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HYDROGEN IN THE ENERGY TRANSITION AS A DRIVER OF ENERGY EFFICIENCY AND SUSTAINABLE ENERGY SYSTEMS

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Abstract. The accelerating energy transition, driven by climate change mitigation goals and the need for low-carbon development, requires a fundamental transformation of energy systems toward higher efficiency and sustainability. In this context, hydrogen has emerged as a key vector for integrating renewable energy sources, balancing energy systems, and decarbonizing hard-to-abate sectors. This article aims to investigate the role of hydrogen in advancing energy efficiency and supporting the development of sustainable energy systems. It focuses on identifying current trends, technological preconditions, and prospects for hydrogen deployment in Ukraine and Europe within the broader energy transition framework. The study applies to a comparative and system-based analysis of hydrogen production pathways, including grey, blue, and green hydrogen, with particular emphasis on the environmental and efficiency implications of green hydrogen. The research also employs energy system analysis to determine the role of hydrogen within the evolving energy balance structure and its interaction with renewable energy sources. The findings demonstrate that hydrogen can significantly improve energy efficiency by enabling sector coupling, enhancing energy storage capabilities, and facilitating the integration of intermittent renewable energy sources. Green hydrogen, produced from renewable

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electricity, is identified as a critical component of sustainable energy systems due to its low environmental impact. The study highlights key application areas, including energy, transport, and industry, and examines technological, economic, and safety challenges related to hydrogen production, storage, and distribution. The value of the research lies in providing a structured understanding of hydrogen's role as a driver of sustainable energy transformation and offering insights into its strategic implementation in the context of energy transition policies.

Keywords: energy efficiency, energy transition, hydrogen energy, climate change, energy balance, energy solutions

Introduction. The global energy sector is currently undergoing a profound transformation, driven not only by the need to rethink energy consumption patterns but also by the restructuring of energy supply systems amid growing geopolitical pressures. Ongoing military conflicts in the Middle East, the war in Ukraine, and political instability in several regions significantly undermine the reliability of energy supply chains. These factors intensify economic challenges by limiting access to conventional energy resources amid increasing global demand and rising energy prices, while simultaneously amplifying environmental risks associated with climate change. Recent statistical evidence confirms these structural shifts. Eurostat data for the period 2015-2023 indicate a steady reconfiguration of the EU-27 energy supply mix, characterized by a gradual decline in the use of solid fossil fuels alongside a consistent expansion of renewable energy sources. Over this period, renewable energy demonstrated continuous growth in both absolute terms and as a share of total energy supply. By 2023, renewables accounted for 261 million tons of oil equivalent, representing 21% of total energy supply, compared to 205 million tons or 14% in 2015 (fig. 1). In contrast, the contribution of solid fossil fuels has significantly decreased, reaching 126 million tons of oil equivalent (10%) in 2023, down from 234 million tons (17%) in 2015 [1]. These dynamics reflect the strategic orientation of eu countries toward accelerating the energy transition, strengthening energy security, and reducing dependence on carbon-intensive energy sources, while aligning with broader climate policy objectives.

