

ENERGY RESILIENCE DURING ARMED CONFLICT: RECONSIDERING HYDROGEN FOR EUROPEAN UNION ENERGY SECURITY

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The Russian-Ukrainian war has raised concerns about the security of energy supply, prompting Europe to make changes in its energy mix. With the launch of REPowerEU, the EU aims to transition as quickly as possible from dependence on Russian fossil fuels to increased energy autonomy and clean energy production. Accelerating renewable hydrogen production by 2030 is part of this plan.

The present study uses clustering algorithms to assess the action capacity of the European Union countries regarding hydrogen perspective, by considering hydrogen production and infrastructure projects. The war has accelerated the transition to clean energy sources and energy independence, which is reflected in the reduction of CO2 emissions and the increased interest of member state governments and private entities in issuing green bonds. Investments in green hydrogen can boost economic growth and resilience but require the creation of a functioning market and a flexible regulatory framework.

Keywords: energy security; hydrogen; war; renewable energy; European Union;

INTRODUCTION

The Russian-Ukrainian war, which began in February 2022, has profoundly affected global energy dynamics, bringing to the fore the energy independence, and accelerating the transition to renewable energy sources. In response to the energy market imbalance, the European Commission launched the *REpowerEU Plan* in May 2022, an initiative aimed at phasing out energy imports from Russia and the significant green energy intensification (European Commission, 2022-a). Green hydrogen is an important component of *REpowerEU*, with estimated total imports and production of around 20 million tonnes by 2030 (European Commission, 2022-b). The plan also includes measures to support the development of hydrogen infrastructure and markets, so that green hydrogen can be produced, transported, and used efficiently in different sectors. However, since the drafting of the *EU Hydrogen Strategy*, opportunities arose regarding its role in the storage of renewable energy and in the reduction of CO2 emissions among certain sectors such as the steel, chemical and transport sectors (European Commission, 2020-a). The strategy aims to develop a European hydrogen economy, by creating new economic opportunities and stimulating the growth of the EU's competitiveness, with focus on research and innovation, which are essential for achieving these goals.

Resulting from the process of water electrolysis, green hydrogen has gained significant interest in the transition to a more sustainable energy system, being considered a potential clean energy solution because it is produced using renewable energy sources such as solar or wind energy. More and more countries have begun to pledge climate neutrality and look for solutions to reduce CO2 emissions, thus investments to stimulate the production and use of green hydrogen have substantially increased in recent years. Recently, approximately €6.9 billion (US\$7.4 billion) has been allocated at the EU level for green hydrogen production projects under the *Important Projects of Common European Interest (IPCEI)* initiative (Hydrogen Insight, 2024-a). The EU has also approved €998 million (about US\$1.1 billion) in state aid for renewable hydrogen production in Netherlands (Hydrogen Insight, 2024-b). To create investment security and business opportunities for both European and global production of hydrogen from renewable sources, the European Commission launched the European Hydrogen Bank (EHB) in 2022. The first EU-wide auction under the EHB awarded almost €720 million to seven renewable hydrogen projects

in Europe and it is expected to produce around 1.58 million tonnes of renewable hydrogen over the next ten years (European Commission, 2022-c).

The EU's efforts to build its own energy fortress while maintaining climate neutrality are numerous, but what happens when geopolitical changes occur? How has the war between Russia and Ukraine changed global energy dynamics and renewable energy discourse? Additionally, how can the EU, given the current context, align energy security with climate goals? Our research aims to fill this gap and analyse how the Russian-Ukrainian war brings to the fore the importance of green hydrogen as an alternative for EU goals. We check out the European green hydrogen market from the launch of the *EU Hydrogen Strategy 2020* until now. We consider variables of interest such as hydrogen consumption and supply, hydrogen infrastructure and production projects, to identify similarities and differences between EU countries from the perspective of hydrogen economy development. The variables are complemented by green bond issuance by corporates and governments, the share of renewable energy in gross final energy consumption and net greenhouse gas emissions, which show these countries' progress in the energy transition. Thus, in the first part of the paper we analyse the main results obtained in the literature on green hydrogen research, so that in the second part we describe our research methodology and results. In conclusion, we highlight the most important ideas and limitations of the paper, to which we add some potential themes for future research.

