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OVERVIEW OF HYDROGEN APPLICATION, PRODUCTION, STORAGE AND DISTRIBUTION IN THE CONTEXT OF UKRAINE

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Abstract. *Hydrogen energy has been rapidly gaining prominence of the past decades. Many new production pathways, applications, storage methods and distribution networks were developed because of this effort. Despite many of these technologies being in their early stages, there is a significant number of experimental projects and theoretical research that promise the introduction of low-cost hydrogen into the worldwide energy system. In the context of Ukraine, where a large proportion of energy infrastructure has been destroyed, hydrogen is considered to be a major potential export, with outlines calling for significant investment and installation of electrolyzers with a capacity of up to 10 GW to be installed in Ukraine. Ukraine has the potential to support up to 500 GW of "green" hydrogen electrolyzers. An overview of the main technologies for the production, storage and distribution of hydrogen, proposals for the development of joint Ukrainian-European projects in wartime are presented.*

Key words: *hydrogen, renewable energy, alternative fuel, Ukraine.*

1.Introduction. The increasing global energy consumption poses a significant challenge for the worldwide community. In the past decade, primary energy use has risen by 21 thousand TWh. Furthermore, 81.79 % of energy consumption in 2022 was from fossil fuels, such as: coal, oil and natural gas [1].

It is widely recognized by the scientific community, that energy production is the leading cause of greenhouse gas (GHG) emissions, especially CO_2 [2]. Multinational action is being taken against climate change, consisting of improving energy efficiency, reducing energy consumption and, most importantly, deploying variable renewable energy sources (VRES) [3]. The sharp growth in the share of VRES in electricity generation globally over the last 30 years can be seen in Fig. 1. Technologies such as photovoltaic cells and wind turbines have proven to be the future of electricity generation. However, a major issue concerning the use of VRES relates to the need for costly storage in low-generation periods [4], and lackluster viability of electric vehicles (EV) due to their limited range [5]. A potential solution for these problems is hydrogen.

Even though hydrogen is the most abundant element in the universe [6], its presence in the pure form is limited on Earth in quantities at around 500 parts per billion in the atmosphere [7]. In recent years, an increasing number of studies have been conducted into hydrogen as an energy carrier in a low-carbon economy due to its high heating value (120MJ/kg) and its only combustion product being water [8]. Presently hydrogen is predominantly used in the chemical industry as a reactant and is well an established aerospace propellant, but it is being evaluated for its use as fuel for internal combustion engines, use in fuel cells and applications in municipal central heating [9]. Moreover, hydrogen can be easily produced through electrolysis and combusted in a gas turbine when VRES energy output is low, and demand is high (Fig. 2) [10]. Apart from electrolysis, there are many promising H_2 production methods which will be investigated in this paper. Despite hydrogen's potential, there are many substantial challenges connected with the inefficiency of electrolysis, its low volumetric energy content and safety hazards due to its extreme flammability [11]. In the context of Ukraine hydrogen may become an invaluable complement to the after-war energy system. Over the course of the war, 40 % of the centralized energy infrastructure in Ukraine has been destroyed and needs to be rebuilt [12]. It makes little sense to reconstruct the Ukrainian energy system using fossil fuels as the main driver for its operation, when VRES are becoming more and more commonplace in energy systems around the world, hence many companies are seeking investment into construction of carbon-free power plants and related projects.