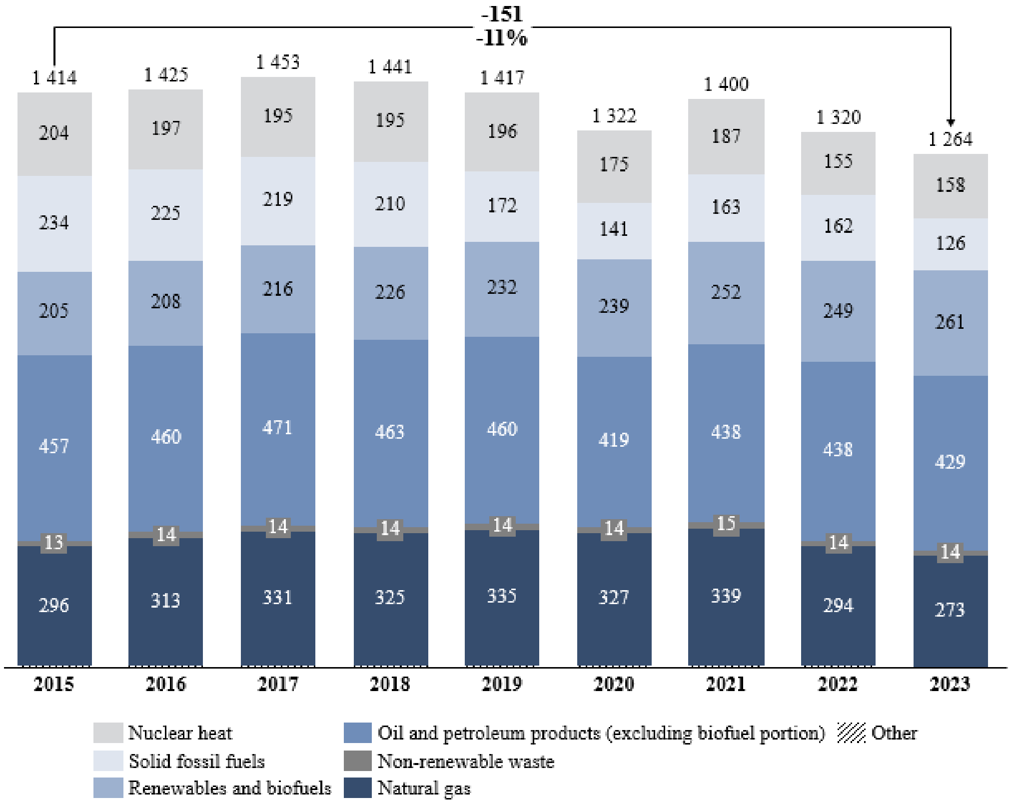

Figure 1 – Total energy supply by product (EU-27), million tons of oil equivalent [1]

During 2015-2023, the EU countries adopted a few decisions in the context of energy transition and energy efficiency that directly affected the energy sector, aiming to transform the structure of energy supply sources. In 2015, the EU countries joined the Paris Climate Agreement (entered into force on November 4, 2016), committing themselves to reducing greenhouse gas emissions.

This was an important impetus for the gradual abandonment of fossil fuels, including coal. As a result, support for renewable energy sources (RES) was strengthened, which stimulated investment in solar and wind energy, among others [2]. In 2018, the European Parliament and Council adopted Directive 2018/2001/EU on the promotion of the use of energy from renewable sources (RED II). This document set a goal of reaching 32% of energy from renewable sources by 2030, which contributed to an increase in the share of biomass and biogas in the energy balance, as well as preparations for a further reduction in the share of natural gas in favor of hydrogen and biomethane [3].

In 2019, the European Commission presented the European Green Deal, a comprehensive strategy to achieve climate neutrality by 2050. This became the basis for large-scale subsidies for renewable energy, accelerated development of the hydrogen economy, and modernization of energy infrastructure. In addition, the Green Deal envisages a transition to a "circular economy," which involves the most efficient use of resources, minimizing waste, and prolonging the use of products and materials in circulation [4].

In 2021, the adoption of the European Climate Law set a legislative goal to reduce emissions by 55% by 2030. This has led to the active development of battery systems for storing energy from renewable sources, as well as to the electrification of transport and industry [5]. In response to the energy crisis in Europe caused by Russia's invasion of Ukraine, the EU launched the REPowerEU plan in May 2022. The plan focuses on saving energy, diversifying supplies, developing clean energy sources, and reducing dependence on Russian gas. REPowerEU accelerates energy transition and promotes investment in renewable energy sources [6]. On October 1, 2023, Regulation 2023/956 (European Union, 2023) came into force, introducing the Carbon Border Adjustment Mechanism (CBAM) in the EU, which restricts imports of energy-intensive goods with high CO_2 emissions, thereby stimulating the energy transition of energy-intensive industrial companies [7;8].

In 2023, the European Union adopted an amendment to the Renewable Energy Directive (RED III), which significantly increased the overall target for renewable energy consumption in all sectors of Europe to 42.5% in 2030, compared to the target of renewable energy consumption in all sectors of 32% under RED II, which was adopted in 2018 [9]. The amendments published in the Directive also aim to support the achievement of the EU's target of annual biomethane production of 35 billion cubic meters by 2030, as well as to accelerate the development of renewable hydrogen, thereby supporting security of supply and climate ambitions [10].

Thus, EU countries are systematically implementing environmental initiatives to realize a just energy transition, setting ambitious goals and gradually achieving them. This ensures rapid development of renewable energy, reduces greenhouse gas emissions, increased energy efficiency, and reduced dependence on fossil energy resources. This trend is expected to continue, contributing to achieving climate goals and ensuring energy security. Hydrogen plays an important role in this process, as it is considered one of the key energy carriers of the future.

Analysis of publications on the research topic. In the context of research on mechanisms for implementing the energy transition [11] and on ways to achieve energy efficiency by increasing investment in innovative technologies [12] and reducing energy consumption [13], it makes sense to study the role and importance of hydrogen. Given that scientists are increasingly considering the prospects of using hydrogen as an alternative to traditional fuels, the authors describe the benefits of using hydrogen and a wide range of its types, determined by production methods [14], which expand knowledge about the potential and areas of its use compared to traditional sources [15].

