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Regional Disparities and Strategic Implications of Hydrogen Production in 27 European Countries

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Abstract: This study examines hydrogen production across 27 European countries, highlighting disparities due to varying energy policies and industrial capacities. Germany leads with 109 plants, followed by Poland, France, Italy, and the UK. Mid-range contributors like the Netherlands, Spain, Sweden, and Belgium also show substantial investments. Countries like Finland, Norway, Austria, and Denmark, known for their renewable energy policies, have fewer plants, while Estonia, Iceland, Ireland, Lithuania, and Slovenia are just beginning to develop hydrogen capacities. The analysis also reveals that a significant portion of the overall hydrogen production capacity in these countries remains underutilized, with an estimated 40% of existing infrastructure not operating at full potential. Many countries underutilize their production capacities due to infrastructural and operational challenges. Addressing these issues could enhance output, supporting Europe's energy transition goals. The study underscores the potential of hydrogen as a sustainable energy source in Europe and the need for continued investment, technological advancements, supportive policies, and international collaboration to realize this potential.

Keywords: hydrogen; industrial production; machine learning; k-means; silhouette method; Europe

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1. Introduction

Hydrogen production plays a strategic role in the European Union (EU)'s transition towards cleaner and more sustainable energy sources. As the world grapples with the urgent need to reduce greenhouse gas (GHG) emissions and mitigate climate change, hydrogen has emerged as a crucial element in the energy mix, offering a versatile and clean alternative to fossil fuels. The European Green Deal, which aims to make Europe the first climate-neutral continent by 2050, underscores the importance of hydrogen in achieving these ambitious goals. By promoting hydrogen production, the EU seeks to decarbonize various sectors, such as industry, transport, and energy, aiming to enhance energy security and create new economic opportunities.

The strategic significance of hydrogen production for European countries is multifaceted. Firstly, hydrogen can be produced from a variety of sources, including renewable energy, natural gas, and nuclear power, providing flexibility in the energy supply. Green hydrogen, produced through water electrolysis using renewable electricity, is particularly promising as it generates zero emissions. This aligns perfectly with the EU's objectives of reducing dependency on fossil fuels and lowering carbon emissions. Countries with abundant renewable energy resources, such as wind, solar, and hydroelectric power, are in a favourable position to lead the production of green hydrogen, thereby reinforcing their renewable energy strategies and contributing to the overall energy transition. Secondly, hydrogen production supports the diversification of energy sources, reducing reliance on imported fossil fuels and enhancing energy security. The geopolitical landscape of energy supply is complex, with many European countries dependent on energy imports from politically unstable regions. By investing in domestic hydrogen production capabilities, European nations can mitigate the risks associated with energy import dependency, ensure a stable and resilient energy supply, and strengthen their energy sovereignty. Moreover, hydrogen offers substantial economic benefits. The development of a robust hydrogen economy has the potential to create jobs, stimulate technological innovation, and drive industrial growth. As countries invest in hydrogen infrastructure, research and development (R&D), and production facilities, new employment opportunities emerge across various sectors, including engineering, manufacturing, and maintenance. The advancement of hydrogen technologies also positions European companies as leaders in a growing global market, providing competitive advantages and fostering economic growth. The integration of hydrogen into the energy system also facilitates the decarbonization of hard-to-abate sectors. Heavy industries, such as steel and cement production, as well as long-haul transportation, including aviation and shipping, face significant challenges in reducing carbon emissions through electrification alone. Hydrogen provides a viable solution for these sectors, enabling them to transition to cleaner energy sources without compromising operational efficiency. This is particularly important for European countries with strong industrial bases seeking to maintain their economic competitiveness while adhering to stringent environmental regulations. Furthermore, the EU's hydrogen strategy emphasizes the importance of creating a hydrogen market with a robust infrastructure and cross-border cooperation. The development of a trans-European hydrogen network, encompassing production sites, storage facilities, and distribution networks, will facilitate the seamless integration of hydrogen into the energy system. This collaborative approach encourages member states to align their policies, share best practices, and invest in joint projects, thereby accelerating the deployment of hydrogen technologies and maximizing the benefits across the continent. Therefore, hydrogen production is strategically vital for European countries as it supports the transition to a sustainable energy system, enhances energy security, drives economic growth, and enables the decarbonization of challenging sectors. The EU's commitment to hydrogen as a key element of its climate and energy policies underscores the potential of hydrogen to transform the energy landscape, positioning Europe at the forefront of global efforts to combat climate change and achieve a greener future.

This paper presents a unique contribution to the literature on hydrogen production by offering a comprehensive analysis of hydrogen production across 27 European countries—a subject of growing importance in the context of global energy transitions. Unlike previous studies that have predominantly focused on the technical aspects of hydrogen production or individual countries, this research adopts a broader, comparative perspective, highlighting significant regional disparities in production capacities and infrastructure. By incorporating an extensive data-driven analysis, the study uncovers the varying degrees of investment, policy support, and industrial capacities among the countries studied, providing a nuanced understanding of the factors influencing hydrogen production across Europe.

The use of ML techniques, specifically the k-means clustering algorithm and the silhouette method, further distinguishes this paper from existing research. These methods allow for a sophisticated classification of countries based on their hydrogen production profiles, revealing patterns and groupings that might not be apparent through traditional analytical approaches. The paper's focus on the economic policy implications of these disparities adds an additional layer of originality, as it connects the technical aspects of hydrogen production with broader economic and strategic considerations. Combining energy policy, industrial economics, and advanced data analysis, this interdisciplinary approach positions the paper as a novel contribution to the ongoing discourse on sustainable energy transition in Europe.

The theoretical framework underpinning this study is grounded in the principles of energy economics, regional development, and industrial policy, providing a systematic exploration of hydrogen production as a critical component of the sustainable energy transition. At the core of the analysis is the theory of comparative advantage, which explains how different regions or countries specialize in certain industries based on their unique resource endowments and capabilities. This paper applies this theory to the context of hydrogen production, arguing that regional disparities in hydrogen infrastructure, technological innovation, and policy support can be understood through the lens of comparative advantage. Countries with abundant renewable energy resources, such as wind or solar power, may have a natural advantage in hydrogen production, which in turn influences their strategic positioning in the emerging hydrogen economy.

Furthermore, the research engages with the concept of path dependency, which highlights how historical investment patterns and industrial development trajectories shape current and future capabilities. In this context, countries that have historically invested in renewable energy infrastructure or have industrial solid bases are likely to continue leading in hydrogen production. The paper also integrates the theory of clusters, drawing on the work of Michael Porter, to explain how geographical proximity and collaboration among firms, research institutions, and governments can create competitive advantages in hydrogen production. This clustering effect enhances innovation and leads to the creation of specialized supply chains and a skilled workforce, further entrenching regional disparities. Through this theoretical discussion, the paper offers a robust framework for understanding the complex dynamics of hydrogen production in Europe.

