bullet impacts might not lead to ignition or tank rupture, it is very likely that larger projectiles or explosive devices could yield different outcomes.[50] Second, there's the possibility that even if a projectile wouldn’t cause a hydrogen tank to explode, it could still lead to fuel leakage. This could pose a significant safety issue especially on a ship’s deck. A liquid hydrogen spill might result in embrittlement and contraction of some of the metals, thereby impacting the vessel's structural integrity.[51] There is also the risk of personnel suffocation if hydrogen were to leak into a confined space.

E-METHANOL

Methanol, also referred to as methyl alcohol or wood alcohol, is a versatile chemical compound that may play a significant role in the energy transition. This colourless, flammable and poisonous liquid can be produced through a number of processes such as natural gas reforming or biomass conversion. Its value lies in the ability to serve as a clean burning fuel, a feedstock for chemicals, and a potential energy carrier. Given its high energy density and liquid form, methanol is considered a feasible alternative to traditional hydrocarbons, especially when produced through sustainable methods.

E-methanol, or electro-methanol, represents a more environmentally friendly variant of methanol. While the bulk of regular methanol is currently sourced from natural gas, e-methanol is produced using renewable electricity. The initial production step of e-methanol mirrors that of green hydrogen, involving electrolysis to split water into hydrogen and oxygen. Then the green hydrogen is combined with CO_2 sourced either directly from the atmosphere or from industries with high CO_2 emissions. This combination of elements is facilitated by a process called methanol synthesis, which applies heat and pressure to transform hydrogen and CO_2 into a liquid fuel.

As it is the case with hydrogen, methanol can power vehicles in at least two different ways. It can be used to electrochemically generate electricity through direct methanol fuel cells (DMFCs) or it can be used in ICEs. From an efficiency perspective the DMFC pathway might seem as a better alternative because fuel cells can extract more useful energy from the same amount of methanol. Also, as DMFCs produce electricity without any direct combustion, they are able to produce less emissions than methanol ICEs. Yet, given the added weight of the fuel cells, most industry players that are interested in harnessing e-methanol for the energy transition are looking at ways of using methanol in ICEs. Therefore, this section will exclusively focus on the methanol combustion pathway.[XXI]

Performance

In most aspects, methanol is a superior alternative for decarbonizing the armed forces to both BEVs and FCEVs. With approximately half the volumetric density of conventional fossil fuels such as gasoline and diesel, methanol-powered combat vehicles or military trucks would require fuel tanks around twice as large to cover the same distance. While this still places methanol-powered vehicles at a significant disadvantage vis-à-vis its fossil fuel-powered peers, the difference is much less stark than with BEVs or FCEVs.

Arguably the greatest advantage of methanol compared to BEVs or FCEVs lies in its versatility. It not only can be used in ICEs as a standalone fuel, but it can also be blended with regular oil-based fuels in varying proportions. This is possible because methanol and oil-based fuels are

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[XXI] Innovative startups that focus on producing e-methanol include the likes of Carbon Recycling, INERATEC, REintegrate and Icodos, among others.

chemically compatible and share similar combustion characteristics. In fact, methanol has already been incorporated into gasoline blends worldwide at low (3% to 5%), medium (15% to 30%), and high (50% to 100%) volume concentrations.[52] Although fuel blends using high concentrations of methanol lead to reduced mileage and lower engine performance, in some circumstances this trade-off might be acceptable given the environmental benefits. Therefore, it is hardly surprising that already in 2019, China's automotive company Geely unveiled the M100, the world's first methanol-powered heavy truck for civilian use.[53] This 6x4 truck has an engine capable producing 480hp and a massive 1,320 liter combination fuel tank, which allows the truck cover distances of over 1,500 km at standard load out.[54]

Figure 11. Geely's M100 methanol-powered heavy truck was introduced in 2019 (credit: zgh.com)

Methanol might also prove to be a reliable alternative to regular oil-based fuels in very cold temperatures. Fuels like gasoline typically freezes at temperatures around -40°C and diesel starts gelling at temperatures below -12°C. In contrast, methanol can remain in liquid form at much colder temperatures due to its freezing point of around -97°C. This property makes methanol more suitable for use in colder climates where the use of gasoline or diesel could become more challenging.

However, when compared to gasoline or diesel, methanol does come with some drawbacks as it does not perform well in high temperatures. In extremely hot conditions (above 40°C), methanol can be prone to vapour lock, a situation where the fuel vaporizes before reaching the ICE.[55] This can disrupt the fuel flow, lead to engine stalling, reduce power and impact the overall drivability of the vehicle. Even if some engines can be optimized to perform better with methanol or methanol-gasoline blends in hot climates, the general trend remains that as temperatures increase, the efficiency of methanol engines decreases.