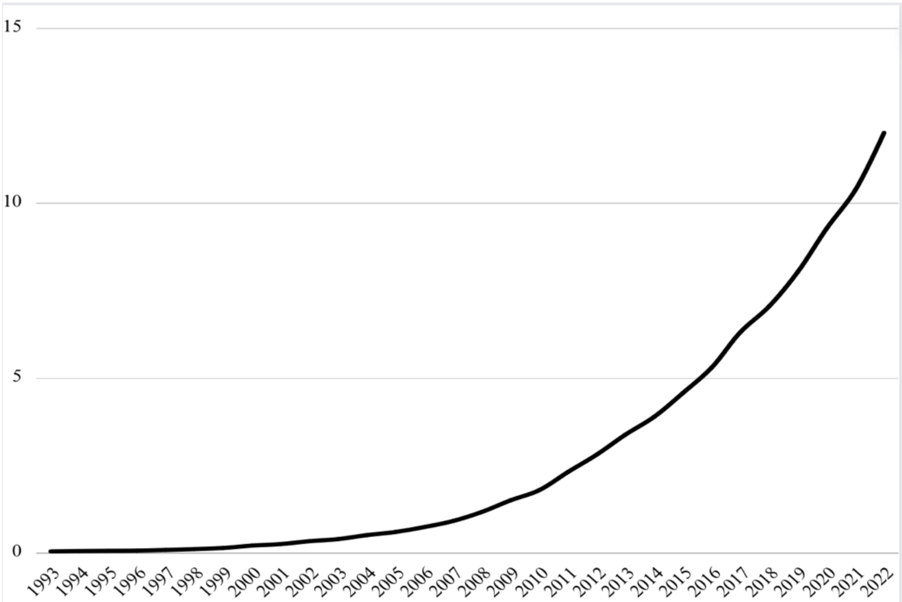

Fig. 1 - Renewable energy share 1993-2022 (%).

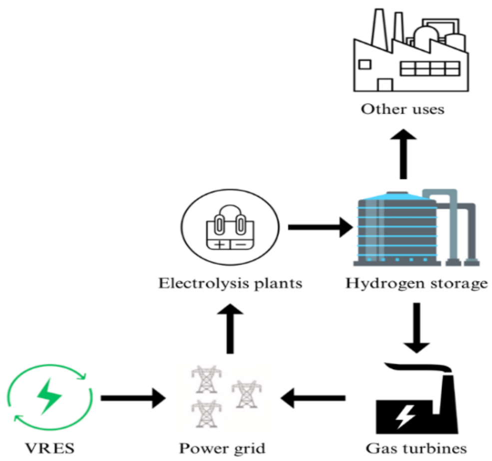

Fig. 2 – Hydrogen VRES storage. can

Plans for hydrogen production in Ukraine and export abroad have been drawn up in 2021 [13] and the Ukrainian company MCL has launched an experimental wind power plant with the aim of producing hydrogen via electrolysis [14]. The number 1 roadblock in the way of hydrogen energy proliferation is the lack of investment and the reluctance to replace existing energy systems [15], but in Ukraine a unique opportunity is formed for foreign investors to test cutting edge technologies and develop models for global application operating on experience gained in Ukraine. To encourage investment, every opportunity and challenge must be analyzed, an overview of, and suggestions regarding applications, production methods and problems related to hydrogen in the Ukrainian energy systems is the purpose of this paper. Firstly, this paper will consider both current and potential applications of hydrogen, then it will provide an overview of hydrogen production methods, storage and distribution challenges, and finally will provide a complex of suggestions for the development of Hydrogen energy.

2. Applications of hydrogen. Hydrogen was used in a range of fields from as early as the first half of the 19^{th} century [16]. Nowadays, hydrogen is widely produced and used in several different industries, however, its utilization in the energy industry so far only be considered experimental. Most hydrogen applications have not yet reached commercial scale due to the significant challenges and a lack of technological background, but as governments and enterprises around the world recognize the potential of H_2, the amount of research into the topic in steadily increasing [17].

Current applications. Agriculture. One of the most important ingredients in nitrogen-based fertilizers is ammonia [18], which is produced via the Haber-Bosch process described in Eq. 1.

$$N_2 + 3H_2 \rightarrow 2NH_3, \quad (1)$$

Agriculture is one of the most important types of human activity, and in Ukraine it accounted for 41 % of exports in 2021, making this use of hydrogen unquestionably ingrained in the current Ukrainian economy [19].

Metallurgic industry. Metallurgy is also a major source of hydrogen demand, especially in reduction of ores into metals. The first and foremost utilization of H_2 is in production of crude iron by utilizing the reducing properties of gaseous hydrogen. Such technology has been proved to work best with pure hydrogen, yielding a 98 % rate of product metal recovery. Another, less widespread application of hydrogen is the production of 3000 °C oxygen-hydrogen flames that are used to melt thermally resistant metals and ores. As demand for high melting point metals increases, this hydrogen utilization may become vital for technological and economic development. In Ukraine, at pre-war rates over 20 million tons of pig iron and crude steel were produced annually [20, 21]. Many of the metallurgic enterprises such as Azovstal were destroyed as a result of the war and in, the context of a potential increase in hydrogen production, reconstruction with novel hydrogen reduction technologies may be a priority. Even if a shift to the use of pure hydrogen is deemed to be economically unviable metallurgy, gaseous mixtures containing H_2 are certain to be used.