The article continues as follows: Section 2 presents the data, Section 3 analyses the relevant variables, Section 4 presents the correlation analysis, Section 5 gives the results of a cluster analysis through the k-means algorithm, Section 6 discusses the economic policy consequences of the production of hydrogen in Europe, and Section 7 concludes.

2. Data

The variables indicated in Table 1 were used in the analysis.

Table 1. Variables' definitions and sources.

Variable	Definition	Source
Hydrogen Production Plants	The total number of hydrogen facilities or plants represents the summation of all operational units for hydrogen production. This includes a wide variety of plants, ranging from large-scale industrial production sites to smaller specialized units and integrated energy complexes where hydrogen is produced through various methods such as electrolysis, steam methane reforming, or biomass gasification [1,2].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/
Hydrogen Production Capacity	The total potential output capacity of all hydrogen production facilities operating within a specific timeframe, such as annually or monthly, represents the maximum amount of hydrogen that can be produced across all plants during that period. This metric defines the upper limit of hydrogen production, assuming each plant operates at peak efficiency without any interruptions or faults. To determine this, the installed capacity of each facility is considered, including the technology employed (such as electrolysis and steam methane reforming) and the scale of operations [3,4].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/
Hydrogen Production Output	The actual quantity of hydrogen produced within a given period refers to the real output generated by all hydrogen production facilities over a specific timeframe, such as a month, quarter, or year. Unlike production capacity, which represents potential output, this measure accounts for real-life operating conditions, including factors like maintenance, downtime, inefficiencies, and demand fluctuations. The actual production volume is a key indicator of how effectively production plants operate relative to their capacity [5–7].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/

Table 1. *Cont.*

Variable	Definition	Source
Difference between Hydrogen Production Capacity and Output	The gap between theoretical production capacity and actual output reflects the difference between what hydrogen production plants can theoretically produce if fully utilized and what they produce in reality. This difference arises from factors like maintenance schedules, operational inefficiencies, unexpected downtimes, and market demand constraints. The gap may also suggest underutilization of resources, indicating that plants are not running at their full potential [8,9].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/
% Difference between Hydrogen Production Capacity and Output	The percentage of production capacity that is not utilized represents the portion of a facility's total possible output that remains unproduced within a given period. It is determined by comparing the difference between the theoretical maximum capacity and the actual production output relative to the total capacity [10–12].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/
Hydrogen Production Output per Plant	The average quantity of hydrogen produced by each plant within a given period, such as a day, month, or year, is determined by dividing the total hydrogen production by the number of plants. This metric allows for meaningful comparisons between the performance of individual plants and helps assess overall production efficiency across multiple facilities. Differences in average production can highlight variations in plant size, technology, operational practices, and efficiency [13–15].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/
Residual Capacity per Plant	The remaining capacity per plant after accounting for actual production refers to the spare capacity within each facility once the current output is subtracted from its maximum capacity. This metric shows how much more hydrogen a plant could produce if fully utilized. It reflects factors like operational efficiency, equipment reliability, and demand alignment. A higher remaining capacity indicates that a plant is underutilized, possibly due to scheduled maintenance, unplanned downtime, or market-driven factors like low demand [16,17].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/
Hydrogen Production per Plant	The average hydrogen production per facility refers to the typical output of any given plant over a specific period, such as daily, monthly, or annually. This is calculated by dividing the total hydrogen produced by the number of operational facilities. This metric is commonly used to benchmark and compare the performance of different plants in terms of productivity, efficiency, and operational practices [18,19].	European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/

3. The Hydrogen Production Plants in Europe

Hydrogen production is a key component in the transition towards cleaner and more sustainable energy sources. This study analyses the number of hydrogen production plants in various European countries, highlighting significant differences in distribution and production capacity. The analysis includes 27 countries, showcasing a wide range in the number of plants, which reflects different energy policies, industrial capacities, and national strategies for hydrogen production (see Figure 1). The analysis begins by examining the total number of hydrogen production plants per country. Germany emerges as the undisputed leader, with a total of 109 plants. This indicates a strong commitment to hydrogen production, likely due to its leadership in the manufacturing industry and its push to reduce carbon emissions. Poland follows with 148 plants—a surprising number that might reflect a growing investment in renewable energy technologies and a response to domestic energy needs. Other countries with a significant number of plants include France (50), the United Kingdom (UK) (44), and Italy (41). These countries have advanced energy industries and are likely investing in hydrogen as part of their strategies to reduce emissions and improve energy security. The next group of countries has a moderate number of plants, including the Netherlands (33), Spain (33), Sweden (21), and Belgium (16). These countries are also investing in hydrogen, but on a smaller scale compared to leaders like Germany and Poland [20,21]. The presence of a considerable number of plants in these countries still indicates a significant commitment to energy transition and the adoption of low-impact environmental technologies. Several countries have a more limited number of hydrogen production plants: Finland (15), Norway (11), Austria (10), Switzerland (10), and Denmark (9). These countries, despite having fewer plants, are often known for their advanced policies on renewable energy and sustainability. For example, Finland and Norway have a long history of using renewable energy, and hydrogen production could represent a natural extension of these policies. Finally, there are countries with very few hydrogen production plants. Estonia, Iceland, Ireland, Lithuania, and Slovenia, each with only one or two plants, represent the lower end of the spectrum. These countries might be in the early stages of developing their hydrogen production capacities or may have a lower domestic demand for this type of energy. The distribution of the number of hydrogen production plants in Europe is clearly uneven. This reflects a variety of factors, including differences in government policies, economic capacities, energy needs, and industrial priorities. For instance, Germany has heavily invested in energy transition and views hydrogen as a key element in achieving its decarbonization goals. Poland, with a high number of plants, might be looking to diversify its energy mix and reduce its dependence on traditional energy sources like coal. Countries like France and the UK are using hydrogen to complement other forms of renewable energy, while the Netherlands and Spain might see hydrogen as a solution to improve energy independence and reduce emissions. The variation in the number of plants among countries also highlights the challenges and opportunities in hydrogen production in Europe. Countries with a limited number of plants may face significant challenges in terms of initial investments, infrastructure development, and domestic demand. However, these countries also have the opportunity to learn from the experiences of industry leaders and adopt more advanced and efficient technologies. On the other hand, countries with a large number of plants face the challenge of maintaining the operational efficiency and sustainability of their plants. Germany and Poland, for example, need to ensure that their hydrogen production is competitive in the global market and sustainable in the long term. Looking to the future, hydrogen production in Europe is set to grow, with many countries likely to increase their number of plants. The EU is pushing for greater adoption of renewable energies, and hydrogen is seen as a key component of this strategy. Government initiatives, funding (for R&D), and partnerships between the public and private sectors will be crucial to expand hydrogen production capacity. In conclusion, the analysis of the number of hydrogen production plants in European countries reveals significant variation that reflects different national strategies and levels of investment in hydrogen technology. While some countries are undisputed leaders, others are just beginning their journey towards hydrogen adoption. The challenges are numerous, but so are the opportunities for growth and development in this emerging sector. Continued collaboration and support at the European level will be essential to realize the full potential of hydrogen as a clean and sustainable energy source [22–24].