While methanol could probably play a role in decarbonizing the land forces, it is in the maritime domain where it would truly excel. Given its ability to virtually eliminate sulfur oxide and particulate matter emissions, while also reducing nitrogen oxide emissions, many shipping companies are increasingly opting for methanol as a cleaner-burning alternative to marine fuel oil.[56] For instance, the Danish shipping giant Maersk recently ordered 19 ocean-going dual-fuel vessels capable of running on both marine fuel and methanol.[57] Additionally, the French shipping company CMA CGM has announced plans to add six new dual-fuel methanol-powered vessels to its fleet.[58] Meanwhile, China's largest shipping company, COSCO, plans to acquire twelve dual-fuel container ships in late 2022.[59] And these are but a few examples of industry leading shipping companies betting on methanol to become one of the main clean fuels of the future.

Figure 12. Maersk unveils its first methanol-powered container ship in 2023 (credit: CNBC.com)

Granted, it is not yet clear if methanol could effortlessly decarbonize the navy, at least in the near term. After all, the aforementioned shipping companies are only eying duel-fuel engine ships and not pure methanol-powered vessels (though this could also be partly because of the limited availability of methanol as a fuel). It is also critical to emphasize that military vessels have stricter operational requirements compared to cargo ships. Warships must accommodate larger crews, carry weaponry and other equipment, and operate at much greater speeds. Therefore, the lower power volume of methanol compared to marine oil fuel could potentially be a deal breaker for some classes of vessels.

Regardless of its potential to clean up the navy, or, at least the merchant fleet, methanol would likely have far less utility in reducing the emissions of the air force. In theory, given the fairly similar combustion properties of methanol and kerosene, it would be possible to design a fighter jet or a large cargo aircraft that would run on methanol. Yet, the fact that such air planes could be built, does not necessarily mean that they would be very practical. These aircraft would require fuel tanks that would be twice as big, which would put them at a massive competitive disadvantage compared to airplanes using regular kerosene.

Logistics

Compared to other types of alternative fuels and propulsion systems, methanol is one of the easiest fuels to handle. This is because it already ranks among the top five chemical commodities shipped globally each year.[60] It is also readily available through existing global container terminal infrastructure and is well positioned to reliably supply the military. Currently, there are 122 ports worldwide equipped with methanol storage facilities and various ports have already established methanol bunkering regulations or are in the process of doing so.[61] While dedicated bunkering infrastructure for ships is presently limited, it is likely that as the shipping industry expands its methanol-powered fleets and associated infrastructure, the navy could capitalize on these developments.

Figure 13. Methanol storage hubs worldwide (credit: man-es.com)

Meanwhile, for land distribution, methanol can be transported either by truck or train, just like oil-based fuels. Methanol is also much easier to handle than hydrogen or some other alternative fuels. This is because it remains in liquid form within the temperature range of -94°C to 63°C, thereby eliminating the need for pressurization, liquefaction, or costly cryogenic fuel tanks. When it comes to out-of-area missions, the only tangible drawback of handling methanol is that the land forces would require around twice as many trucks to transport an equivalent amount of energy, compared with regular oil-based fuels.

Ease of integration

The introduction of methanol in the military, particularly within the land forces and the navy, would not be a very challenging task. This is especially true if methanol would be introduced in the form of a blend. In some instances, retrofitting of equipment might not even be required, as some ICEs designed for oil-based fuels could readily accommodate methanol blends of up to 10%.

Meanwhile, if the goal was a complete departure from fossil-based fuels in favour of relying solely on methanol, the task would be more complex, but still achievable. With additional investments in the fuel storage and supply systems, and certain engine modifications, it would possible to convert some existing vehicles to run on methanol. Estimates suggest that the conversion costs of a ship could fall in the range of $5 million to $15 million.[62] While at first glance, these costs might seem exorbitant, they are relatively low compared to the expenses of building a new ship, which could reach tens or hundreds of millions of dollars. Similarly, retrofitting a diesel engine in a truck might cost between $40,000 and $50,000 — a fraction of the vehicle's original price.[63]

However, the greatest advantage of methanol, in comparison to most other types of alternative fuels, is that it would be possible to transport it using use existing fuel handling infrastructure. Due to the relatively similar chemical properties of oil-based fuels and methanol, only some modification to existing pipelines, storage tanks and distribution systems would be necessary. This approach would not only significantly cut the energy transition costs, optimize the utilization of current infrastructure, but also ensure that newly deployed fossil fuel handling systems are as future-proof as possible.

Safety

In many aspects, methanol is a safe fuel to handle, comparable to kerosene or diesel. In fact, a recent analysis by the shipping industry body “Together in Safety”, which compared the safety risks of alternative fuels to heavy fuel oil, found that methanol is the safest option for the energy transition.[64] Other fuels that were compared in the study included the likes of hydrogen, liquefied natural gas, and ammonia.

