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The Energy Strategy of Eu Member States from The Perspective of Opportunities and Limitations Related to the Replacement of Natural Gas with Hydrogen*

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Abstract

The European Union's goal of carbon neutrality by 2050 requires a rapid transition from fossil fuels, particularly natural gas, to low-carbon alternatives. This study is motivated by the strategic role hydrogen is expected to play in this transition. Despite numerous national hydrogen strategies, there is a lack of comparative research evaluating whether hydrogen can feasibly and economically replace natural gas across EU member states—representing a significant gap in the current literature. To address this, we conduct a comparative policy analysis of hydrogen strategies in selected EU countries, combined with a techno-economic assessment of hydrogen and natural gas. Key parameters include energy efficiency, infrastructure requirements, and cost structures, alongside physical and chemical characteristics. Our findings show considerable disparities in national hydrogen strategies, particularly in ambition, implementation timelines, and investment levels. While hydrogen offers several technical advantages, high production and infrastructure costs limit its near-term economic viability. The analysis suggests hydrogen is unlikely to fully replace natural gas by 2050 under current conditions, but it could play a complementary role if supported by further technological innovation and coordinated EU-wide policies.

Keywords*:* European Union, Hydrogen, Natural Gas, Carbon neutrality

JEL: Q42, F00, F18, F50

Introduction

Global warming and carbon are currently bringing hydrogen to the forefront of the energy sector. Hydrogen is one of the possible solutions to shift to a low-carbon economy that would comply with all ratified conventions and agreements, such as the UNFCC, the Kyoto Protocol, the Paris Agreement and the European Green Deal. It is estimated that green hydrogen could meet 24% of the world's energy demand by 2050. It is also projected that the share of hydrogen in Europe's energy mix will grow from the current 2% to 13% by 2050. An analysis of the EU energy mix shows that natural gas is the second most used energy carrier, with a share of 23.7% of the total EU energy mix, after 34.5% for other fossil fuels. Renewables account for 17.4% and nuclear electricity for 12.7% of the total energy mix (EUROPEAN ENVIRONMENT AGENCY, 2022). With energy demand expected to grow in the future, the question arises as to how the European Union will cover the remaining 10% of natural gas supply that will not be replaced by hydrogen. However, we must not forget that the issue of energy security, which includes the possibility of replacing natural gas with hydrogen, is part of all national energy and environmental policies. We should also bear in mind various economic players lobbying either for hydrogen or natural gas. It is therefore essential to perceive the substitution of natural gas with hydrogen not only as a technical issue, but also

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to take into account all the political and economic parameters that could affect the application of hydrogen and the substitution of natural gas. With the current themes of global warming and reducing carbon emissions, hydrogen is becoming an increasingly prominent topic in the energy sector.

Global hydrogen demand is currently around 70 million tonnes, mainly in the chemical industry. To produce such a volume, about 3% of the world's produced energy[1] is consumed, and of this, only 1% comes from water electrolysis and, therefore, only 1% of the energy is produced from green hydrogen. However, in the European Union, around 90 percent of hydrogen produced from natural gas (called grey hydrogen) is currently used for energy production, which generates significant emissions (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, NORWEGIAN MINISTRY OF CLIMATE AND ENVIRONMENT, 2020). When using hydrogen as an energy carrier, it is therefore crucial how it is produced and what volume of emissions it generates.

Unlike hydrogen, natural gas is a fossil fuel that has been used for decades. It is composed mainly of methane (CH_4) and is widely used for electricity generation, in industry and for home heating. Its main advantages are its considerable availability, the existing infrastructure and its combustion efficiency. What is more, it costs much less than alternative fuels. The disadvantages related to natural gas include methane emissions, dependence on natural gas supplies and reserves, and its limited supply. The comparison of natural gas and hydrogen in the context of the current energy industry and environmental challenges thus provides key aspects and inputs for the future energy strategy of the European Union. This paper aims to assess whether hydrogen can serve as a technically and economically viable alternative to natural gas, in line with the EU's goal of achieving carbon neutrality by 2050. To achieve this, the article is structured as follows: The first part provides an overview of the role of natural gas in the EU energy mix and introduces hydrogen as a potential substitute. The second part explores and compares the physical, chemical, and economic properties of both energy carriers. The third section offers a comparative analysis of national hydrogen strategies across selected EU member states, identifying common patterns and divergences. Finally, the paper concludes by evaluating the feasibility of hydrogen replacing natural gas and outlines policy recommendations for supporting this transition.

Literature Review

The comparison of the properties of hydrogen and natural gas is a broad topic that encompasses production, storage, transportation, energy efficiency, environmental impacts and economic aspects. In Slovakia, it is actively explored by Slovenský plynárenský priemysel, a.s., which is mainly involved in hydrogen blending into the gas distribution network. The company is conducting the research on the effects of hydrogen on gas pipelines. It carried out its pilot project in Blatná pri Ostrove in 2022, where 10% of hydrogen was added to the natural gas mixture (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, NORWEGIAN MINISTRY OF CLIMATE AND ENVIRONMENT, 2020). The company's vision is to enable 5% hydrogen blending by 2025. Another Slovak company, US Steel Košice, intends to produce hydrogen by water electrolysis and thus contribute to the decarbonisation of its production. It plans to produce 580 tonnes of hydrogen annually (SITA, 2024). The company intends to invest 5 million euros in the project and to start construction in 2026. Blending hydrogen into natural gas and the subsequent complete replacement of natural gas are reflected in many EU documents. The most important of these is the 4th Gas Package, which seeks to open the way for low-carbon and renewable gases. It also specifies hydrogen certification and the rules pertaining to renewable hydrogen. The EU member states have adopted national hydrogen strategies, but these are very different from each other and have different targets. These strategies will be analysed in more detail in one of the chapters of this article. Hydrogen is also gaining significant attention from the International Renewable Energy Agency, the International Energy Agency, which published an analysis entitled Global Hydrogen Review in 2023, and Hydrogen Europe. In Slovakia, the topic is actively covered by Energie Portal and Euractiv. There is very little academic work on natural gas and hydrogen in Slovakia. In foreign sources, the topic is mainly elaborated in the form of hydrogen strategies and research on pipeline infrastructure for blending hydrogen into natural gas infrastructure. The books dealing with the topic that are worth mentioning: John Tabak: Natural Gas and Hydrogen (2009), Marcello De Falco, Angelo Basile: Enriched Methane, The First Step Towards the Hydrogen Economy (2016), Duncan Seddon: The Hydrogen Economy, The: Fundamentals, Technology, Economics (2022).

