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Correlation Between Major Economic Indicators and Green Hydrogen Production in the EU

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Abstract. The European Union's Green Deal agenda emphasises the major importance of cleaner and more environmentally friendly energy sources for further economic development. Hydrogen is one of the potential renewable fuels that can replace fossil fuels in a variety of economic applications. The green hydrogen production across Europe is a key factor in achieving this goal. The aim of the study is to determine the influence of the connection between the availability of renewable energy sources, innovation, and economic development patterns on hydrogen production advancement. The research provides a comprehensive correlation analysis between the number of green hydrogen production sites and their capacity with statistical indicators describing economic growth, population, innovation, and particular economic characteristics within a particular EU Member State. The statistical data of this research outline the period from 2021 until the beginning of 2024.
The results of the study suggest that nine of the 23 indicators examined – population size, gross domestic product, investment in research and development, total manufacturing value, overall industry value, total electricity produced, renewables in electricity production, solar power, and wind power in electricity production – have a strong or very strong positive correlation with hydrogen production. Furthermore, the analyses revealed that countries with large populations and high GDP volumes are more likely to develop hydrogen production in existing market circumstances.
Key words: green hydrogen, EU economy, hydrogen production, economic indicators, correlation analyses, renewable energy.

Introduction

The EU's Green Deal agenda, supported by the Paris Agreement on global climate goals, highlights the overall demand for cleaner and more nature-friendly energy sources. Hydrogen is one of the potential renewable fuels that can be produced in large quantities from renewable energy sources such as wind or solar energy. In addition, it can replace fossil fuels in different fields of application within the economy. To fulfil this goal, the introduction of a large number of new energy infrastructure objects across all EU countries is required. Furthermore, the common EU hydrogen strategy and national roadmaps for the hydrogen sector development of 18 Member States emphasise the importance of hydrogen as a fuel for future economic development. On the other hand, the application of green hydrogen will be beneficial for EU Member States to achieve energy independence from third-party fossil fuel exports.

According to the International Energy Agency, the use of hydrogen in the global economy increased from 18 Mt to 94 Mt per year between 1975 and 2021 (International Energy Agency, 2019, 2022). The World Bank estimates that market demand for hydrogen will be around 600 Mt per year by 2050. Currently, only 5% of the hydrogen produced comes from renewable resources, mostly wind and solar power (World Bank, 2022). In 2020, 8.1 Mt of hydrogen was produced in the EU (Fuel Cells and Hydrogen Observatory, 2022).

The authors of this paper have analysed data on renewable hydrogen production facilities across the EU. The hydrogen production capacities are crucial for scaling up hydrogen production to encourage faster commercialisation of this fuel and facilitate the overall energy transition process from fossil fuels to renewable energy sources. The EU members have different approaches to the hydrogen production matter and distinct situations concerning the general

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hydrogen industry evolution process. Within this process, an important question arises: Is there a visible distinction between large and small EU economies in terms of hydrogen application?

The paper aims to distinguish the correlation between statistical data on renewable energy and the number of hydrogen production facilities and their capacity in EU Member States. According to the assumptions set in this research, the availability of renewable energy resources will drive more effort into green hydrogen production. Moreover, countries with a more complex economy must have broader possibilities and tools to ensure a more continuous and faster transition from fossil fuels to renewables, including the production and use of more green hydrogen within their economies.

The object of the study is the development of green hydrogen production in EU Member States. The subject of this research is the evolution of green hydrogen production capacity with the availability of renewable energy, innovation, and the development potential of the economy in EU Member States.

The aim of the research is to determine the influence of the connection between the availability of renewable energy sources, innovation, and economic development patterns on hydrogen production advancement. The defined goal is accompanied by the following tasks: reviewing the major factors for economic development in synergy with the evolution of the hydrogen industry in the EU; identifying and analysing statistical data regarding renewable energy, innovations, and economic development capacity of the EU Member States; and determining the correlation between data on renewable energy and economic development with hydrogen industry development indicators.

The study is designed to serve as a guide for field professionals, scholars, and policy developers in creating and updating initiatives in the area of hydrogen production and, with it, connected fields of the economy. In light of differences between the EU Member States in hydrogen strategies and pathways, there are connections and indicators that must be taken into consideration in the process of creating business strategies and policy guidelines.