However, despite its reliable safety record, methanol does come with several drawbacks. First, methanol is toxic to humans through ingestion, inhalation, or skin absorption. To ensure safety when working with methanol, it is important to follow safety guidelines and use the appropriate personal protective equipment. Second, methanol has a very low flash point compared to traditional fuels, making it susceptible to ignition from even minor sources. Hence, additional fire prevention measures are required during storage and handling. Third, dealing with methanol fires can be difficult due to its relatively low-temperature flame, which may not be visible under certain conditions. While all of these issues can be effectively managed in controlled environments, handling methanol in a battlefield environment might prove to be a challenge.

E-AMMONIA

Ammonia is yet another substance that might play a key role in the energy transition. This colorless gas, characterized by a distinctive pungent odour, is composed of three hydrogen atoms bonded to a nitrogen atom. Historically, ammonia or its products have been widely used in fertilizers, chemicals, and refrigerants. However, in recent years its potential as an energy carrier has been gaining attention due to its high hydrogen content by weight.

Electro-ammonia, or e-ammonia, represents a more environmentally friendly variant of regular ammonia. Unlike the traditional production method that relies on natural gas as a feedstock, e-ammonia shares its initial production steps with green hydrogen and e-methanol. This process involves electrolysis to generate green hydrogen from renewable energy sources, which is later used in the Haber-Bosch process to synthesize e-ammonia.[XXII] This synthesis entails combining hydrogen gas and nitrogen gas under high pressure and temperature.

Ammonia can serve as a fuel through three distinct pathways.[XXIII] First, it can be burned in ICEs, similar to conventional fuels like gasoline or diesel.[XXIV] Second, it can be directly employed in fuel cells, where the chemical energy stored in ammonia is converted into electrical energy through electrochemical oxidation. Third, ammonia can be transformed into green hydrogen and subsequently utilized in a hydrogen fuel cell. The process involves an additional step, in which ammonia is “cracked” or chemically decomposed into its elemental components: nitrogen and hydrogen.[XXV] This enables the far simpler and more economical storage and transport of hydrogen in the form of ammonia, thereby reducing storage and operational costs. While significant efforts are being directed towards making ammonia ICEs and direct ammonia fuel cells commercially viable, these technologies are still at a relatively low technological readiness level.[65]

Therefore, it is important to note that the following discussion of ammonia's potential role in decarbonizing the armed forces will largely be of a speculative nature. This is because most of the technologies needed for scaling up ammonia use as an energy carrier are not yet deployment ready.

[XXII] It is worth noting that the Haber-Bosch process is used to produce both regular and e-ammonia.

[XXIII] Innovative startups that focus on producing e-ammonia include the likes of Starfire Energy, Eneus Energy and Nium, among others.

[XXIV] Burning pure ammonia is difficult in ICEs due to its low flammability. However, in 2023, the Japanese automotive giant Toyota and the Chinese carmaker GAC unveiled the world's first liquid ammonia-powered ICE for light vehicles. According to the developers, this 2 liter engine produces 161hp and emits 90% fewer carbon emissions compared to its petrol-powered counterpart.

[XXV] It is important to mention that the process of “cracking” ammonia into hydrogen poses significant efficiency problems. This is because the “cracking” process requires thermal energy and results in auto consumption of around 30% of the original ammonia input.

Performance

In some respects, ammonia would have a similar utility to methanol. While it has a slightly lower power density than methanol, it surpasses hydrogen by a considerable margin. As a result, it would be theoretically possible to use an ammonia-powered ICE in combat vehicles or military trucks without experiencing the massive operational drawbacks of BEVs or FCEVs.

Given the favorable chemical properties of ammonia, it is no wonder why developers are eyeing the use this substance as a fuel for heavy duty transportation. In fact, in 2023, a US-based start-up named Amogy, has successfully tested the world's first ammonia-powered semi-truck.[66] Following an eight-minute-long fueling, the semi-truck, having 900-kWh of total stored net electric energy, was tested for several hours at a university campus. It relies on an ammonia fuel cell, which then cracks the ammonia into hydrogen and uses it to power the fuel cell.

Figure 14. Amogy's ammonia-powered semi-truck (credit: amogy.com)

One practical challenge that sets ammonia apart from methanol is its state at ambient temperatures: ammonia is a gas, not a liquid. Consequently, if it were to be used as fuel on combat vehicles, it would likely need to be either compressed (10-15 bar) or cooled to -33°C.[67] While this is easier done than compressing or liquefying hydrogen (which requires pressures of 350-700 bar or temperatures as low as -253°C), the mere need for compression would likely impact the vehicle's design and performance. This is because pressurized and cryogenic fuel tanks are heavier than regular tanks due to their design and materials. These tanks are also typically cylindrical in shape, which might result in reduced on-board space and, consequently, negatively affect operational capabilities.