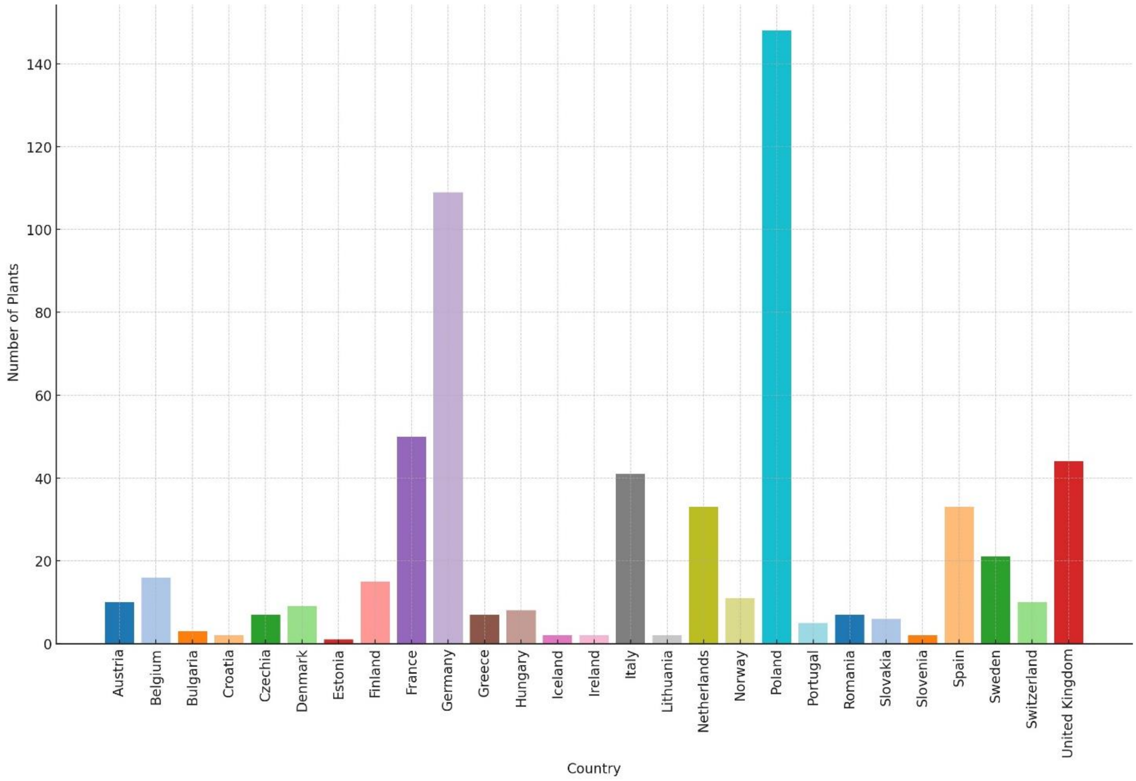

Figure 1. Number of hydrogen production plants by country (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

3.1. Hydrogen Production Capacity in Europe

The landscape of hydrogen production capacity in Europe reflects a diverse range of contributions from different countries, highlighting both the current capabilities and the potential for growth within this critical sector. The data provided outline the annual hydrogen production capacity in tonnes for various European countries. This analysis will delve into the specifics of these capacities, discussing the implications for energy policy, economic development, and the broader transition towards a sustainable energy future. The production capacities vary significantly across Europe, from Estonia's modest 24.79 tonnes per year to Germany's substantial 2,148,947.98 tonnes per year (see Figure 2). This wide range illustrates the varying levels of industrial development, resource availability, and investment in hydrogen technology [25]. The countries that have highlighted significant trends in hydrogen production are the following:

- Germany: Leading the pack with a production capacity of over 2.1 million tonnes per year, Germany's dominant position is indicative of its robust industrial base and a strong commitment to renewable energy and technological innovation. Germany's significant capacity is supported by its advanced infrastructure and substantial investments in R&D.
- France: With a production capacity of 822,712.19 tonnes per year, France is another major player in the European hydrogen market. France's capacity is buoyed by its strong nuclear industry, which provides a substantial amount of low-carbon electricity, an essential input for hydrogen production through electrolysis.
- Italy and the Netherlands: Both countries exhibit strong production capacities, with Italy at 829,240.25 tonnes per year and the Netherlands at 1,424,258.52 tonnes per year. These highlight their significant industrial activities and strategic initiatives in the energy sector. The Netherlands, in particular, benefits from its extensive natural gas infrastructure, which can be repurposed for hydrogen.

- United Kingdom: The UK's production capacity is 783,673.96 tonnes per year. The country has been making concerted efforts to boost its hydrogen economy as part of its broader decarbonization strategy. Investments in hydrogen production, particularly in green hydrogen, are central to the UK's goal of achieving net-zero emissions by 2050.
- Poland: With a capacity of 1,104,771.64 tonnes per year, Poland's hydrogen production is noteworthy. The country's reliance on coal and its significant industrial base provides a context for its hydrogen production capabilities. Poland is gradually shifting towards greener technologies, leveraging its existing industrial capacity.

Several countries fall into the medium-scale production category, with capacities ranging from 200,000 to 500,000 tonnes per year. These include Greece (359,741.44), Hungary (257,620.11), Lithuania (266,934.46), Norway (287,882.26), and Sweden (242,345.79). Additionally, Spain, with a production capacity of 797,029.03 tonnes per year, has a significant production scale. These countries have well-established industrial bases and are increasingly focusing on integrating hydrogen into their energy systems. For instance, Belgium's strategic location and industrial sector make it a key player in the hydrogen market, while Norway's abundant renewable energy resources position is good for green hydrogen production. Similarly, Greece and Hungary are leveraging their industrial infrastructures to expand their hydrogen capabilities, whereas Lithuania and Sweden are exploring ways to enhance their energy mix through hydrogen. Spain's robust production capacity underscores its commitment to diversifying its energy portfolio and reducing carbon emissions. Collectively, these nations are not only enhancing their energy security but also contributing significantly to the broader European hydrogen economy by adopting innovative approaches and technologies in hydrogen production [26–28].