Methodology

This paper will analyse the readiness of legislation, energy networks and customers, and the commitment of governments to implement hydrogen in energy networks in an analysis of the hydrogen strategies of the EU countries. The main scientific methods used in the paper are the analysis of the data collected and their comparison. The research assumption and therefore the hypothesis that we will try to refute or confirm in this article is as follows. "In the European Union, natural gas can be fully replaced by hydrogen by 2050". To answer the hypothesis, we set two research questions. Is it economically and physically feasible and profitable to fully replace natural gas with hydrogen? At what stage are the different hydrogen strategies of the European Union Member States and what do they tell us? The theoretical background that we use to approach the issue of replacing natural gas with hydrogen in the EU market focuses on a few key concepts, namely the declaration of carbon neutrality of the individual EU states based on their hydrogen strategies, and the targets set in the individual strategies, the author then focuses on the technological feasibility of replacing natural gas with hydrogen. The main point is that hydrogen, as a "clean energy carrier", has the potential to play a key role in the transition to renewable energy. However, as it points out, there are significant technological hurdles, such as challenges in storage, transportation and treatment infrastructure for hydrogen, as it has different physical properties than natural gas. The article analyses the hydrogen strategies of each EU Member State. It compares the different approaches and targets for hydrogen production, distribution and consumption in different countries, focusing on the readiness of these countries to implement hydrogen in their energy systems. In addition to the environmental benefits, the paper also outlines the geopolitical factors that play a role in the transition to hydrogen. The EU has a strong dependence on natural gas imports, which increases the need to replace fossil fuels with indigenous sources such as hydrogen. These theoretical backgrounds allow the authors to comprehensively assess the feasibility of hydrogen as a substitute for natural gas in the EU energy mix, combining environmental, technological, economic and geopolitical perspectives to determine whether the substitution of natural gas with hydrogen is feasible and beneficial.

Comparison Of Hydrogen And Natural Gas Properties

The comparison between hydrogen and natural gas is based on their chemical composition. Hydrogen is a pure element. Its molecule is composed of two atoms, hence H_2. Methane, on the other hand, is a compound made up of carbon and hydrogen – CH_4, and other hydrocarbon tracers and impurities. It is the absence of carbon in the pure hydrogen element that is the main driving force in the debate about replacing natural gas with hydrogen. The problem with natural gas is that when methane burns, the carbon within the compound combines with oxygen during combustion to form carbon dioxide, or CO_2 (KOESTNER, 2021). When hydrogen is burned, no such problem occurs, making it „clean energy". But with hydrogen, one has to be more cautious about what kind of hydrogen is involved. We should focus on whether we are talking about green, blue or grey hydrogen. When it comes to grey hydrogen, we are talking about hydrogen produced from natural gas using steam methane reformation, with carbon emissions escaping into the air. Blue hydrogen is produced in the same way as grey hydrogen, but the carbon emissions from the production of blue hydrogen are stored in a Carbon Capture Storage (CCS) system. Renewable sources (wind, solar,...) are used to create green hydrogen. The production processes will be dealt with in a later part of this article, so in the current chapter, we will discuss the chemical composition of hydrogen and natural gas. It is known that the periodic table sorts the elements by their atomic mass. Hydrogen is the first element in the table, e. i. it is the lightest element of all (1.0079g.mol-1). Carbon's atomic number is 6 ($12.0107 g.mol^{-1}$), so it is heavier than hydrogen (PERIODIC TABLE, 2024). Carbon is also an essential building block of all organic compounds. Thus, it is also part of the compound methane, which makes up a significant portion (approximately 97%) of natural gas. Methane is heavier and thus less volatile compared to hydrogen. Hydrogen readily passes through porous substances, which is not such a problem with methane. Another property of hydrogen is that it is a gas with a simple bond between hydrogen atoms, and it is very well absorbed by some metals (Mg, Ni, Pd, Pt), which is used for its storage or in electric vehicles powered by hydrogen propulsion (KMEŤOVÁ, SKORŠEPA, MÄČKO, 2012). Hydrogen is not very reactive due to the large atomic binding energy. Therefore, molecular hydrogen reacts with most elements only at higher temperatures. Hydrogen is stored in water, hydrocarbons and other organic substances. However, it should also be noted that hydrogen is not a source of energy but an energy carrier, more specifically, a chemical electron carrier composed of molecules. Other chemical characteristics include boiling points. For natural gas this point is at -161.6 degrees Celsius (WIKIPEDIA, 2012), for hydrogen, it is -252.76 degrees (90 degrees lower than liquefied natural gas).

What is more, hydrogen has much higher combustion heat than natural gas. This means that if we burn 454 grams of hydrogen vs 454 grams of natural gas, we get 2.5 times the energy. The problem, however, is that hydrogen is much lighter and, therefore, less dense than natural gas. So, to get the same amount of energy, we need about 3 times the volume of hydrogen as compared to the volume of natural gas.

The chemical compositions of hydrogen and natural gas show significant differences in their structure, energy content and environmental impact. Hydrogen, especially green hydrogen, represents a clean alternative with high energy potential, but its high cost and its weight and density remain problematic. Natural gas, on the other hand, remains an important energy source today, but the environmental challenges and its limited supplies require a shift to more sustainable solutions or carbon capture systems and, not least, the gradual introduction of hydrogen into the energy mix.

Comparison Of Production and Extraction

As mentioned above, hydrogen is produced in a variety of ways. Hydrogen is referred to as green, blue or grey, depending on how much CO2 is emitted into the air during its production.