On the flip side, ammonia could offer a slightly better chance of decarbonizing naval forces than other alternative fuels. While there is currently limited interested in ammonia from the navy, the shipping industry has long believed that, alongside methanol, ammonia could emerge as one of the most viable long-term alternatives to marine fuels. In fact, shipping companies such as Finland's Meriaura and Norway's Amon Maritime aim to launch their pilot ships equipped with ammonia-powered ICEs in 2024 and 2025, respectively.[68] Also, some estimates suggest that ammonia might account for up to 25% of all maritime fuels by mid-century.[69]

Meanwhile, the prospects of using ammonia for the air force are not particularly promising. Right now there are at least several companies that are exploring the potential of using ammonia as aircraft fuel. The most notable among them — Aviation H2 — intends to retrofit a nine-seat passenger jet in such a way that that ammonia could be used to power its turbofan engine.[70] While acknowledging the potential of using hydrogen fuel cells on air planes, the company claims that its approach of using ammonia is more cost-effective and efficient. This is because it would avoid the need to completely replace ICEs in existing aircraft with electric motors.

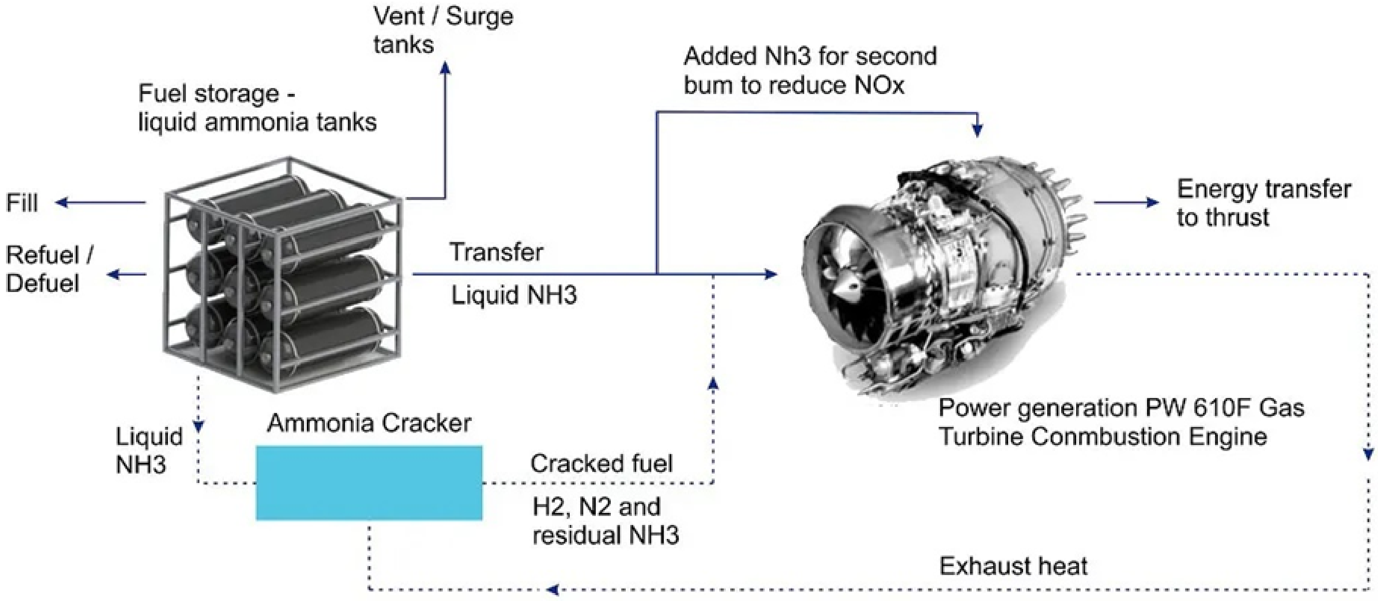

Figure 15. Aviation H2's ammonia-powered engine scheme (credit: aviationh2.com.au)

Still, even if Aviation H2 or some other company succeeds in harnessing ammonia for medium-sized business aircraft, due to its low power density compared to kerosene, it is very unlikely that this fuel could be used on fighter jets or long range cargo aircraft.

Ultimately, it is important to note that unlike hydrogen or carbon based fuels such as methanol or kerosene, ammonia is not a particularly clean burning fuel, even if produced from carbon neutral sources. More specifically, the problem is that ammonia produces large amounts of nitrogen oxides and nitrous oxide when burned.[71] These nitrogen emissions contribute to air pollution and play a role in the formation of both smog and acid rain.