On the other hand, several countries have relatively low hydrogen production capacities, often below 100,000 tonnes per year. These include Denmark (31,361.16), Estonia (24.79), Finland (199,123.21), Iceland (1107.4), Ireland (9872.81), Portugal (110,876.37), Romania (247,355.24), Slovakia (221,860.37), Slovenia (2419), and Switzerland (24,727.68). These countries, while currently having lower capacities, are actively focusing on expanding their hydrogen production capabilities. Denmark, for example, is leveraging its strong wind energy sector to boost green hydrogen production, positioning itself as a future leader in renewable hydrogen. Similarly, Finland and Iceland are exploring ways to utilize their abundant renewable energy resources, such as hydroelectric and geothermal power, for hydrogen production. Portugal and Ireland are also making strides in incorporating hydrogen into their energy strategies, emphasizing the use of green hydrogen to meet sustainability goals. Despite their smaller current outputs, these countries recognize the strategic importance of hydrogen and are investing in the necessary infrastructure and technology to enhance their production capacities. By doing so, they are not only aiming to increase their domestic energy security but also to contribute to the broader European hydrogen network, ensuring a diversified and resilient energy future [29,30].

The disparities in hydrogen production capacities across Europe highlight several key points:

- Investment and infrastructure: Countries with higher production capacities generally invest more in infrastructure and technology. Germany, France, and the Netherlands serve as prime examples where substantial investment in hydrogen infrastructure and supportive policies have driven high production capacities. These nations have established robust frameworks for both the production and distribution of hydrogen, ensuring that they are well-positioned to capitalize on future advancements and market demands.
- Renewable energy integration: The transition towards green hydrogen is crucial for meeting climate targets. Countries with abundant renewable energy resources, such as Norway, Denmark, and Iceland, are well-positioned to become leaders in green hydrogen production. This integration is vital for reducing the carbon footprint of hydrogen production and leveraging renewable sources, such as wind, hydroelectric, and

geothermal power. These countries are setting benchmarks for sustainable hydrogen production, demonstrating the feasibility and benefits of a green hydrogen economy.

- Economic opportunities: Hydrogen production offers significant economic opportunities. Countries can enhance their energy security, create jobs, and drive economic growth by investing in hydrogen technologies. For instance, the UK's focus on hydrogen aligns with its broader economic and environmental goals. By fostering a strong hydrogen sector, countries can stimulate local economies, spur technological innovation, and ensure energy resilience. This transition not only supports environmental sustainability but also paves the way for economic rejuvenation through new industries and job creation.
- Policy and regulation: Effective policies and regulatory frameworks are essential for fostering hydrogen production. The EU hydrogen strategy and national policies are crucial in shaping the hydrogen economy. Countries with supportive policies are likely to see faster growth in their hydrogen sectors. Policies that incentivize green hydrogen production, streamline regulatory processes, and support infrastructure development are critical for accelerating the adoption and integration of hydrogen technologies.
- Collaboration and innovation: The development of hydrogen technology benefits from international collaboration and innovation. Joint ventures, cross-border projects, and partnerships between industry and academia are crucial for advancing hydrogen technologies and reducing costs. Collaborative efforts enhance knowledge sharing, foster technological breakthroughs, and build a cohesive framework for scaling hydrogen production. These partnerships are pivotal in overcoming technical and economic barriers, ensuring the hydrogen economy's robust and sustainable growth.

