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Prospects for the Use of Hydrogen in the Armed Forces

Andrzej Soboń [1], Daniel Słyś [2], Mariusz Ruszel [3] and Alicja Wiącek [4,*]

[1] National Security Faculty, War Studies University, 00-910 Warsaw, Poland; a.sobon@akademia.mil.pl
[2] The Faculty of Civil and Environmental Engineering and Architecture, Rzeszow University of Technology, 35-959 Rzeszow, Poland; daniels@prz.edu.pl
[3] The Faculty of Management, Rzeszow University of Technology, 35-959 Rzeszow, Poland; mruszel@prz.edu.pl
[4] Doctoral School of Engineering and Technical Sciences, Rzeszow University of Technology, 35-959 Rzeszow, Poland
* Correspondence: d513@stud.prz.edu.pl; Tel.: +48-733-07-99-66

Abstract: The energy security landscape that we envisage in 2050 will be different from that of today. Meeting the future energy needs of the armed forces will be a key challenge, not least for military security. The World Energy Council's World Energy Scenarios forecast that the world's population will rise to 10 billion by 2050, which will also necessitate an increase in the size of the armed forces. In this context, energy extraction, distribution, and storage become essential to stabilizing the imbalance between production and demand. Among the available solutions, Power to Hydrogen (P2H) is one of the most appealing options. However, despite the potential, many obstacles currently hinder the development of the P2H market. This article aims to identify and analyse existing barriers to the introduction of P2H technologies that use hydrogen. The holistic approach used, which was based on a literature survey, identified obstacles and possible strategies for overcoming them. The research conducted presents an original research contribution at the level of hydrogen strategies considered in leading countries around the world. The research findings identified unresolved regulatory issues and sources of uncertainty in the armed forces. There is a lack of knowledge in the armed forces of some countries about the process of producing hydrogen energy and its benefits, which raises concerns about the consistency of its exploitation. Negative attitudes towards hydrogen fuel energy can be a significant barrier to its deployment in the armed forces. Possible approaches and solutions have also been proposed to eliminate obstacles and to support decision makers in defining and implementing a strategy for hydrogen as a clean energy carrier. There are decisive and unresolved obstacles to its deployment, not only in the armed forces.

Keywords: armed forces; energy security; energy conversion; renewable energy sources; hydrogen

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1. Introduction

One of the priorities of the North Atlantic Alliance (NATO) is to increase the resilience of states and their armed forces with respect to continuity of energy supplies for military operations. At the same time, the North Atlantic Alliance seeks to increase its activities in protecting critical infrastructure and strategic transport routes for energy resources [1,2]. Until now, energy security has been seen mainly in terms of diversification of oil and gas supply sources. Despite growing proven natural gas reserves, the benefits of renewable energy development based on new technologies are being recognised globally. However, electricity storage and the stabilisation of energy systems remain fundamental challenges. A progressive electrification process facilitating an energy transition based on sectoral pooling and climate policy is a catalyst for technological processes. These trends are recognised by NATO, which is seeking to transform its armed forces in compliance with its climate and energy policy. In the context of the research conducted, the perception of the military sector as an antagonist to green development is observable. It is worth noting, however, that the adoption of a suitable supply chain, including the use of renewable energy sources to produce hydrogen and its use in fuel cells, will make it possible to ensure continuity of energy supplies in critical situations. This means that it is in the interests of the member states themselves to have such technologies for their armed forces that enable them, in the event of conflict, to act swiftly and deliver energy supplies, thus ensuring operational mobility. NATO's open and active commitment to developing renewable energy sources in the military sector will also contribute to decarbonising the global economy, thereby creating a sustainable economy in line with the European Green Deal. European Union (EU) member states are working collectively to reduce greenhouse gas emissions. Accordingly, the parties are obliged to take measures in all sectors of the economy to contribute to achieving the planned climate goals. It is assumed that current measures will help reduce greenhouse gas emissions by 55% by 2030. However, in an effort to achieve the targeted climate neutrality by 2050, energy transition in "protected" sectors needs to be considered. In the defence sector, the 2019 EU carbon footprint was 24.8 million tCO2e, equivalent to the average annual CO2 emissions of around 14 million internal combustion vehicles [3]. Due to the protection of classified information in the armed forces, not all countries provide information on the scale of the problem in this sector—contrary to the obligation to report emissions from fossil fuels and energy production, according to ISO 14064 [4]. Consequently, NATO faces contemporary climate and energy security challenges that will require the adoption of new technologies and the establishment or amendment of legal regulations in this area [5,6].