Logistics

Considering that ammonia is already one of the most produced and traded chemicals in the world, there would be far fewer troubles in transporting it compared to fuels like hydrogen. In fact, over 120 ports worldwide can already handle ammonia on a large scale.[72] Moreover, there is no shortage of ships to transport ammonia globally. This is because ammonia is shipped in fully refrigerated tankers often designed to carry liquefied petroleum gas and there are about 200 gas tankers in operation across the world capable of performing this task.[73] Consequently, all this this civilian infrastructure could accelerate the integration of ammonia in the navy.

By contrast, the outlook for land-based transportation of ammonia doesn't appear as promising. While ammonia is already transported by pipeline over thousands of kilometers all around the world, its transportation by cargo truck would be much more challenging. Not only would these trucks need to have pressurized or cryogenic tanks, but more trucks would be required to transport the same amount of energy during out-of-area missions. In fact, it might take between three to four times as many cargo missions to accomplish the same task compared to diesel or kerosene.

Ammonia would also pose significant challenges in terms of fuel handling for the air force. This is primarily due to the need for regular venting of aircraft fuel tanks. Ventilation is done to equalize pressure within the fuel tank, accommodate altitude changes, prevent vapour lock, and fulfil other crucial safety-related functions. However, if ammonia fuel tanks were to undergo venting, the aircraft would effectively release a very toxic gas directly into the atmosphere.

Moreover, there is the question of what happens during an emergency fuel dump.[74] This is a procedure carried out by aircraft to rapidly reduce their overall weight by expelling fuel while in flight. It is typically performed in cases of emergencies or critical situations where the aircraft needs to land shortly after take-off. While the rapid release of regular jet fuel can have negative consequences to the environment, the act of dumping thousands of litres of liquid ammonia would not only be detrimental to the atmosphere, but could also pose a danger to the aircraft and personnel in the airport as well.

Ease of integration

The hypothetical challenge of integrating ammonia into the armed forces is comparable to that of hydrogen. In both scenarios substantial funding would be required to train personnel and establish entirely new refueling infrastructures alongside the existing ones that handle liquid fossil fuels. Such efforts would prove very costly and inefficient unless ammonia, much like hydrogen, were to establish itself as the dominant carbon neutral fuel in the transportation sector.

However, in comparison to hydrogen, ammonia boasts several advantages. First, it might be possible to leverage the existing ammonia handling infrastructure to make it easier for navies to have access to this fuel. This, in turn, might provide greater motivation for the air force and army to follow suit. Second, unlike it the case with hydrogen fuel cells, some vehicles equipped with ICEs could be retrofitted to accommodate liquid ammonia as a fuel. Granted, this would be neither cheap nor easy, but it still could help to reduce the overall energy transition costs and extend the life cycle of existing hardware.

Safety

While ammonia squares up against other alternative fuels fairly well across most categories, it completely falls flat when it comes to safety.

To begin with, ammonia is extremely toxic — more so than any other fuel. At ambient temperature and pressure, it exists as a corrosive and flammable gas, posing a high risk to human exposure through inhalation and skin contact. Exposure thresholds vary depending on the regulating body, but even minimal levels in the atmosphere, such as a mere 30 parts per million (ppm) that can result from minor leaks or routine functioning, can lead to respiratory issues.[75] The danger increases significantly between 500 to 700 ppm, as any level of exposure becomes hazardous, potentially leading to blindness. As concentrations rise further, the likelihood of fatality experiences a significant increase. Therefore, handling ammonia requires very rigorous safety measures, specialized training and the use of protective equipment. Hence, given its high toxicity, it is very unlikely that ammonia could ever play a significant role in decarbonizing the armed forces. This fuel would be simply deemed too risky and hazardous for military use.

Figure 16. Specialized equipment is required when handling ammonia (credit: fertilizercanada.ca)

However, the problems with ammonia do not end there. Instances of ammonia spills, such as those occurring during collisions at sea that may lead to tank ruptures, also pose significant risks.[XXVI] They can be exacerbated if ammonia comes into contact with water, initiating a reaction with air moisture that generates a dense and toxic mist. If such an incident would take place within a port or an industrial zone evacuation of the impacted area would likely be neces-

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[XXVI] To date, the safety record for ammonia transportation has been notably better than that of fossil fuels. However, it's worth noting that this could partly be attributed to the fact that smaller quantities of ammonia are transported worldwide.

sary.[76] The need for evacuation comes not solely due to the presence of the toxic mist, but also because of risk that a major leak might trigger a fire or even an explosion, as it would also be the case with some other fuels.