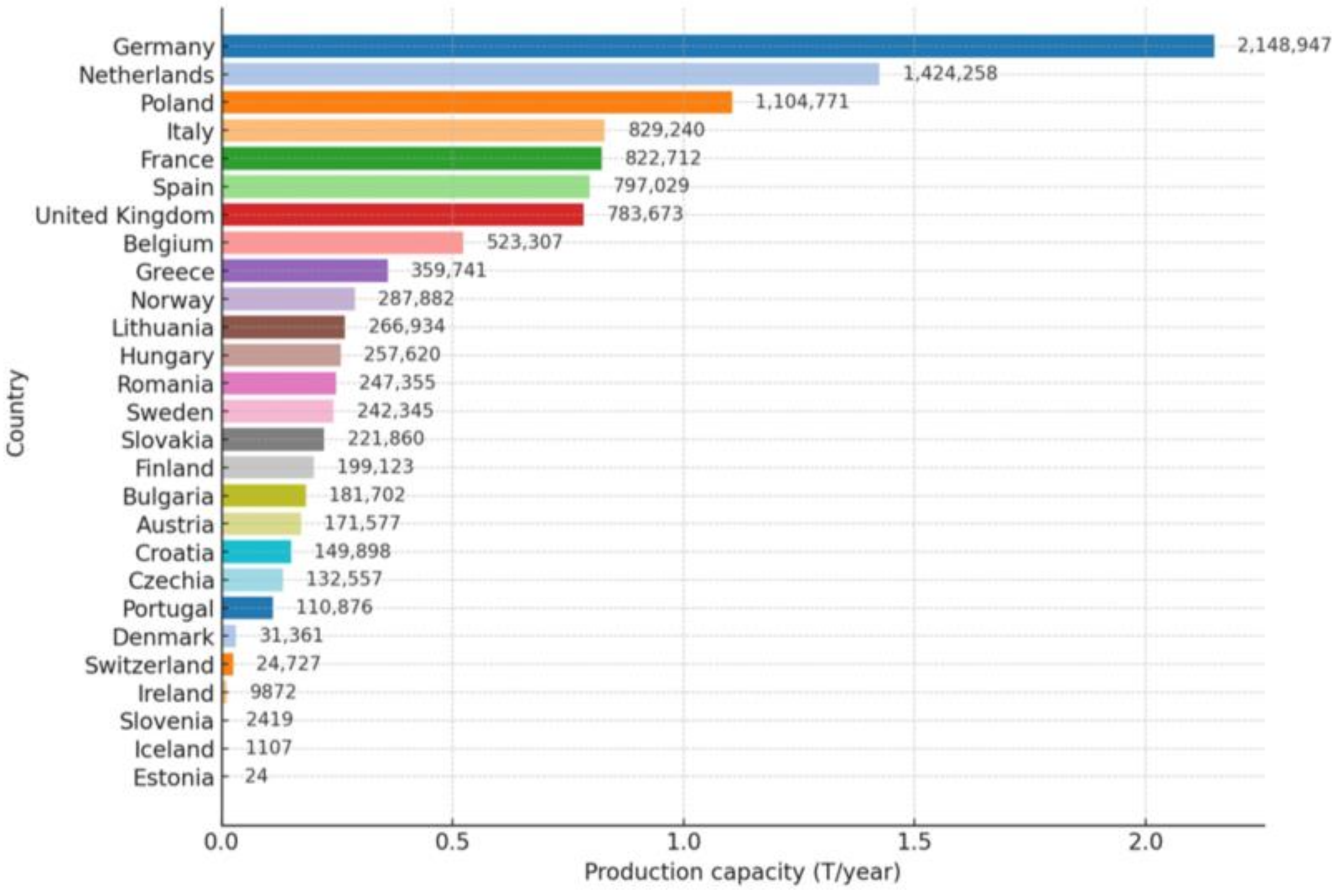

Figure 2. Hydrogen production capacity by country (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

The future of hydrogen production in Europe looks promising, with several trends likely to shape its trajectory [31–33]. The focus on green hydrogen, produced using renewable energy, will intensify as investments in electrolysis technology and renewable energy capacity drive the scale-up of green hydrogen production. This will be instrumental in meeting decarbonization targets and providing a sustainable energy alternative for various sectors, including transportation and industry. Continued R&D will lead to technological advancements that improve efficiency and reduce hydrogen production costs. Innovations in electrolysis, carbon capture and storage, and hydrogen storage are particularly important, making hydrogen a more viable and competitive energy source and facilitating its broader adoption. The hydrogen market is set to expand, with increased demand from various sectors, including transportation, industry, and power generation, necessitating the development of robust supply chains and distribution networks. This expansion will require significant investment in infrastructure, logistics, and end-user applications, ensuring a seamless integration of hydrogen into the energy ecosystem. Strong policy support at both the national and EU levels will be critical for driving the hydrogen economy. Incentives for green hydrogen production, carbon pricing, and investment in hydrogen infrastructure will play key roles, along with policies that support R&D, provide financial incentives, and establish clear regulatory frameworks to accelerate the hydrogen sector's growth. As production capacities increase, international trade in hydrogen is likely to grow, positioning Europe as both a major producer and importer of hydrogen, leveraging its technological expertise and strategic partnerships. The development of international hydrogen markets will enhance global energy security, diversify energy sources, and foster international cooperation on energy and environmental issues. In conclusion, the hydrogen production capacity in Europe is characterized by significant variation across countries, reflecting different levels of industrial development, resource availability, and policy support. Countries like Germany, France, and the Netherlands lead the way with substantial capacities while emerging players are making strides to enhance their production capabilities. The future of hydrogen in Europe will depend on continued investment, technological innovation, supportive policies, and international collaboration, paving the way for a sustainable and prosperous hydrogen economy. The concerted efforts across various domains will ensure that hydrogen plays a pivotal role in the transition to a low-carbon energy future, providing environmental, economic, and social benefits [34–36].

3.2. Analysis of Hydrogen Production Output by Country

The hydrogen production output data for various countries provide insight into the landscape of hydrogen production across Europe. The data indicate the annual hydrogen production in tonnes for each country, revealing significant variations in output levels (see Figure 3). It is possible to identify the following groupings among the countries considered:

- Leading producers: Germany, France, and the Netherlands are the leading hydrogen producers in Europe. With an output of 1,743,512.41 tonnes per year, Germany significantly outpaces other countries, highlighting its advanced industrial capacity and substantial investment in hydrogen technology. France follows with 552,822.84 tonnes per year, while the Netherlands produces 975,233.67. These countries benefit from robust infrastructure, supportive policies, and strong industrial bases.
- Major contributors: Italy, Poland, Spain, and the UK are also major contributors to hydrogen production. Italy produces 607,913.12 tonnes per year, reflecting its significant industrial activities and strategic focus on hydrogen as part of its energy transition. Poland's output is 784,637.12 tonnes per year, underscoring its substantial industrial capacity and reliance on hydrogen for energy diversification. Spain and the UK produce 614,470.56 and 569,135.5, respectively, highlighting their commitment to integrating hydrogen into their energy systems.

- Medium-scale producers: Countries like Belgium, Greece, and Hungary fall into the medium-scale production category, with outputs ranging from 188,005.18 tonnes per year in Hungary to 411,229.64 tonnes per year in Belgium. These countries have well-established industrial bases and focus on expanding their hydrogen production capabilities.
- Emerging players: Several countries have relatively lower hydrogen production outputs but are actively working to enhance their capacities. These include Austria (115,472.34 tonnes/year), Bulgaria (121,173.05 tonnes/year), Finland (176,435.79 tonnes/year), and Sweden (175,366.87 tonnes/year). These countries are leveraging their renewable energy resources and industrial capacities to boost hydrogen production.
- Small-scale producers: Countries with smaller production outputs include Denmark (24,952.85 tonnes/year), Estonia (16.86 tonnes/year), Iceland (753.02 tonnes/year), Ireland (7864.37 tonnes/year), and Slovenia (1846.5 tonnes/year). These nations are at the early stages of developing their hydrogen production capabilities but have growth potential, particularly through investments in renewable energy sources.

