Zero Emission Technology: Potential Energy Carriers for the Norwegian Armed Forces in a Decarbonized Future

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ABSTRACT

The global energy market is changing. Climate change pushes civil society towards a low-carbon economy. Due to its reliance on civil actors, the defence industry must follow. This paper investigates potential energy carriers for the Norwegian Armed Forces in a decarbonized future. It seeks to identify operational benefits and limitations caused by utilizing green energy in a military context. Multiple carbon-free energy carriers are evaluated, including electricity, hydrogen, ammonia and nuclear fuel. Additionally, carbon-based alternatives in the form of biofuel and e-fuel are evaluated. Comparisons are carried out with regard to energy density, energy efficiency, greenhouse gas emissions and costs, and the results are used to assess each energy carrier's suitability for different military platforms. The study intends to act as decision support for research commitments related to energy carriers, military platforms and long-term defence planning. The nature of the world's energy supply transforms rapidly, whereas military acquisitions can impose a multi-decade restriction on the type of energy an armed force is able to apply. Hence, researchers and decision-makers must come together and act now.

Keywords: Climate, Energy, Fuel, Long-Term Defence Planning, Technological Development, Logistics

1.0 INTRODUCTION

The Norwegian government has set a goal to reduce greenhouse gas emissions to net zero by 2050. Similarly, the Norwegian Parliament has passed the *Climate Change Act*, which legally commits to a 90% to 95% reduction of national emissions by 2050 compared to 1990 [1]. This will impose vital changes in the energy markets and civil society, with the hope of addressing the climate crisis. The defence sector will have to adapt to these changes in order to continue receiving support from civil actors. Today, the Norwegian Armed Forces are entirely dependent on fossil fuels. Such dependency will pose a significant vulnerability when the fossil energy market disappears, leading to uncertainty regarding costs and energy supply. Thus, the Norwegian Armed Forces must consider alternative energy carriers to ensure its operational capability in the future. NATO's strategic concept asserts that climate change is a factor strongly affecting our security, and the alliance is committed to reducing greenhouse gas emissions [1]. The concept emphasizes that emission reduction should not adversely affect operational capability. Consequences for operational capabilities must therefore be considered when assessing the performance of potential energy carriers. The research questions to be answered in this paper are:

> *If the Norwegian Armed Forces are to eliminate the need for fossil energy and fossil fuels, what are the technological possibilities? In what parts of the military is it relevant to apply the different technologies, and how will the technologies affect operational capabilities?*

This paper presents a literature study. Data is gathered from research literature, publicly available reports and online portals with up-to-date information on various technologies. Where comparable data exists, quantitative comparisons are made in regard to relevant physical properties, such as energy content and energy efficiency. Our own knowledge and expertise in military operations is utilized to assess potential applications for the different technologies. Moreover, this is a technical feasibility study covering an extensive range of alternatives, but not an exhaustive analysis of all potential energy sources and carriers. It is also not an analysis of all relevant factors, such as Norwegian security policy related to the technologies. The most relevant energy sources and carriers have been selected based on our expertise and judgement. There are many other types of fuels besides the ones explicitly mentioned in this paper, such as dimethyl ether, hydrazine, glycerol and others. Missile propulsion technology and rocket propellants are also not considered.

In Section 2.0, an introduction to selected energy sources and carriers with potential of being climate-neutral is given. In Section 3.0, a comparison of the energy carriers is carried out. Section 4.0 explores potential applications in the military. Section 5.0 discusses how the technologies will affect military operations and key decisions to be made. In Section 6.0, final recommendations for the Norwegian Armed Forces are presented.

2.0 CLIMATE-FRIENDLY ENERGY SOURCES AND ENERGY CARRIERS

It is not obvious what the best and most effective path to a zero emission society is. What is certain is that the path consists of a combination of technologies based on different energy sources and energy carriers. This section focuses on a selection of the most relevant energy technologies and describes the key aspects of their production, storage, utilization and technological development.

2.1 Electricity

The main source of electricity worldwide is production through combustion of coal and natural gas. Fossil fuels accounted for 62% of global electricity production in 2021 [3]. Thus, not everything powered by electricity is climate-neutral. Electricity generation from renewable sources such as hydro, wind and solar is increasing each year. The remaining share of non-fossil electricity comes from nuclear power, which is less affected by season or weather conditions than renewables. Nuclear energy is discussed further in Section 2.4. Electricity from wind and solar involves irregular starts and stops in production. Consumers of electricity can only adapt to this intermittency to a certain extent. For most purposes, a continuous power supply is required. This is achieved by storing a portion of what is produced. To transition away from fossil energy sources and eliminate emissions, technology for electricity storage is becoming increasingly important. Electrochemical storage using batteries is the most versatile and widely used method for electricity storage. Recent developments within battery technology are discussed briefly below. Chemical energy storage through conversion of gases and liquids is another relevant storage method. Chemical energy storage is discussed in Sections 2.2, 2.3 and 2.5 to 2.7, which address hydrogen, ammonia, hydrocarbons, and alcohols, respectively.

Current advancements within battery technologies are rapid. Lithium-ion batteries dominate the market, and their performance continues to improve while their costs decrease every year. However, intensive research is being conducted on a wide range of other battery types [4]. Lithium-ion batteries are not suitable under all circumstances, and they rely on limited raw materials, such as nickel and cobalt. It can lead to scarcity of such raw materials if all efforts are focused on one single technology. Examples of alternative raw materials are sodium, zinc, aluminium and potassium [5]. Conventional lithium-ion batteries include a liquid electrolyte, which makes them easily flammable. Solid-state batteries, which do not contain any elements in liquid form, are a promising alternative that can provide both increased safety and higher energy density. For now, the performance of solid-state batteries is much lower than batteries with liquid electrolytes. An alternative technology that contrasts with solid-state batteries is flow batteries. In flow batteries, the liquid electrolyte is stored in separate tanks outside the battery itself. Flow batteries are less prone to fires than conventional lithium-ion batteries, and they are also easier to scale up to the desired energy and power capacity. However, challenges related to low energy density and energy efficiency need to be addressed.

2.2 Hydrogen

Hydrogen is found everywhere around us. In fact, around 90% of all atoms in the universe are hydrogen atoms [6]. Here on Earth, a significant portion of hydrogen is chemically bound in the form of water, while pure hydrogen gas, H_2, only occurs in very small quantities. To obtain considerable amounts of hydrogen gas, it must be separated from other chemical compounds, such as water, oil or natural gas. The most common production methods require three main elements: a material containing hydrogen, energy supplied to this material, and a catalyst increasing the speed of the chemical reaction. The energy supplied to the material can be in the form of electricity, heat, light, biological energy and chemical energy, either alone or in combination with each other [7], [8]. The production method and the source of energy for the production plant are crucial factors in determining whether the hydrogen gas can be deemed environmentally friendly. To keep track, hydrogen is categorized with colours. The main categories are grey, blue and green hydrogen. Grey hydrogen refers to hydrogen with a polluting origin, for example, hydrogen produced through steam methane reforming of natural gas. Steam methane reforming dominates today's hydrogen market because it is the most cost-effective production method, with 96% of the world's hydrogen production based on natural gas, oil or coal [9]. On the other end of the scale is green hydrogen, which is hydrogen separated from a non-fossil material using 100% renewable energy. Electrolysis, where water is split into hydrogen and oxygen, is the most commonly used method. Conventional electrolysis requires a lot of electricity and heat. Technological development in the form of increased energy efficiency and higher production rate is crucial to make this production method competitive [9]. Blue hydrogen represents an intermediate between grey and green hydrogen. The production of blue hydrogen is based on fossil sources, but the greenhouse gas emissions are reduced by capturing and storing the resulting CO_2. A fourth category used in the literature is purple hydrogen, which involves hydrogen produced using nuclear power [10]. Purple hydrogen is not widely adopted, but it shows potential to be a highly energy efficient production alternative.