In the academic literature, studies can be found that analysed the problem of increasing energy efficiency in the armed forces, with a special focus on the use of renewable energy sources [7]. In 2011, NATO developed the Smart Energy LibGuide programme, in an effort to improve the international exchange of defence sector energy-efficiency expertise [8]. NATO's efforts in this regard are primarily based on the introduction of modern, "green" technologies that will minimise the use of fossil fuel in the armed forces, thereby contributing to decarbonisation [9]. As part of the Green Defence Framework, NATO also seeks to increase operational effectiveness, improve environmental protection in terms of global climate change, and increase the energy efficiency of allied armed forces [10]. At the July 2018 NATO Brussels summit, it was decided to develop further measures in this area: "We will also further improve the energy efficiency of our military forces, including through the use of sustainable energy sources, when appropriate" [11]. It was emphasised that the problem is widespread, and that deepening research and education and the use of cutting edge and green technologies (RES) in the pursuit of a "green Armed Forces" were considered as solutions. The use of renewable energy in the defence sector will help to optimise the operational effectiveness of alliance forces. However, in order to build a tactical, rapidly deployable, and sustainable force, special attention must be paid to the prospects for creating and implementing innovative technological solutions. The energy transition process is characterised by innovation, particularly evident in the area of transport. However, it seems essential to increase the transfer of expertise in this area from the civilian to the military sector. It is recognised that research into the production, storage, and use of hydrogen will make an important contribution to creating a low-carbon and reliable economy in this sector. Scientific studies indicate the use of modern methods of hydrogen production using microchannel reforming to reform hydrocarbon fuels, along with its storage in carbon nanotubes [12–20]. A consistent position on the use of the above-mentioned technologies was also presented by Ashok S. Patil et al. [21], who analysed portable fuel cell systems for military applications using the US Army as an example, and focused on the use of energy-dense hydrogen (high energy density is needed to sustain long missions >24 h). Another equally innovative approach calls for the use of ammonia to produce hydrogen using generators and its storage in the defence sector. Furthermore, scientific studies indicate a significant relationship between the performance of an ammonia hydrogen generator and the capacity of this device in terms of energy storage for long-term stability [22]. It was assumed that with a low power load (5 W), the described electrolysers could operate autonomously for about 50 h. Studies and analyses to date pointing to the possibility of using hydrogen as a military fuel do not always agree on the issue of possible technical barriers. A commonly held concern in the adoption of hydrogen technology in the armed forces is fire safety in combat scenarios, both for the use of hydrogen as a fuel and in portable fuel cell power systems. Despite the rapid development of hydrogen technology, these barriers also relate to the flexible logistics infrastructure, where refuelling for the armed forces is a key decision-making factor [23]. As a consequence, measures should also be taken to make military stakeholders aware of the applicability of new technologies that can meet the global challenges of providing reliable, stable, and diverse sources of supply, while reducing the dependence of domestic supply on foreign oil and gas [24].

Clearly, there is a need to develop projects involving the optimal use of hydrogen as a transport fuel in the defence sector. Current analyses indicate that hydrogen fuel is less efficient than the use of petroleum fuel in, for example, military turbojet engines [25]. A comprehensive life cycle assessment (LCA) should also take into account the environmental impact of greenhouse gases, which are noticeably less when using H2 hydrogen fuels compared to the traditional approach-the use of military aviation paraffin (JP-8) [26–28]. Research is currently underway into safe and cost-effective technologies for the production, storage, and use of hydrogen, which would justify the transfer of developed solutions from the civil to the military sector. The literature highlights the dual use of the innovations in question. Individual solutions used in the civilian sector, following prior adaptation, can be successfully used in the military sector [29].