The significance of the study lies in the effort to define the macroeconomic circumstances and statistical data that emphasise the potential for new industrial growth in the particular area, in this instance the evolution of the green hydrogen industry in the EU. Furthermore, this study can serve as a foundation for future studies on the rapidly expanding number of renewable hydrogen projects across Europe, as well as their relationship to the general economic conditions in a given region.

Methodology

According to the goal of this research on the development of green hydrogen production in the EU, a statistical data on the hydrogen industry, innovation, energy and various criteria for economic growth in a specific territory are provided.

In the beginning, the study provides a list of assumptions for the increase in renewable hydrogen production, and the overall development of the hydrogen industry. This list of assumptions consists of the overall economic indicators, industry-specific aspects, people concentration data, and economic growth indicators. At the same time, there are references to 18 EU Member States hydrogen strategies that provide industry development directions: the primary type of hydrogen to be used in the economy, the hydrogen supply pathways, and the primary sectors of application.

The statistical data of this research describe the period from 2021 until the beginning of 2024. The largest amount of statistical information was acquired from Eurostat, the World Bank, and the International Energy Agency databases and publications.

In accordance with the study framework, secondary data on hydrogen production in the EU Member States was collected and analysed. The main emphasis in the analyses falls on hydrogen production sites and their capacity as one type of variable, and their linkages with other types of variables – statistical indicators describing economic growth, population, innovation, and particular economic characteristics within a particular EU Member State. Pearson correlation analyses were applied to identify these linkages, and to determine their strength according to the correlation coefficient. The analyses were conducted by gathering data on each EU Member State in a given year and comparing these values with the hydrogen production facilities and their capacity in that country. Pearson correlation coefficients are described as follows: no correlation -0.29–0.29, moderate positive correlation 0.3–0.59, strong positive correlation 0.6–0.79, and very strong positive correlation 0.8–1. The correlation analyses were carried out using Microsoft Excel.

The correlation analyses are applied in a wide field of studies regarding macroeconomic data and sectoral indicators. For example, to determine the links between data-forming GDP volumes and container throughput (Yang, Zhao, & Yanagita, 2017), to identify the impact of macroeconomic and financial drivers from the largest economies on the volatility and correlation in precious metal markets (Dinh *et al*., 2022), or to discover the determinants of economic growth within industrialisation in Latin America throughout the twentieth and early twenty-first centuries (Forero & Tena-Junguito, 2024). Moreover,

Table 1

Five pillars and 23 criteria for analysis

Social-economic data	Business environment	Innovation	Industry	Energy sources
1. Population size 2. Population density 3. Gross domestic product 4. Gross domestic product per capita 5. Foreign direct investment 6. Foreign direct investment per capita	7. Credit rating 8. Doing business rating 9. World competitiveness ranking	10. Investments in research and development 11. Investments in research and development per capita 12. Global innovation index 13. Economic complexity index	14. Manufacturing value added 15. Manufacturing value added per capita 16. Industry percentage of gross domestic product 17. Industry value added	18. Total electricity produced 19. Renewables in energy balances 20. Renewables in electricity production 21. Solar power in electricity production 22. Wind power in electricity production 23. Hydro power in electricity production

Source: Author's framework for correlation analysis.

the correlation analyses may be seen as what allows to identify the connections between distinct variables and lay the foundations for more detailed research employing different methods in the future.

Within the research framework, 23 indicators were divided into the five pillars of analysis: major social-economic data, business environment assessment, innovation criteria, industry data, and energy balances (Table 1).

Apart from that, correlation analyses were performed to identify the connection between the existence of hydrogen roadmaps and the development of hydrogen production. The hydrogen strategies of the EU Member States were ranked by adding values from 2 to 5, with the highest value representing the oldest strategies from 2020.

Within the study, the descriptive study method is applied for the analysis of publications, scientific literature, and policy planning documents; statistical analysis methods are used to analyse the potential connections between green hydrogen production and different indicators describing specific fields of the economy.

Literature review

This chapter of the study discusses the most essential components and indicators for general economic growth, specific factors for individual industrial development, and the synergy between these domains. The paper focuses on green hydrogen production, as well as specific requirements for its evolution.