LITERATURE REVIEW

The biggest challenge in producing clean hydrogen is the energy source utilised. The desirable framework to meet both climate neutrality and energy security goals is for green hydrogen to be produced using entirely renewable sources. Thus, the whole process does not require the depletion of natural resources and does not involve CO₂ emissions. Moreover, the production of green hydrogen can create a sustainable energy system, thereby harnessing renewable energy sources and helping to reduce dependence on fossil fuels. However, the high cost of renewable energy technologies and the need for significant development of storage and distribution infrastructure represent a challenge.

The specialized literature focuses mainly on this issue. There are numerous studies that have attempted to classify hydrogen according to the type of technology used in its production. Pilavachi et al. al (2009) analysed seven common hydrogen production processes, depending on different types of cost and CO₂ emissions,

respectively: steam methane reforming (SMR), partial oxidation of hydrocarbons (POX), coal gasification (CG), biomass gasification (BG), photovoltaic-electrolysis system (PV-EL), wind-electrolysis system (W-EL) and hydropower-electrolysis system (H-EL). Their results demonstrated that, in most cases, the processes that combine renewable energy sources with electrolysis were considered to be better than conventional processes, with the hydropower-electrolysis system ranking first in the production process, and coal gasification at the opposite pole (Ib., p. 9). *EU Hydrogen Strategy* classifies it according to the technology and energy source used into the process: electricity-based hydrogen, renewable hydrogen, clean hydrogen, fossil fuel-based hydrogen, fossil fuel-based hydrogen with carbon capture, low-CO₂ hydrogen, and hydrogenated synthetic fuels. The Commission's communication noted that "*neither renewable hydrogen nor low-carbon hydrogen, particularly fossil fuel-based hydrogen with carbon capture, is cost-competitive with carbon-based hydrogen fossil fuels*" (European Commission, 2020-b, p. 5).

For a better classification of hydrogen types, the International Renewable Energy Agency (IRENA) has proposed a nomenclature of colour codes for each type, depending on the energy source used: grey (produced from fossil fuels, more precisely steam methane reforming – SMR or coal gasification), blue (grey hydrogen, but with carbon capture technologies – CCS), turquoise (combines the use of natural gas as a raw material, without the production of CO₂; thus, through the pyrolysis process, the carbon from methane becomes solid black carbon) and green (water electrolysis powered by electricity from renewable energy sources) (IRENA, 2020, p. 9).

There have also been specialized studies that have made technical and economic comparisons between hydrogen production technologies to understand their feasibility. Thus, other colours have been added such as: aqua, brown or black, white, yellow, pink or purple and red (Ji, Wang, 2021; Ajanovic et al., 2022; Arcos, Santos, 2023; Dash et al., 2023). Ji and Wang (2021) demonstrated that, in the short term, SMR remains the dominant technology due to its maturity, and CG may be more applicable in some regions due to the local distribution of resources. But to change this status quo, one option is to combine carbon capture technology to control CO₂ emissions, which is less feasible given the limited reserves of fossil fuels. The second option is the gradual transition to green hydrogen production, with electrolysis and thermochemical methods, demonstrating considerable development potential from an economic and ecological point of view (Ji, Wang, p. 18). Arcos and Santos (2023) showed that green hydrogen remains the most expensive of all other

types, followed by purple or pink hydrogen (obtained by nuclear power), and aqua hydrogen (derived from oil sands extraction, natural bitumen, and conventional oil fields) is the cheapest, but it must be emphasized that this type of hydrogen is still at an early stage and has not been adequately tested. Each method of producing hydrogen has different factors that must be considered. The composition of the energy mix, for example, determines the amount of CO₂ emissions generated. Therefore, although technologies with significant GHG emissions currently have the highest levels of maturity and lower costs, it is important that they are phased out and low-carbon production methods must continue to evolve and improve to achieve low cost and no GHG emissions. (Arcos, Santos, p. 15).

In the context of the war against Ukraine, energy researchers have mainly focused on issues related to transport infrastructure, supply chain and cooperation with different countries to ensure hydrogen partnerships.