Aerospace propulsion. Hydrogen-oxygen mixtures are commonplace in rocket propulsion due to the high energy produced by burning such fuels. More specifically, liquid hydrogen (LH_2) is used as combustible fuel and liquid oxygen (LOX) is used as an oxidizer for the reaction. The tremendously high specific impulse of LH_2 – LOX fuel allows for creation of high-speed water vapor that propels the rocket [22]. In aviation, the use of hydrogen fuels so far has been limited to experimental and theoretical. However, as the push for green aviation is becoming stronger and stronger, fuels such as kerosene, which is derived from fossil fuels, are due to be replaced by carbon-neutral propellants. Hydrogen's only combustion by-products are steam and nitrogen oxides (NO_x) making it significantly cleaner than current options, and its energy density is highest among widely researched fuels [23], but due to its low volume density, H_2 has to be compressed or cooled to be used efficiently. These processes are extremely energy intensive and are not developed on a scale required to be implemented into commercial aviation yet [11]. Aerospace sector in Ukraine has collapsed after the Russian invasion, and no plans for continuation of commercial flights have been drawn up yet [24]. Despite this, companies such as Antonov may, with proper management, become a major component of the Ukrainian economy and develop novel technologies in the sphere of aviation, hydrogen fuels included.

Potential applications. Transportation.

Hydrogen powered vehicles, along with EV, are the crux of the transition to environmentally friendly personal and cargo transport. It is expected that the share of EV in light-duty vehicles will rise to 58 % by 2050, however, heavy-duty vehicles are unlikely to adopt the use of conventional battery-motor setup, due to a higher energy demand. Hydrogen technologies may be utilized to fill this gap [3].

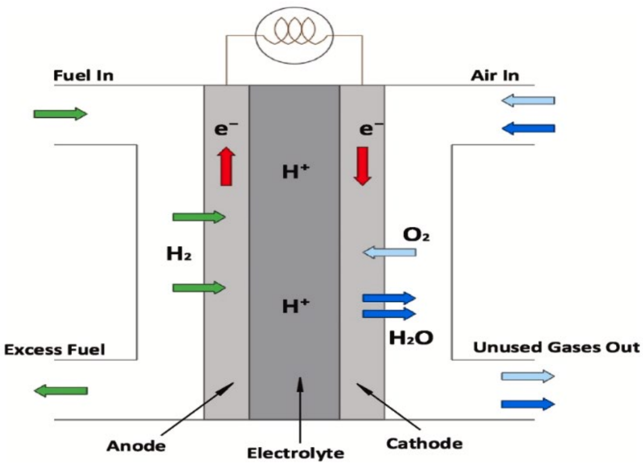

Fig. 3 – FC operation principle

The most promising hydrogen-based technology in transportation are fuel cells (FC). Similar to a battery, a fuel cell is a device that converts chemical energy into electricity or heat, but it is different in that it does not use internal energy of its materials, but rather a constant stream of hydrogen and oxygen. This is advantageous, because lengthy EV charge times are replaced by relatively fast hydrogen refueling. Polymer Electrolyte membrane fuel cell (PEMFC) is the most common types of FC. Its three main components are anode, cathode and electrolyte that are used to generate electricity by using H_2 and O_2 (Fig. 3). Currently, all types of hydrogen FC are in the early stages of development and require face major challenges such as: high operating temperatures, low power output, short lifetimes and high production and operations costs. Significant research and investment are needed to make FC viable commercially. Despite the roadblocks, Volvo, Toyota, Daimler, and hundreds of startups are developing and have released prototypes for hydrogen powered trucks and other heavy-duty transport. In addition, to land-based vehicles, hydrogen is being considered as a clean fuel for ocean-going ships in order to reduce shipping-related emissions. In 2018 international shipping accounted for 1.2 % percent of global emissions but is excepted to sharply rise to 18 % by 2050. Utilization of direct hydrogen combustion engines or fuel cells in marine vessels would be an important step in accommodating the growing international economy. Several major engineering challenges need to be overcome, such as fuel storage, energy density and safety risks, before hydrogen can be used to power ships on a large scale [25-31].