Furthermore, in contrast with hydrogen or methanol, a serious ammonia spill would also be devastating under the waves. Ammonia dissolves in water to form ammonium hydroxide, which is a highly toxic substance to marine life.[77] It is estimated that a concentration of 1 ppm of ammonia in water is sufficient to kill multiple marine organisms. By some estimates, a ship sinking with a cargo of ammonia could potentially extinguish most life forms across several cubic miles of ocean.[78]

E-HYDROCARBONS

In many ways, e-hydrocarbons like e-kerosene and e-diesel are similar to e-methanol.[XXVII] They follow a similar production path as both require green hydrogen and CO_2 as feedstock. Moreover, both of these processes involve the use of chemical reactions which merge the carbon and hydrogen molecules together. In the case of e-kerosene and e-diesel a process called the reverse water gas shift (RWGS) and then the Fischer-Tropsch (FT) synthesis are most commonly used. However, unlike it is the case with e-methanol, in order to produce e-kerosene and e-diesel, it is also necessary to process the FT synthesis product to obtain liquid fuels for ICEs.[79] The final production phase parallels the production process of regular oil-based fuels as it involves steps like cracking and distillation. In the end, a liquid fuel is created, closely resembling the conventional counterparts of e-kerosene, e-diesel or similar e-hydrocarbons.[XXVIII]

Figure 17. The world's first e-hydrocarbon fuel pilot plant was opened in 2022 in Haru Oni, Chile (credit: porsche.com)

[XXVII] The term hydrocarbon refers to any class of organic chemical compounds composed only of the elements carbon and hydrogen. Unlike e-kerosene or e-diesel, fuels like e-methanol does not fit this category as it also includes molecules of oxygen.

[XXVIII] Innovative startups that focus on producing e-hydrocarbons include the Air Company, Synhelion, HIF Global, Dimensional Energy and OXCCU, among many others.

Performance

Compared to other e-fuels such as green hydrogen, e-ammonia or e-methanol, e-hydrocarbons such as e-kerosene or e-diesel are unsurpassed across all efficiency aspects. This is because for all practical purposes they have the exact same physical and chemical properties of regular kerosene or diesel. Introducing them would not adversely impact the operational capabilities of the armed forces. Therefore, it's not surprising that in 2021, the US Air Force teamed up with the chemical company Twelve to investigate the potential of producing and using synthetic jet fuel as a means to reduce CO_2 emissions.[80]

From a practical perspective, the only real difference between e-hydrocarbons and their conventional counterparts is that the former burn cleaner.[81] This is because fuels like e-kerosene contain fewer particles and aromatic chemicals that produce soot, which in aviation is a by-product of incomplete combustion. Engine soot is the primary contributor to contrail formation, which significantly exacerbates climate warming due to its greenhouse effect on terrestrial radiation.

Logistics

The handling of e-kerosene and e-diesel mirrors that of regular kerosene or diesel. Hence, it offers a clear advantage over vehicles that would rely on batteries, hydrogen, or fuels like e-ammonia and e-methanol. The same exact military vehicles that currently transport liquid fossil fuels across the land, sea and air domains could be used to haul e-hydrocarbons without any adjustments. Owing to their high volumetric density, these fuels would also prove to be a superior alternative to other e-fuels because they are the only ones that would not exacerbate the military's acute dependence on long supply lines during out-of-area missions.

Ease of integration

The introduction of e-kerosene and e-diesel into the armed forces would benefit from two pivotal factors. First, owing to their inherent similarity to oil-based counterparts, both e-diesel and e-kerosene could seamlessly power existing ICEs with minimal, if any, modifications. This adaptability would future-proof the current and upcoming fleets of tanks and fighter jets, reducing the need for untimely retirements and extending the operational lifespans of these vehicles. Similarly, e-hydrocarbons would provide a much cheaper alternative to other e-fuels from a handling perspective. After all, there would be no need to invest in a completely new refueling infrastructure or make any modifications to existing pipelines, storage tanks or distribution systems.

Second, categorized as "drop-in" fuels, e-kerosene and e-diesel are engineered to directly substitute or blend with traditional fuels. This, in turn, can help ensure a smooth transition from oil-based to e-hydrocarbons. For instance, jet fuel blends could vary in e-kerosene concentration from as low as 1% to as high as 99%, depending on military requirements, with the remainder consisting of conventional kerosene. Such an approach could allow a gradual introduction of carbon-neutral fuels, while also keeping the costs in check.

Safety

Compared to other e-fuel alternatives, either e-kerosene or e-diesel emerges the most reliable alternative to oil-based fuels. Their relatively high flashpoint and low reactivity set them apart from fuels like e-methanol or hydrogen. Their reduced toxicity, when compared with substances like e-ammonia, also eliminates the need for specialized protective and handling equipment. They also surpass lithium-ion batteries in terms of safety because they do not carry the risk of battery runaway in the event of a collision or projectile damage. Yet, perhaps most significantly, unlike it is the case with all other e-fuel alternatives, armed forces across the globe have a very good understanding of the risks involved and ample of experience in handling oil-based fuels. As a result, if militaries were to decide to adopt fuels like e-kerosene or e-diesel, there would be no need for specialised training for the logisticians.