Transport infrastructure is a critical component for the development of the hydrogen economy. Although it could be seen as a long-term goal, it was trying to find some short-term solutions. An alternative intensively researched by specialists is the use of the current gas infrastructure and the mixing of hydrogen in the natural gas network. Vadaszi et al. (2023) found that hydrogen can be directly blended in the distribution network, transported through the natural gas system, and stored in underground gas storages, but it must be considered that the implementation method differs from country to country depending on the existing infrastructure, the available legal framework, and the specific geological conditions. Their study proposes as a strategy the interconnection of the gas and electricity sectors and the increase of biogas production. Thus, if there is a surplus in the electricity system due to intensive renewable energy generation, then hydrogen can be produced with the excess energy and transported through the existing infrastructure. The conclusions highlight that the replacement of natural gas with 100% hydrogen remains only at a theoretical level for now, requiring a special infrastructure and technology (Vadaszi et al., p. 3). Bin Jumah (2024) showed that it is essential to improve the energy density of hydrogen to make its transport and storage possible, but specialized infrastructure is needed, which requires additional costs for processes such as compression, liquefaction, or the use of chemical carriers (bin Jumah, p. 18). The question was raised including the production of hydrogen in eco-industrial parks (EIP), which involve the creation of a cluster of industrial and commercial activities with the aim of minimizing waste and optimizing the use of resources. Eco-industrial parks can provide the necessary infrastructure for hydrogen

production and distribution and reduce production, transport, and distribution costs, thereby creating economies of scale (Reda et al., 2024, p. 15).

But hydrogen storage is not only determined by storage tools or transport infrastructure, but also by the evolution of supply and demand, as well as the interaction with other sectors. Münster et al. (2024) showed that the decrease in demand for natural gas led to an increase in the short-term demand for hydrogen. In the long term, the availability of green and blue hydrogen increases the demand for hydrogen imports, which can impact the necessary infrastructures. According to their study, the limited availability or high price of natural gas, accompanied by a high demand for hydrogen can increase the production of green hydrogen. Also, rising natural gas prices affect the cost of blue hydrogen, while rising electricity prices affect the cost of green hydrogen, thus there are cost variances due to uniform natural gas prices versus electricity prices (Münster et al., p. 22). Erdoğan and Güler (2023) projected the hydrogen supply chain for hydrogen fuel cell electric vehicles (HFCEV) in Turkey over a 25-year period (2026–2050). Low demand and high capital cost lead to an increase in the unit cost of hydrogen until 2031 but will reach the lowest values by 2050 due to the supply chain maturation. Their study considers the best strategy to be mixed production, based on SMR (cost oriented) on the one hand, and on electrolysis (oriented to zero CO₂ emissions), on the other hand (Erdoğan, Güler, p. 13).

The potential of green hydrogen relies also on geographical location and abundant natural resources. In August 2020, Germany and Ukraine launched an energy partnership that includes the development of a hydrogen-based economy. Ukraine has vast renewable energy resources that can contribute to the production of “green” hydrogen, as well as a gas transportation system useful for hydrogen distribution. For this, it is necessary to accelerate the development of the regulatory framework in Ukraine and harmonize it with Germany, considering the already existing norms and obligations of Ukraine in the field (Hritsyshyna, Hutarevych, 2021, p. 21). The regulatory framework also remains a challenge for the EU-Morocco partnership on hydrogen production, but it is not a major barrier like market readiness, water shortages and territorial disputes in Morocco.

We therefore consider the analysis of renewable energy sources in the EU that can contribute to the production of green hydrogen, taking into account the potential transport infrastructure, as well as the potential clean hydrogen demand and supply.

METHODOLOGY

Starting from the results obtained in the literature, we propose to analyse the potential of hydrogen in the EU-27 regarding the transition to green energy, given the armed conflict in Ukraine. *Table 1* includes variables description.

Table 1: Variables description

Acronym	Variable	Period	Unit of measure	Source
GRB	Green bond issuance by corporates and governments	2022	% of total	Eurostat
REN	Share of renewable energy in gross final energy consumption	average 2019-2022	%	Eurostat
GES	Net greenhouse gas emissions	average 2019-2022	tonnes per capita	Eurostat
H2IP	Hydrogen Infrastructure Projects	NA	no. of projects	European Hydrogen Observatory
H2PP	Hydrogen Production Projects	NA	no. of projects	European Hydrogen Observatory
H2TC	Hydrogen - Total Consumption	average 2019-2024	thousand metric tons oil equivalent	S&P Energy Portal
H2TS	Hydrogen - Total Supply	average 2019-2024	thousand metric tons oil equivalent	S&P Energy Portal

The research utilized clustering methods to examine the similarities and disparities among EU countries in relation to their hydrogen development. Three principal *clustering methodologies* were employed: *hierarchical clustering* (also known as joining or tree clustering), *k-means clustering*, and *two-way joining*. These methodologies were selected for their capacity to discern patterns

and categorize countries according to various characteristics associated with hydrogen development. The level of countries’ progress in producing and using hydrogen was captured by 4 variables:

- (1) Hydrogen Infrastructure Projects – H2IP;
- (2) Hydrogen Production Projects – H2PP;
- (3) Hydrogen – Total Consumption, average 2019-2024 (thousand metric tons oil equivalent) – H2TC;
- (4) Hydrogen – Total Supply, average 2019-2024 (thousand metric tons oil equivalent) – H2TS.