According to different pathways of theoretical thought in economics, there is a wide field of determinants for economic growth. Among these determinants, the government's role in economic development stands out. It can be argued that government actions have a major impact on the economic processes in a particular territory. Defenders of larger government participation in economic processes highlight the relevance of public administration measures promoting employment, demand, investments, and other significant aspects of economic growth (Higgins & Savoie, 1988; Keynes, 2018; Myrdal, 1957; Thirlwall, 2002). Additionally, government policy strategies and roadmaps are important guides for ensuring sustainable economic development in the EU (Trusina & Jermolajeva, 2023).

Foreign direct investment and government spending are perceived as the main tools to support economic growth and regional development (Abebe, McMillan, & Serafinelli, 2022; Berger, 2009; Keynes, 2018; Myrdal, 1957). According to the traditional view, foreign investment inflows into a certain territory are frequently accompanied by new technology, skills, and practices (Blalock & Gertler, 2008; Gherigi & Voytovych, 2018; Wang & Blomstrom, 1992). New technologies are the primary component of new economic mechanisms that provide a sustainable economy and maintain high living standards during the transition from fossil fuels to renewable energy sources.

The entry of new technologies and methods of operations is mainly due to interactions with foreign intermediates, whose modes of operations are often more efficient than that of domestic companies. Often, these links are beneficial in attracting foreign investors, which encourages domestic producers to take on the practice of foreign partners, which increases the competitiveness of the final product on the market (Javorick, 2004; Markusen & Venables, 1999).

An area with a high population concentration can promote economic development in the particular territory because it is an attractive place to host production due to the availability of large markets, local goods and services. In addition, people from less economically developed regions try to move to these more developed areas. Population concentration has an additional cumulative impact on economic growth as the market potential for different sectors and services increases. Industrial volumes increase when there is a large market, but a significant market emerges in the areas where manufacturing is concentrated. Investment and industrial activity are the main forces of development (Fujita & Thisse, 2009; Krugman, 1991; Nakamura, 2013).

For the economic growth within the climate-neutral path in the EU, hydrogen is one of the most encouraging energy sources. Many authors examine hydrogen application possibilities in different sectors of the economy, synergy with the energy sector, and costs and benefits within these related undertakings (Azadnia *et al.*, 2023; French, 2020; Jansons, *et al.*, 2023; Kakoulaki, *et al.*, 2021; Lejnieks & Pelse, 2023; Pomaska & Acciaro, 2022). Inside the hydrogen industry, technological challenges are interconnected with market, infrastructure, production scaling, and other challenges.

Regarding the EU's hydrogen policy, it must be noted that at the beginning of 2024, 18 of the 27 EU Member Countries had government-approved hydrogen strategies or roadmaps. These policy pathways are important to determine the role of a particular country in the hydrogen market, the primary ways of applying hydrogen in economic sectors, and the possibilities of hydrogen production. Moreover, in 2020, the European Commission approved a strategy for the use of hydrogen for a climate-neutral Europe. One of the five main areas of action in the strategy is to increase hydrogen production to create a sustainable industrial value chain (European Commission, 2023).

Results

In this part of the research, a list of the economic indicators for the EU Member States and statistical data on renewable hydrogen are provided. It also identifies and explains the synergy between these two types of data. Understanding the connection between these indicators is crucial for finding the right pathways for government policies towards the hydrogen industry development for environmentally neutral energy practices.

The major focus of this part of the research is concerned with the identification of the correlation

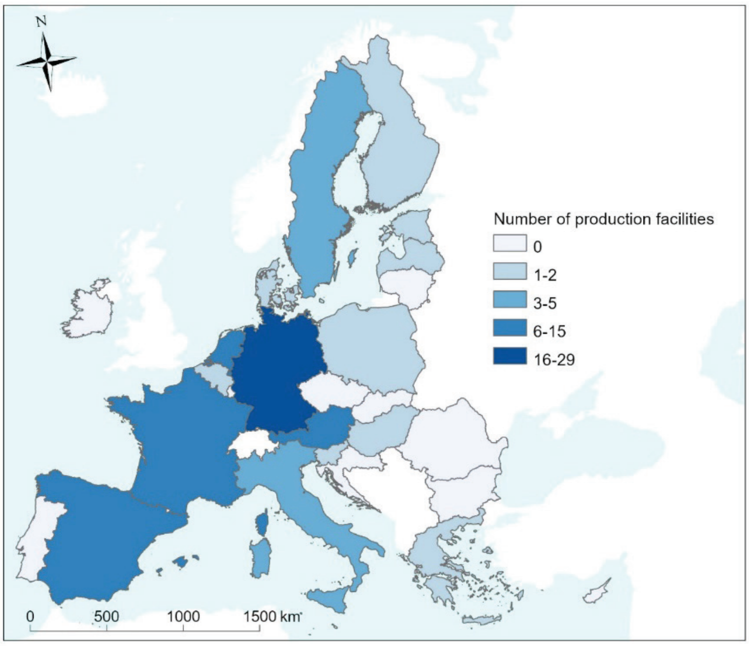

Figure 1. The number of green hydrogen production sites in EU, 2023.