THE GOOD, THE BAD, THE UGLY

The good news is that most of the necessary technologies required for the decarbonization of the armed forces exist and that the remaining could be introduced in the near future. These technologies are by no means perfect or polished – in fact, some of them are still at a fairly low maturity level. Yet, they still can provide a solid foundation for future technological improvements that could help bring the armed forces closer to net-zero. To get the ball rolling, military planners need to collaborate with governments, industries, and researchers to identify the most promising technological pathways that meet their needs, mobilize the necessary resources, establish regulatory frameworks, and either commence or expedite experimentation with these new technologies.

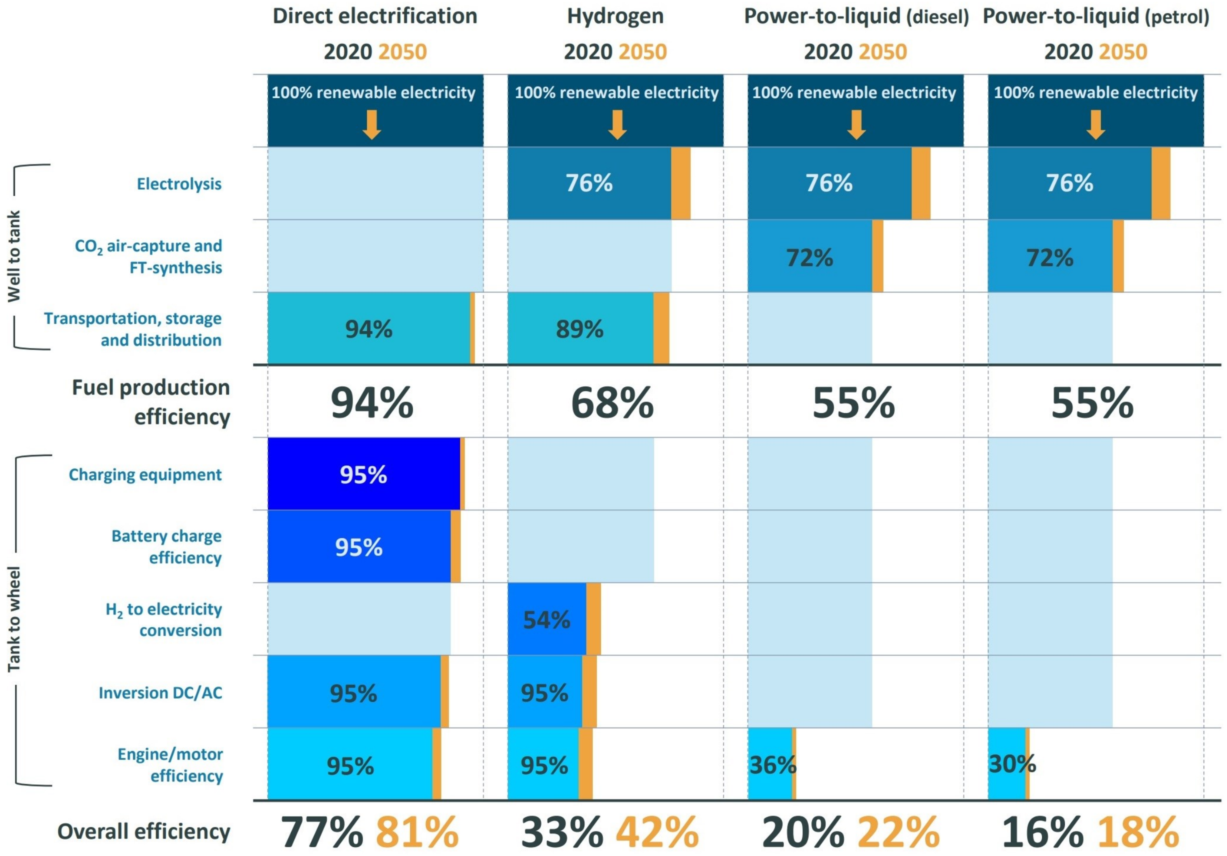

Figure 18. Comparison of different fuel and propulsion efficiencies (based on: transportenvironment.com)

The bad news is that there is no one single fuel or technological pathway that could realistically decarbonize the armed forces across all three domains. Within this context, the word "realistically" means that there has to be a balance between the tasks of reducing CO_2 emissions, maintaining, or, ideally, improving the operational capabilities of the armed forces, and keeping the costs of the energy transition as low as possible. In practice this means that it does not make sense to assume that we should use highly refined e-hydrocarbon fuels on ships because of their prohibitive costs. After all, the reason most navies across the world opt for less refined marine fuels over liquids like gasoline is not because of the efficiency, but because of the cost.