To them, we added 3 more variables that describe EU countries’ net greenhouse gas emissions, as an average 2019-2022 (in tonnes per capita) – GES, as well as their progress in the green transition: REN – Share of renewable energy in gross final energy consumption, average 2019-2022 (%), and GBR – Green bond issuance by corporates and governments, 2022 (% of total). Data was collected from Eurostat, European Hydrogen Observatory and S&P Energy Portal, for all 27 EU countries between 2019 and 2024, depending on availability.

The *hierarchical clustering*, employing Ward’s amalgamation method and Euclidean distances, generated a dendrogram that visually depicts the links across countries (Murtagh, Legendre, 2014). This method facilitated the recognition of embedded clusters without predefining their number. *K-means clustering*, an iterative partitioning technique, was subsequently employed to form distinct, non-overlapping groupings of countries exhibiting analogous hydrogen development trajectories (Jain, 2010). The number of clusters was established through the elbow approach and silhouette analysis to enhance intra-cluster similarity and inter-cluster dissimilarity. A *bi-clustering technique* known as two-way joining was utilized to concurrently cluster countries and variables, uncovering correlations between distinct subsets of countries and specific dimensions of hydrogen development, also in relation to countries’ progress in the energy transition (Madeira, Oliveira, 2004). The application of Euclidean distances across all three methods guarantees uniformity in assessing the similarity among data points. Ward’s approach, utilized in *hierarchical clustering*, minimizes within-cluster variance, resulting in compact and distinctly differentiated clusters (Murtagh, Legendre, ib.). The integration of various clustering methodologies established a comprehensive framework for discerning leaders, followers, and prospective partnership prospects within the European hydrogen sector.

RESEARCH RESULTS

In order to distribute the analysed countries in groups as homogeneous as possible, but differentiated from one cluster to another, two clustering algorithms were applied: the *iterative algorithm* (Figure 1) and the *k-means clustering* (Figure 2). All variables were standardized to remove the impact of different measurement units and were introduced into the algorithm using Tibco Statistica.