Electricity generation. The use of hydrogen in electricity generation has so far been very limited since it takes more energy to electrolyze water than is produced when H_2 is burned, although the margin is relatively small – 3.55 kWh/m^3 for generation and 3.3 kWh/m^3 for combustion [11]. While, other methods of hydrogen production may be more sensible for direct electricity production, electrolysis using VRES is considered to be the most viable option for large-scale use of H_2 as an energy carrier. On the other hand, it is argued that direct use of power generated by VRES is favorable. However, it is important to take into account the fact that VRES are variable and constant generation is not guaranteed. One of the proposed solutions are hybrid renewable energy systems (HRES), which consists of a conventional petroleum-based generator and VRES. This approach accounts for intermittent power production, but it is reliant on the use fossil fuels. While creating HRES systems may be a temporary solution for energy systems globally, it is not a carbon zero method and cannot be adopted in the long term, therefore, an environmentally friendly electricity storage technology must be implemented into green energy systems. The most popular approach are lithium-ion batteries which provide a low cost per cycle storage and are a very well-established technology, accounting for 85.6 % of energy storage in 2015. The production of lithium metal carries serious environmental risks at every stage of the life cycle, from extraction to waste disposal. Lithium is an extremely limited resource on Earth, 9 countries of the world produce this metal, 53.2 % - Australia, which creates geopolitical and economic tensions [34]. Hydrogen is proposed as a substitute for traditional batteries for the storage of RES electricity [32-34].

Hydrogen is a key element of the future carbon-free energy system due to its energy and environmental properties, it has a high calorific value, does not form pollutants except water and nitrogen oxides (NOx), is non-toxic, and its production methods have been in the focus of the scientific community and private enterprises for decades. In periods of high generation excess electricity is used to electrolyze water into H_2 and O_2, hydrogen is then stored until power output drops and supplemental energy sources are needed. Combustion of hydrogen in a gas turbine is a sparsely researched topic, but it has been shown that hydrogen combustion provides a similar to natural gas power output, efficiency and can be engineered in a way to comply with NO_x emissions [35]. The most major problem with hydrogen in VRES system is storage, since H_2 under normal conditions cannot be stored efficiently. Like for transport applications, compression or cooling are possible solutions for this issue.

Overall, hydrogen has a potential in VRES systems, but many experimental systems must be built to determine the best configuration.

Municipal heating. Building heating systems accounted for 11 % of global GHG emissions in 2021, largely due to the use of natural gas or other fossil fuels as a driver for municipal heating. Consequently, an interest in alternative systems has been taken by the wider public. Electricity based systems such as the heat pump, which uses electricity to transfer heat to needed spaces, or direct electric heaters are promising, but provide less utility compared to natural gas. Hydrogen has the potential to restructure the building heating industry. While large-scale pure hydrogen storage and distribution is unfeasible, due to infrastructure limitations and safety concerns, blending of hydrogen into natural gas networks is a promising idea for reducing GHG emissions. An example of such a project is HyDeploy in the UK, which used a mixture of 20…80 % natural gas to heat 133 buildings on the territory of Keele University. The project has demonstrated that a 20 % injection of hydrogen into heating systems is safe and efficient [36-39]. Even though the concept of hydrogen municipal heating has been proven experimentally, it is essential to take into account the fact that this approach does not eliminate GHG emissions completely, but rather dampens the impact. Furthermore, the cost of green hydrogen is far too high compared to natural gas to be viable [30].

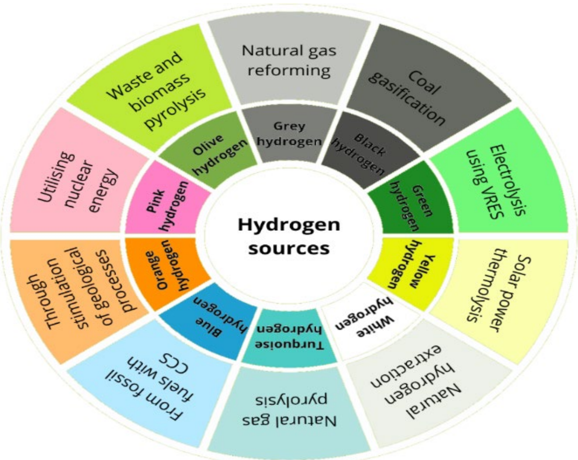

Fig. 4 – Hydrogen color spectrum

3. Production pathways. For extensive integration of hydrogen into world energy systems, it must be produced at a much larger scale compared to current amounts (90 million tons annually [40]). Additionally, new ways of production must be explored, as currently prevalent methods rely exclusively on fossil fuels and are not suitable for a carbon free economy. Research into hydrogen production pathways is becoming more and more abundant, hence more and more methods are being proposed and evaluated for their viability. Both established and emerging hydrogen production methods and their relevant colloquial nicknames are presented in Fig. 4 [41]. This section of the paper will provide an overview for the most promising methods and analyze their viability for use in Ukraine.

