Ukraine has tremendous potential for renewable energy production. With sources such as solar and wind, coupled with a strong industrial sector (primarily in metallurgy and chemical industry), Ukraine is well positioned to play a significant role in large-scale production of green hydrogen. This is particularly relevant today with the global shift towards green hydrogen production. Currently, Ukraine’s hydrogen production stands at approximately 360,000 t/year, which is primarily used for ammonia production. While this only accounts for 0.5% of the total global demand, with technological advancement and investment, Ukraine could significantly increase its hydrogen production capacity.

Central European directives, in particular the European Commission’s “Energy System Integration. Hydrogen” and the “Green Hydrogen for a European Green Deal: A 2x40 GW Initiative,” identify Ukraine as a strategic partner in the development of renewable hydrogen. These strategic documents envision the construction of up to 10 GW of electrolysis capacities in Ukraine by 2030, intended for renewable hydrogen production. About 1.8 GW of this capacity is for the domestic market, primarily for the production of green ammonia, a critical commodity for the agro-industrial complex.

Implementing these initiatives could significantly reduce Ukraine’s energy dependence on imported fuels and significantly reduce harmful emissions, in line with international efforts towards sustainable development. This transition could play a pivotal role in the decarbonization of Ukraine’s economy and contribute to its national energy security. However, realizing this requires significant advancement in hydrogen production technology and infrastructure.
This includes infrastructure for efficient storage and transportation of hydrogen. Furthermore, it requires government policy support, namely investment incentives, research and development subsidies, and assistance in the infrastructure development.

Thus, the prospects for the evolution of hydrogen economy in Ukraine are indeed attractive. The production of green ammonia is an important step in this direction. Under favourable conditions, it is possible to produce hydrogen for consumption both domestically and for export to European Union countries.

**Keywords:** Ukraine's energy sector, renewable energy sources, hydrogen, green hydrogen, green ammonia, hydrogen derivatives, decarbonization.

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**Introduction**

Considering Ukraine with the population of over 40 million people, rich in various types of energy resources, high demand for energy, and a developed gas transport system, as well as a unique location between the European Union and the Black Sea-Caspian region, it can be said that the country has all the basics to become an important player in the transition to energy stability. At the same time, global trends towards transition to renewable energy sources and sustainable development create new opportunities for the use of green hydrogen. In this regard, it is relevant to study the potential of Ukraine for the development of renewable energy production, green hydrogen, and also to consider possibilities of cooperation with the European Union in this direction.

The aim of this work is to analyze the energy situation in Ukraine, to evaluate the technical potential of the country in terms of creating capacities based on renewable energy sources, production of green hydrogen and its derivatives, as well as to consider the prospects for cooperation with the European Union within the framework of its ambitious plans for renewable hydrogen development.

To achieve this goal, statistical data on fossil fuel extraction, electricity generation, hydrogen production and its derivatives, reports and documents related to Ukraine's energy policy and development strategy, as well as a review of scientific literature on hydrogen production and use, and an analysis of official documents and strategies of the European Commission regarding renewable hydrogen and energy systems integration will be used and analyzed in the paper.

Recent studies acknowledge Ukraine's abundant solar and wind resources as potential catalysts for green hydrogen production. However, a more rigorous exploration of other renewable sources and strategies for their effective deployment for hydrogen production remains unaddressed in the current literature. Though the technology for hydrogen production via renewable resources is an active area of investigation, a detailed examination of these technologies, particularly optimized for the unique energy infrastructure of Ukraine, is still required. The transformative potential of hydrogen and its derivatives (such as green ammonia) in reshaping Ukraine's industrial sectors, particularly metallurgy and chemical industries, has been deliberated in recent literature. Nevertheless, comprehensive studies detailing the transition strategies and technical feasibility of incorporating hydrogen as an energy carrier and raw material across different industries remain elusive. The essential requirement of significant electrolyzer capacity installations and robust infrastructure for hydrogen storage and transportation is underscored in several works. However, research focusing on the development of infrastructure solutions, uniquely suited to Ukraine's geographical and economic context, is currently limited. While numerous documents emphasize the need for supportive government policies, R&D investments, and infrastructural development, a detailed understanding of the most effective policy measures and investment strategies that will stimulate the hydrogen economy in Ukraine is absent. Despite the recognition of the hydrogen economy’s potential in bolstering Ukraine's energy security and decarbonization efforts, comprehensive studies investigating wider socio-economic implications, job creation prospects, and industrial development opportunities are insufficiently explored.