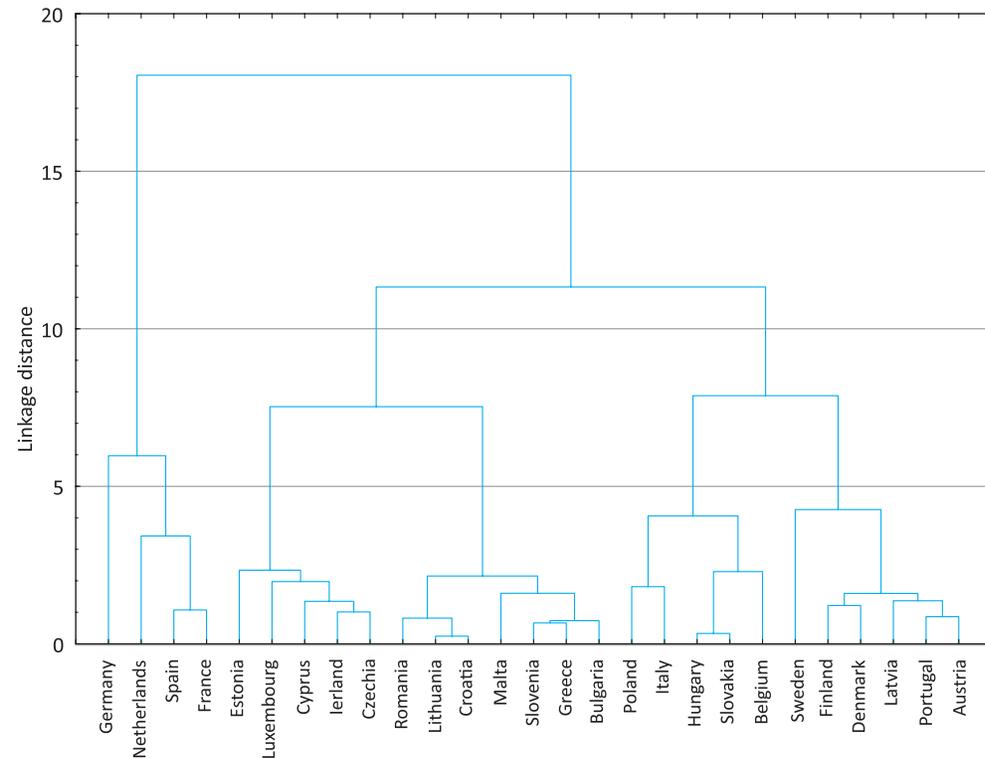


Figure 1. The dendrogram – hierarchical clustering (authors' calculations and representations in Tibco Statistica)

Figure 1 presents the results obtained from applying the *iterative algorithm*. The horizontal axis contains the number of identified clusters and the countries that are part of these clusters, and the distance between the cluster centres is shown on the vertical axis. Thus, 2 clusters of countries were obtained: Germany, the Netherlands, Spain, and France (Cluster 1) and the rest of the EU-27 countries (Cluster 2). Cluster 1 contains countries with specific particularities in terms of renewable energy and especially the production and use of hydrogen, compared to the countries in cluster 2. Germany, the Netherlands, Spain, and France are among the top countries in terms of both resources of renewable energy and significant

investments and hydrogen production capacity. Together with Poland, Italy, the UK, and Belgium, they together account for 74% of Europe's total hydrogen production capacity. (European Hydrogen Observatory, 2023, p. 12). In our analysis, Poland and Italy show similar characteristics and belong to cluster 2.

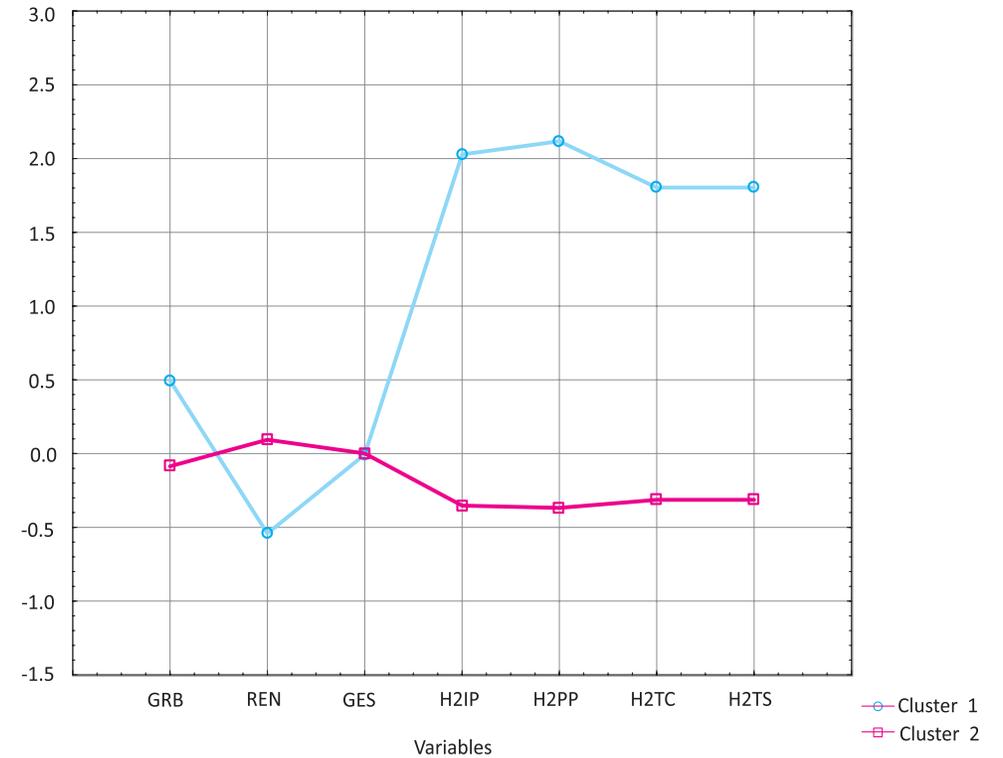


Figure 2. The k-means clustering (Ib.)