The growing role of hydrogen is evidenced by projects aimed at producing green hydrogen [16]. The study highlights the prospects for developing hydrogen energy and integrating it into energy grids and microgrids to increase energy independence [17]. The benefits of green hydrogen are also considered, with the authors highlighting various technologies for its production and its use in everyday life [18]. The authors analyze the economics of renewable hydrogen at different stages of technological development and market introduction and indicate that green hydrogen costs are expected to decrease by 2030 [19].

Ukraine is actively developing its hydrogen strategy in line with European energy transition trends, positioning hydrogen as a key element of post-war recovery, decarbonization, and integration into the EU energy system. Strategic documents and roadmaps emphasize the production of low-carbon, green hydrogen based on the country’s significant renewable energy potential, with targets of up to 1.3 million tons by 2035 and 3 million tons by 2050, alongside a strong focus on exports to the EU market. Ukraine is also considered a strategic partner in European hydrogen initiatives, including cross-border corridors and supply chains that support the EU’s decarbonization goals. This approach aligns with broader EU policy, which makes hydrogen a central pillar of achieving climate neutrality, with targets of 10 million tons of domestic production and 10 million tons of imports by 2030.

Generally, the Hydrogen Strategy, aligned with the European Green Deal, aims to expand hydrogen use, noting that although the war in Ukraine initially slowed decarbonization, it can, in the long run, accelerate hydrogen development [20]. It has been concluded that removing barriers to renewable energy is crucial to expanding hydrogen production from renewable sources. This includes not only expanding wind power but also expanding grid access and developing renewable energy capacities [21].

In their publications, scientists and researchers also analyze the key advantages and weaknesses of hydrogen. In particular, the advantages include that its use does not generate carbon dioxide emissions and that the only by-product is water [22]. Hydrogen can play an important role in reducing dependence on fossil fuels and in helping countries improve energy security, especially in regions without access to traditional energy sources [23]. Another important advantage of hydrogen is its high energy content per unit mass (3-4 times that of fossil fuels, depending on the type), which allows it to be used efficiently in the automotive and electricity sectors. In addition, it can be obtained from a variety of sources, including renewable ones such as solar and wind energy, making it an important element in the transition to a sustainable energy future [24]. When studying the issue of disadvantages, attention should be paid to studies related to the need for additional costs and specialized infrastructure [25]. Since hydrogen is a flammable gas, the risks of its storage and use are being investigated, especially in industrial production and transportation [26].

When studying the energy efficiency of hydrogen, scientists note that, as a partial or complete replacement for natural gas, it improves the energy efficiency of continuous furnaces, reduces fuel consumption, and significantly reduces CO_2 emissions, making it a promising fuel for sustainable production [27]. Hydrogen is considered a key energy carrier for improving the energy efficiency of transport, as its use in onboard fuel cells reduces fuel consumption and better adapts to temperature conditions, supporting the development of hydrogen mobility [28].

Thus, the principles for using hydrogen as an energy source have been developed and are gradually being implemented, meeting the requirements of the energy transition and largely enabling higher energy efficiency. However, a comprehensive assessment of hydrogen based on energy value, CO_2 emissions, and production cost is warranted, enabling us to objectively assess its competitiveness with other energy sources. At the same time, insufficient attention has been devoted to the systematic study of hydrogen as an alternative energy source, particularly to its integrated economic, environmental, and technological evaluation.

Purpose of the article. The article examines hydrogen as a promising energy source capable of transforming the energy balance. The main goal is to analyze the prerequisites, current trends, and prospects for the development of hydrogen energy in Ukraine and Europe.

Research methodology. The article uses content analysis to examine trends in energy policies and strategies. It describes changes in energy structures and political initiatives of the European Union and Ukraine in the context of the energy transition, the reduction of fossil fuel use, and the development of renewable energy sources. To assess hydrogen as an energy source that meets the goals of sustainable development, the requirements of the energy transition, the potential for increasing energy efficiency, and is comparable to other energy sources, the article uses the results of a previous investigation based on the Necessary Condition Analysis (NCA) method, allowing determining which factors are necessary to achieve a sustainable result.