Source: International Energy Agency

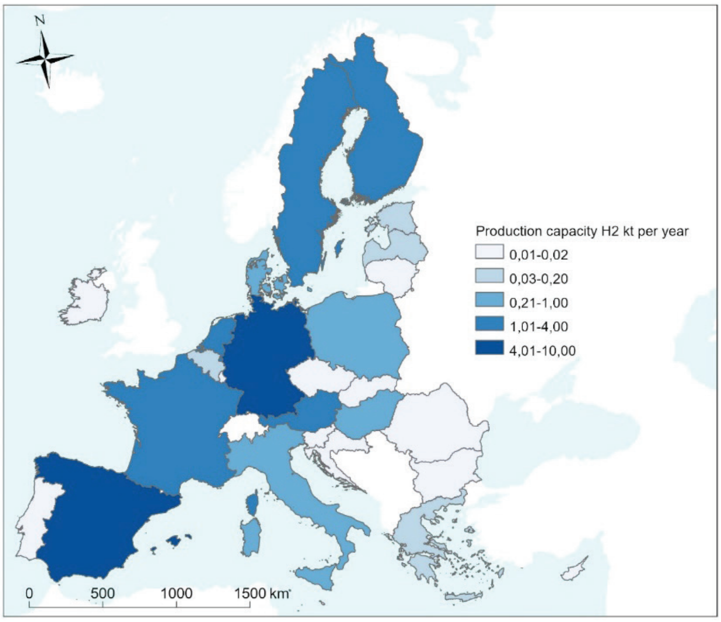

Figure 2. The capacity of green hydrogen production sites in the EU, 2023.

Source: International Energy Agency

between economic growth, population, and innovation indicators, and the number of existing green hydrogen production sites in the EU. The calculations concerning the capacity of renewable fuel production among the EU Member States are also presented.

At the beginning, it must be pointed out that the number of existing renewable hydrogen production sites and their corresponding capacities are distinctive among the EU Member States. According to data from the interactive map of the International Energy Agency, the countries with the highest number of production facilities in the EU are Germany, France, Spain, the Netherlands, and Austria (Figure 1).

The distribution of green hydrogen production capacity across Europe has a similar pattern as the hydrogen production locations within the EU (Figure 2). Germany and Spain have the largest renewable hydrogen production capacities in the region.

The correlation analyses were conducted regarding the major social-economic data, business environment assessment, innovation criteria, industry data, and energy balances, compared to the hydrogen production projects and their fuel production capacity in the EU Member States (Table 2).

In the first section, or pillar, correlation analyses were conducted regarding the major economic indicators of the EU Member States, such as the gross domestic product, foreign direct investment, and population concentration, and compared to the hydrogen production projects and their fuel production capacity. The results revealed that the number of hydrogen projects and their total capacity in a given EU Member State have a strong and very strong positive correlation with GDP and population size, but no correlation with FDI. Moreover, there is no connection between GDP per capita or FDI per capita and hydrogen production data.

In the second pillar, the correlation analyses were conducted regarding the business environment and credit ratings provided by the major companies in this area, such as Moody's, Standard & Poor's, and Fitch. Credit rating is one of the major indicators for companies and private investors to decide on investment in a particular country. The state of the economy has a strong influence on the inflow of finance and technologies needed for the hydrogen industry growth. In order to perform the analyses, each EU Member State's letter-based score from the mentioned credit rating organisations was assigned a value from 2 to 6, and then the average credit score of the specific state was calculated, and a proper value was provided. The conducted analyses indicate that there is no obvious correlation between business environment data and credit ratings on the one hand, and the number of hydrogen production facilities and their capacity on the other.