Green hydrogen is usually produced by electrolysis of renewable sources. In this production, fluctuations in renewable energy sources are problematic as the produced electricity cannot be stored efficiently. Therefore, it is ideal to produce green hydrogen only when there is a surplus of such energy, which can often be difficult to predict and store. However, hydrogen produced in this way accounts for only 0.1% of all hydrogen produced in the world so far (DRIVEMAGAZINE, 2023). Green hydrogen is expected to be used to meet energy requirements during peak demand periods in the electricity grid. However, hydrogen production from low-carbon energy is currently costly. The IEA analysis shows that the cost of producing hydrogen from renewable electricity could fall by 30% by 2030, as a result of declining renewable electricity costs and increasing hydrogen production. The process of hydrogen production by electrolysis involves the separation of two hydrogen atoms and an oxygen atom using electricity (NORWEGIAN MINISTRY OF PETROLEUM AND ENERGY, NORWEGIAN MINISTRY OF CLIMATE AND ENVIRONMENT, 2020). The production of hydrogen by electrolysis requires 9 litres of ultrapure water for 1 kilogram of hydrogen and the by-product of electrolysis is heat and 8 kilos of oxygen (EUROWATER, 2024). Thus, another problem with green hydrogen is the high consumption of water, which is becoming an increasingly scarce commodity with global warming and needs to be managed carefully.

Blue hydrogen is produced by steam reforming of methane (CH4), during the production of which the resulting carbon dioxide is captured and stored (JURKOVIČ, 2020). The largest European plant to produce such hydrogen is expected to be commissioned in 2026 in Rotterdam. One of the greatest challenges regarding such plants and hydrogen production is the capture and storage of waste carbon dioxide. Carbon dioxide is stored in geological formations that cannot be permanently secured and might be damaged after a certain period of time. The complex technology has not been tested in practice on a large scale either. In addition, it is not considered sustainable, is energy-intensive and thus increases energy/fuel consumption. The cost calculations are rather uncertain, but in Europe, the price per kWh is expected to rise by 1.3 - 3.0 euro cents, so again we would be talking about price increases for end users. It is estimated that using this technology in fossil fuel electricity generation in the United States would increase the price of electricity per kWh by 50 percent (UNIVERSITY OF CALIFORNIA, 2024).

Grey hydrogen is produced by steam-methane reforming, but without the capture and storage of carbon dioxide, which is released freely into the air and thus contributes to air pollution. In the European Union, grey hydrogen production releases 100 million tonnes of greenhouse gases into the air annually (HOLÝ, 2021).

Hydrogen can be also produced in nuclear reactors. It might then be transported through the existing pipeline infrastructure (HOLÝ, 2021).

The problem is that the production of 1 million tonnes of hydrogen requires up to 60 TWh of electricity. According to Vladimír Slugeň, who works for the Institute of Nuclear and Physical Engineering of the Faculty of Electrical Engineering and Informatics of the Slovak Technical University in Bratislava, two units in the nuclear power plant Jaslovské Bohunice with a capacity of 1000 MW produce about 7.5 TWh per year. Therefore, the production of one million tonnes of hydrogen will require construction of 8 new nuclear power plants with a capacity similar to Jaslovské Bohunice.

When it comes to natural gas, we are not talking about its production, as with hydrogen, but about its extraction. Natural gas is extracted from underground deposits on land or under the seabed. It is generally stored in porous rocks, where it accumulates above layers of water or oil. The biggest disadvantage of natural gas is that its combustion emits air pollutants. Nevertheless, it also brings some benefits, including the existing distribution infrastructure and a relatively low price, which is currently around 26 euros per MWh (KURZYCZ, 2024).

Challenges Relating To Global Consumption, Storage And Distribution

The current global consumption of pure hydrogen is more than 70 million tonnes, which is equivalent to around 2,750 TWh of energy (OLEJ, 2020). Hydrogen is mainly used in the chemical industry, for oil refining and transportation. In the future, it can be used for domestic heating in its pure form or as an admixture in natural gas grids. Hydrogen consumption is expected to grow significantly, especially in the transport and energy sectors, as a result of the transition to a low-carbon economy. By 2050, hydrogen could meet up to 24% of world energy demand and account for 13% of Europe's energy mix.

The global natural gas consumption in 2023 amounted to roughly four trillion cubic meters (ENERGOKLUB, 2023). Natural gas is used for electricity generation (gas-fired power plants), in combined heat and power generation to increase overall energy efficiency, in steel production, in the chemical industry, for home heating and in transport. Natural gas consumption is expected to grow in the short term, but may be limited in the long term due to the transition to renewables and low-carbon alternatives.

Blending hydrogen into natural gas infrastructure, or just transporting hydrogen via pipelines, requires heavy investment in the existing infrastructure as well as changes in some materials in the pipelines through which natural gas was previously transported. The environmental impact of hydrogen depends on how it is produced. The cost of grey hydrogen, which is much more polluting, is lower than the cost of green hydrogen (produced from renewable sources). However, life cycle assessment of hydrogen production suggests that electrolysis from renewable energy has environmental advantages over natural gas reforming, but is still energy-intensive.

The problem with hydrogen is the already mentioned low volumetric energy density. This means that a larger volume of hydrogen is required compared to natural gas for the same energy output. An example might be as follows. A typical gas system can apparently handle about 3-4 hours of average demand using only the gas stored in the pipelines. Pure hydrogen, being 1/3 as dense in per unit volume, would reduce this to about one hour. This could make a huge difference in distribution system reliability, the frequency and duration of outages, and the ability of the grid as a whole to cope with variations in demand - a big increase when everyone gets home to start their furnaces, boilers, or gas stoves.

In addition, production of low-carbon energy from hydrogen is currently very expensive (ENERGOKLUB, 2024). That is why the current industrial hydrogen production is almost entirely based on fossil fuels.

Stimulating the demand will be crucial to hydrogen use. Clean hydrogen technologies are available, but costs remain high. Policies that create sustainable markets for clean hydrogen to reduce emissions from fossil fuel-based hydrogen production will have to encourage investment from suppliers, distributors and users. They will also need to support research and development of technology to reduce costs and harmonise the standards. Enhanced international cooperation will be necessary in all areas, especially when it comes to standards, sharing best practices and cross-border infrastructure.

Hydrogen has a high energy content per mass but not per volume. As a result, its storage poses a significant challenge. In order to preserve sufficient quantities of hydrogen gas, it is compressible and storable at high pressures. For safety reasons, hydrogen tanks are equipped with pressure relief devices to prevent the pressure in tanks from rising too high. As far as storage is concerned, hydrogen can be stored for relatively long periods of time, as can natural gas. Storage in underground reservoirs, which has not yet been explored in any way, might present a challenge in the future. So far, hydrogen has only been stored in aboveground tanks, which raises the question of how much and in what quantity hydrogen can be stored.