Although Ukraine’s potential role in the global hydrogen economy has been acknowledged, more research is warranted to solve unexplored aspects and refine strategies for Ukraine’s transition to the hydrogen economy. An integrative approach, encapsulating technology, policy, infrastructure, industrial application, and socio-economic aspects are instrumental to advance this research field.

The work aims to identify opportunities and challenges related to the energy sector in Ukraine, with an emphasis on renewable energy sources and hydrogen production, for the formulation of a development strategy that would take into account global trends and local peculiarities, allowing Ukraine to realize its energy potential and ensure a sustainable future for the next generations.

According to statistical data, Ukraine has energy reserves of coal, natural gas, oil, and uranium. The consolidated information on annual fossil fuel extraction in Ukraine for the years 2011-2021 is provided in Fig. 1 below [1].

According to Fig. 1, from 2011 to 2021, the production of crude oil in Ukraine decreased from 2.4 million tons to 1.7 million tons. During this period, a gradual decline was observed, except for a slight increase between 2018 and 2021. Regarding natural gas, throughout this period, the total production, measured in oil equivalent, fluctuated from 171 million tons in 2011 to 163 million tons in 2021. At the same time, coal production in the oil equivalent in Ukraine fell from 36.1 million tons in 2011 to 13.7 million tons in 2021. A significant decrease in production was recorded starting in 2014, which is associated with a temporary occupation of territories in Donetsk and Luhansk regions. It should be noted that statistical data from 2014 is provided without considering the temporarily occupied territory of the Autonomous Republic of Crimea, the city of Sevastopol, and temporarily occupied territories in Donetsk and Luhansk regions.

At the same time, Ukraine is actively working on the development of renewable energy sources, which contribute to reducing dependence on fossil fuels. According to statistical data, as of the beginning of 2021, the total power of RES in Ukraine

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**Fig. 1. Annual fossil fuel extraction in millions of tons of oil equivalent**
amounted to over 74 GW, compared to 3.3 GW in 2016 and only 0.4 GW in 2011 [3, 4]. Here are some data on different types of RES in Ukraine:

- Solar energy: in 2020, solar generation was over 6.6 GW, indicating a large increase compared to 1 GW in 2016, or 0.1 GW in 2011 [3].
- Wind energy developed not as fast as solar: wind power increased from 151 MW in 2011 to 426 MW in 2016 and to over 1.3 GW in 2020 [4].
- Bioenergy and hydroelectric power: the volumes of energy production from biomass and mini-HPPs increased by 11% in 2019 compared to 2016 [5, 6].

Significant changes have occurred in the energy sector in Ukraine over the past decade, especially in the context of electricity production. These changes reflect the growth of renewable energy sources and the country’s attempts to reduce dependence on fossil fuels. The obtained results indicate a gradual reorientation of the Ukrainian energy policy towards renewable energy sources and the country’s attempts to reduce dependence on fossil fuels. Fig. 2 contains statistical data on the production of electricity in Ukraine from 2011 to 2021, taking into account all types of generation, such as thermal power plants (TPPs), nuclear power plants (NPPs), hydroelectric power stations and pumped storage power plants (HPPs and PSPs), wind power plants (WPPs), and solar power plants (SPPs).

Based on the analysis of data on electricity production in Ukraine for the period from 2011 to 2021, we can conclude that there was a significant growth in electricity production from renewable sources, specifically wind and solar energy systems. At the same time, energy production from thermal power plants decreased noticeably, while electricity production from nuclear power plants and hydroelectric power plants remained stable. The obtained results indicate a gradual reorientation of Ukraine’s energy policy towards renewable energy sources and a reduction in dependence on fossil fuels. Considering the effects of massive rocket attacks on Ukraine’s energy infrastructure, the development of renewable energy and decentralization of generation could be a significant factor in ensuring Ukraine’s energy security, as well as reducing the environmental impact of the energy sector.

One of the possible directions for further development of renewable energy is the production of green hydrogen from renewable energy sources. The use of hydrogen obtained by electrolysis using renewable energy sources can play a crucial role in reducing carbon footprint and ensuring energy transition. In addition, this could contribute to the creation of new jobs, attracting investments, and the development of advanced technologies. Hydrogen production can also provide new opportunities for export cooperation with other states in the field of clean energy.