The physical properties of hydrogen present many challenges related to storage and transportation. Therefore, a vast amount of current research is focused on developing new storage methods. Continuous advancements in materials technology and cryogenics will lead to storage tanks that are better suited for hydrogen, both in terms of cost-effectiveness and safety [11]. In addition to storing pure hydrogen, new possibilities for storing hydrogen in combination with other substances are being explored. Nanotechnology plays a crucial role, especially in solid-state hydrogen storage [12]. Furthermore, hydrogen combined with nitrogen forms ammonia, NH_3, a substance that is considerably easier to store in liquid form than pure hydrogen. Using ammonia as a hydrogen carrier and then separating the hydrogen before use may be a viable option.

2.3 Ammonia

Today's ammonia production is primarily based on fossil sources such as natural gas and coal. Over 70% of the world's ammonia production relies on natural gas, as it currently is the most cost-effective option [13]. The most commonly used production method is known as the Haber-Bosch process, where hydrogen and nitrogen are combined under high pressure to form ammonia, NH_3. Nitrogen used in the process can be obtained from the air, while hydrogen can be obtained from various sources. Fossil-based hydrogen is the main reason why ammonia production is also heavily linked to fossil sources. Ammonia production can be environmentally friendly if green hydrogen produced through electrolysis is used. In other words, green ammonia production is feasible, but the environmental friendliness of the technology is limited by its reliance on hydrogen. With a focus on higher energy efficiency and a greener footprint, alternative methods for ammonia production are being developed. A promising technological alternative is what is referred to as electrochemical reduction of nitrogen [14]. Electrochemical reduction of nitrogen has several advantages compared to conventional ammonia production using the Haber-Bosch process. Firstly, production can take place with irregular power supply. Temporary power outages do not harm the process. This is a significant advantage when connecting production to renewable energy sources such as solar and wind power. Secondly, the process is less sensitive to impurities in the nitrogen feed. Lastly, it is highly advantageous that the production can occur at room temperature and atmospheric pressure [15]. Research and development are focused on increasing the production rate and cost-effectiveness of the technology. Over time, this will contribute to ammonia becoming an even stronger energy carrier candidate in the green transition.

Moderate requirements for pressure and temperature make ammonia significantly easier to store and transport compared to hydrogen. Additionally, the mass density of liquid ammonia is much higher than that of liquid hydrogen. At a pressure of 10 atm and a temperature of 25 °C, one cubic metre of liquid ammonia contains 121 kg of hydrogen [16]. In comparison, liquid hydrogen at -253 °C has a mass density of 70.8 kg/m^3. Thus, liquid ammonia offers a storage and transportation option for hydrogen that is both less physically demanding and more space efficient. The challenge, however, lies in separating out the hydrogen again before its use. The separation process occurs at temperatures above 400 °C and requires large amounts of energy, significantly reducing the overall energy efficiency. This is a challenge that must be addressed through technological development if ammonia is to be used as a hydrogen carrier.

2.4 Nuclear Energy

Nuclear power is the utilization of controlled nuclear reactions to extract energy. The term encompasses energy production from all nuclear reactions: fission, radioactive decay, and fusion. However, traditional nuclear power exclusively harnesses energy from fission processes. Energy from radioactive decay is utilized in some very specific applications such as spacecraft and remote lighthouses [17]. Such applications are referred to as nuclear batteries [18]. Regarding fusion, Lawrence Livermore National Laboratory announced a historic breakthrough in December 2022. The headlines that followed could give a misleading impression of the energy balance in the process and how far fusion still is from being a viable energy source. The lasers delivered 2.05 MJ of energy to the target, a pellet containing deuterium and tritium, and this initiated a fusion process that generated 3.15 MJ of output. However, the lasers used have an efficiency of less than 1% and required around 300 MJ to deliver 2.05 MJ of energy to the target [19]. In other words, only about 1% of the energy input was obtained, and researchers are still far from harnessing fusion power in an energy efficient manner. Therefore, the rest of this section mainly focuses on nuclear fission power.

Nuclear power is primarily used for electricity production in large nuclear power plants or for propulsion in ships. In both cases, a so-called fissile material, typically uranium, is utilized to initiate and sustain a stable nuclear reaction, where the material is split into smaller components, releasing energy. Natural occurrences of uranium consist of two different isotopes: 99.3% is uranium-238 and 0.7% is uranium-235. The numbers 238 and 235 refer to the nucleon number of the isotope and indicate the number of nuclear particles (protons + neutrons). A material is said to be fissile if it can sustain a chain reaction. Uranium-235, when struck by a neutron, will split into smaller components and release new neutrons. Uranium-238 is not a fissile material, since it does not have this chain reaction property. To facilitate a chain reaction, it is common to increase the concentration of uranium-235. This process is called enrichment. The enrichment level for uranium used as fuel in traditional nuclear power plants is typically 3% to 5%. Enrichment levels above 20% are called highly enriched uranium and are often used in nuclear-powered submarines, aircraft carriers or icebreakers. When the enrichment level is around 90% or higher, it is referred to as weapons-grade uranium and can be used in nuclear weapons.

Another relevant element is thorium. Thorium can be found in the Earth's crust, just like uranium. Natural occurrences consist almost exclusively of the isotope thorium-232, which is slightly radioactive. Unlike uranium-235, thorium-232 is not fissile. However, if exposed to neutron radiation, it initiates a process that produces uranium-233, which is fissile. Thus, thorium can be used as fuel to sustain a nuclear reaction, but it requires a "spark" to get started, for example a neutron source like uranium-235. Research is being conducted on several concepts that can utilize thorium since it offers several advantages compared to uranium [20]. Among other things, the thorium cycle allows for much more efficient utilization of the fuel, significantly increasing the effective energy density of the fuel and reducing the need for mining. Additionally, it produces less long-lived radioactive waste, and it is significantly more difficult to create nuclear weapons based on stolen fuel or waste. However, there are some challenges that must be addressed. For example, it is slightly more difficult to produce solid fuel with thorium, and it produces some highly radioactive isotopes that require even stricter radiation protection measures. Research activity within nuclear energy is high, especially with regard to Small Modular Reactors (SMRs). Different reactor technologies are being explored and developed, among these are water cooled reactors, high temperature gas cooled reactors, liquid metal cooled reactors, and molten salt reactors. In addition to new reactor designs and fuel research, alternatives to traditional mineral extraction are being studied. The ocean contains around 1,000 times more uranium compared to known mineral deposits [21], and therefore research is being conducted on extraction of uranium from seawater [22].