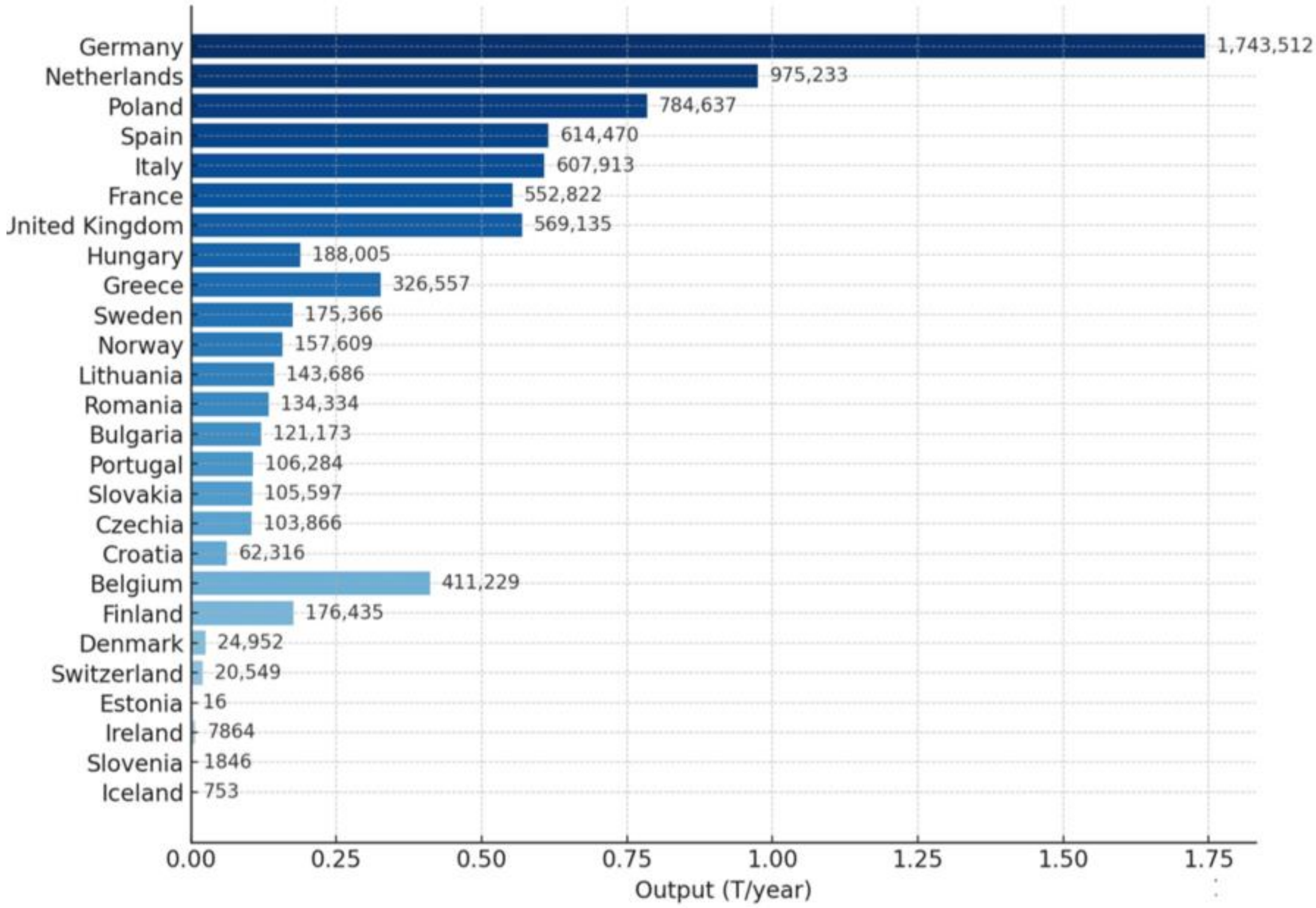

Figure 3. Hydrogen production by country (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

The disparities in hydrogen production outputs across European countries are significant, with Germany's output being particularly notable, reflecting its leading position in the hydrogen market. Countries with larger economies and more developed industrial sectors, like Germany, France, Italy, and the UK, tend to have higher hydrogen production outputs due to substantial industrial activities. Countries with abundant renewable energy resources, like Norway and Finland, are focusing on green hydrogen production to meet climate targets and reduce the carbon footprint of hydrogen production. Supportive policies and substantial investments in hydrogen infrastructure and technology are key drivers of high production outputs, positioning countries with strong governmental support and strategic investments to scale their production capacities. Scaling up hydrogen production in countries with lower outputs will require significant investments in infrastructure and technology, leveraging renewable energy resources, and enhancing industrial capacities. Continued R&D in hydrogen production technologies, such as electrolysis and carbon capture, will be essential for improving efficiency and reducing costs, making hydrogen a more competitive and viable energy source. Strong policy support at both national and EU levels is critical for fostering the growth of the hydrogen economy, with policies that provide incentives for green hydrogen production, streamline regulatory processes, and support infrastructure development. Collaboration between countries and industries will be essential for advancing hydrogen technologies and creating a cohesive European hydrogen market through joint ventures, cross-border projects, and partnerships between industry and academia. The growing demand for hydrogen across various sectors, including transportation, industry, and power generation, will drive market expansion, necessitating the development of robust supply chains and distribution networks for seamless integration into the energy ecosystem. The hydrogen production output data highlight significant variation across European countries, reflecting different levels of industrial development, resource availability, and policy support. Leading producers like Germany, France, and the Netherlands dominate the market with substantial outputs, while emerging players are making strides to enhance their production capabilities. The future of hydrogen production in Europe will depend on continued investment, technological innovation, supportive policies, and international collaboration. By addressing these key areas, Europe can pave the way for a sustainable and prosperous hydrogen economy, contributing to the global transition towards low-carbon energy [37,38].

3.3. Difference between Hydrogen Production Capacity and Output

The data on the difference between hydrogen production capacity and output across various European countries provide significant insights into the efficiency and utilization of hydrogen production facilities. The percentage difference between production capacity and output provides a measure of how well each country is utilizing its potential production capabilities (see Figure 4). Austria shows a 67.3% difference, with an actual output significantly lower than its capacity, indicating room for improving operational efficiency. Belgium, with a 78.58% difference, also highlights a substantial underutilization of its hydrogen production capacity. Estonia, intriguingly, has a negative value, meaning it slightly overproduces relative to its capacity, an anomaly in the dataset. Finland, with an 88.61% difference, indicates significant underperformance, possibly due to operational or infrastructural constraints. France and Germany, despite being leading producers, show differences of 67.2% and 81.13%, respectively, suggesting that even top producers have substantial unused capacity. Greece exhibits a high efficiency with a 90.78% difference, indicating near-optimal utilization of its capacity. Ireland and Italy display differences of 79.66% and 73.31%, respectively, indicating substantial underutilization. The UK, with a 72.62% difference, reflects a substantial gap between its capacity and actual production. Overall, the data indicate that most European countries are significantly underutilizing their hydrogen production capacities. Urgent regulatory changes are needed to address the factors leading to these disparities, such as infrastructure bottlenecks, operational inefficiencies, and regulatory hurdles, which could substantially boost actual hydrogen output, aligning production more closely with capacity and supporting Europe's energy transition goals [39,40].