A review of the scientific literature showed that there have been studies on modern methods of producing, manufacturing, and using hydrogen. There also have been studies on the obstacles to the use of hydrogen as a fuel in the armed forces. However, there is a lack of current position papers on the development of such innovations with regard to renewable energy sources in the military sector in support of the EU's energy and climate policy. Another interesting and promising issue is the use of artificial intelligence in the armed forces. Bearing these aspects in mind, the following research questions were formulated: To what extent can the use of green hydrogen in the defence sector support EU energy and climate policy? Are the regulations sufficiently contextualised to require NATO, as an organisation, to reduce greenhouse gas emissions? Are the highly developed countries at the forefront of the green revolution taking action with respect to the use of hydrogen technology in the defence sector? What are the current obstacles to the development of hydrogen in this sector? Will current hydrogen technologies used in the civil sector find their way into the military sector? In which combat assets can hydrogen be used? At the same time, a research hypothesis was formulated that the production of hydrogen from renewable energy sources and the use of artificial intelligence would contribute to energy security on the battlefield and enhance interoperability between allies.

2. Materials and Methods

In the comparative analysis carried out, a subject criterion was applied based on the selection of three countries: Germany, Japan, and the United States. All these countries have as a key objective to become leaders in the hydrogen economy, and are thus building up a wide scientific output that is of interest to the armed forces, among others. The selection of the subject criteria (production, storage, distribution, technology perspective in the armed forces, applicability within the armed forces, and international cooperation), was carried out based on an in-depth analysis of the scientific literature, which identified a shortfall in research of analysed comparative factors in the military sector, which is the main objective of this article.

Many countries around the world have assigned renewable hydrogen a strategic role in their national energy and climate plans. Germany's hydrogen strategy pursues a dominant role for green hydrogen in achieving the goals of the Paris Agreement. The development of Germany's hydrogen economy will thus also contribute to the EU's goal of climate neutrality by 2050. Japan's hydrogen strategy was also developed in an effort to meet the targets agreed in the Paris Agreement, adopted at the Paris Climate Conference. However, the United States has tended to shy away from renewable hydrogen generation for economic reasons. Prior to January 2021, the US government was the leading opponent of lowering CO_2 emissions, as evidenced by the Kyoto Protocol and withdrawal from the Paris Agreement. This position has now changed (after the 2020 presidential election), with climate protection and the establishment of the Paris Agreement being given greater priority.

A comparative analysis showed that in the strategies examined, there was a noticeable lack of direct reference to the defence sector in relation to the assumptions of hydrogen use and decarbonisation. However, due to the universality of hydrogen technologies, it is possible to transfer the solutions developed from the heavy transport sector, the maritime sector, the aviation sector and, at a later stage, also the construction sector to the armed forces, which, according to the terms of the Paris Agreement, are not obliged to reduce greenhouse gas emissions, but at the same time are not automatically exempt from reducing them. Germany's hydrogen strategy calls for the reduction of greenhouse gas emissions in "other sectors" that are unable to fully deploy renewable energy technologies by using hydrogen-based carbon capture and utilisation (CCU) technology. This seems to be an appropriate approach for decarbonising the defence sector as well. It is advisable to legislate on these issues and define them in a precise manner.

An important role in the implementation of hydrogen technology perspectives in the armed forces can be played by Japan's hydrogen strategy, which includes the development of an international supply chain, thus contributing to the improvement of relations between allies and ensuring security of supply to conflict zones.

On the other hand, Germany envisages a common hydrogen roadmap to contribute to defence reliability. The hydrogen strategies of Japan and Germany also recognise that importing renewable hydrogen from countries with relatively low production costs can be more economically viable than producing it domestically. This is even more important from the perspective of the high ratio of renewable energy demand to production capacity in these countries.