2.5 Hydrocarbons Part 1: Biofuel

Hydrocarbons are chemical compounds that contain only hydrogen and carbon. Methane, CH_4, is the simplest hydrocarbon and is the main component of natural gas. Crude oil contains a mixture of hydrocarbons with varying numbers of carbon atoms. Currently, the energy and transportation sectors are dominated by fossil, non-renewable hydrocarbons, but hydrocarbons can also be produced from renewable sources, such as biological raw materials or CO_2 from the air. Hydrocarbons produced from biological raw materials are called biofuels, while hydrocarbons produced from CO_2 are called e-fuel. E-fuel is typically a chemically pure product, while the purity of biofuels depends on the production method and the raw materials used. E-fuels will be further discussed in Section 2.6.

Biofuels can be produced from many different raw materials in various ways. A common form of biodiesel is fatty acid methyl ester (FAME), which is made from vegetable oils or animal fats that react with methanol using a catalyst. As the chemical name suggests, FAME is not a pure hydrocarbon and it has a different chemical structure than fossil diesel. In regular Norwegian diesel, up to 7% blending of FAME is allowed [23]. An alternative to FAME is to process vegetable oils or animal fats with hydrogen into hydrotreated vegetable oil (HVO). Such hydroprocessing produces hydrocarbons that are chemically very similar to fossil diesel. Thus, diesel engines can in fact run on 100% HVO.

Biogas is formed when organic matter is broken down by microorganisms in an oxygen-free environment. Biogas mainly consists of methane and CO_2. After the breakdown, a nutrient-rich residue remains, which can be used as plant fertilizer. By increasing the utilization of biogas, a “double benefit” is achieved, where biogas replaces natural gas and the residue can replace artificial fertilizers. Another gas that plays an important role in the biofuel industry is syngas. Syngas is a mixture of hydrogen, H_2, and carbon monoxide, CO. Traditionally, this gas is produced from natural gas, but it can also be produced from biomass [24], [25]. Syngas can be used to produce liquid fuels using the so-called Fischer-Tropsch (FT) process. The FT process combines H_2 and CO to form a mixture of hydrocarbons with a varying number of carbon atoms, C_nH_{2n+2}, and water. The different hydrocarbons can then be separated into purer products, similar to how crude oil is separated to make gasoline, diesel and so forth.

The overarching challenge of biofuels with today’s raw materials and technology can be described as a trilemma involving sustainability, volume / scale and production cost, where none of the current products score satisfactorily on all three simultaneously. Research, development and innovation within biofuels aim to improve this by finding or developing new sustainable sources of biomass and new processing methods to better utilize existing sources of biomass. Moreover, finding ways to reduce costs and/or increase the scale and efficiency of production [26], [27].

2.6 Hydrocarbons Part 2: E-Fuel

E-fuel is a synthetic fuel in which hydrocarbons are produced from captured or collected CO_2 and green or purple hydrogen. CO_2 can be captured from the air through a process called Direct Air Capture (DAC) or collected from industrial CO_2 emissions. E-methane can then be produced using the Sabatier process, a process where CO_2 and H_2 is combined to form methane and water. For the production of heavier hydrocarbon compositions, such as e-diesel, the FT process described in Section 2.5 is used. When using the FT process, the captured or collected CO_2 must first be converted to CO [28]. This requires energy and contributes to the fact that production of e-fuels with heavier hydrocarbon compositions is more energy demanding than production of e-methane.

In April 2022, the International Energy Agency (IEA) reported that there were a total of 18 operational DAC facilities located in Europe and North America [29]. These facilities operate on a small scale and collectively capture only 10,000 tons of CO_2 annually, an amount equivalent to the annual emissions from approximately 2,000 cars [30]. Only two out of the 18 facilities store the captured CO_2, while the rest capture CO_2 for industrial use, such as for carbonation in beverages. Two different technologies are used for capturing CO_2 from the air. One is based on solid-state absorbents, known as S-DAC. The other is based on liquid absorbents, known as L-DAC. Research is ongoing to develop new solid-state absorbents and liquids that can improve the energy efficiency of S-DAC and L-DAC. Other methods of capturing CO_2 from the air, such as electro-swing adsorption and membrane-based DAC, are still in the laboratory stage of research [29], [31].

2.7 Alcohols

Alcohols are organic chemical compounds that resemble hydrocarbons, but one or more of the hydrogen atoms are replaced by one or more OH groups. The simplest alcohols are methanol, CH_3OH, and ethanol, C_2H_5OH. Like hydrocarbons, alcohols can be produced from fossil sources, biological sources and from captured CO_2. Current production is mainly based on natural gas, thus resulting in grey methanol. E-methanol can be produced by combining green hydrogen and CO from captured or collected CO_2. Biomethanol can be produced in several ways. For example, biomethanol can be extracted as a by-product of paper pulp production, or biomass can be gasified into syngas and then synthesized into biomethanol using the same process as for e-methanol [32].

Methanol is considered an attractive alternative for future fuels, in part due to its clean combustion with minimal particle emissions. Additionally, methanol is a viable hydrogen carrier as it is easy to transport and hydrogen can be separated from it in an energy efficient manner [33].

3.0 COMPARISON OF TECHNOLOGIES

All the energy carriers presented in Section 2.0 have different properties, and they may not be suitable for the same applications. In this section, the properties of the energy carriers are compared in order to identify advantages and disadvantages related to each energy carrier. These advantages and disadvantages will be crucial when evaluating potential technology applications for the Norwegian Armed Forces.

3.1 Energy Content

An energy carrier must, as the term itself implies, have the ability to carry energy. It is advantageous to carry as much energy as possible with the lowest possible weight and/or the least possible volume. This ability is characterized by two parameters: specific energy and energy density. Specific energy is defined as the energy content per unit mass. Energy density is defined as the energy content per unit volume. Energy content can have multiple meanings because energy exists in various forms. For the considerations presented in this section, energy content refers to the amount of energy that can be utilized. For a battery, the energy content will be the amount of electrical energy stored in the battery. For a chemical compound, on the other hand, the energy content will be the amount of thermal energy released upon complete combustion of the substance. This combustion energy is referred to in the literature as the heating value, and it is distinguished between the upper and lower heating values. All values for energy content in chemical compounds provided in the following comparisons refer to the lower heating value.

Specific energy and energy density for a selection of energy carriers is presented in Figure 1. The data has been compiled from [16], [34], [35], [36], [37], [38], [39], [40] and [41]. Energy carriers such as diesel, gasoline and methanol are liquid at room temperature and atmospheric pressure, while hydrogen, ammonia and methane must be compressed or cooled down to become a liquid. The primary fuel used by the Norwegian Armed Forces is an aviation fuel designated with NATO code F-34. This fuel has a composition relatively similar to the most commonly used fuel in the aviation industry, Jet A-1, but it contains additional components for extra protection against corrosion and icing [40].