All of this means that in the coming years military planners will likely have to make tough decisions about which technologies to adopt for specific platforms and how to manage resources in the most efficient way. Granted, the armed forces are not alone in this predicament, as nearly all hard-to-abate sectors, including shipping, aviation, and heavy-duty transportation, face similar challenges. For instance, a recent survey revealed that most leaders in the shipping industry believe that marine oil will remain the dominant shipping fuel at least until 2030.[82] Yet, when it comes to 2050, it is anyone's guess. Broadly speaking, respondents were nearly evenly split on whether the shipping industry will be powered by green hydrogen, e-ammonia, e-methane, or some other type of alternative fuel. In other words, despite the significant research work that has already been undertaken, it is still too early to predict which technological pathways will emerge as the industry gold standard in the years and decades to come.

The downright ugly news is that the energy transition will not come cheap. It is no secret that the existing electricity-based fuel alternatives are many times more expensive than their oil-based counterparts. Although part of the reason is that most of these alternative fuels are at their technological infancy, it is highly unrealistic to assume that this trend would change significantly in the future. This is because unlike oil-based fuels, which follow a well-established production process, electricity-based fuels have incredibly long, costly and complicated value chains, which will face scalability challenges for many years to come.

Table 2. Estimated production costs of different e-fuels[83]

	Fossil fuel-based	Electricity-based (present)	Electricity-based (2050)
Hydrogen	USD 0.5-1.7/kg	USD 3-5/kg	USD 1.5/kg
Methanol	USD 100-250/t	USD 800-1600/t	USD 250-630/t
Ammonia	USD 270-370/t	USD 720-1400/t	USD 310-610/t
Hydrocarbons (jet fuel)	USD 0.3-0.8/l[XXX]	USD 7/l[XXXI]	USD 1-3/l

The main reason why e-fuels are so expensive to produce lies in their inherent energy intensive production process. All of these fuels experience significant energy losses at each and every conversion stage. This means that there is a significant difference between the initial electricity input and the end product that comes in a liquid or a gaseous form. As a result, compared to direct electrification via the battery route, the production of e-hydrocarbons such as e-kerosene or e-diesel is so much more inefficient and costly.[XXXII] While, it is reasonable to assume that gradual reductions in e-hydrocarbon costs might happen due to the effect of learning curves, greater production scales, cheaper electricity and CO_2 feedstock, it would be unwise to expect that e-hydrocarbons could become as cheap as or even cheaper than their oil-based counterparts.[XXXIII] Based on the second law of thermodynamics, each physical or chemical process results in energy losses, and this is nowhere as evident as in the production of e-hydrocarbons.

Therefore, in an effort to decarbonize the armed forces, it makes the most sense to utilize direct electrification via the lithium-ion battery route wherever possible, and to opt for the convenient yet highly energy-inefficient e-hydrocarbons in areas where better solutions do not exist. E-ammonia is likely to find some success in decarbonizing the shipping industry. However, due to safety considerations, it is far less certain whether it could ever meet the military's strict expectations. Meanwhile, hydrogen or e-methanol might also warrant some attention in niche applications, but due to performance, logistical, or integration challenges, it remains unclear if they could play a decisive role in bringing the military closer to net-zero.

[XXX] These figures only refer to the production costs. They do not include factors like taxation.

[XXXI] E-hydrocarbon producers currently do not supply volumes beyond pilot projects. Therefore, the real per liter costs of e-hydrocarbons are still very speculative. However, recent announcement made by industry players such as Norsk e-Fuel and Arcadia eFuels, just to name a few, indicate that a growing number volumes of e-hydrocarbons is expected to reach the market over the coming years.

[XXXII] Broadly speaking, the cost of renewable electricity and those of CO_2 account for the bulk of the e-hydrocarbon production costs. Green hydrogen alone is responsible for up to 80% of the overall cost.

[XXXIII] There's plenty of examples of clean energy technologies being incredibly costly at an early stage of development, but seeing their costs eventually fall. For example, the cost of solar cells decreased by 99.6% between 1976 and 2019. It has also been observed that the costs of hydrogen fuel cells fell by 60% between the years 2006 and 2018. Yet, it's fairly unlikely that e-fuels could follow such a trajectory. An extremely high oil price is arguably one of the few ways how kerosene and e-kerosene could reach price parity.

About the author

Lukas Trakimavičius is a Subject Matter Expert at the Research and Lessons Learned Division of the NATO Energy Security Centre of Excellence where he focuses on clean technologies and the geopolitics of energy. He is also a Non-Resident Fellow at the Center for European Policy Analysis (CEPA), a think-tank in Washington DC. Trakimavičius is also affiliated with the World Energy Council where he contributes to the Council's work on the energy transition.

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