Presentation of the main material. Hydrogen, as the lightest and most abundant element, is increasingly recognized as a key energy carrier capable of supporting the transition to more efficient and sustainable energy systems. However, its actual contribution to energy efficiency and decarbonization is determined not by its inherent properties but by the technologies used to produce it. This has led to the emergence of a diversified classification of hydrogen types, commonly distinguished by color codes that reflect the primary energy source and production method, ranging from fossil-based pathways (grey, brown, black), through transitional low-carbon options (blue, turquoise), to renewable and near-zero-emission solutions (green, yellow, and certain bio-based or nuclear-based variants). Despite growing interest in low-carbon hydrogen, current production remains dominated by fossil-fuel-based processes, particularly natural gas reforming, which produces significant CO_2 emissions. At the same time, the expansion of renewable-based hydrogen production – especially via electrolysis powered by renewable energy – creates opportunities for improving overall system efficiency through sector coupling, energy storage, and the integration of intermittent energy sources. Thus, the classification of hydrogen not only reflects technological diversity but also highlights the critical link between production pathways, environmental impact, and hydrogen's potential to enable energy-efficient, sustainable energy systems [20].

However, clean hydrogen produced from renewable or nuclear energy sources, or from fossil fuels with carbon capture, can help decarbonize a few economic sectors [29]. Hydrogen, as a universal energy carrier, is classified in various ways. For example, within the framework of the EU hydrogen strategy [30], the classification focuses on the level of CO_2 emissions during production and the type of energy source, distinguishing:

- renewable/clean hydrogen produced by electrolysis of water based on electricity from renewable energy sources, or by biogas (instead of natural gas) or biochemical conversion of biomass, if it meets the requirements of sustainable development;
- hydrogen produced from electricity by electrolysis of water, regardless of the source of electricity;
- hydrogen from fossil fuels produced by various processes using fossil fuels as feedstock, mainly natural gas reforming or coal gasification;
- fossil fuel-based hydrogen with carbon capture, produced through a variety of processes using fossil fuels as feedstocks, but where greenhouse gases emitted during the hydrogen production process are captured
- low-carbon, which includes fossil fuel-based hydrogen with carbon capture and electricity-based hydrogen with significant greenhouse gas emission reductions over its full life cycle.

Despite the wide range of hydrogen types, the classification proposed in the EU strategy remains insufficiently detailed and needs to be further expanded and clarified. It is necessary to consider the latest approaches to hydrogen production, including innovative technologies that enable environmentally friendly production with minimal greenhouse gas emissions. Another important aspect is the unification of terminology. To provide a more structured, widely applicable framework for analysis, it is useful to refer to the most used approach across academic and policy discourse.

The most common classification is the "color" classification of hydrogen (table 1), which includes about 14 types and continues to evolve as new production technologies develop. Among the best-known types of hydrogen are green, blue, grey, pink, and black/brown hydrogen. Green hydrogen is produced by electrolyzing water using renewable energy sources, making it the most environmentally friendly. Blue hydrogen is produced from fossil gas using carbon capture and storage (CCS) technologies, reducing harmful emissions. Grey hydrogen, which still dominates the market, is produced from natural gas but without CO_2 capture. Similarly, black/brown hydrogen is produced by coal gasification and is associated with significant environmental pollution.

There are also lesser-known types of hydrogen, including yellow, purple, red, pink, turquoise, and white. For example, yellow hydrogen is produced by electrolysis using energy from solar power plants; pink and violet hydrogen are produced by electrolysis using electricity generated by nuclear power plants, and by thermolysis using nuclear heat and electricity, respectively. Red hydrogen is also produced using electricity generated by nuclear power plants, but by catalytic fission. Turquoise hydrogen is produced from natural gas by pyrolysis. White hydrogen is found in natural deposits and is extracted industrially, with no additional processing.

In addition, scientists are identifying new types of hydrogen at the early stages of research and commercialization. These include gold and orange hydrogen. Gold hydrogen is a relatively new color classification of hydrogen that lacks a clear, generally accepted definition. It is produced by fermenting microbes found in depleted oil wells, thereby extending the life of those fields. Another way to produce golden hydrogen is to use special solar hydrogen generators, which combine all the physical and chemical processes required to directly produce hydrogen from water using sunlight. Orange hydrogen is a proactive variant of white hydrogen and involves injecting a special carbon-enriched solution into wells. This method uses natural geochemical processes, but with active intervention to stimulate the reaction. Geochemical reaction results in the precipitation of solid carbonates, while hydrogen is generated and recovered from the fluid. Another way to produce orange hydrogen is to use plastic waste or biomass as a feedstock. This approach has the potential to provide both a source of clean energy and a solution to the problems associated with plastic waste disposal. Orange hydrogen is still in the early stages of development, with various technologies and production processes.