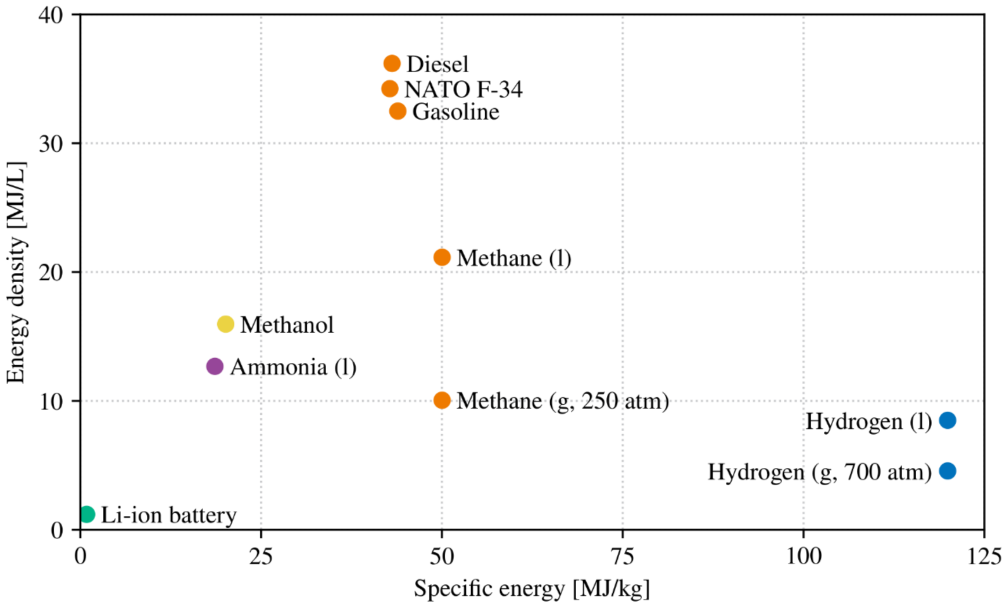


Figure 1: Specific energy and energy density for various energy carriers. NATO F-34 is the primary fuel used by the Norwegian Armed Forces today. (g) Indicates compressed gas at room temperature. (l) Indicates cooled liquid under atmospheric pressure.

One technology that is not shown in Figure 1 outperforms all others when it comes to energy content, namely nuclear power. To give an example, the energy density of pure U-235 is over 40 million times higher than the energy density of diesel [42]. As described in Section 2.4, nuclear power plant fuel typically has an enrichment level of 3% to 5%. Hence, this type of fuel has a significantly lower energy density than pure U-235, but compared to other fuels, the energy density is still extremely high. In practice, the high energy density means that a nuclear-powered vessel can operate for years without refuelling [43].

3.2 Energy Efficiency

It is of little use to employ an energy carrier with high energy content if the energy cannot be effectively utilized. Energy efficiency indicates to what extent a process can make use of the energy supplied to it. In this section, the efficiency of different energy carriers as vehicle fuels is assessed.

Tank-to-wheel efficiency for combustion of various fuels in different engine types is presented in Figure 2. The data is compiled from [44], [45], [46] and [47]. In this context, tank-to-wheel efficiency refers to the ratio between the amount of energy delivered from the wheels of a vehicle and the energy content of the amount of fuel being combusted. It should be noted that tank-to-wheel efficiency is affected by factors that vary among the different studies, such as vehicle design, transmission, tires, maintenance, and so forth. Moreover, the efficiency of an engine is highly dependent on operating conditions. An engine may have significantly lower ability to convert energy when operating at non-optimal loads. The percentage values provided in Figure 2 correspond to efficiency in the upper range, when the engine is operating at optimal conditions.

Energy carriers such as hydrogen and ammonia can be used as fuels for both internal combustion engines and electric motors. Through fuel cells, the chemical energy can be converted into electrical energy. To use hydrogen or ammonia in internal combustion engines, certain modifications need to be made. Spark-ignition engines can be adapted to run on ammonia, but this technology is still in its early stages of development. Currently, other substances, such as additional hydrogen, are blended in to give ammonia-based fuels more favourable properties [48]. Therefore, no percentage value for direct combustion of pure ammonia is provided in Figure 2.

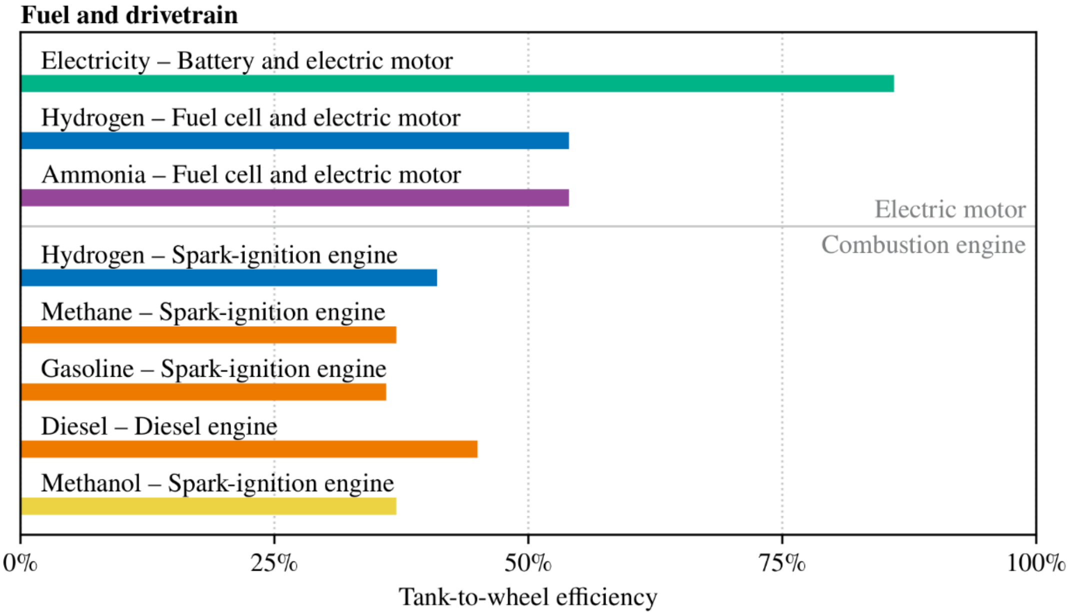


Figure 2: Tank-to-wheel efficiency for various vehicle configurations. The percentage value indicates the ratio between the amount of energy delivered from the wheels of a vehicle and the amount of energy in the consumed fuel.

3.3 Lifecycle Greenhouse Gas Emissions

When using what we refer to as zero emission technology, it is important to be aware that none of the alternatives are completely emission-free in their entirety. All forms of human-made energy production, energy transport, and energy transformation are to some extent dependent on materials, infrastructure, land area and/or adapted environments. This, in itself, can incur significant energy costs and result in considerable greenhouse gas emissions. A carbon-free energy carrier does not directly generate CO_2 upon combustion, but despite the absence of carbon, such an energy carrier can be associated with CO_2 emissions by looking at the entire value chain. These types of emissions are referred to as indirect emissions. In this section, the amount of direct and indirect greenhouse gas emissions related to various energy sources and energy carriers is evaluated.