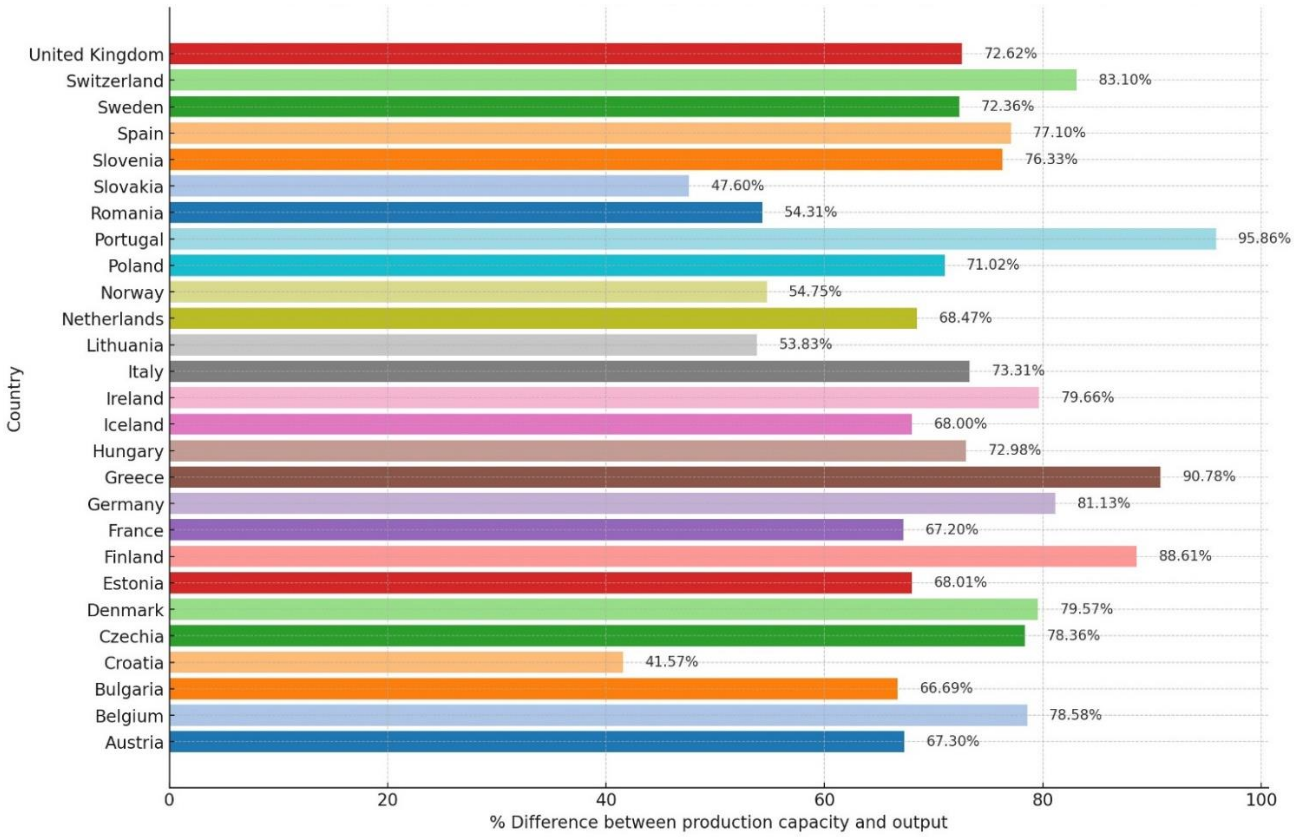

Figure 4. Percentage difference between production capacity and output by country (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

3.4. Hydrogen Production per Plant across European Countries in 2022

The analysis of hydrogen production per plant across various European countries reveals a diverse landscape regarding the efficiency and scale of hydrogen production facilities (see Figure 5). Lithuania stands out with the highest production per plant at 133,467.23 tonnes, indicating highly advanced and efficient operations. Similarly, Bulgaria, Croatia, and Greece exhibit significant production per plant, reflecting robust industrial capabilities. Countries like Belgium, Hungary, and the Netherlands demonstrate moderate production per plant, balancing scale and efficiency. In contrast, Denmark, Estonia, Finland, and Sweden have lower production per plant, suggesting a need for technological upgrades and capacity expansion. Notably, some large economies like Germany, France, and the UK have relatively lower production per plant, potentially indicating a higher number of smaller-scale facilities rather than a few large ones. This highlights different strategic approaches to hydrogen production. Countries with notably low production per plant, such as Estonia, Iceland, and Slovenia, are likely in the early stages of developing their hydrogen infrastructure. The data underscore the potential for growth and optimization, particularly for countries with lower production per plant, through strategic investments in technology and capacity expansion. This emphasizes the importance of tailored investments and the sharing of best practices, inviting the audience to be part of the solution to enhance efficiency and scale across Europe's hydrogen production sector, contributing to greater energy security, economic growth, and sustainability [41–43].