Hydrocarbons reforming. Currently most of the world's commercial hydrogen production comes from fossil fuels, more specifically from steam methane reforming

(SMR). This technology is considered to be mature in the petrochemical industry and is believed to be at its theoretical limits of efficiency. The SMR process consist of several steps, the main ones being stem reforming of methane into carbon monoxide and hydrogen (Eq. 2), and water-gas shift of carbon monoxide into carbon dioxide and hydrogen (Eq. 3).

$$CH_4 + H_2O \rightarrow CO + H_2, \quad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2, \quad (3)$$

Further hydrogen is purified as needed by using pressure swing adsorption (PSA), or amine scrubbing [42]. The SMR process yield efficiency is estimated to be 74 % and the cost is \$1.8 (64₴) kg^{-1} [9]. However, while this process is economically viable for H_2 production it is unsuitable for a carbon-neutral economy, as the main byproduct of SMR is CO_2 with a production rate of 10-15t CO_2/t H_2 [43]. This deficiency can be alleviated by using carbon capture and storage (CSS). It is possible to store separated CO_2 underground in depleted oil and gas wells, aquifers, or in the liquid form using dedicated facilities. Even though, CSS is a promising technology, but it is important to consider that a 15% efficiency drop is associated with implementing CSS [44]. Furthermore, it should be considered that the petrochemical industry may be interested in continuing to supply hydrocarbons under the mask of CSS and a complete shift from fossil fuels would be the only true way to mitigate climate change.

In Ukraine hydrogen is mostly produced through SMR for the production of ammonia-based fertilizers. In 2021 2.1 million tons of ammonia were produced and, at a rate of 180 kg H_2 per ton of NH_3 it can be approximated that the pre-war annual hydrogen production in Ukraine was 360 thousand tons [45], this translated to almost 4 million tons of CO_2 released into the atmosphere, which accouns for 2 % of annual GHG emissions in Ukraine [46]. It is clear that there is established demand for hydrogen in Ukraine, but current methods of production do not allow for expansion of applications, as using SMR derived hydrogen for energy would be neither cost-effective, nor environmentally friendly, hence other H_2 production pathways must be explored to create a sensible development plan for Ukraine.

Water electrolysis. Undoubtedly, the most widespread developing hydrogen production technology is water electrolysis. Crucially, renewable energy has been recognized by the general public as one of the solutions to climate change and most countries around the world are engaging in both internal and international projects to develop renewable energy infrastructure, therefore, VRES are believed to be the future of the world energy system. However, as mentioned in section 2, “green” energy storage is the main roadblock for system wide VRES implementation. It is proposed that storing electricity in the form of hydrogen may become an important way of mitigating this VRES flaw. Furthermore, if electrolysis facilities are created, hydrogen can, relatively easily, be directed into the production of FC or used in the chemical industry. The water electrolysis reaction is described in Eq. 4.

$$H_2O \rightarrow H_2 + 1/2O_2, \quad (4)$$

Product hydrogen purity depends on the purity of water used in the process, so high concentration of H_2 needed for FC and other processes can be achieved through water purification before electrolysis [47]. It is essential that electrolysis is performed using carbon-free electricity, since electricity from mixed grid sources may produce up to 1.5 times more pollution compared to SMR during hydrogen production [43]. Another problem that must be considered is that 80 % of the products by mass is oxygen, considering that production of hydrogen is expected to reach 660 million tons by 2050 [48], largely fueled by VRES, 2.4 billion tons of additional O_2 will be produced. Presently, oxygen is widely used in the medical and metallurgic industries, however, the demand for oxygen is not sufficient to use the excess O_2 from electrolysis, therefore, unless new fields for large-scale oxygen use are found, it would have to be released into the atmosphere, decreasing the overall economic viability of the process.

Ukraine is considered to have an enormous potential for hydrogen production through electrolysis. It has been estimated that up to 45 million tons of "green" hydrogen can produced in Ukraine [49], however, for this level of production to be possible, over 500 GW worth of VRES generation would need to be installed in Ukraine [45]. The possibility of large-scale electrolysis facilities in Ukraine has been recognized by the European community through the Green Hydrogen for a European Green Deal: 2x40 GW Initiative. This 2020 document developed by Hydrogen Europe outlines the possibility of installing electrolysers with combined capacity of 10 GW in Ukraine with 80 % of hydrogen production being oriented for export to Europe and 20% allocated for sustainable ammonia fertilizer production [50]. Several hydrogen production projects developed by Ukrainian companies exist and most of them focus on the scheme VRES → Hydrogen → Ammonia. An example of such a project is the development of a wind energy facility "Volodymyrets" by the energy consultant firm MCL. The project's goal is installation of 72 MW wind turbine array with the goal of electrolyzing water into hydrogen. Another company focused on "green" H_2 synthesis is LLC "Argus service", it proposes a photovoltaic solar power plant with a capacity of 125 MW dedicated to water electrolysis. Both projects plan to convert the hydrogen produced into ammonia for fertilizer production, however, if such projects are a success, a broader utilization of H_2 in Ukraine is bound to follow [48-50].