Natural gas is stored in underground reservoirs in natural porous underground formations. Storage facilities are divided into seasonal storage facilities, those that are filled in the summer and supplied to the grid in the winter, and peak storage facilities, which are used during periods of peak demand.

Transportation of natural gas is a key part of the supply chain, enabling the safe and efficient delivery of this energy source from extraction points to end consumers. There are two main methods of transporting natural gas: pipelines and liquefied natural gas (LNG). The advantages of transporting gas via pipelines are as follows: efficient long-distance transport with minimal losses, stable supply and less dependence on the weather. The other option is to transport LNG by tankers, which are designed to minimise heat loss of natural gas cooled to minus 162°C (the liquefaction point). At the point of delivery, gas must be regasified in terminals and then transported through pipelines to end users. The advantages of such transport are the flexibility of transport and the origin of the supplier. The drawbacks include especially high costs related to liquefaction, transport, and regasification.

Considering the EU's decarbonisation targets and the slow transition from natural gas to hydrogen, we should not forget about hydrogen distribution infrastructure. The recent publication of a report by Marcogas entitled "Estimating the Cost of Hydrogen Entry into Existing Natural Gas Infrastructure and End Use" analyses 225,000 km of gas pipelines in the EU. The Marcogas report concludes that the transformation of Europe's existing gas infrastructure can be achieved cost-effectively and quickly. Blending H2 in up to 10% of the volume results in very low transformation costs (less than 1% of the cost of building new H2 infrastructure). Even in the case of 100% pure H2, the transformation costs are low, less than 30% of the cost of building new H2 transmission infrastructure and less than 20% for the whole infrastructure chain. This is a key statement because energy transformation requires large-scale and costly measures that will put the EU budget under heavy strain. If we plan to produce hydrogen, which is expensive for the time being, it still has to get from where it is produced to where it is consumed. Natural gas pipelines - especially pipelines transporting natural gas over long distances or underwater - are not made of mild steel. They are made of harder, stronger steels - and these steels are, by many reports, susceptible to hydrogen embrittlement or other hydrogen-related damage mechanisms, especially in their welds and heat-affected zones, even at relatively moderate pressures and temperatures. Therefore, the replacement of natural gas with hydrogen raises questions about the necessity of "repurposing" and thus redesigning pipelines to transport hydrogen, which also requires financial costs. It can, therefore, be assumed that the initial distribution costs will be higher in order to repay these investments.

The industrial sector has the potential to become the largest user of low-carbon hydrogen due to the lack of alternative decarbonisation options. Sub-sectors requiring very high temperatures (>200 °C), such as steel or chemicals, due to the specificities of their processes, represent a significant challenge in decarbonising industry due to the lack or limited potential for their large-scale electrification. Hydrogen represents an opportunity to reduce emissions in this sector.

Transportation through pipelines modified for hydrogen is not yet widely studied, which may cause various concerns. As mentioned above, hydrogen is more explosive than natural gas and, therefore, transport will definitely have to be more monitored, secured and adjusted to different standards.

Adding hydrogen to natural gas, also known as blending, is an innovative approach to using existing gas infrastructure to reduce greenhouse gas emissions and support the transition to cleaner energy. Such a process involves blending a certain amount of hydrogen into natural gas. For example, blending 20% hydrogen into natural gas is a 20% by volume blend (ENERGOKLUB, 2023). This mixture has only 86% of the energy of average natural gas, which means you would have to burn 14% more gas to create the same number of joules or BTUs of heat. According to experts, a maximum of 5% hydrogen can be blended into natural gas without impacting the operation of the gas grid and end-use equipment (gas stoves, boilers, etc.). For concentrations above 5%, experts believe that changes in the gas infrastructure will have to be made, and that end-use equipment will have to be adapted as well.

The main idea behind replacing natural gas with hydrogen is to eliminate greenhouse gas emissions, improve the air quality in cities and villages, and ensure the security of the energy supply. On the other hand, hydrogen is not currently a cheap option, as we have already mentioned above. It is, therefore, highly likely that it will never be as cheap as natural gas or the electricity from which it is produced. The role of hydrogen as a substitute for natural gas has more to do with the need for gas production and distribution companies to stay in business by having something to sell than with any real greenhouse gas emissions benefits or significant technical demands.

National Hydrogen Strategies of the Eu Member States

Pursuing their efforts to reduce emissions and increase the share of renewable energy sources, the EU member states have developed and are implementing various national hydrogen strategies. These strategies are aimed at promoting the production, distribution and consumption of hydrogen as a clean energy source. This chapter will analyse them in detail and examine to what extent these initiatives represent a step towards a sustainable and cleaner energy future. The problem remains, however, that such a step is not yet economically viable and, as studies show, will not be completed in the short term.

Austria is committed to achieving climate neutrality by 2040. Sector-specific requirements call for differentiated solutions, which include decarbonising the energy system, according to the Austrian Hydrogen Strategy. Combined with the large-scale increase in the use of renewables and the Austrian government's goal of ensuring 100% of the national electricity consumption from renewable sources by 2030 - decarbonisation through direct electrification - climate-neutral hydrogen can be an important sustainable option for a secure energy supply in Austria in the future (FEDERAL MINISTRY REPUBLIC OF AUSTRIA, 2023). Austria has published a hydrogen strategy based on renewable energy. The strategy is to be part of the Austrian Climate and Energy Strategy 2030 (FEDERAL MINISTRY REPUBLIC OF AUSTRIA, 2023). Due to the demand for clean hydrogen in key sectors, blending hydrogen and natural gas is not preferred and is not considered a viable option. The document states that the objective is to enable the supply of climate-neutral hydrogen and its derivatives, which requires close cooperation with international partners. Austria's ambitious initiative aims to produce 40,000 tonnes of hydrogen per year from wind and solar energy (DOKSO, 2024). In 2022, the government presented a national hydrogen strategy.