In 2020, Ukraine’s GDP amounted to 155.58 billion US dollars and constituted 0.14% of the world economy [7]; GDP per capita reached 3.115 US dollars (12.377 US dollars at purchasing power parity). In the second quarter of 2021, GDP growth compared to the same period in 2020 was 5.7% [8], which is the highest figure since 2011, and was due to increased consumer spending, investments, and public expenditures.

Among the important industrial sectors that are relevant for the development of hydrogen economy, it is worth mentioning the most specific sectors, such as the metallurgical industry (production of steel, iron, aluminum/aluminum products and other non-ferrous metals) and industries that already use hydrogen as a raw material, for example, the chemical industry (production of ammonia and methanol) and the oil refining sector [9].

**Metallurgical industry**

From 2014 to 2020, Ukraine’s export decreased by 3.5 billion USD (from 59.4 billion USD in 2014 to 55.9 billion USD in 2020), however, steel and iron are significant export commodities (about 16% of the total export value) [10]. Ukraine plays an important role in the global iron ore sector, producing around 21 million tons of steel per year and having significant iron ore deposits, totaling 19.8 billion tons [11]. The country’s metallurgical industry comprises over 800 enterprises, including 19 large metallurgical and mining companies, 12 pipe-rolling mills, 10 refractory materials production enterprises, and several ferroalloy plants [12]. Notably, the main iron production process in Ukraine is based on blast furnace production, in which coal (converted to coke) is used as a reductant for iron ore [13]. It is important to note that currently the direct reduced iron (DRI) technology, using hydrogen as a reductant, is not applied in Ukraine. Ignoring the decarbonization of metallurgical production places Ukrainian steel and iron lower compared to global manufacturers that have already announced the reconstruction of production with the aim of using hydrogen to reduce the carbon footprint.

**Aluminum industry**

The main products of the aluminum industry are alumina and aluminum. Aluminum production involves the conversion of bauxite ore into alumina, and then the reduction of aluminum at aluminum plants with large energy consumption [15]. The Ukrainian aluminum industry is based on two strategically important enterprises located in Mykolaiv and Zaporizhzhia. At the same time, the production of aluminum alloys in secondary metallurgy enterprises, such as a plant in the city of Dnipro, where aluminum scrap is used, is developing in Ukraine [16]. This indicates a search for alternative development paths for the aluminum industry in Ukraine. The future of the aluminum industry may be associated with the use of hydrogen as an energy source, where hydrogen has the potential for environmentally friendly and energy-efficient aluminum production, although its use possibilities are currently limited [15, 16].

**Refinery**

Before the active phase of the war, the main source of oil for Ukraine’s oil refining industry was imported from the Russian Federation, although Ukraine also extracted a small amount of oil independently. Refining products are used by six petrochemical enterprises inherited from the Soviet Union with the total refining capacity of over 42 million tons per year. From 1990 to 2000, the industry experienced a significant decline of 71%. In 2007, several oil refineries were closed, and by 2012, only one of the six was operational – Kremenchuk oil refinery, located in Poltava region, with the capacity of 18.6 million tons per year. The plant’s technological processes include raw and vacuum distillation, flu-

![Fig. 2. Produced electricity, billion kWh](image-url)
id catalytic cracking, catalytic reforming, hydro treating, and isomerization. The plant does not produce hydrogen specifically, and hydrogen needs are met through the byproduct of hydrogen in the reforming process [17]. In the future, the use of hydrogen as an alternative fuel for oil refineries is possible, but the potential of this direction is limited.

**Production of ammonia and methanol**

Ukraine is among the top ten countries producing ammonia and nitrogen fertilizers, having six production locations. Before the active phase of the war, the country also provided transit for ammonia produced in Russia [18]. Odesa Port Plant is the leader in the production of this product and one of the largest producers of ammonia in Ukraine [19, 20]. Sea Trade Port Pivdennyi plays a significant role in global ammonia exports, serving as a major hub for the industry, and has unique reloading capabilities and direct access to international markets [21–23]. Methanol production in Ukraine depended on the availability of hydrogen, which is an integral component of the methanol production process. Before the war, there was only one enterprise in Ukraine, located in the city of Severodonetsk, engaged in the production of methanol [24], but methanol production is currently suspended [25]. Ammonia and methanol are important chemical compounds that have broad applications in industry and agriculture. Their production requires a significant amount of hydrogen. Hydrogen for this process is usually obtained from natural gas (methane) using steam methane reforming (SMR). The main method of ammonia production is the Haber-Bosch process, which involves the reaction of hydrogen and nitrogen under high pressure and temperature in the presence of an iron catalyst [26, 27].