Thus, white, gold, and orange are relatively new forms of hydrogen that are poorly understood and require further research. It is necessary to investigate safe production methods and their feasibility for integration into existing energy systems. The lack of sufficient scientific data makes it difficult to assess their role in the future energy balance. Therefore, further research is critical for the development of effective hydrogen-use strategies.

In addition to the color classification, alternative approaches to hydrogen categorization are based on criteria such as fuel type and production method (table 1). In 2022, hydrogen accounted for less than 2% of Europe's energy consumption, and it was mainly used to produce chemical products such as plastics and fertilizers. 96% of this hydrogen was produced from natural gas, resulting in significant CO_2 emissions [31]. Therefore, to achieve the EU climate goals and reduce dependence on fossil fuels, it is necessary to scale up low- or zero-emission hydrogen production. In this context, green hydrogen produced by electrolysis using renewable energy is a priority development area. However, green hydrogen production remains expensive, as it depends on the price of electricity from renewable sources, electrolyzer efficiency, and the availability of infrastructure for transportation and storage.

In addition to green hydrogen, other low-carbon types with lower production costs are promising options, such as white, gold, orange, and blue. Thus, combining different types of low-carbon hydrogen will not only reduce CO_2 emissions but also reduce production costs thanks to technological diversity and a gradual transition to a fully renewable hydrogen sector.

Table 1 – Place of hydrogen in the classification of energy sources by different characteristics

<table>
<tr><th rowspan="2">№</th><th rowspan="2">Type of hydrogen</th><th rowspan="2">Type of fuel</th><th colspan="3">Classification characteristic</th></tr>
<tr><th>Traditionality</th><th>Renewability</th><th>Primary/Secondary</th></tr>
<tr><td>1</td><td>White</td><td>Natural fossil fuel without additional processing</td><td rowspan="10">Non-traditional</td><td rowspan="4">Renewable</td><td>Primary</td></tr>
<tr><td>2</td><td>Gold</td><td>RES or biogenic fuel</td><td rowspan="13">Secondary</td></tr>
<tr><td>3.1</td><td>Green</td><td>RES</td></tr>
<tr><td>4</td><td>Yellow</td><td>Solar energy</td></tr>
<tr><td>5</td><td>Purple</td><td>Nuclear power</td><td rowspan="3">Non-renewable</td></tr>
<tr><td>6</td><td>Pink</td><td>Nuclear power</td></tr>
<tr><td>7</td><td>Red</td><td>Nuclear power</td></tr>
<tr><td>3.2</td><td>Green</td><td>Biogas/biomass</td><td>Renewable</td></tr>
<tr><td>9</td><td>Blue</td><td>Natural gas</td><td rowspan="5">Non-renewable</td></tr>
<tr><td>10</td><td>Turquoise</td><td>Natural gas</td></tr>
<tr><td>11</td><td>Grey</td><td>Natural gas</td><td rowspan="3">Traditional</td></tr>
<tr><td>12</td><td>Brown</td><td>Hard coal</td></tr>
<tr><td>13</td><td>Black</td><td>Lignite</td></tr>
<tr><td>14</td><td>Orange</td><td>Biomass/household waste</td><td>Non-traditional</td><td>Renewable</td></tr>
</table>

Source: formed based on the authors' conclusion, and [32;33]

Therefore, expanding the production of low-carbon hydrogen is a key task to ensure the sustainability of the European energy sector. However, for effective integration of hydrogen into the energy system, it is important to consider it within a broader classification of energy sources.

International organizations and scientists have developed various approaches to classifying energy resources depending on their renewability, origin, physical properties, and methods of use. One of the widely used classifications is based on data from the World Energy Council, which divides energy sources according to the criteria of renewability and traditionality. According to this approach, non-renewable sources include traditional resources such as coal (including lignite), crude oil, natural gas condensate, heavy oil, oil shale, bitumen, natural gas, and nuclear energy. Renewable traditional sources include peat, firewood, hydropower, and animal and human muscle power. Non-traditional renewable sources are distinguished separately, which include biomass (except firewood), solar energy, geothermal energy, wind energy, tidal energy, wave energy, and ocean thermal energy. This approach allows us to distinguish energy sources based on their sustainability and future availability.

Another approach to classifying energy sources is to divide them into primary and secondary energy [34]. Primary energy is extracted directly from natural resources, such as crude oil, firewood, natural gas, or coal. Secondary energy products (such as electricity) are produced by conversion from a primary or another secondary energy product [35].

In the presented classifications of energy sources, hydrogen as an energy carrier is not directly mentioned. However, its place can be determined by considering the basic principles of the classifications. Hydrogen as an energy carrier occupies a unique place in energy classifications, as it can have different origins and characteristics depending on the production method.