Germany's exclusive hydrogen strategy emphasises the development of Power-to-X (PtX)-based mobility in military settings that can help ensure interoperability between allies. That said, the use of hydrogen as a fuel for transport and fuel cells in the residential sector, once adapted, has the potential to be fully utilised in the military sector.

Japan's polymer electrolyte (FC) technology, and the use of polymer electrolyte fuel cell (PEFC) and solid oxide fuel cell (SOFC) technologies to provide sustained heat for building infrastructure, could be a key measure in the armed forces' pursuit of mobility. Japan is establishing an energy plan based on the "3E+S" objective—"energy security", "economic efficiency", "environment", and "safety". One of the objectives of this plan is to address existing concerns relating to the safe use of hydrogen technology on the battlefield. Measures taken to increase safeguards against hydrogen leakage and its detection can be equally important for the defence sector. The flammability of hydrogen appears to be a significant issue facing the armed forces in their efforts to deploy hydrogen technologies.

Germany's approach places a high requirement on the implementation of a legal framework for the safe use of hydrogen technology, which may influence public acceptance and the building of trust among potential users, which will increase demand, thereby driving the development of the hydrogen economy itself.

Table 1 summarises the key elements of the hydrogen strategies of Japan, Germany, and the United States, focusing on the use of hydrogen in their armed forces.

Table 1. Key elements of the hydrogen strategies of Germany, the United States, and Japan.

Action	Germany	United States of America	Japan
Production	-Renewable hydrogen, including: offshore, electrolysis, bioprocesses, methane pyrolysis (turquoise hydrogen), artificial photosynthesis.	-Hydrogen production from fossil fuels (steam reforming of natural gas (SMR)); -Low-carbon hydrogen (CCUS gasification of coal, biomass, plastic waste); -Renewable hydrogen.	-Renewable hydrogen (RES, efficient water electrolysis, artificial photosynthesis, hydrogen permeable membranes; -Low-carbon hydrogen (CCS).
Storage	-Salt caverns; use of existing hydrogen storage facilities.	-Salt caverns, saline aquifers; -Exhausted oil and gas fields; -Cryogenic vessels; -High-capacity sorbents; -The use of hydrogen turbines to ensure grid stability and energy storage; -Porous nanomaterials.	-The use of Power-to-Gas and battery technologies for the storage of surplus energy from RES.
Distribution	-Methanol and ammonia tanks; -Pipelines; -Use of existing gas infrastructure.	-Use of existing gas pipeline networks, pipelines; -Direct feed into the final distribution network; -Use of tanker trailers and high-pressure cylinders; -Ships; -Tankers; -Railway wagons; -Road transport.	-Development of an international integrated supply chain; -Liquefied hydrogen carriers; -Transporting methylcyclohexane (MCH) and ammonia by ship; -Pipelines; -Local hydrogen networks; -Use of existing gas pipeline infrastructure with the help of methanisation.
Technology perspective of the armed forces	-Aviation: paraffin from renewable sources; -Development of hybrid electric aviation (combination of hydrogen/fuel cells/battery technology); -Development of zero emission ships based on hydrogen; -Maritime and aviation sector: use of synthetic fuels; -The use of electricity-based fuel for jet engines; -PtX-based military mobility ("Power-to-Gas" (PtG) or "Power-to-Liquid" (PtL)).	-Aircraft engines, trains: use of solid oxide fuel cell (SOFC) and solid oxide electrolysis cell (SOEC) technologies, development of hydrogen gas turbines; -Development of high-efficiency polygeneration facilities.	-Transport sector: hydrogen tanks for trucks and fuel cells for ships (FC); -Residential sector: development of domestic fuel cells (Ene-Farms) using polymer electrolyte fuel cells (PEFCs) and solid oxide fuel cells (SOFCs).