The Czech Republic presented its national hydrogen plan in 2021. The country has two strategic goals for achieving climate neutrality. The first is to reduce greenhouse gases and the second is to promote economic growth. The hydrogen strategy is closely linked to achieving these goals. The Czech Republic has divided different hydrogen steps into three stages. The first is to be completed by 2025, the second by 2030 and the last by 2050. The priority of the first stage is the use of hydrogen in mobility. In this period, according to the Czech government, the best-integrated projects will be those in which hydrogen produced will be directly consumed. In the second stage, the government plans to start using hydrogen in industry and start planning an efficient mode of transport. The Czech Republic intends to be a net importer of hydrogen (due to the lack of low-carbon energy sources), just as it was a net importer of natural gas. The strategy points out that, although plans are underway to continue building solar and wind power plants, the efficiency of green hydrogen production will never reach the levels of those in coastal or equatorial countries. Therefore, the government wants to concentrate initially on natural gas generation with CCS/U (carbon capture technology). In the third stage, established hydrogen pipeline transport is foreseen, without the need for further subsidies. Thus, the Czech Republic envisages in this third phase the repurposing of pipelines into "hydrogen pipelines", assuming that large hydrogen producers and consumers are already established on the market (MINISTRY OF INDUSTRY AND TRADE, 2021). The Czech Republic emphasises that transporting hydrogen through gas networks is essential to maintain and expand the Czech Republic's position as a transit country. The country relies on the use of schemes such as "The Country for the Future", IPCEI, programmes of the Technology Agency of the Czech Republic, funding from various ministries and the State Environmental Fund. Based on the country's estimates, the consumption of 1,728 thousand tonnes of low carbon hydrogen per year is expected to be achieved by 2050. The strategy foresees the production of 284,000 tonnes of hydrogen per year by 2035. The strategy explains that for this amount of energy to be produced, the electrolysis production needs to be approximately 3.2 times the annual production of the Temelín and Dukovany nuclear power plants combined (30.2 TWh/year in 2020). The Czech government estimates that the highest consumption in 2050 will be in transportation, followed by metallurgy, industry, heat production and households.

Poland is the fifth largest hydrogen producer in the world. Poland's Ministry of Climate and Environment has issued a hydrogen strategy until 2030 with an outlook for 2040. Poland currently ranks among the top 3 hydrogen producers in Europe (MINISTRY OF CLIMATE AND ENVIRONMENT, 2020), just behind Germany and the Netherlands, with an annual production of about 1.3 million tonnes of hydrogen. However, only a very small amount of this hydrogen comes from renewable sources. Poland's hydrogen strategy has three priority areas: energy, transportation and industry (MINISTRY OF CLIMATE AND ENVIRONMENT, 2020). By 2030, Poland expects around 800-1,000 hydrogen buses to be in operation (MINISTRY OF CLIMATE AND ENVIRONMENT, 2021). Within the same time frame, 5 hydrogen valleys should be established as hubs for the implementation of the hydrogen economy and the integration of individual sectors. Poland's strategic goal for hydrogen production by 2030 is to provide the conditions for the start-up of hydrogen production facilities from low- and zero-emission sources. The Polish government intends to promote only low-carbon hydrogen. For transport, Poland also relies on the existing gas infrastructure and its necessary repurposing to transport hydrogen. When it comes to the country's specific targets, by 2030, the low-carbon hydrogen production capacity by electrolysis is set to reach the target of 2 GW. What is more, 800 -1,000 buses should be powered by hydrogen.

Slovakia adopted an action plan in 2023 aimed at the successful implementation of the National Hydrogen Strategy (approved by the government in 2021) by 2026. The action plan will allocate €60 million for its implementation and its main objective is to accelerate the transformation of the national economy to a low-carbon one (SITA, 2023). The proposal will be financed through the Slovak Recovery and Resilience Plan, the state budget and the EU-Slovakia Programme. The plan foresees the creation of a hydrogen roadmap and the creation and modification of legislation for hydrogen technologies. Slovakia has also established the Hydrogen Technology Research Centre in Košice. The indicative target of the Action Plan is the production of 45,000 tonnes of green and blue hydrogen, of which all the hydrogen produced is to be consumed in industry, transportation and energy (MINISTRY OF ECONOMY, 2022). Slovakia also intends to distribute and store natural gas mixtures with hydrogen content up to 5% by 01.10.2025 (MINISTRY OF ECONOMY, 2022). The country lacks a legislative framework that explicitly addresses hydrogen in the energy sector. According to the National Hydrogen Association, Slovakia has the capacity to produce 45,000 to 50,000 tonnes of hydrogen per year by 2030, of which 25,000 tonnes should be produced by water electrolysis (using electricity from renewable sources and the core) and 20,000 tonnes by gasification, fermentation and plasma decomposition.

Hungary's National Hydrogen Strategy, adopted in 2021, sets a goal of producing 36,000 tonnes of green hydrogen (MINISTRY OF INNOVATION AND TECHNOLOGY, 2021). Hungary is preparing to introduce two new hydrogen valleys by 2030 - Transdanubia and the Northeast Valley. 10,000 tonnes of green hydrogen should be used for emission-free transport by 2030. As all the European Union member states mentioned so far, Hungary deems changes in legislation and improvements in national regulatory frameworks necessary. These frameworks should be predictable and should support the hydrogen economy in the long term. As regards the targets for the years between 2030 and 2040, Hungary intends to promote carbon capture, use hydrogen propulsion technologies in rail transport, and prepare a gas distribution network and systems that will use clean hydrogen.

France has a well-developed hydrogen legal framework. Its hydrogen strategy includes EUR 100 million in funding and goals for the years 2023 and 2028 relating to low-carbon hydrogen in industrial applications, transport, and renewable energy storage. France has also set a target of achieving a 20-40% share of hydrogen use in industry by 2028 (WATSON FARLEY AND WILLIAMS, 2021). The future of the French hydrogen sector will depend on the ability of stakeholders to significantly increase the production of low-carbon and renewable hydrogen by electrolysis and to create a competitive hydrogen industrial cluster.

The Netherlands has the highest number of large-scale hydrogen projects and pilot projects in the European Union (FLEISHMANHILLARD, 2022). In 2018, the Dutch transmission system operator started transporting hydrogen via a repurposed natural gas pipeline (FLEISHMANHILLARD, 2022). By 2026, the Dutch TSOs intend to focus on regional interconnectors and interconnections with Germany. Between 2026 – 2028, the aim will be to connect all large industrial plants (MINISTRY OF ECONOMIC AFFAIRS AND CLIMATE POLICY, 2022). By 2030, the country is to be connected by 5 interconnectors with other neighbouring countries. However, there is no specific hydrogen legislation yet.