In terms of dividing energy sources into traditional and non-traditional, grey, brown, and black hydrogen should be considered traditional (for example, in 2022, 96% of hydrogen consumption came from natural gas, which led to significant CO_2 emissions). At the same time, other types of hydrogen, such as green, white, purple, etc., are less common and more consistent with the category of non-traditional sources. If we consider the renewability of the energy source, these include natural white hydrogen and hydrogen produced using renewable energy, in particular green, yellow, and gold. However, other types of hydrogen, such as grey, blue, and brown, are non-renewable, since their production relies on fossil fuels. According to the criterion of primary or secondary energy carrier, white hydrogen is the only type that can be classified as a primary energy source, since it exists in nature in a ready-made form and can be directly extracted [36]. All other types of hydrogen are secondary energy carriers, since their production requires converting other energy sources, such as natural gas, electricity, or biomass.

Therefore, given the variety of ways to obtain hydrogen and their environmental footprint, it is important not only to classify this energy carrier correctly, but also to assess its efficiency of use. The efficiency of hydrogen as an energy carrier is determined by factors such as its energy content, production costs, and CO_2 emissions. In this context, the question arises: how competitive is hydrogen compared to other energy carriers?

NCA analysis was used to compare the energy efficiency of different energy sources. This method allows us to determine the minimum conditions under which a given energy source can be considered viable in a sustainable future and to assess how essential a given criterion is to achieve the desired result. If the criterion value falls below a threshold, the corresponding energy resource becomes unsuitable for effective use. Three key criteria were selected to assess the efficiency of different energy sources: energy value, CO_2 emissions, and production cost (table 2). These parameters are fundamental for the analysis, as they reflect the technical efficiency, environmental safety, and economic feasibility of using energy resources.

Table 2 – Comparing energy sources

Type of energy	Energy value (MJ/kg)	CO_2 emissions (t CO_2/TJ)	Production cost (€/kg)
Green hydrogen	120	0*	5–8
Grey hydrogen	120	101*	1,5–2,5
Lignite	17,4	101	0,09774 *
Natural gas	42	56,1	0,611*

Sources: [33]

The energy value determines how much energy can be obtained from a unit of fuel or energy carrier. This is critically important since the higher the energy level, the fewer resources are required to generate the same amount of energy. The level of CO_2 emissions determines the energy source's environmental sustainability, a key factor in today's climate change. CO_2 emissions play a central role in the choice of energy resources, as high levels contribute to global warming and negative environmental impacts. In addition, international climate agreements (e.g. The Paris Agreement) and other ambitious environmental goals of countries require emission reductions, which affects the political and economic support for certain energy sources. The cost criterion determines the economic feasibility, or financial aspect, which is crucial when choosing energy resources for large-scale implementation. Green and grey hydrogen, brown coal, and natural gas were selected to analyze the efficiency of different energy sources. These energy carriers have significant differences in key characteristics: energy value, CO_2 emissions, and economic feasibility, which allow us to assess their viability in the future energy system. Green hydrogen is considered the most promising low-carbon fuel because it is produced from renewable energy and emits no CO_2. However, its main drawback is its high production cost, which has so far limited its widespread implementation. Grey hydrogen, which currently dominates the market, is much cheaper but produces high greenhouse gas emissions. It is included in the analysis because it remains the main source of hydrogen and can serve as a transitional option on the path to decarbonization. Brown coal (lignite) is chosen for its widespread use in the energy sector and its low cost, especially in countries with significant reserves. However, it has a low energy value and the highest CO_2 emissions, which makes it unpromising in the context of the transition to sustainable energy. Natural gas is more environmentally friendly than coal and has higher energy efficiency. It plays a key role as a transitional fuel on the path to low-carbon energy and is used to produce grey hydrogen.

Based on the nca method, we have performed the necessary calculations to determine the energy source for sustainable development (table 3).

Table 3 – Comparison of energy sources by the NCA method

Type of energy	Energy value (MJ/kg)	Score (1-10)	CO_2 emissions (t CO_2 /TJ)	Score (1-10)	Cost (€/kg)	Score (1-10)	Total score
Green hydrogen	120	10	0	10	5–8	0	7.5
Grey hydrogen	120	10	101	0	1.5–2.5	6.9	5.73
Lignite	17.4	1.5	101	0	0.09774	9.9	3.08
Natural gas	42	3.5	56.1	4.45	0.611	9.2	5.26

Sources: [33]