Natural hydrogen extraction. The vast majority of current hydrogen projects focus solely on producing hydrogen through different chemical processes; however, an emerging field of study is natural geological hydrogen that can be extracted using technology similar to established fossil fuels extraction methods. It is estimated that 20 million tons of hydrogen is released yearly from the earth with even larger volumes trapped underground, with concentrations of hydrogen reaching 98 %. Natural hydrogen deposits could potentially supply 1000 million tons per year for 100 000 years, although such estimation is only theoretical, it puts the amount of hydrogen underground into perspective. Furthermore, it has been approximated that natural hydrogen could account for 85 % of global production, provided sufficient investment is present. The equipment needed to extract natural hydrogen is very similar to that used in gas extraction, hence, the investment needed to begin H_2 mining is significantly lower than that which is needed for "green" hydrogen. The equipment needed to extract natural hydrogen is very similar to that used in gas extraction, hence, the investment needed to begin H_2 mining is significantly lower than that which is needed for "green" hydrogen. Companies focused on extracting hydrogen from the ground are already in present, Helios Aragon in Spain and Gold Hydrogen in Australia have already achieved sizable H_2 extraction with a cost comparable to that or SMR. Natural hydrogen production exists in Ukraine, 11 significant hydrogen deposits with a concentration of up to 80 %. Additionally, this field of study is being investigated by Ukrainian scientists, studies by Bahrii I. et al 2022 [53], 2023 provide insight into occurrence of hydrogen as a part of hydrocarbon wells. Little progress in term of creating plans for extracting geological hydrogen in Ukraine has been done so far, but it is a promising field of research [51-54].

Natural gas pyrolysis. Another developing hydrogen production pathway is fossil fuel thermal decomposition, also known as pyrolysis. Like SMR, thermal decomposition of methane (TDP) is grounded in existing petrochemical technology, although due to a more complex process it has not been implemented on a scale similar to SMR. The principle of TDP is very simple, methane is thermally decomposed into carbon and hydrogen at temperatures above 700°C. (Eq. 5).

$$CH_4 \rightarrow C + 2H_2, \quad (5)$$

The advantage of TDP is the lack of direct GHG emission, potentially making the process carbon neutral [44]. However, several significant limitations of TDP must be considered. Firstly, by mass 75 % of products of the reaction is carbon and, similar to the issue with oxygen oversupply from electrolysis, there is no sufficient demand for such amount of carbon, considering current demand for hydrogen (90 million tons), if all of it were produced through TDP, 270 million tons of solid carbon would be produced, which is 13…18 times more than current global annual carbon demand [43]. This issue can be solved by introducing pyrolyzed carbon into soil, which has been shown to increase soil fertility, especially in Chernozems which are extremely widespread in the south of Ukraine [55]. The second problem connected with TDP is interconnected with the argument that CSS is a tool for petrochemical companies to stay in business in a climate-conscious world. TDP may be presented to the public as a remedy for GHG emissions, while fossil fuels keep being extracted and used.

For Ukraine TDP can become an alternative for SMR, however, replacing established fossil fuel-based hydrogen production infrastructure with another type of hydrocarbon dependency would not be sensible, when truly environmentally friendly technologies like VRES have been proven to be effective for H_2 synthesis.

Nuclear energy utilization. Nuclear energy, despite its poor reputation caused by accidents such as Chornobyl and Fukushima, is believed to be one of the cleanest and most environmentally friendly options available [56]. It has been proposed that byproduct heat from nuclear power plants can be used in thermochemical water-splitting reactions. Canada, China, and Japan have developed nuclear to hydrogen systems that use primary of secondary heat from a nuclear reactor to thermolyze water into H_2 yielding a cost per kilogram of \$2.7/kg H_2 (20…45 % cheaper than conventional electrolysis), although these projects did not consider storage and transportation cost [57]. However, nuclear energy is not favored by the general public, hence little development or investment has been done into nuclear power plants.