The third pillar of the analysis was focused on the EU Member States economic innovation aspirations as measured by the economy complexity index, investments in research and development, and the global innovation index. The conducted study suggests that there is a high correlation between the number of hydrogen production facilities and overall

Table 2

Correlation coefficient between existing green hydrogen production sites, their production capacity, and 23 indicators of the EU Member States

Indicators of the analysis	Green hydrogen production sites Oct 2023	Green hydrogen production capacity Oct 2023
Social-economic data		
Population size, Jan 2023	0.78	0.67
Population density, 2022	-0.01	-0.06
GDP, 2022	0.90	0.75
GDP per capita, 2022	0.11	0.13
FDI, 2022	0.22	0.18
FDI per capita, 2022	-0.13	-0.13
Business environment		
Credit rating, Jan 2024	0.42	0.42
Doing business, 2020	0.25	0.35
IMD Word Competitiveness Ranking, 2024	0.22	0.28
Innovation		
Investments in R&D, 2022	0.96	0.82
Investments in R&D per capita, 2022	0.41	0.46
Global innovation index, 2023	0.47	0.52
Economic Complexity Index, 2021	0.42	0.37
Industry		
Manufacturing, value added, 2022	0.88	0.76
Manufacturing, value added per capita, 2022	0.05	0.06
Industry, percent of GDP, 2022	0.03	0.07
Industry, value added, 2022	0.89	0.77
Energy		
Total electricity produced, 2022	0.86	0.77
Renewables in energy balances, 2022	-0.01	0.21
Renewables in electricity production, 2022	0.88	0.90
Solar power in electricity production, 2022	0.86	0.81
Wind power in electricity production, 2022	0.91	0.93
Hydro power in electricity production, 2022	0.34	0.48

Source: Author's correlation analysis of gathered data.

investments in research and development. Meanwhile, only a moderate correlation is observed with the particular state economy complexity index and the global innovation index.

The fourth section, or pillar, of the correlation analysis focused on the relationships between the amount of manufacturing and industry and hydrogen production in the EU Member States. According to the calculations, industry and manufacturing have a very strong link with the research topic regarding statistical data on total amounts.

The value of manufacturing per capita and the share of industry in GDP have no connection with hydrogen production sites or their capacity.

The fifth part, or pillar, of the analyses was concerned with correlation analyses regarding the availability of renewable energy sources in the EU Member States and whether they influence the number of hydrogen production projects and their capacity. The results revealed that the hydrogen production data has a strong positive correlation with the availability of renewable energy sources and the total electricity produced. In addition, the amount of solar and wind energy used in electricity production has a very strong correlation coefficient regarding the number of hydrogen production facilities and their capacity. It must be mentioned that hydroelectric energy has only a moderate correlation with the number of hydrogen production.

Discussion

Data on renewable green hydrogen production, as well as statistical analyses, suggest that countries with large populations and high GDP are more likely to develop hydrogen production. The examined statistical data indicate that overall numbers are more important than amounts per capita, and the size of the economy plays a key role. The capacity of a country's economy to use produced hydrogen and create sufficient demand for this renewable fuel is essential to the evolution of the hydrogen industry. The numbers are crucial for demand generation within a particular market.

On the other hand, the overall business environment and credit rating of a country have limited influence on the evolution of hydrogen production projects in EU countries. The possibility of utilising produced hydrogen is of major importance. In many observed cases, the new hydrogen production facilities are located at existing energy-producing sites like refineries, solar, and wind farms. Moreover, the capacity of many production facilities is relatively low and can be used in or near production sites. According to calculations performed on IEA data on green hydrogen production, the average capacity of hydrogen production sites in the EU is 0.36 kt H2 per year, but the mode value is 0.01.

According to the results of the correlation analysis, investments in research and development have a crucial influence on the topic. For example, the development of the green hydrogen industry in Germany has a strong synergy with existing water electrolyser production capacities, and the availability of related cost-effective technologies. With regard to the study conducted by Lauther and her co-authors, companies that develop, produce, and sell water electrolysers have to identify the right time to enter the market. They acknowledge that the data concerning the hydrogen industry is incomplete and some guidelines can be derived from the solar and wind industry experience, especially concerning government subsidies, long-term political initiatives, and clear normative acts (Lauther *et al*., 2023). Investments in research and development indicate the potential of interconnectivity within different cross-sectors, contributing to technology development within the hydrogen agenda. In 2022, 25% of electrolyser manufacturing capacity was based in Europe, while China accounted for more than 50% of electrolysers produced (International Energy Agency, 2023).