To objectively compare different energy sources in terms of efficiency, environmental friendliness, and economic feasibility, the calculations were provided. We can see that a comprehensive assessment of the sustainable use of hydrogen from different sources indicates a significant advantage of using green hydrogen, given its energy value, CO_2 emissions, and production costs. Green hydrogen received the highest score of 7.5, as it combines high energy value, zero CO_2 emissions, and sustainability. Grey hydrogen, with a score of 5.73, is significantly inferior to green hydrogen due to its high CO_2 emissions, although its production is currently more affordable. Natural gas scored 5.26 - it has better characteristics than lignite but still has higher emissions than hydrogen. Lignite, with a score of 3.08, was the least efficient source due to its low energy content and high emissions. These results demonstrate that no single source meets all the requirements. However, green hydrogen is the only option that meets both key requirements (environmental friendliness and efficiency), and its main drawback (high price) may be overcome in the future.

Thus, hydrogen energy has significant potential for clean energy, but its widespread adoption across sectors, including household consumers, is hampered by significant obstacles. Given the range of hydrogen applications across industries, we note that in the transportation sector, it is used in fuel cells for cars, buses, trains, and airplanes. This can significantly reduce greenhouse gas emissions and make the transportation sector more environmentally friendly. In the energy sector, hydrogen is used for energy storage, helping compensate for the instability of renewable sources such as solar and wind. This can help improve the reliability of the electricity supply and reduce dependence on traditional energy resources. In industry, renewable hydrogen can be used for ammonia production, metallurgical processes, and petrochemicals, thereby reducing CO_2 emissions and making these industries more environmentally friendly.

For Ukraine, hydrogen development aligns with EU strategies, positioning the country as a key producer and exporter, particularly through large-scale electrolysis projects. Ensuring infrastructure for transportation – via pipelines or ammonia – will be essential for integration into the European hydrogen market.

The growing potential of hydrogen is not limited to Ukraine. The experience of other countries, particularly Poland, demonstrates that hydrogen is increasingly viewed as a strategic element of the energy transition, a tool for decarbonizing hard-to-abate sectors, and a means of strengthening energy security and industrial competitiveness. The country is expanding its hydrogen pipeline infrastructure and exploring ammonia-based transport to support the EU's clean energy transition. Both nations face challenges in infrastructure investment, regulatory frameworks, and reducing production costs, but hold strong potential as hydrogen hubs in Central Europe. In Poland, PKN Orlen has announced a Hydrogen Strategy for 2030 with investments of about $1.9 billion, including the construction of more than 100 hydrogen filling stations across Central Europe [37]. Ukraine is also witnessing a growing interest in hydrogen technologies, particularly in the energy sector, where green hydrogen projects are being considered to reduce CO_2 emissions and improve energy efficiency. Currently, Ukraine's hydrogen production is about 360,000 tons per year, mainly used for ammonia production, accounting for only 0.5% of total global demand. With technological development and investment, Ukraine can significantly increase its hydrogen production capacity [38].

However, hydrogen energy has serious technical and economic limitations. The main challenge is the high cost of hydrogen production, especially when produced by environmentally friendly methods such as electrolysis, which is a key obstacle, according to the NCA. Studies show that water electrolysis remains an expensive process due to the significant energy costs [39]. Production costs need to be reduced to make hydrogen competitive with traditional energy sources. Another critical aspect is the complexity of hydrogen transportation and storage. Efficient and cost-effective hydrogen storage and transportation are crucial for large-scale adoption. Underground salt caverns have proven to be a reliable storage solution, while major projects in the UK and the US [40] are advancing large-scale hydrogen storage capacity. Short-distance transportation is best achieved through pipelines and trucks, whereas long-distance transportation requires carriers such as ammonia, liquid organic hydrogen carriers (LOHC), and liquid hydrogen [41]. The European hydrogen grid envisions five large-scale pipelines to transport hydrogen from high-production regions to high-demand areas [42]. A key aspect of this vision is integrating Ukraine and Poland into the European hydrogen network. Ukraine, with its vast renewable energy potential, is poised to become a major producer and exporter of green hydrogen, supplying Central Europe via pipeline infrastructure. Poland, as a strategic transit hub, plays a crucial role in distributing hydrogen across the region and supporting industrial decarbonization. Both countries are central to developing the Eastern European hydrogen corridor, with their infrastructure development being a priority for the 33 energy infrastructure operators involved in project [43].