Figure 2 shows the normalized means for the two clusters. Cluster 1 is superior to cluster 2 in all variables except for REN, and equal in GES, but for all hydrogen variables, cluster 1 is clearly at a much higher level than cluster 2. The result is surprising regarding the share of renewable energy in gross final energy consumption for cluster 1 countries, but when we consider the hydrogen variables, we associate the share of renewable energy resources in hydrogen production. 91% of the total hydrogen production capacity comes from natural gas reforming or coal gasification. In contrast, clean methods such as reforming with simultaneous carbon capture and water electrolysis production have a minor contribution – less than 1% of the total hydrogen production capacity (Ib., p. 15). The GES variable is similar for both clusters, suggesting that EU countries have aligned with climate neutrality directives and made significant progress in reducing greenhouse gas

emissions. This variable is therefore not significant from the perspective of grouping EU countries into the two clusters.

When looking at green bond issuance by corporations and governments, we see no significant difference between the two clusters. In addition, the level is also slightly close to the GES variable for both clusters, which could mean that together with the EU’s climate neutrality objectives, the interest of member state governments and private entities in issuing green bonds has also increased. Green bonds help finance the assets needed for the transition to a low-carbon economy. Thus, in 2023 the European Green Bond Standard (EUGBS) entered into force with the aim of establishing a clear and transparent framework, as well as improving the impact of green bonds at EU level (European Commission, 2023).

Regarding hydrogen production and infrastructure projects, *k-means clustering* results show that states in cluster 1 are clearly superior to states in cluster 2 (figure 2). This can be seen through the massive investments they are making in hydrogen projects. Following European Commission approval in February 2024, the German government has awarded €4.6 billion to 23 green hydrogen projects under *Hy2Infra*. With these, Germany provides up to 1.4 GW of hydrogen production capacity powered by renewable energy, up to 370 GWh of storage solutions and 2000 km of hydrogen infrastructure (Hydrogen Insight, 2024-c). The Netherlands is also making great progress in green hydrogen production. Groenvermogen NL’s new project, *HyPRO*, is the largest green hydrogen research and development project in the Netherlands to date and focuses on improving electrolysis technology to reduce the cost and increase the production of green hydrogen (Hydrogen Central, 2024). As early as 2020, when the *National Hydrogen Strategy* was published, France aimed to become a leader in green hydrogen, with the ambitious goal of creating an installed electrolyser capacity of 6.5 GW by 2030, capable of producing 680,000 tonnes of renewable hydrogen every year (France Hydrogène, 2023). In 2022, as part of the *Important Project of Common European Interest*, the European Commission selected 15 French initiatives, among them: the Belfort electrolyser factory (with McPhy), the hydrogen production plant in Dunkirk (with Air Liquide) and the research project and H2 mobility development in Flins-sur-Seine (Hyvia – Renault Group and Plug Power) (H2 Energy News, 2022). The Spanish energy company Enagás is also part of the *European Commission’s Projects of Common Interest*, which estimates a renewable hydrogen production of approximately 2.5 million tons per year in 2030. The Spanish infrastructure projects will be connected to the future H2Med corridor, through which Enagás aspires to transform

the Iberian Peninsula into Europe’s main hydrogen hub. This corridor also includes the section between Celorico da Beira in Portugal and Zamora (CelZa) and the maritime connection between Barcelona and Marseille (BarMar). This pipeline will be essential for Spain to be able to export its energy surpluses, thereby helping to achieve Europe’s goal of producing around 10 million tonnes a year of the 20 million tonnes expected to be consumed by 2030 (Invest in Spain, 2024).

The hydrogen consumption and supply variables are also high for cluster 1 compared to cluster 2. The consumption level of countries in cluster 1 is also high, similar to the production level. Germany (21%), the Netherlands (12%), and Spain (7%) account for almost 50% of Europe’s combined hydrogen demand (4.12 Mt/year). In contrast, most European countries show relatively modest hydrogen consumption – less than 10% of each country’s total hydrogen demand (European Hydrogen Observatory, 2023, p. 44). The similar level of the two variables indicates that for each country, regardless of the cluster, the current domestic production fully covers domestic demand/consumption.

The *k-means clustering* algorithm method indicates the optimal number of clusters based on ANOVA testing. *Table 2* shows the distances between the clusters and demonstrates that it is the hydrogen-related variables that discriminate between the two groups of countries. Thus, the larger the distance, the more different the clusters are.