Table 1. *Cont.*

Action	Germany	United States of America	Japan
Implementation (armed forces mirroring lead sector implementation)	-Heavy transport (trucks); -Maritime transport; -Aviation.	-Heavy transport (long-distance lorries, heavy trucks, vans); -Ships; -Aircraft.	-Heavy goods vehicles; -Vehicles for long-distance transport; -Ships.
Implementation (intermediate sector; application mirrored for the armed forces)	-Building sector: use of high-efficiency fuel cell heating systems; -Development of RES-based heating systems.	-Construction, if hydrogen solutions can be made cost-competitive compared to existing ones (conversion of hydrogen into methane to power homes).	-Heating systems; -The use of heat from energy generation on user premises.
International cooperation	-Cooperation with international organisations IPHE, IRENA, and IEA; -Participation in a European project (IPCEI) in the field of hydrogen technologies; -Cooperation with EU member states regarding hydrogen, given the large volume of green energy imports [30].	-Lack of specific policies to promote cooperation in the international arena; -Intention to implement updated regulations and procedures for the export of hydrogen [31].	-Research and scientific cooperation with international organisations IEA and IPHE; -The adoption of international standards for hydrogen filling stations and FCVs in order to unify the market and expand opportunities for domestic products to enter foreign markets [32].

3. Results

As early as the sixth century BC, Sun Tzu determined that the outcome of war is determined by the Moral Law, Heaven, and Earth, and also that to wage war, one must have "a thousand light fighting wagons and a thousand leather-covered heavy wagons of rolling stock" [33]. In the envisaged concepts of organisation and conduct of combat operations, regrouping (is) of forces plays a very important role. It is one of the core activities, and is directly relevant to the success of ongoing operations. Its most important metrics are distance and time understood as rates of vehicle movements. Vehicles need to ensure the safety of crews, manoeuvrability, and reliability, and thus have a significant impact on achieving superiority over the enemy. Modern military transport is mainly dependent on the use of internal combustion engines. The authors conducted a study against the background of the civilian alternative and current and future comparisons of possible "civilian to military" and "military to civilian" development paths, which can be described as a "reference path" or "benchmark" [34]. We also used unstructured interviews conducted at the Inspectorate of Support of the Polish Armed Forces and a literature review of popular electric vehicles [35].

The respondents jointly and unanimously confirmed that with the current state of technology, the use of electric vehicles (EVs) in the armed forces on a "mass scale" may only be possible outside combat operations. The main vehicles that can be partially or fully powered by electric motors are those providing support for the functioning of military units and institutions in peacetime. These can be battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and range extended electric vehicles (REEVs) [36]. Experts draw attention to the experience of the Norwegian armed forces experimenting with electrification of transport vehicles, and Ingeborgrud and Ryghaug suggested that the experience of Norway, which is considered to have an energy culture, should be followed [37]. In addition, in this case, the vehicles fleets used in daily support operations of the state have insufficient range and this is considered to be an issue for the adoption of electric vehicles. The needs of the armed forces cannot be met by only planning for short, urban journeys. The speed of the charging infrastructure for electric vehicles is closely related to its potential use in the armed forces. This creates a disconnect between the likelihood of electric vehicles being used in the armed forces and by civilian users [38], especially with confirmed research about the growing demand for hydrogen [39]. This disparity is a direct result of the difference in purpose and function of the vehicles and the degree of operational readiness required.