A commonly used method for quantifying environmental impact and total greenhouse gas emissions associated with a product or activity is called life cycle analysis. Such analyses examine energy consumption, material use, waste, and pollution over the entire life cycle. The National Renewable Energy Laboratory (NREL) has collected data from various studies that have conducted life cycle analyses of different types of electricity production [49]. As expected, the results show that fossil-based power production performs the worst, with coal-fired power being the least environmentally friendly option. Furthermore, the results related to bioenergy are interesting. The median of the results suggests that bioenergy is a relatively environmentally friendly alternative, but the variation in the results is significant. The lowest estimate is -1000 g CO_2-eq./kWh. A negative emission in these studies means that emissions are avoided, not that greenhouse gases are removed from the atmosphere. For example, the utilization of biomass may prevent emissions of methane gas that the biomass would otherwise have generated in a landfill. On the other end of the scale, the highest estimate for bioenergy is as high as 1300 g CO_2-eq./kWh, indicating that bioenergy can be a significant environmental concern under certain circumstances. Renewable energy sources, as well as nuclear power, perform well in most life cycle calculations, but some estimates show that these technologies can also result in considerable greenhouse gas emissions [49].

To make a quantitative comparison of indirect emissions related to potential energy carriers for the Norwegian Armed Forces, we can look at life cycle analyses that address future fuels. A relevant study was conducted by Kanchiralla et al. in 2022 [50]. The study examines fossil-free fuel alternatives for a ferry operating between Gothenburg and Kiel. Life cycle calculations are made for different scenarios in which the ferry uses either an electric motor or an internal combustion engine, and on-board energy storage is done using batteries, e-hydrogen, e-ammonia or e-methanol. Here, the “e” designation indicates that these are synthetic fuels produced using renewable energy. All scenarios are compared to a reference scenario where the ferry operates on diesel, and the extent to which the different scenarios contribute to global warming over a period of 100 years is evaluated. Battery-powered vessels are highly energyefficient, which is beneficial in terms of greenhouse gas emissions. However, it is not a battery-powered ferry that performs best among the scenarios in the study by Kanchiralla et al. This is due to significant indirect emissions from battery production. In the study, it is assumed that the ferry operates for 25 years, while the batteries used have a lifespan of 8 years. Hence, the batteries need to be replaced at least twice during the ferry’s lifetime. The footprint of battery production leads to the fact that a ferry with an electric motor and fuel cells running on e-hydrogen or e-ammonia being more favourable from a life cycle perspective. The fourth fuel alternative, e-methanol, differs from the above. E-methanol is a carbon-based fuel, and the direct emissions from combustion are significant. However, e-methanol for the ferry is produced using carbon capture from the air, making the indirect emissions from fuel production negative. This offsets parts of the direct emissions and greatly reduces the global warming potential. The various electricity-based fuels evaluated in the study all have their advantages and disadvantages, but one of the key points highlighted by Kanchiralla et al. is that all of them provide enormous environmental benefits compared to vessels powered by fossil diesel [50].

3.4 Costs

Cost calculations are a fundamental part of long-term defence planning. In this section, the investment and operating costs associated with the various energy carriers presented in Section 2.0 are discussed.

The price of lithium batteries fell by 97% from 1991 to 2018 [51]. However, 2022 marked a trend reversal where lithium battery prices increased by 7% [52]. Reported reasons for the increase include higher raw material prices and logistic challenges due to the COVID-19 pandemic. It is expected that technological advancements will continue for both lithium batteries and other battery technologies, which will help reduce battery prices in the long term. However, raw material shortages and trade wars may contribute to increased prices, and it is difficult to predict the extent of these effects in the coming years.

Green hydrogen can be produced in Norway at approximately 60 NOK/kg, assuming an electricity price of 0.6 NOK/kWh, according to a recent report from Enova [53]. The electricity price makes up about 2/3 of the total cost. Under these assumptions, hydrogen can be competitive with fossil fuels in terms of cost per kilometre, since the specific energy of hydrogen is almost three times that of fossil diesel, and modern fuel cells in combination with electric motors have slightly higher energy efficiency than internal combustion engines. However, as future electricity prices are highly uncertain, the future price of hydrogen is also highly uncertain. In addition to the fuel cost itself, transitioning to hydrogen as a fuel will require significant investments in hydrogen infrastructure. Since hydrogen is a key input in ammonia, synthetic biofuels and e-fuels, some expansion of hydrogen infrastructure will be necessary regardless.

Using ammonia as fuel also requires substantial infrastructure investments, but since it is easier to store ammonia than hydrogen, the infrastructure itself will be cheaper than equivalent hydrogen infrastructure. The cost of green ammonia also correlates with the electricity price. Grey ammonia has seen a significant price decrease in recent years and is only slightly more expensive than fossil fuel. However, green ammonia remains consistently much more expensive [54].

The investment costs for nuclear power plants vary greatly [55]. Generally, nuclear power is associated with low operating costs. Using Sweden as an example: It costs 0.15 to 0.18 SEK to produce one kWh, with the fuel cost accounting for approximately 0.03 SEK [56]. Swedish nuclear power plants also pay a fee of 0.03 to 0.06 SEK/kWh to a fund for waste management [57]. If nuclear power were to be used in the Norwegian defence sector, development costs must be considered, since there are few solutions available on the market, and there may not be existing solutions tailored to Norwegian military needs.

The costs of biofuels vary depending on the raw material and production method. Typically, the most sustainable and superior biofuel is the most expensive, and more expensive than fossil fuels. An exception to this rule is biogas, where the production cost is much lower than the price of natural gas due to the current energy situation in Europe [58]. How this will develop in the future is highly uncertain. A cost advantage of biofuels is that they do not require significant infrastructure development or equipment adjustments. Hence, it is not associated with an investment barrier.

The production costs of e-fuels are significantly higher than those of biofuels and fossil fuels. Much due to high energy consumption and low production volumes. Similar to green hydrogen and ammonia, the fuel cost strongly correlates with the electricity price. Research, development and economies of scale are expected to drive the costs down, but there is great uncertainty about future cost levels [59]. Increased carbon taxes and additional economic incentives will be necessary for many years to come, to eventually match the price of fossil fuels [60]. Like with biofuels, an advantage here is that existing infrastructure can be utilized.

Methanol as an alternative fuel is gaining popularity in the maritime industry. A reason for this may be that grey methanol has relatively high availability, and it is competitive in price with other fossil fuels. However, biomethanol and e-methanol are significantly more expensive [54].

3.5 Summarized Assessment

The comparisons made in Sections 3.1 to 3.4 form a complex picture of the advantages and disadvantages of each energy carrier. To provide a comprehensive overview, a summarized assessment is presented in Table 1, which roughly summarizes the considerations made in the above sections. Fossil diesel is used as the reference value in the assessment. Fossil diesel has similar properties to NATO F-34, the primary fuel used by the Norwegian Armed Forces today, and weighting against the reference value therefore gives an impression of whether each energy carrier has a positive or negative effect on the military.