Table 2: ANOVA testing
(authors’ calculations and representations in Tibco Statistica)

	Between	df	Within	df	F	p value
GRB	2.016	1	23.984	25	2.101	0.160
REN	1.056	1	24.944	25	1.059	0.313
GES	0.865	1	25.135	25	0.861	0.362
H2IP	18.768	1	7.232	25	64.872	0.000
H2PP	10.625	1	15.375	25	17.277	0.000
H2TC	17.122	1	8.878	25	48.216	0.000
H2TS	17.122	1	8.878	25	48.216	0.000

The hydrogen infrastructure projects (H2IP) variable shows greater heterogeneity between clusters compared to the hydrogen production projects (H2PP) variable. We can associate these results with consortium projects and initiatives that focus on creating hydrogen supply corridors, which increases their importance

at the consortium level and less for each individual country. Also, when we refer to hydrogen infrastructure, we consider distribution and storage infrastructure. Germany, for example, already has a network of over 1,800 kilometres of converted and newly built hydrogen pipelines and is working on developing a central hydrogen network by 2028 (The Federal Government, 2024). Thus, the results coincide with the conclusions of the study by Vadaszi et al. (2023), who found that hydrogen can be transported through the natural gas system and stored in underground storages, but it must be considered that the implementation method is different from country to country, depending on the existing infrastructure, the available legal framework, and specific geological conditions. Conversely, within the cluster, the variable of production projects has a much higher relevance, which may suggest that they have become increasingly interested in starting green hydrogen production projects. It is also supported by the ANOVA results regarding GRB, REN and GES at the intra cluster level. In addition, some countries such as Spain benefit from favourable climatic conditions for the generation of renewable energy (solar, wind etc.) to support the production of green hydrogen.

Figure 3 shows the result of the two-way joining clustering, in the form of a heatmap of countries according to the selected variables. Markings with yellow, orange and red show a better positioning of the countries on the respective variables, except for GES, where the better positioning is given by the colours in the green spectrum. Regarding the GRB variable, in 2022 Sweden, Slovakia and Hungary topped the ranking in terms of green bond market, supporting environmental protection projects. Our results are also confirmed by the analysis of the European Environment Agency (2023). Some countries, like Sweden, have been active in the green bond market for several years. In 2013, Gothenburg, from Sweden, became the first city in the world to issue green bonds (SEK 500 million). The proceeds from issued green bonds are used to finance climate change projects that promote the transition to green energy (United Nations, 2023). But the increased interest in financial instruments designed to finance climate change projects has also been fuelled by the war in Ukraine. Although in the short term the war created imbalances in financial markets, in the long term it accelerated the transition to clean energy sources and energy independence, prompting governments and corporations to invest more in renewable energy. In terms of hydrogen consumption and supply, Germany, Netherlands, and Poland remain the main players on the market, results also confirmed by the European Hydrogen Observatory report (2023). Germany, France, and Netherlands take the main places in terms of hydrogen infrastructure projects, and Germany, France and Spain stand out for production projects.