Conclusions. Prospects for further research. The role of hydrogen from renewable sources in the energy transition remains a subject of considerable debate among scientists. Successful implementation of hydrogen energy requires comprehensive public policy solutions, research investment, and international cooperation. Although hydrogen from renewable sources plays a role in decarbonization, its implementation should be strategic and focused on sectors where it offers clear advantages over direct electrification, such as industrial processes that currently depend on fossil-based hydrogen. The main challenges to hydrogen use include high production costs, technical barriers to industrial applications, and infrastructure requirements. Although hydrogen from renewable sources has great potential, its transportation and storage are still energy-intensive. In addition, there are risks of dependence on hydrogen as an energy source, including high costs and potential supply instability. Equally important are the environmental and social impacts of large-scale hydrogen production, which require additional research and a strategic approach for the sustainable development of hydrogen energy.

Current trends in energy development in Europe and Ukraine point to a significant transformation of energy systems towards renewable energy sources (RES) and a reduction in dependence on traditional fossil fuels. EU countries are actively working to achieve the ambitious climate goals set by the Paris Agreement, the RED II and III Directives, and the European Green Deal. Support for renewable energy sources, such as solar and wind, is a key part of this process. One of the key areas of the energy transition is the development of hydrogen energy. Hydrogen is a potentially important energy carrier that can ensure energy security and contribute to achieving climate goals, such as reducing greenhouse gas emissions. Under the European Green Deal and other initiatives, hydrogen is an important component for modernizing energy infrastructure, particularly in the transport and industrial sectors.

The key benefits of hydrogen include increased energy efficiency, reduced CO_2 emissions, integration with renewable energy sources, and prospects for use across various industries. The types of hydrogen and their environmental friendliness are characterized. The environmental aspects of hydrogen production are studied, with special attention to "green" hydrogen produced from renewable energy sources. The analysis of the results of the analysis led to the following conclusions: green hydrogen is the best option in terms of efficiency and sustainability in the case study, and meets the requirements for environmental and efficiency, despite the high price; grey hydrogen and natural gas have similarly, but both have disadvantages in terms of CO_2 emissions, making them less efficient than green hydrogen; lignite has the lowest score, which indicates its shortcomings in all categories: energy value, CO_2 emissions, and production cost. Hence, a general trend has emerged indicating that green hydrogen is the most promising energy source that meets the requirements for sustainable development and the environment, with the potential to reduce production costs in the future.

Further research should continue to evaluate the dynamics of hydrogen production costs and efficiency, its integration into broader energy systems, and improvements in hydrogen production, storage, and transportation technologies that will make it more accessible and cost-effective.

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ВОДЕНЬ В ЕНЕРГЕТИЧНОМУ ПЕРЕХОДІ ЯК РУШІЙ ЕНЕРГОЕФЕКТИВНОСТІ ТА СТАЛИХ ЕНЕРГЕТИЧНИХ СИСТЕМ

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Анотація. Прискорення енергетичного переходу, зумовлене цілями пом'якшення зміни клімату та необхідністю низьковуглецевого розвитку, вимагає фундаментальної трансформації енергетичних систем у бік підвищення ефективності та сталості. У цьому контексті водень став ключовим вектором для інтеграції відновлюваних джерел енергії, балансування енергетичних систем та декарбонізації секторів, які важко піддаються скороченню викидів. Ця стаття має на меті дослідити роль водню у підвищенні енергоефективності та підтримці розвитку стійких енергетичних систем. Основну увагу зосереджено на визначенні сучасних тенденцій, технологічних передумов і перспектив впровадження водню в Україні та Європі в межах ширшого контексту енергетичного переходу. У дослідженні застосовується порівняльний та системний аналіз шляхів виробництва водню, включаючи сірий, блакитний та зелений водень, з особливим акцентом на екологічні та ефективні переваги використання зеленого водню. У дослідженні також використовується аналіз енергетичних систем для визначення ролі водню в структурі енергетичного балансу, що розвивається, та його взаємодії з відновлюваними джерелами енергії. Результати дослідження свідчать, що водень може суттєво підвищити енергоефективність завдяки забезпеченню секторальної інтеграції, розширенню можливостей зберігання енергії та сприянню інтеграції нестабільних відновлюваних джерел енергії. Зелений водень, що виробляється з відновлюваної електроенергії, визначено як ключовий елемент сталих енергетичних систем завдяки його низькому впливу на навколишнє середовище. У дослідженні висвітлено ключові сфери застосування, включаючи енергетику, транспорт та промисловість, а також розглянуто технологічні, економічні та безпекові проблеми, пов'язані з виробництвом, зберіганням та розподілом водню. Цінність дослідження полягає в забезпеченні структурованого розуміння ролі водню як рушійної сили сталої енергетичної трансформації та наданні інформації про його стратегічне впровадження в контексті політики енергетичного переходу.

Ключові слова: енергоефективність, енергетичний перехід, воднева енергетика, зміна клімату, енергетичний баланс, енергетичні рішення