The assessment in Table 1 is based on the current status of the different energy carriers. The table does not provide any insights into future prospects. Many of the green alternatives discussed in this paper have low technological maturity compared to the fossil-fuelled technology currently used by the Norwegian Armed Forces. Costs in particular appear to be a barrier to green transformation. As the various technologies mature, costs and other parameters will increasingly favour green technology. Large-scale production of green energy carriers will make the solutions more cost-effective, and the threshold for a green transformation will become lower with each passing year.

Table 1: Summarized assessment of the properties of different energy carriers compared to fossil diesel.

	Energy content	Energy efficiency	Greenhouse gas emissions	Costs
Electricity Li-ion batteries	🔴	🟢	🟢	🟢^{o} 🟡^{i}
Hydrogen E-hydrogen	🔴^{e} 🟢^{s}	🟢^{f} 🟡^{c}	🟢	🟩?^{o} 🔴^{i}
Ammonia E-ammonia	🟡	🟢^{f} 🟡?^{c}	🟢	🔴^{o} 🔴^{i}
Nuclear energy U-235	🟢	N/A	🟢	🟢^{o} 🔴?^{i}
Hydrocarbons				
Biomethane	🟡^{e} 🟩^{s}	🟡	🟢	🟩?^{o} 🟩^{i}
E-methane	🟡^{e} 🟩^{s}	🟡	🟢	🔴^{o} 🟩^{i}
Biodiesel	🟩	🟩	🟢?	🔴?^{o} 🟩^{i}
E-diesel	🟩	🟩	🟢	🔴^{o} 🟩^{i}
Alcohols				
Biomethanol	🟡	🟡?	🟢	🔴^{o} 🟩^{i}
E-methanol	🟡	🟡?	🟢	🔴^{o} 🟩^{i}

Color indicators

🟢	Better than fossil diesel
🟩	Equal to fossil diesel
🟡	Slightly worse than fossil diesel
🔴	Much worse than fossil diesel

Comments

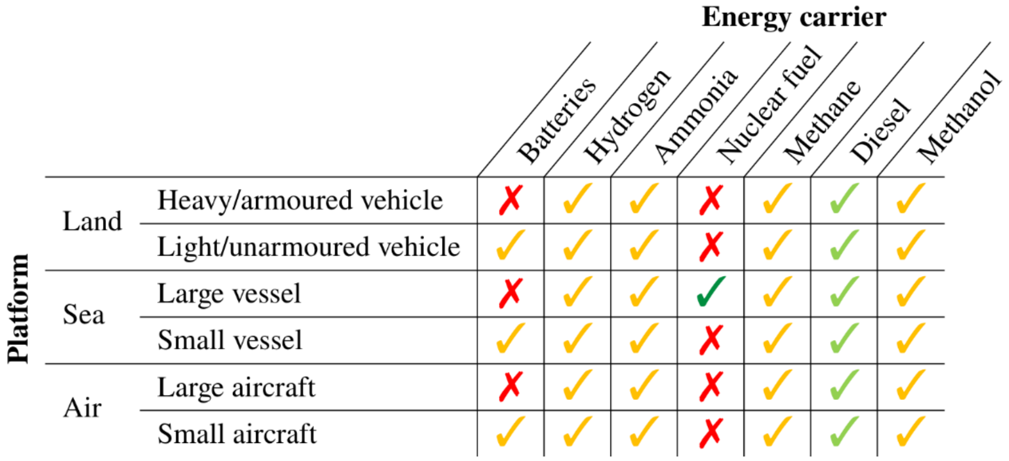
●^{e}	Energy density	●^{s}	Specific energy
●^{f}	Fuel cell	●^{c}	Combustion
●^{o}	Operating	●^{i}	Investment
❓	High uncertainty assessment		

4.0 POTENTIAL APPLICATIONS FOR THE NORWEGIAN ARMED FORCES

The comparisons presented in Section 3.0 form the basis for identifying potential applications for the various technologies. In this section, the extent to which the technologies are suitable for powering different military platforms is evaluated.

Table 2 presents an assessment of which energy carriers are suitable fuels for propulsion on military platforms in the land, sea and air domains. The energy carriers that are suitable for each platform are marked with a checkmark in the table. In addition, the checkmarks are given a colour to indicate how the range of the platform is affected compared to a diesel-powered platform. The impact on range is based on the energy density of each energy carrier relative to diesel, as evaluated in Table 1. A dark green checkmark indicates that the energy density is higher than diesel and that the platform's range is increased, while a yellow checkmark indicates that the energy density is lower than diesel and that the platform's range is reduced. The term "diesel" is used in this assessment, but in practice, it refers to liquid hydrocarbons in many forms, including fuels like NATO F-34.

Table 2: Assessment of energy carrier suitability for different military platforms. The colours dark green, light green and yellow indicate whether a platform's range is increased, unchanged, or reduced, compared to a diesel-powered platform. The assessment does not include hybrid propulsion alternatives.



Platform		Batteries	Hydrogen	Ammonia	Nuclear fuel	Methane	Diesel	Methanol
Land	Heavy/armoured vehicle	✗	✓	✓	✗	✓	✓	✓
	Light/unarmoured vehicle	✓	✓	✓	✗	✓	✓	✓
Sea	Large vessel	✗	✓	✓	✓	✓	✓	✓
	Small vessel	✓	✓	✓	✗	✓	✓	✓
Air	Large aircraft	✗	✓	✓	✗	✓	✓	✓
	Small aircraft	✓	✓	✓	✗	✓	✓	✓

Battery-powered propulsion is strongly limited by the low energy content of batteries. In all domains, batteries are considered unsuitable for the heaviest and largest platforms. Heavy / armoured vehicles, large vessels and large aircraft require so much propulsion energy that using batteries results in very poor space utilization and unreasonably high total weight. In the civil sector, battery-powered propulsion is used on certain heavy vehicles and large vessels, but these operate with fixed routes and/or predictable charging cycles. Such predictability is not suitable for military operations. Furthermore, it should be noted that the evaluation presented in Table 2 does not include hybrid propulsion, where a platform alternates between drawing energy from batteries and one or more other energy carriers. Hybrid propulsion can be highly advantageous and is definitely applicable for even the heaviest and largest platforms. For smaller platforms, pure battery-powered propulsion is suitable in all operational domains. Here, the propulsion energy requirements are lower, and batteries are applicable due to their high energy efficiency and other operational advantages, such as the benefit of a low signature from electric motors.

Hydrogen-powered propulsion is considered relevant for all platform categories in Table 2, but hydrogen storage is so technically demanding that it is not suitable for every platform. Especially for the smallest platforms, hydrogen's requirements for heavy and robust storage tanks with extremely high pressure or advanced cooling systems for liquid storage make it less advantageous. Hydrogen's very high specific energy is what distinguishes it from several other energy carriers discussed in this report. This property can potentially be utilized on platforms where low weight is more important than small volume. For example, it can be considered whether a surveillance aircraft should be powered by hydrogen. An aircraft using hydrogen-powered fuel cells would be highly energy efficient, have a low signature, and only emit water vapour into the atmosphere. One of the challenges with choosing a fuel with low weight and large volume is that an increase in volume indirectly leads to an increase in weight as well. If the fuel tank construction consists of heavy, robust materials, the total weight will become higher despite the fuel itself weighing significantly less.