Ukraine relies heavily on nuclear power, as 58 % of Ukrainian electricity production in 2022 was from nuclear energy [1], and due to Russian attacks on the Ukrainian energy system nuclear is expected to stay an integral component of Ukrainian energy system. Existing nuclear power plants in Ukraine would require extensive and expensive modifications to allow for hydrogen production, and due to Europe's reluctance to accept nuclear energy as an invaluable component of the world energy system, it is unlikely that significant foreign investment will be present, making full-scale nuclear hydrogen unlikely.

Waste and biomass pyrolysis. The world municipal waste production has been rapidly increasing for the past decades and, if current trends stay the same, by 2100 it is projected to reach 4 billion tons a year [58]. Consequently, recycling, and other waste disposal methods are needed to avoid an environmental catastrophe. Waste to energy model has gained quite some prominence due to its efficiency and many projects around the world have been developed. It is estimated, that in 2019 approximately 19% of municipal waste was incinerated and 9 % recycled leaving the remaining 72 % to lay in landfills and contaminate the environment [59]. It is proposed that organic waste can be pyrolyzed into syngas, a combination of CH_4, CO, CO_2 and H_2, which can be combusted for energy. The principle of this process is similar to TDP in that more complex organic compounds are broken down into their simple components at high temperatures (700…1000°C). This method, although not carbon zero is significantly less harmful to the environment and may aid the world energy system in the transition from fossil fuels [60].

Ukraine has a significant waste management problem, as 45 million m^3 of waste is produced annually, with the vast majority of it ending up in unsanitary and often severely mismanaged landfills and dumps [61]. Odessa landfill may become an example of successful waste management and disposal. In 2019 degassing systems were installed at Odessa landfill with a capacity of 3 MW. Through pyrolysis of organic matter, which accumulates at the Odessa landfill at the rate of 157 000 tons per year, syngas is produced and then either burned for energy or separated and sold. This method is capable of producing at least 1 kg of hydrogen per 10 kg of biomatter [62]. If such systems are implemented on a wider scale, they can not only lessen the problem of waste accumulation in Ukraine, but also synthesize hydrogen from organic matter with a ration of at least 1 …10.

Hydrogen storage. Hydrogen in the under normal conditions is a gas with a density of 0.082 kg/m^2 [63], making its storage highly space inefficient, and rendering gaseous H_2 practically unusable in vehicles. To alleviate this problem several ways of compressing hydrogen were developed, including mechanical compression, liquefication and geological storage, as well chemical methods such as conversion into ammonia, metal hydrides, formic acid or carbohydrates. Hydrogen compressed at pressures between 25…70 MPa, however, for industrial applications H_2 is usually stored in metallic cylinders at 20…30 MPa to achieve the lowest cost. For applications in vehicles 70 MPa is considered optimal, requiring the use of costly carbon fiber composite pressure vessels, and incurring an energy penalty of at least 7 % [64]. To achieve reliable and cost-effective hydrogen compression more research must be done into long term storage and the impact of operating conditions of the materials [65]. An alternative to compression is liquefication at temperatures below to 30K [9]. It is considered the most space effective option, offering a density of 70 kg/m^3 [66], and has achieved technological maturity. On the other hand, liquefication incurs an energy penalty of over 30 % [64]. Furthermore, it is important to consider that liquid hydrogen vessels must be well insulated, adding to capital costs, and continuously refrigerated, adding to operational costs. Liquid hydrogen storage is not suitable for commercial applications and should be used exclusively when no other option is available.

Among chemical storage, metal hydrides provide by far the highest hydrogen density ranging from 70 kg/m^3…150 kg/m^3 [9]. Although, metal hydrides incur an energy penalty moderately higher than hydrogen compression and thus, a higher cost [31]. Therefore, even though both of these technologies have the potential for efficient H_2 storage, it must be considered which of the two methods is more sensible in a given case. Ammonia is also a candidate for hydrogen storage and transportation. It is uniquely suited for Ukraine, as most current production and even developing projects mentioned in section 3.2 focus on converting H_2 into ammonia for either fertilizer production, or more efficient storage and distribution. Ammonia is production is approximately 1.3 times more expensive than hydrogen, however, storage of NH_3 is almost 30 times more cost effective than hydrogen, making it very well suited as a hydrogen-derived energy carried [67]. Despite these incredible advantages, ammonia is incredibly toxic to humans and produces NO_x in the process of combustion [3]. Therefore, more research is required to mitigate these issues.