Belgium adopted a national hydrogen strategy in 2021. The country has set a target of importing 3-6 TWh of hydrogen by 2030 and 100-165 TWh by 2050 (FLEISHMANHILLARD, 2022). Belgium plans to build hydrogen infrastructure on top of its existing natural gas infrastructure. The first project would include 100-160 km of hydrogen pipelines, which should be operational by 2026. By 2030, the country plans to link the hydrogen network with the neighbouring countries (MINISTRY OF ECONOMY OF BELGIUM, 2021).

Denmark has some of the most ambitious plans to reduce emissions by 70% by 2030 and achieve carbon neutrality by 2050 (DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES, 2021). These plans are part of the Power-to-X ambition.

Like many other European countries, Germany lacks a comprehensive legal framework for hydrogen production. In 2021, the government amended the Energy Act to include a regulatory framework for hydrogen. In 2020, the government approved the National Hydrogen Strategy, which identifies 13 goals and ambitions, including an increase in green hydrogen production to 14 TWh by 2030 and to 19 TWh by 2040. This strategy was supplemented and modified in 2023. Domestic electrolyser capacity should be expanded to 10 GW by 2030. By 2027/2028, Germany intends to run 1,800 km of repurposed and new pipelines to transport hydrogen (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS, 2023). By 2030, the government plans to use hydrogen and its derivatives in industry, commercial vehicles, aviation and water transport. The strategy assumes to reach hydrogen demand between 95 and 130 TWh in 2030. Another objective is to create a competitive domestic market for hydrogen production and consumption. Germany also introduced the H2 mobility programme. In doing so, the German government intends to increase the maximum possible capacity of hydrogen electrolysers to ten thousand MW by 2030. As Handelsblatt notes, given the current installed capacity of 60 MW, this target sounds very ambitious (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND CLIMATE ACTION, 2023).

Norway has set an objective to reduce emissions by 90-95% by 2050 compared to 1990. This country, rich in hydrogen as well as natural gas reserves, has considerable potential to replace its role as a natural gas exporter with a hydrogen exporter. This country, rich in hydrogen as well as natural gas reserves, has considerable potential to replace its role as a natural gas exporter with that of a hydrogen exporter. That is why we have also included this country in the research with the EU Member States. As a strong export player for gas imports for EU member states with significant hydrogen resources, it is very likely that Kariyna will play an increasingly important role in the EU energy sector. Norway's first hydrogen strategy was launched in 2005. For a competitive and energy-efficient hydrogen chain, Norway launched the national funding scheme PILOT-E (together with the Research Council of Norway, the government agency Innovation Norway and the state-owned company ENOVA) to support the transition to green energy technologies. Norway has also issued a roadmap in 2021, focusing on the maritime sector, which it envisions as the greatest potential for hydrogen applications. By 2025, the government has set a target of 5 hydrogen hubs for maritime transport and one or two industrial projects with associated hydrogen production (FLEISHMANHILLARD, 2022). However, Norway's main goal is to make hydrogen competitive by 2030, especially in the transport sector.

Finland also has one of the boldest strategies to become a carbon-neutral country by 2035 and carbon-negative by 2050. The government has set a target of selling 250,000 electric vehicles by 2030. Finland aims to produce 10% of the EU's clean hydrogen (H2 CLUSTER FINLAND, 2023).

Sweden aims to achieve zero emissions by 2045. It is therefore logical that, with an already significant share of energy production coming from renewable sources, the government is also promoting hydrogen technology. In 2021, it published a national strategy for green hydrogen, electric fuels and ammonia, with the decarbonisation of the industry as the main goal. Currently, most of the hydrogen used in the chemical and refining industries is produced from fossil fuels. The government intends to reach 5 GW of electrolyser capacity by 2030 and a further 10 GW by 2045 (MINISTRY OF ENVIRONMENT AND ENERGY, 2017).

In 2021, Estonia approved an action plan for the development and hydrogen strategy, allocating €50 million from the National Recovery and Resilience Fund (REPUBLIC OF ESTONIA, GOVERNMENT, 2022). The country plans to develop the world's first national hydrogen ecosystem in the coming years, which will consist of hydrogen production units, distribution networks and applications.

Lithuania aims to reach 1.3 GW of electricity generation capacity by 2030 and 8.5 GW by 2050 (EPSOG, 2023). The country will be part of the Baltic hydrogen backbone. Lithuania plans to use hydrogen to reduce the country's dependence on fossil fuel imports. The country plans to prioritise domestic production of green hydrogen over imported or hydrogen produced from fossil fuels. In 2020, the Hydrogen Platform was established to serve as a collaborative platform that brings together national research institutions and the public sector to promote the development of hydrogen technology in the country. Lithuania has allocated 20 million euros from the Recovery Plan and 50 million euros from the Modernisation Fund and hydrogen-related pilot projects. In total, the country plans to invest 300 million euros in the hydrogen sector by 2030 (FLEISHMANHILLARD, 2022).

Latvia perceives hydrogen as an alternative fuel of the future. The country should be part of the „Nordic-Baltic Hydrogen Corridor“, which is a cross-border hydrogen infrastructure project that allows hydrogen to be transported through Finland, Estonia, Latvia, Lithuania, Poland and Germany (ELERING, 2023). The corridor will connect different hydrogen supply, demand and storage points. The project also strongly supports the European Hydrogen Strategy and the REPowerEU plan.

In Portugal, several small- and large-scale hydrogen projects are currently in operation. Some of them focus exclusively on decarbonisation of industry and energy production. Among the most important are the Green Flamingo initiative, which aims to create a hydrogen solar power plant, and the Synthetic Fuel for Aviation project, the goal of which is to increase the use of green hydrogen in the production of alternative aviation fuels. Portugal announced its hydrogen strategy in 2020, in which it commits to achieving 5% of hydrogen consumption in road transport of total final energy consumption, 15% of hydrogen to be blended into the grid with natural gas, 2 to 2.5 GW of installed hydrogen generation capacity and to invest €7 billion in hydrogen generation projects by 2030 (PACHECO, BRANCO, 2021)

Spain currently consumes around 500,000 tonnes of hydrogen per year. There is currently no legislative preparation regarding hydrogen production. According to the hydrogen plan adopted in 2020, the country aims to achieve 4 GW of installed electrolyser capacity, a minimum 25% share of green hydrogen in total hydrogen consumption, a minimum of 150-200 hydrogen-powered buses and the use of hydrogen-powered trains by 2030. The estimated investment to achieve these targets is €8.9 billion (FLEISHMANHILLARD, 2022).