Similar to hydrogen, ammonia-powered propulsion is considered relevant for all platform categories in Table 2. Storage of ammonia is not very technically demanding, but it requires somewhat larger storage tanks and weighs more compared to diesel. In other words, the range of an ammonia-powered platform will be slightly reduced compared to an equivalent diesel-powered platform. In the civil sector, the focus is largely on shipping when discussing ammonia as a fuel. For the military, the technology may initially be most relevant for large vessels, where batteries and hydrogen are not sufficient due to low energy density. Currently, reduced technological maturity is one of the biggest challenges related to ammonia. However, the research activity is significant, and in a few years, ammonia may become a viable fuel for both large and small platforms on land, at sea and in the air.

Nuclear fuel is the option with the most red crosses in Table 2. In other words, this fuel is relevant in few platform categories. Despite being a very compact fuel, the technology is relatively space-consuming due to the requirements for support systems and safety measures. Thus, nuclear fuel is considered impractical for the smallest platform categories. Furthermore, the technology requires stable operating conditions. Platforms operating on land and in the air may experience significant vibrations and conditions that make it very challenging to operate with mobile nuclear power. The conclusion is that propulsion based on nuclear power is only feasible for large vessels. By using nuclear fuel, environmental emissions from large military vessels can be significantly reduced, and the vessels themselves can become less dependent on fuel logistics.

A large number of the military platforms used by the Norwegian Armed Forces are currently powered by hydrocarbon fuels. For this reason, it is easy to argue that methane and diesel are relevant in all platform categories in Table 2. A methane-powered platform will have slightly reduced range compared to an equivalent diesel-powered platform. On the other hand, bio- and e-methane are likely to be both less costly and more environmentally friendly than bio- and e-diesel. Bio- and e-diesel are the options that are the easiest to implement since they do not involve significant structural changes for the military. However, bio- and e-diesel have challenges related to sustainability and costs that must be taken into consideration. The primary energy carrier for propulsion should only be bio- or e-diesel if none of the other options are sufficient. This will typically apply to compact platforms with high energy consumption, such as fighter jets.

Methanol is the last energy carrier evaluated in Table 2. Methanol has lower energy density than diesel and, therefore, the range of a methanol-driven platform will be somewhat reduced compared to an equivalent diesel-driven platform. One significant advantage of methanol compared to methane, hydrogen and ammonia is that it is a liquid at room temperature and atmospheric pressure. This simplifies storage requirements and makes methanol very suitable for both small and large platforms in all operational domains. Methanol can be used directly in internal combustion engines and fuel cells, or indirectly as a fuel for hydrogen-driven propulsion systems. Hydrogen can be extracted in a relatively energy-efficient manner from methanol, suggesting that methanol may be a more favourable hydrogen carrier than ammonia, for example.

A notable aspect of Table 2 is the dominance of the yellow markers indicating reduced range. It is essential to nuance these considerations and to not undermine all alternatives in favour of diesel. As described above, reduced range is based on the energy carrier having lower energy density than diesel. In practice, lower energy density does not necessarily mean reduced range. It simply means that the platform must be designed differently to achieve a corresponding range, either by dedicating more space to fuel or by reducing the platform’s total weight. Additionally, fuel logistics must be considered when discussing range. In theory, a platform with poorer storage capacity could have an equally good range if the platform can produce its own fuel while operating. This is easy to implement for battery-driven propulsion with solar panels, but it may also be relevant for hydrogen-driven propulsion and other chemical substances as e-fuel production technologies advance.

In addition to propulsion energy for the platforms specified in Table 2, the Armed Forces rely on large amounts of energy used for other purposes, such as powering operating bases, infrastructure, ground sensors and satellites. For a system to be self-sufficient, it requires energy production and energy storage. With regard to energy production, renewable power and nuclear power are both relevant. Solar, wind and hydropower are viable options, but topography and local conditions play a crucial role. Far north, solar power is poorly suited due to the lack of sunlight during the winter months. Wind power is suitable in many locations, as long as the system can store energy for periods without wind. Hydropower is more predictable, but only applicable in locations where the topography allows it. The closer the power production can be to the system is powers, the easier it is to protect against physical sabotage. Nuclear power is an option that does not depend as heavily on topography and local conditions. With their own nuclear power, operating bases and systems can be self-sufficient for a very long period of time. With regard to energy storage, relevant options include batteries and chemical storage using hydrogen, ammonia, methane, methanol, or similar chemical substances. Batteries alone are not suited for systems that require large amounts of energy and/or long-term energy storage. A large battery bank is expensive, space-consuming, and not very energy efficient over time. Thus, chemical storage is better suited for large-scale, long-term energy storage. Hydrogen is one of the energy carriers that most efficiently can be transformed to and from electricity, but the choice of energy carrier must be based on available storage space and technological suitability in relation to the system's energy needs, usage patterns and operational requirements. Moreover, the choice of energy carrier for an operating base or system can be made based on the energy carrier that associated platforms use for propulsion. If a system and a platform use the same energy carrier, energy storage and fuel production are achieved in the same process, resulting in cost advantages, increased supply security, and a unified force structure with greater operational capability.

5.0 DISCUSSION

As shown, there are many potential applications for zero emission technologies in the military. In this section, we discuss to what extent benefits can be derived from such technology in military operations, and point out some key decisions to be made by the Norwegian Armed Forces.

5.1 Can Zero Emission Technology Reduce Military Fuel Logistics Needs?

The supply chain is an attractive target in a military conflict. Successful attacks on the supply chain can have significant impacts on the battlefield, and protecting against such attacks ties up substantial military resources. A military force that manages to reduce its logistics needs will, therefore, gain a significant operational advantage. Replacing fossil fuels with non-fossil energy carriers does not necessarily reduce the logistics needs. On the contrary, it may increase if the alternative fuel has lower energy content and needs to be transported in larger quantities to the field. To reduce logistics needs, a military force must either reduce energy consumption or produce some of the energy / fuel themselves. Reducing energy consumption on mobile platforms will decrease fuel consumption and thus the logistics requirements. This can be achieved through battery hybridization or modifications that reduce air / water resistance, or it can be done by using alternative operational concepts.

If the goal is to eliminate the need for fuel logistics, energy and fuel must be produced locally where it is needed. Jet fuel, in the form of e-fuel, can be produced locally at an airbase using Direct Air Capture of CO_2 and the Fischer-Tropsch process. However, this is very energy-intensive, requiring access to large quantities of renewable energy or nuclear power. A concept with self-produced jet fuel could not only make aircraft climate-neutral, it could also help ensure operational capability through reduced fuel supply vulnerability.