The analysis of data on ammonia production in Ukraine, depicted in Fig. 3, for the period 2011-2021, provided by the State Statistics Service of Ukraine [1], indicates a significant decrease in production over the last decade. The gross production of ammonia dropped from 4.3 million tons in 2011 to 2.1 million tons in 2021. However, despite the decrease in production, ammonia remains an important industrial product for Ukraine.

Current hydrogen production in Ukraine is estimated at approximately 360 thousand tons per year, considering that about 180 kg of hydrogen is typically required to produce one ton of ammonia [26–28]. In the context of this level of hydrogen production, if all this hydrogen were to be produced as green hydrogen from water electrolysis, the installed electrolyzer capacity would be approximately 2.5 GW. The total global hydrogen production volume (excluding secondary product production) is about 70-80 million tons per year, so the current demand for hydrogen in Ukraine is about 0.5% of the total global demand. Considering the global trend towards renewable energy sources and sustainable development, further research and innovation in the field of ammonia are of great importance for ensuring the competitiveness of the Ukrainian chemical industry on the international market.

The Institute of Renewable Energy of the National Academy of Sciences of Ukraine conducted an assessment of Ukraine’s technical potential for creating capacities based on renewable energy sources [29]. According to the study results, the potential for renewable energy production exceeds 500 GW, which allows for the production of more than 30 million tons of hydrogen (about 1200 TWh).

According to the information on the official website of the European Commission in the “Energy System Integration: Hydrogen” section [30], the European Commission has ambitious plans for the development of renewable hydrogen and its use in the energy sector of Europe. In 2022, hydrogen accounted for less than 2% of Europe’s energy consumption and was primarily used for the production of chemical products, such as plastics and fertilizers. 96% of this hydrogen was produced using natural gas, leading to significant CO2 emissions. The European Commission aims to produce 10 million tons of renewable hydrogen by 2030 and import another 10 million tons by 2030.

Within the framework of the document “Green Hydrogen for European Green Deal: 2x40 GW Initiative” [31], the emphasis is placed on the need to develop renewable hydrogen to achieve the goals of the European Green Deal and decarbonize the energy sector.

In these documents [30, 31], Ukraine is considered a priority partner. The roadmap envisages the construction of 40 GW of electrolyzer capacities by 2030 in North African countries and particularly in Ukraine [31]. It suggests the creation of 75 GW of capacity for the domestic market, mainly intended for the production of green ammonia, and 32.5 GW for the export market – primarily for pipeline export to the European Union countries, about 3 million tons or 118 TWh of hydrogen in 2030, which accounts for 17% of the total hydrogen market in the EU in 2030.

In the above-mentioned documents [30, 31], the role of Ukraine in achieving the goals of the European Green Deal is emphasized and highlighted. It mentions the possibility of building up to 10 GW of installed electrolyzer capacity for the production of renewable hydrogen, 1.8 GW of which is intended for the Ukrainian domestic market, specifically for the production of green ammonia.

**Conclusions**

In summary, it can be concluded that Ukraine has significant potential for hydrogen production using renewable energy sources, in particular, solar and wind. Hydrogen can become a key component in Ukraine’s energy transition, decarbonization of the economy, and energy security of the state. Renewable energy sources can help reduce Ukraine’s energy dependence on imported fuels and contribute to the reduction of harmful emissions into the atmosphere. There are prospects for the development of the metallurgical and chemical industries in Ukraine using hydrogen as an energy carrier and raw material for the production of ammonia-based on renewable hydrogen. The potential for the production of green ammonia is the first step towards creating the hydrogen economy. However, to achieve higher levels of hydrogen production and its derivatives, both for consumption in the domestic market and for export to the European Union.
countries, more detailed research into production technologies using renewable energy sources and the development of the necessary infrastructure for hydrogen storage and transportation are required. The government should promote the development of renewable hydrogen production and alternative energy by stimulating investment, supporting research and development, and developing the necessary infrastructure, and businesses should consider the possibilities of using hydrogen in their operations and developing new lines of business related to the production, storage, and transportation of hydrogen.

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