One of the major sources for hydrogen applications is industry. Genovese and his colleagues emphasise the relevance of hydrogen as a feedstock in a number of processes in refining, fertiliser manufacture, steel works, and other industries, replacing fossil fuels and highlight hydrogen's potential to play a large part in the decarbonisation of diverse industries. (Genovese *et al*., 2023). The synergy of green hydrogen with different industries is a key factor in promoting demand for green hydrogen. The retrieved data demonstrate that the total industry and manufacturing amounts have a connection to the evolution of hydrogen production sites and their capacity in particular territories. This aspect confirms the previous assumption concerning GDP and population data that the overall size of the economy has a strong impact on green hydrogen production development.

At the same time, it must be noted that the overall amount of renewable energy available in the particular territory has a strong positive correlation with green hydrogen production projects, too. Furthermore, solar and wind energy have a direct influence on the analysed topic because of hydrogen production being located near these facilities. According to Kakoulaki and her co-authors' study on the possibility of replacing existing fossil fuel-based hydrogen production with renewable-powered electrolysis, switching the annual EU hydrogen production to electrolysis would require approximately 10% of the current total electricity production. The available potential for producing green electricity from wind, solar, and hydro can balance the current electricity consumption and additional demand for green hydrogen. In 2021, hydrogen production was taking place in 82 NUTS2 regions in the EU, with 76 of them having enough solar, wind, and hydropower resources to fully decarbonise both electricity consumption and hydrogen generation (Kakoulaki *et al*., 2023). Further evolution of the hydrogen industry can be seen from the EU Member State boarders in a more flexible regional perspective. On the other hand, the availability of green energy sources has a positive influence on the green energy demand. The amount of solar and wind energy used in electricity production has a very strong correlation coefficient regarding the number of hydrogen production facilities and their capacity. It must be mentioned that the amount of hydroelectric power has only a moderate correlation with the number of hydrogen production sites in the region.

Finally, correlation analyses were performed to identify the synergy between the hydrogen roadmaps of 18 EU Member States and the development of hydrogen production in these countries. According to the acquired results, hydrogen strategies have a moderate correlation coefficient of 0.34 regarding hydrogen sites and a slightly higher coefficient value of 0.42 concerning hydrogen production capacity. It can be assumed that hydrogen policy documents have a limited influence on hydrogen production within a particular EU Member State. Economic factors play a more important role in renewable hydrogen production and overall industry development in this area.

Conclusions

The paper highlighted the connections between the 23 major economic indicators, industry indexes, business ratings, and renewable energy data on the one hand, and green hydrogen production facilities and their capacity in the EU Member States on the other. The relevance of the research is endorsed by the study framework focused on the links between major indicators describing a particular economy and its energy sources, and hydrogen production initiatives in the specified territory. These connections must be taken into consideration in the process of creating business strategies and policy guidelines within the particular field. Moreover, according to the acquired results, hydrogen policy strategies themselves have a moderate correlation with this fuel production.

Within the research framework, statistical data was divided into the five pillars of analysis: major economic indicators, business ratings, innovation, industry, and energy sources. From the 23 analysed indicators, nine – population size, gross domestic product, investments in research and development, total manufacturing value, overall industry value, total electricity produced, renewables in electricity production, solar power, and wind power in electricity production – have a strong or very strong positive correlation, and six have a moderately positive correlation with the existing green hydrogen production sites. The highest correlation variable (0.96) was calculated concerning the field of investments in research and development in the country.

It must be mentioned that the fifth pillar of the analysis highlighted a strong and very strong correlation between hydrogen production and the availability of solar and wind power capacities in the EU countries. In addition, solar and wind energy have a direct influence on the analysed topic because hydrogen production is localised in many cases near these facilities.

The analyses conducted revealed that countries with large populations and high GDP volumes are more likely to develop hydrogen production in existing market circumstances. The examined data suggests that overall numbers are more important than per capita indicators, and the size of the particular economy is a fundamental factor. The capacity of hydrogen utilisation within the economy creates sufficient demand for this renewable fuel, which is essential for the development of the hydrogen industry.

The research identified a list of major indicators influencing hydrogen production in EU countries. To examine the results presented in this paper, historical data must be collected and analysed. Moreover, there are large numbers of new hydrogen projects in different stages of development all over the EU, and further research could determine if these projects are driven by the identified factors or if there are other variables to be discovered.

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