Bulgaria is one of the countries with an underdeveloped hydrogen strategy. The country has adopted a National Hydrogen Plan, which is part of the National Recovery and Resilience Plan. The plan defines strategic goals that include decarbonising the economy, replacing energy sources with hydrogen, and building capacity to harness the potential of hydrogen technologies (MURGINSKI, 2023).

Croatia also has underdeveloped strategies. The country is primarily focused on the development of hydrogen projects in the transport sector. With regard to hydrogen, the Integrated Plan envisages in particular the development of the transport sector, where the target is to deploy 32 GWh of hydrogen-powered vehicles by 2030. Currently there are no hydrogen-powered vehicles in the sector, but the goal is to increase this figure to 2.7 percent by 2030 (CMS, 2021).

Slovenia views hydrogen as a way to achieve decarbonisation and sufficient energy supply for the country. The country has not adopted any hydrogen strategy yet.

Greece plans to be climate neutral by 2050. The country intends to use green hydrogen where renewable energy cannot be used. Greece would like the EastMed pipeline to become part of the European Hydrogen Backbone for hydrogen supply in the long term (LIAGGOU, 2022). In 2040, according to the strategy, Greece will be able to produce approximately 3 metric tonnes of oil equivalent (Mtoe) of green hydrogen and export 1 Mtoe (LIAGGOU, 2022). However, its National Energy and Climate Plan adopted in 2019 does not specify any quantitative targets for the deployment of hydrogen (LIAGGOU, 2022).
Malta has established three focal points for the deployment of hydrogen. The first is infrastructure, the second is the decarbonisation of industry and the last is the transport sector and green hydrogen production. However, the country has not yet set any specific targets. Malta also lacks a comprehensive legislative framework regulating hydrogen production. The Maltese government is exploring the possibility of having hydrogen and renewable fuels, including biomethane, delivered to Malta via a pipeline from Gela in Sicily from 2030 onwards (DEBONO, 2021).

Romanian authorities presented the country's hydrogen strategy in 2022 (BEEUREN, BALAN, CATUTI, DUDAU, 2021). The package focuses on hydrogen use in the most promising applications, such as industrial transport and long-term storage. The strategy prioritises clean hydrogen produced from renewable sources. According to the Romanian Renewal Plan, around 2,000 km of gas pipelines will have to be repurposed for transporting hydrogen or blending it into the grid. By 2026, hydrogen should account for 20% of the mix with natural gas in the pipeline and by 2030, the infrastructure will be used for 100% hydrogen transportation (OPREA, 2023). General targets are set to reduce emissions by 2 million top CO2 by 2030, using renewable hydrogen.

In 2020, the Italian Ministry of Economic Development adopted the Italian Hydrogen Strategy. The document sets medium- and long-term targets, according to which the national consumption of hydrogen energy is expected to account for 2% by 2030 and 20% by 2050. The ministry predicted that 10 billion euros of investment will be needed by 2030 to kick-start a low-carbon hydrogen economy (WATSON FARLEY AND WILLIAMS, 2021). In order to support the development of the hydrogen market, the Italian government expects the installation of approximately 5 GW of electrolysis capacity by 2030. However, the current regulatory framework for hydrogen production in Italy only covers hydrogen production using fossil fuels.

Ireland, like most EU countries, aims to be carbon neutral by 2050. Given its vast renewable resources, Ireland has the potential to produce renewable hydrogen for its own consumption in the long term. Domestic hydrogen energy demand could range between 4.6 and 39 TWh by 2050 (DEPARTMENT OF ENVIRONMENT, CLIMATE AND COMMUNICATIONS, 2023). Such a huge expansion only highlights the uncertainty about the nascent nature of this market. Local hydrogen infrastructure is also expected to emerge where demand will be directly linked to production. According to the hydrogen strategy, 2 GW of green hydrogen should be produced from wind power by 2030 (DEPARTMENT OF THE ENVIRONMENT, CLIMATE AND COMMUNICATIONS, 2023).

The European Union has adopted several strategies and action plans to decarbonise its economy. The European Hydrogen Strategy has set the objective of increasing hydrogen demand, and has proposed a framework for hydrogen infrastructure. The Energy System Integration Strategy aims to apply the principle of energy efficiency, accelerate electrification and energy demand while promoting renewable and low-carbon sources, and echo the need to develop more integrated energy systems (EUROPEAN COMMISSION, 2020). The European Union has adopted the Fourth Gas Package, which contains new hydrogen-related targets and regulations. The package provides for a new entity in the hydrogen sector - ENOOH. The package will set tariffs and other measures necessary for the functioning of the hydrogen market. The European Commission's RePowerEU plan aims to reduce the EU's dependence on fossil fuels, especially those imported from Russia. Its goal is to achieve this by diversifying supplies and accelerating the deployment of renewable gases. It sets an EU target of importing 10 million tonnes of hydrogen and consuming 10 million tonnes by 2030 (EUROPEAN COMMISSION, 2023). The Fit for 55 package refers to the EU's target of reducing greenhouse emissions by at least 55% by 2030. The package includes targets for hydrogen in end-use sectors such as transport, aviation and shipping (EUROPEAN COUNCIL, 2022). The EU supports many projects such as the European Hydrogen Backbone. 28 EU member states have signed the "Hydrogen Initiative" to promote cooperation on sustainable hydrogen technologies.

There are several other significant contributors to the global economy which invest in hydrogen projects. For example, Australia has announced over AUD 100 million to support hydrogen pilot projects and research (IEA, 2019). China, one of the largest consumer markets, has established a "10-City Programme", according to which electric cars will be replaced with hydrogen vehicles in 10 cities. Wuhan is expected to become the first hydrogen city by 2025. South Korea published a hydrogen economy plan which sets out the targets for the years 2022 and 2040 regarding buses and gas stations. The country aims to convert all commercial vehicles to hydrogen by 2025. South Korea has also announced that it will actively work on a technology roadmap for the hydrogen economy.