For the country's defence needs, the adoption of new solutions must be a priority, but must not result in risks for crews and operators. Hydrogen fuel cell vehicles are one option for meeting the challenges of the modern battlefield. Despite the fact that there are already some early prototypes, there are technological, infrastructural, and economic challenges that must be overcome before fuel cell vehicles become real combat or support vehicles [40]. Hydrogen concept vehicles have many advantages due to their longer range and shorter refuelling times. For example, 100 hydrogen taxis are in operation in Paris and the number of taxis is expected to reach 50,000 by the end of 2030 [41]. The Chevrolet ZH2 is an example of the near-silent implementation of a hydrogen vehicle. Based on this, it is believed that hydrogen fuel will be introduced to power vehicles [36,42,43]. Researchers at the Ground Vehicle Systems Center (GVSC) and the US Army Research Laboratory are investigating the potential role of fuel cell technology in powering the combat vehicles of the future. Hydrogen propulsion could generate electricity without smoke, noise, smell, or heat, which would make combat vehicles stealthier [44]. So, when and how will hydrogen infrastructure be introduced to power military vehicles replacing diesel with hydrogen infrastructure [39,45]? In addition to the aforementioned Chevrolet, Daimler-Chrysler has confirmed the direction of development (Cipriani et al., 2014), using compressed hydrogen in its fuel cell car prototypes (NECAR H, NECAR I, NECAR 4, and NECAR 4a). Further examples of cars using hydrogen are the Ford P2000, the Fiat 600 Elettra, and the Opel Vivaro-e HYDROGEN. Hydrogen technology has been successfully implemented in trucks and buses [46]. Hydrogen trucks are being tested in Norway and the Netherlands, and a German company is working on converting heavy-duty diesel trucks to hydrogen drivetrains. Trials of hydrogen buses are being conducted in many countries such as Sweden, Germany, the UK, and the USA, where hydrogen technology has been described as proven.

On this basis, military researchers are primarily interested in using clean hydrogen to reduce reliance on oil. Ongoing research aims to replace diesel with hydrogen to power compression ignition engines. A hydrogen–air mixture burns seven times faster than a gasoline–air mixture [47–49]. A current technology is dual-fuel diesel combustion (DDF), which uses two different fuels, one as the main fuel and the other as an igniter. Hydrogen is mixed with air and then introduced into the engine. According to diesel engine principles—after compression—there is a measured injection of diesel fuel, followed by ignition of the mixed gas. Hydrogen results in better thermal efficiency, reduced fuel consumption, improved mixture flammability, and better engine operating conditions [50–53].

Today, fuel cell vehicles are becoming a viable option for the armed forces. Fuel cell vehicles have begun the slow process of displacing electric cars powered by lead–acid batteries, in which the main problems are the weight of the battery packs and long charging times. Hydrogen fuel cells reduce these problems [54]. The nature of combat operations demanding operations over long distances means that vehicles should be supplied with full fuel cell power. A level of hybridisation can also be planned; e.g., during the approach to the enemy, vehicles would use electric drives, obtaining energy from sets of capacitors and under conditions of contact with the enemy full power from fuel cells. Such solutions can be based on electric vehicles with high-efficiency motors.

In addition to tracked and wheeled vehicles, hydrogen is being introduced into usage in ships [55] and aircraft. Airbus has declared its ambition to build the first hydrogen-powered commercial aircraft by 2035 [41]. Boeing Research & Technology Europe has flown an electric unmanned aerial vehicle (UAV) powered with a hydrogen generator producing 900 Wh of energy from 1 litre of chemical solution. The Boeing UAV is capable of achieving flight times approaching 4 h [56]. The UAV industry has grown significantly, mainly through military development and applications. Some of the prototypes; e.g., Global Observer, AeroVironment, mini-BSP, micro-BSP, Spider-Lion, Hyfish, SAE Pterosoar, Puma, Endurance, Boomerang, and WanderB, are capable of 10 h long range flights. At their current stage of maturity, fuel cells already meet the target weight requirements, while at the same time offering a unique competitive advantage over conventional power sources. There are also designs known to be powered by hydrogen fuel cells: Skywalker X8, and Thunderbird LN60F, a prototype from the Liaoning General Aviation Academy. One of the main challenges is the production and storage of hydrogen on board, as well as safety during flight operations [43].

Some hydrogen projects are exploring its use in the building sector by developing dedicated hydrogen-fuelled boilers. Hydrogen applications for heating buildings have comparatively fewer advantages over low-carbon renewable energy technologies and heat pumps. Some researchers have proposed local hydrogen storage to guarantee year-round self-sufficiency for buildings equipped with RES systems such as photovoltaic (PV) to compensate for seasonal variations in output [41].