Storage of hydrogen can also be performed without physical or chemical modification of the gas through underground storage. A number of human-made and natural geological formations can serve as spaces for H_2 storage, more specifically depleted natural gas and oil wells, aquifers, salt caverns, abandoned mines and rock caverns [10]. A 2016 study analyzed the potential for geological hydrogen storage in Poland, it has identified 26 sites in the Carpathian fore deep and the Carpathians proper, it can be inferred from this study, that Ukrainian Carpathians must also have a high potential for underground hydrogen storage. However, proper surveys must be conducted to determine the possibility of hydrogen storage in the Ukrainian Carpathians [68].

Hydrogen distribution. The problem of cost and space-effective hydrogen distribution is closely related to hydrogen storage. The problems being low volumetric energy density and high cost of transportation if traditional hydrogen storage technologies are used. Hydrogen gas pipelines have already been tested and proven as a viable distribution method, as 3000 kilometers of high-pressure hydrogen pipes have been installed in Europe [64]. Compressed hydrogen can be transported by trucks and delivered directly to a refueling station without the need for intermediate distribution nodes [69]. Furthermore, hydrogen can and is transported overseas by using conventional tanker ships [70]. While these methods are undoubtedly viable for certain situations, converting hydrogen into ammonia allows for transportation by using practically the same technology as that which is used for natural gas, although additional safety measured must be installed to mitigate ammonia's toxicity. Hydrogen energy has the potential to revolutionize the world energy industry, by providing a cost-efficient method for VRES-generated electricity storage and making clean transportation possible by utilizing FC technology. Water electrolysis has now practically reached technological maturity and can be safely implemented without the risk of investment loss. Other H_2 production pathways need significantly more research and experimental projects to reach commercial scale. Storage and distribution remain the main roadblocks on the way to a hydrogen economy, but more and more solutions are being proposed and some of them, such as hydrogen pipelines and hydrogen tankers have already been proven to be effective method of distribution. Chemical storage of H_2 promises high efficiency and low cost but has serious flawed connected with safety and commercial implementation, hence, more research and testing are needed.

In Ukraine, there is a major hydrogen market directed at ammonia fertilizer production, with most of the hydrogen being produced through SMR, but the potential for "green" hydrogen is immense and recognized by European investors. Ukraine can provide low land and labor costs together with a high energy yield; however, the current war deters investors from engaging with Ukrainian projects. It is unlikely that this fear of losing their investment will disappear fully until the war is over, hence, Ukrainian companies and startups must develop comprehensive, low-risk and appealing projects for investors. It is possible that dispersed VRES such as photovoltaic could be paired with low-scale electrolysis plants to reduce the risk of complete system destruction in case of a Russian attack on the facility. Natural hydrogen extraction projects cannot be reduced in scale and still remain viable, however many of H_2 formations occur in regions with already developed mining infrastructure, therefore it should be possible to begin extraction with relatively low capital costs. Conversion of hydrogen into ammonia may be significantly more dangerous, as refineries capable of such processes are generally not scalable and are a greater target for attack. Hydrogen storage must be decentralized to avoid destruction similar to that of oil storage facilities. Compressed hydrogen could be transported and stored by trucks domestically, and by exported to high-demand European countries via train, although this would require creating either construction of compression facilities or conversion of H_2 into NH_3. Hydrogen pipelines are a possibility, but in order to reduce the risk of complete destruction, they would need to be low scale, at least until crossing the border into the European Union. These propositions should be evaluated by the scientific community and investigated by Ukrainian developers interested in attracting European investment in wartime. The most important component of this investigation should be the creation of proof-of-concept production and distribution projects that would bring theoretical models to life, so that it can be scaled with relative ease. Furthermore, it is essential that Ukrainian and Global scientific communities engage in deeper collaboration to provide both the needed data and capabilities to analyze it and develop realistic models for hydrogen energy in Ukraine.

Thus, an overview of hydrogen applications in agriculture, metallurgy, transport, renewable energy storage and municipal heat supply, hydrogen production routes such as SMR, water electrolysis, geological hydrogen production, TDP, nuclear thermolysis and pyrolysis of organic waste is presented. Additionally, H_2 storage utilizing physical and chemical manipulation and the possibility of underground storage were investigated, together with relevant distribution methods. Finally, several suggestions for developing Ukrainian hydrogen economy in the conditions of war were proposed, more specifically, focusing of dispersed facilities and expanding Ukraine-Europe scientific and commercial cooperation. Further research could focus on economic analysis of different steps of hydrogen production in Ukraine, surveying potential production sites and developing models for hydrogen delivery to Europe. The production of hydrogen through the use of solar energy or other renewable and safe sources can be considered promising [71, 72].

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