Comparison of Eu Member States' National Hydrogen Strategies

CONTRY	HYDROGEN INITIATIVES	TARGETS	YEAR	CLIMATE NEUTRALITY
Austria	National Hydrogen Strategy	1GW	2030	2040
the Czech Republic	National Hydrogen Strategy	Consumption: 1,728 thousand tons of low-carbon hydrogen	2050	2050
Poland	Hydrogen Strategy	2GW	2030	2050
Slovakia	National Hydrogen Strategy	45,000-50,000 tons of hydrogen per year	2030	2050
Hungary	National Hydrogen Strategy	240 MW electrolysis capacity	2030	2050
France	Hydrogen Plan	6,5GW	2030	2050
the Netherlands	Hydrogen Strategy	4GW	2030	2050
Belgium	National Hydrogen Strategy	3 – 6 TWh of imported hydrogen	2030	2050
Denmark	Government's strategy „Power to X"	4 – 6 GW	2030	2050
Germany	National Hydrogen Strategy	Production:19 TWh of green hydrogen	2040	2050
Norway	Norwegian Hydrogen Strategy	-	-	2050
Finland	Clean Hydrogen Strategy for Finland	98TWh	2035	2035
Sweden	National Hydrogen Strategy	10 GW of electrolysers	2045	2045
Estonia	Hydrogen Valley	the first national hydrogen ecosystem in the world	-	2050
Lithuania	Hydrogen Strategy	8,5 GW	2050	2050
Latvia	-	-	-	2050
Portugal	National Hydrogen Strategy	5,5 GW	2030	2050
Spain	Hydrogen Strategy	150 – 200 fuel cell buses, 4 GW of electrolysers	2030	2050
Bulgaria	National Hydrogen Roadmap (Ministry of Innovation and Growth)	-	-	2050

Slovenia	-	-	-	2050
Greece	National Energy and Climate Plan	-	-	2050
Malta	-	-	-	2050
Romania	National Hydrogen Strategy	8GW	2030	2050
Italy	National Hydrogen Strategy	2% of the total energy demand	2030	2050
Ireland	National Hydrogen Strategy	4.6 – 39 TWh	2050	2050
European Union	REPowerEU, Fit for 55, Energy Hydrogen Backbone, Hydrogen Strategy for Climate-Neutral Europe, REDIII,	To consume 10 million tonnes of hydrogen and import 10 million tonnes	2030	2050

Source: author's own

The analysis of the EU countries' strategies shows that most of them have vague targets, especially by 2030. Due to the considerable ambiguity in the development of the hydrogen market, some countries have a wide range of unclear targets. The Scandinavian countries have the highest hydrogen readiness. Even though they have not set clear targets yet, they show the greatest potential for hydrogen applications. The creation of hydrogen valleys and the emergence of hubs with direct hydrogen production and consumption are the most considered action plans in national strategies. In production, we have seen that so far only a very small fraction of green hydrogen is being produced and used, which is a worrying figure when it comes to carbon neutrality achieved by 2050. Many countries suggest that most low-carbon hydrogen applications are not cost-competitive without direct government support.

In the long term, the growth of hydrogen technologies and the development of hydrogen value chains will support the increasing share of renewables (owner's energy storage technologies), give a new role to the gas industry in terms of storage, transportation and distribution of natural gas and hydrogen mixtures, and be a tool for decarbonising transport and industry. However, hydrogen does not yet play a competitive role in energy supply and it is hard to imagine that it ever will on a large scale. In the meantime, costs need to be optimised, infrastructure has to be adapted and the EU needs to assess whether it has sufficient resources. The question arises as to whether it would not be more profitable to use controversial nuclear energy to produce hydrogen, as they are both low-emissions energies.

Conclusion

Hydrogen has the potential to play a significant role in the EU's future energy transition. Combining hydrogen technologies with other low-carbon energy sources such as nuclear power could be an effective approach to achieving carbon neutrality and ensuring energy security in the EU. Replacing natural gas with hydrogen within the EU by 2050 is technically possible but faces significant challenges in terms of economic feasibility and infrastructure needs. The successful implementation of this transition will depend on a coordinated approach among EU Member States, significant investment in the development and implementation of hydrogen technologies and commitment at political and legislative level. The main challenge in replacing natural gas with hydrogen is the adaptation of existing infrastructure. As we have noted, there are technologies that allow hydrogen to be blended with natural gas in existing pipelines (up to 10% hydrogen), with the concomitant significant cost of infrastructure transformation being unavoidable. The lower energy density of hydrogen compared to natural gas poses a challenge for its storage and distribution. However, technological advances in hydrogen storage (e.g. compressed gas and liquid hydrogen) are enabling rapid progress in this area. Important studies, such as those by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), highlight the importance of increasing hydrogen production through electrolysis and developing the infrastructure for hydrogen storage as an important part of the transition to a hydrogen economy. Several pilot projects, such as hydrogen blending in existing gas networks (e.g. in Slovakia) and large-scale hydrogen infrastructure projects in countries such as the Netherlands and Germany, demonstrate the technical feasibility of integrating hydrogen into existing systems. These projects have shown that, although challenges are still present, the infrastructure and technology for hydrogen is gradually reaching a level that allows its wider use, but as far as the energy sector is concerned, most studies so far show the greatest advantage in blending it into the existing gas grid, as the authors of the book "Enriched methane: a first step towards a hydrogen economy" also point out. The result of our analysis has shown that achieving the goal of fully replacing natural gas with hydrogen is not yet possible, as nuclear power plants would also have to be relied on to produce hydrogen in the quantities announced. However, such energy is also strongly criticised in EU structures. On the basis of the above, we conclude that it is not possible to replace natural gas entirely with hydrogen in the European Union by 2050 and therefore reject the hypothesis. The European Union member states have adopted different approaches to the development of hydrogen technologies, with some countries more advanced than others. This lack of clarity in the strategies of the EU countries also indicates the uncertainties about hydrogen use in the near future and in large volumes.

Different EU Member States have adopted different approaches to the development of hydrogen technologies, with some countries being more advanced in this process than others. Also, such a confused set of strategies by individual EU Member States indicates uncertainties in the future of hydrogen use in the near future and in large volumes.

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