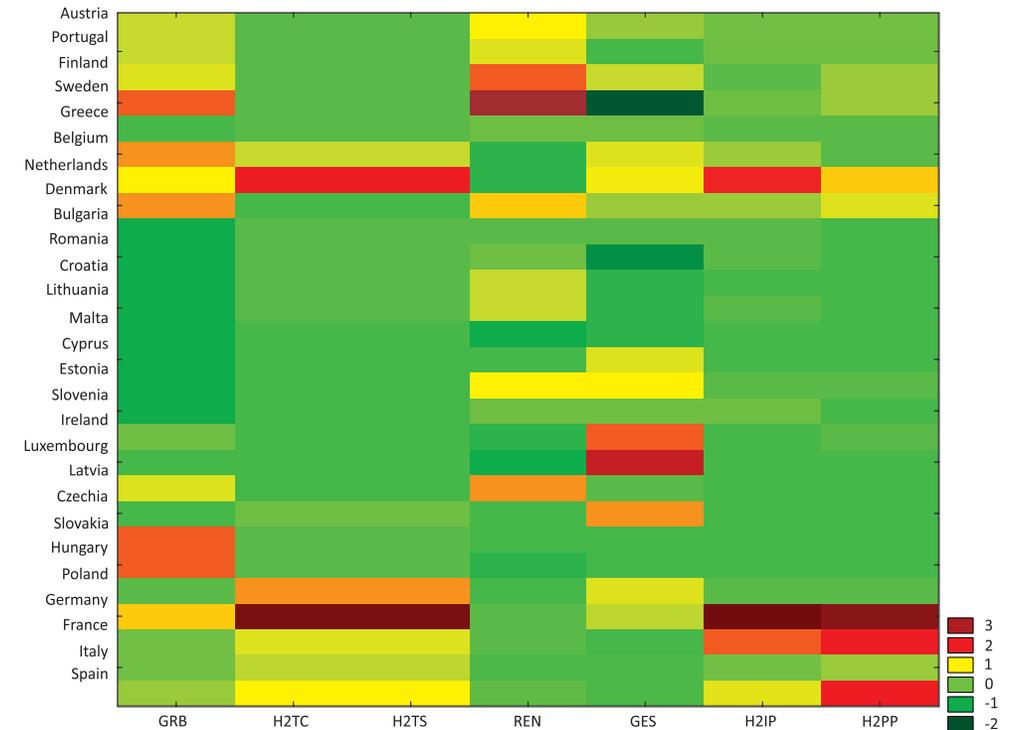


Figure 3: Two-way joining clustering – grouping map (authors' calculations and representations in Tibco Statistica)

CONCLUSIONS

Our study applied clustering methods to examine similarities and differences among the EU-27 countries in hydrogen development, considering the armed conflict in Ukraine.

Germany, Netherlands, Spain, and France remain the countries with the most significant development in terms of both renewable energy resources substantial investments, and hydrogen production capacity. When we consider the share of renewable energy resources and relating it to hydrogen production, we notice that in these countries, natural gas reforming or coal gasification remains the most used method compared to energy from renewable sources. It may also be due to the local distribution of resources, as demonstrated by Ji and Wang (2021). It is also easy to understand that the electrolysis method is the most expensive of all the other methods due to the high consumption of renewable energy used, but it must continue to evolve and improve to achieve low costs and no GHG (Arcos, Santos, 2023).

In terms of reducing carbon dioxide emissions, our results show that EU-27 countries have aligned with climate neutrality goals and made significant progress towards it, which is also reflected in the increased interest of member state governments and private entities for the issue of green bonds. Although the war created short-term imbalances in financial markets, in the long term it accelerated the transition to clean energy sources and energy independence, prompting governments and corporations to invest more in renewable energy.

Germany, the Netherlands, and Poland are the main players in the market in terms of hydrogen consumption and supply, but the similar level between the two variables for all countries analysed indicates that domestic production fully covers domestic demand/consumption.

Hydrogen infrastructure projects have a greater contribution at the level of country groups, which can be associated with consortium projects and initiatives focusing on creating hydrogen supply corridors, thus increasing their importance at the consortium level and less for each country individually. Also, some countries such as Germany already have distribution and storage infrastructure, including networks built from converted gas pipelines. It complements the results of the study by Vadaszi et al. (2023), which demonstrates that hydrogen can be transported through the natural gas system and stored in underground storage, but it must be considered that the method of implementation differs from country to country, depending on the existing infrastructure, the available legal framework, and specific geological conditions. Conversely, hydrogen production projects are of much greater interest for each country individually, which is also reflected in the reduction of carbon dioxide emissions, as well as the increased interest of member state governments and private entities issuing green bonds. Moreover, some countries such as Spain benefit from favourable climatic conditions for the generation of renewable energy (solar, wind etc.) to support the production of green hydrogen.

The level of interest in projects aimed at the transition to renewable energy is increasing more and more for EU governments, as well as for actors from the private sector. Although expensive, green hydrogen remains the alternative for eliminating dependence on Russian fossil fuels, but also for ensuring energy security from renewable sources, contributing to the goal of climate neutrality. Massive investments and grants for the development of green hydrogen production, infrastructure, distribution, and storage projects demonstrate its importance in meeting current and future energy security challenges.

European states must continue to develop a more resilient and sustainable energy system, considering the geopolitical impact of regional conflicts on energy

security. Thus, the creation of a clear and stable regulatory framework helps to attract investment in green hydrogen and renewable energy, as well as fiscal incentives and subsidies to improve efficiency, investment in distribution networks and storage facilities, and to reduce the costs of green hydrogen technologies.

Our study is limited by the lack of data availability, especially for green hydrogen, given the embryonic stage of the production technology. However, many future research topics remain. Beyond the topics related to hydrogen production, cost, and distribution and storage infrastructure, a first topic of interest could be the expansion of hydrogen in military technologies, but also as an energy resource, given the current context of the conflict in Ukraine. Moreover, it is also necessary to study in detail the transformation of Ukraine into an energy hub, also for hydrogen production, taking into account its renewable resources and infrastructure.

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