The main drawback of hydrogen use is storage [57,58]. One possible solution to this problem is to produce hydrogen with electrolysis equipment [59]. Compared to fossil fuels, hydrogen is neither toxic nor corrosive [54]. It is also less flammable, as hydrogen has an auto-ignition temperature of 550 °C, compared to 230 °C for petrol. Hydrogen is very volatile and dissipates very quickly into the surrounding environment. A hydrogen explosion is also virtually impossible. Its low thermal radiation results in low flammability, which shortens the duration of a fire, and furthermore it is very quickly consumed. Hydrogen does not cause environmental contamination.

4. Conclusions and Policy Recommendations

Progressive climate change triggered by an increase in fossil fuel combustion products has forced fundamental steps to be taken by humanity to transform economic models based on traditional fossil fuels into ones using nuclear, wind, hydro and solar energy, and with an increasing contribution from the hydrogen sector. There is a worldwide consensus that sees hydrogen as the fuel of the future, with production linked to renewable energy sources. Currently, 96% of global hydrogen production is sourced from fossil fuels, which is not conducive to reducing greenhouse gas emissions into the atmosphere. However, the uptake and development of renewable energy technologies will encourage a decline in the price of green energy, which in turn could stimulate hydrogen projects as well.

Despite the fact that production of hydrogen from renewable energy sources does not ensure continuous supply of its carriers due to the varied production potential, which results in performance fluctuations (instability) in the generated power, it is still worth investing in low-carbon hydrogen technologies, because they will contribute to diversification of fuel and energy bases, which will undoubtedly improve the stability of energy systems in the armed forces, and will affect energy security in conflict conditions. In addition, it is worth noting that the development of local hydrogen networks in countries at risk of armed conflict not only provides energy security, but also makes the economy independent of fossil fuels and their imports from countries that can be both enemy and ally in difficult conditions.

In addition, hydrogen has a favorable energy content. In one kilogram of hydrogen, the calorific value is 120 MJ/kg, compared to 25 MJ/kg in coal and 47 MJ/kg in gasoline. This means that hydrogen, due to its mass, is more efficient than the fuels used at the time. Assuming high energy consumption by combat vehicles during the conflict, calorific value of a given fuel is very important, because it ultimately affects energy efficiency in the military sector. At the same time, these measures will contribute to strengthening global efforts to reduce greenhouse gas emissions. NATO has made it a priority to increase energy efficiency by reducing the use of fossil fuels in favour of renewable energy. The use of hydrogen is particularly promising in aviation, maritime, and vehicular transport, and will thus enhance the mobility of military units and facilitate the energy storage. At the same time, there are currently major barriers to developing the use of this fuel.

The most likely scenario seems to be that the development of P2H technology will be driven and sustained by civilian use, especially within heavy transport. Decision makers in the field of commercial transport are more rational and pragmatic in the assessment of the risks of using hydrogen technologies than individual users, who may be more susceptible to personal biases; e.g., regarding the explosiveness of vehicles. Furthermore, economic and legal considerations may play an important role in the transition of institutions and large companies to hydrogen technology, and the armed forces may directly follow the lead set by these users. It seems that in the case of hydrogen technology, its development will have a polarised-diffusion character, with strong poles of development; e.g., commercial road transport and maritime shipping, which will indirectly trigger the development of further sectors of the economy. Taking all these considerations into account, it is perceived that the use of hydrogen in the armed forces will contribute to the mobility of these units and will enhance the security of sustained energy supply for military needs.

In this closing section, we present the recommendations for the fields of hydrogen utilization, hydrogen storage, and development of hydrogen technology and infrastructure in the armed forces:

1. It is in NATO's interest to increase funding for research and development of hydrogen technology for use in the armed forces.
2. It is essential to transform the results of research into the use of hydrogen and to implement pilot projects.
3. NATO member states should support the development of P2H technology both nationally and internationally.

4. Of key importance will be the implementation of hydrogen storage technology, which will eliminate one of the barriers to development.
5. It is in the interest of NATO member states to develop strategic guidelines to support the development of hydrogen infrastructure, which is an essential part of its adoption by the armed forces.

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