For electricity, heating, and cooling needs in the field, mobile energy supply systems based on solar, wind and batteries can be utilized. In many parts of the world, this could provide sufficient energy to a mobile operations base, but this may not be the case in the dark winter periods in northern Norway. An alternative energy source in the field is a mobile micro-reactor placed in a container, similar to what is being developed for Project Pele in the United States [61]. Such a solution is weather-independent and thus provides good supply security. Similar to fuel production at an airbase, fuel can theoretically also be produced in the field. To reduce the need for fuel logistics, fuel production in the field must be based on locally available resources. At a minimum, air and water are needed to produce hydrogen and ammonia. To produce hydrocarbons and alcohols, a carbon source is also required, either in the form of biological material or captured CO_2 from the atmosphere.

On-board renewable energy production like solar and wind can contribute to covering parts of the energy needs for military vessels and thus reduce fuel consumption. However, it is not realistic that renewable energy sources alone can cover the entire energy needs of large military vessels. To eliminate the need for fuel logistics at sea, only nuclear power has sufficient energy density. A possible concept could be a supply vessel powered by nuclear power that produces e-fuel and accommodates the vessel group it operates within. A more direct approach would be that all vessels of sufficient size are themselves powered by nuclear fuel. This would provide greater operational flexibility and eliminate the need for fuel logistics.

It is theoretically possible to reduce or eliminate the need for fuel logistics in several ways, but more in-depth analyses must be conducted before concluding on the most appropriate types of fuel, raw materials, and production methods. It is also too early to assess the costs associated with these concepts.

5.2 Key Decisions for the Norwegian Armed Forces

The Norwegian defence sector's climate and environmental strategy states that climate and environment should be assessed on an equal footing with time, cost and performance [62]. This gives rise to important and challenging trade-offs.

A decision that will have great impact on direct greenhouse gas emissions in the decades ahead is the decision regarding a new maritime surface structure. Further investment in hydrocarbon-based propulsion provides short- and medium-term flexibility but entails significant risks for long-term supply security and costs. The military risks being left as the sole or one of very few users of hydrocarbons for propulsion and may need to take responsibility for its supply, possibly through their own production facilities for e-fuels. A commitment to nuclear propulsion for new surface vessels carries risks related to time and costs. However, this solution offers the best long-term operational capability. A focus on alternative energy carriers like hydrogen, ammonia or alcohols appears premature for the military in today's situation, but cannot be ruled out in the longer term. Development in the civilian sector becomes a crucial premise provider in this regard. An alternative worth considering is the possibility of dual-fuel propulsion systems, meaning propulsion systems that can run on two different fuels, such as the current marine gas oil and either ammonia or methanol.

When it comes to aviation fuel, liquid hydrocarbons in the form of e-fuels or biofuels are the only feasible alternatives to fossil fuels in the foreseeable future. There are important considerations regarding supply security and costs that must be made. Should the defence sector continue to rely on civilian suppliers as it does today, or take on a greater responsibility for producing its own fuel, thereby ensuring both supply security and sustainability in the value chain? Besides, how much more is the Norwegian Armed Forces willing to pay per litre of fuel for a bio-/e-fuel concept?

Furthermore, should the Norwegian defence sector invest in a concept for fuel production in the field? This could provide significant operational advantages if feasible, but there is still much investigative work to be done before such a concept can be decided upon. Likely, nuclear power will be a necessary component of such a concept. This raises another important question: Is military use of nuclear power a viable option for a non-nuclear state like Norway? Nuclear propulsion, mobile micro-reactors, and fuel production using nuclear power could offer significant operational advantages, but the costs of such systems are currently unknown. Deploying nuclear technology in a military context also requires considerations of factors beyond the purely technological aspects discussed in this paper.

5.3 What About the Single Fuel Concept?

NATO has a fuel policy that stipulates the use of a single type of fuel by all member countries, referred to as the Single Fuel Concept. The chosen fuel is NATO F-34. From a technical perspective, biofuels and e-fuels can be approved as F-34, as long as the correct composition and performance can be documented. Other alternative energy carriers, such as ammonia, hydrogen and methanol, will not be compatible with the fuel policy. Having said that, the Single Fuel Concept does not represent an inflexible limitation. For instance, the German-Norwegian submarines currently being procured by the Norwegian Armed Forces will have two propulsion systems: one for fossil hydrocarbon fuel and one for hydrogen, which is used for air-independent propulsion. As long as the volume and scope of alternative fuels remain low, NATO can likely accommodate this. With a larger adoption of various alternative fuels, however, the policy could become a troublesome limitation. This is a concern highlighted by several actors. In last year's report regarding climate and security, one of the recommendations of the International Military Council on Climate and Security (IMCCS) was for NATO to transition away from the Single Fuel Concept towards more sustainable solutions [63].

6.0 FINAL RECOMMENDATIONS

In this paper, electricity, hydrogen, ammonia, nuclear fuel, hydrocarbons, and alcohols have been evaluated as potential climate-friendly energy carriers. Only hydrocarbons in the form of biofuel and e-fuel have similar energy content to the fossil fuels currently used by the military. Hydrogen, ammonia, and methanol have lower energy density, resulting in reduced range and decreased operational capability. Biofuel and e-fuel therefore appear as the most viable solutions, but there are significant challenges related to sustainability, production scale-up and costs. It is recommended that the Norwegian defence sector initiate research, development and experimentation with sustainable biofuels and e-fuel, and consider establishing its own production facilities for enhanced supply security. Additionally, it is recommended that the defence sector consider dual-fuel propulsion systems that can use both current fossil fuels and alternative fuels.

Nuclear energy and propulsion stand out with enormously high energy content compared to the other alternatives. However, nuclear propulsion is only suitable for relatively large vessels at sea. Additionally, nuclear power can be utilized for field energy supply and fuel production. A more thorough assessment of military use of nuclear power is recommended, which should encompass technical, societal and security policy considerations. Related to this, nuclear propulsion should be considered in the development of the new maritime surface structure.

Renewable energy sources, like solar and wind power, can contribute to local energy production at operational bases and in the field. The weather dependence of these energy sources necessitates well-designed concepts with complementary energy sources and energy storage to achieve satisfactory energy supply. Hence, it is recommended to develop concepts and conduct experiments with renewable energy supply in the field.

Electricity stored in electrochemical batteries that power electric motors represents the most energy efficient option for converting energy into propulsion. However, due to the low energy content of batteries, there are significant limitations on what can solely rely on electricity in the military. Battery hybridization is highly relevant for most platform types and has the potential to enhance operational capability and reduce costs. It is recommended investments in battery technology in the defence sector be increased, particularly for battery hybridization of existing and new equipment, as well as energy storage in the field.

Climate-friendly technologies are progressing rapidly, and the assessments made in this report will not be valid forever. As a result, it is crucial to closely monitor technological developments. The transition of civil society to alternative energy sources and carriers will change fuel availability and costs, and the defence sector needs to adapt to these changes. The remaining question is whether the Norwegian Armed Forces should wait for the rest of society, or if they should adopt a proactive stance and actively participate in decision-making to affect when and how these changes occur.

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