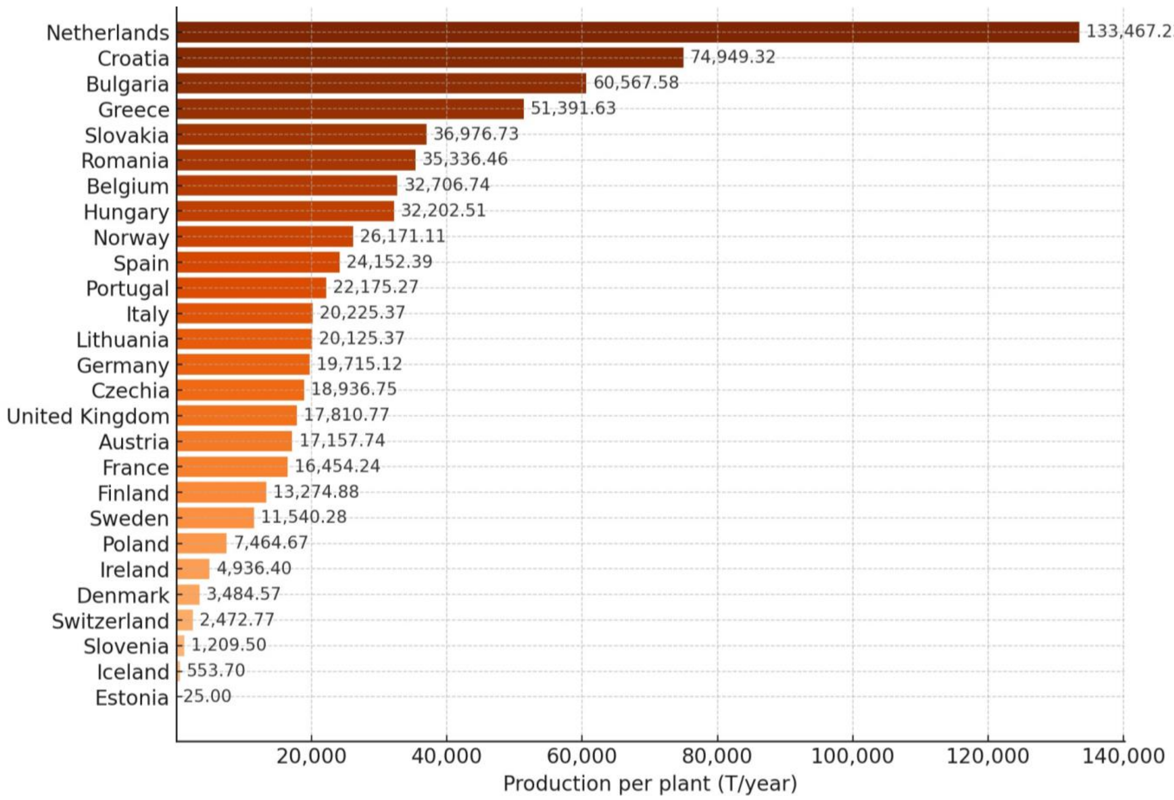

Figure 5. Hydrogen production per plant by country (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

3.5. Hydrogen Production Output per Plant in 2022

The analysis of hydrogen production output per plant across European countries provides insights into each nation's operational efficiency and scale of hydrogen production facilities. The data highlight the variations in average production per plant, which can be influenced by factors such as technological advancement, investment levels, and industrial capacity (see Figure 6). It is possible to identify the following sub-groups:

- High output per plant: Lithuania stands out with the highest output per plant at 71,843.47 tonnes, indicating exceptionally large and efficient production facilities. Similarly, Greece (46,651.07 tonnes) and Bulgaria (40,391.02 tonnes) demonstrate high outputs per plant, reflecting advanced infrastructure and significant investment in hydrogen production technologies.
- Moderate output per plant: Countries like Belgium (25,701.85 tonnes), the Netherlands (29,552.54 tonnes), and Hungary (23,500.65 tonnes) exhibit moderate output per plant. These suggest well-developed facilities that balance efficiency and scale. Croatia (31,158.4 tonnes) also falls into this category, indicating a robust production capacity.
- Lower output per plant: A number of countries have lower hydrogen production outputs per plant, which may be due to smaller-scale facilities or less efficient production processes. For example, Austria (11,547.23 tonnes), France (11,056.46 tonnes), and Germany (15,995.53 tonnes) have lower outputs compared to their overall capacities. This could indicate a larger number of smaller-scale plants rather than fewer, larger ones, reflecting different strategic approaches to hydrogen production.
- Small-scale producers: Countries with notably low outputs per plant, such as Estonia (16.86 tonnes), Iceland (376.51 tonnes), and Slovenia (923.25 tonnes), are likely in the early stages of developing their hydrogen production infrastructure or operating very small-scale facilities. These nations might need to invest significantly in technology and infrastructure to scale up their production capacities.

- Potential for improvement: Several countries show potential for improved hydrogen production efficiency. For instance, Denmark (2772.54 tonnes), Ireland (3932.19 tonnes), and Switzerland (2054.98 tonnes) have relatively low outputs per plant. Investments in advanced technologies and expansion of production facilities could help these countries enhance their hydrogen production efficiency.
- Strategic investments and technological upgrades: The data underscore the need for strategic investments and technological upgrades, especially in countries with lower outputs per plant. Enhancing operational efficiency and scaling up production facilities could significantly boost their hydrogen production capabilities.
- Economic and policy implications: The variations in hydrogen production output per plant also have economic and policy implications. Countries with higher outputs per plant, like Lithuania and Greece, can serve as benchmarks for others, showcasing best practices in efficiency and scale. Conversely, countries with lower outputs ought to focus on policy support, infrastructure development, and technological innovation to improve their production efficiency.

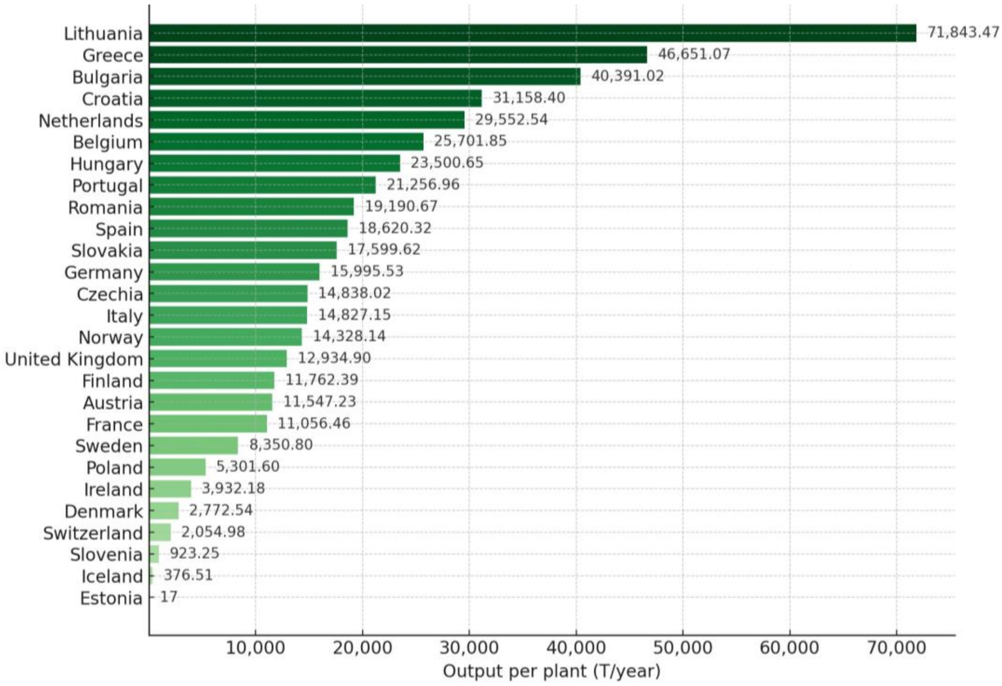

Figure 6. Hydrogen production output per plant by country (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

In summary, the analysis of hydrogen production output per plant across European countries highlights significant disparities in operational efficiency and scale. While some countries like Lithuania, Greece, and Bulgaria demonstrate high efficiency, others have substantial room for improvement. Strategic investments in technology, infrastructure, and operational practices can help bridge these gaps, fostering a more efficient and cohesive hydrogen production ecosystem across Europe. This approach will not only enhance individual countries' energy security and economic growth but also contribute to Europe's overall sustainability and leadership in the global hydrogen economy [44–46].

3.6. Residual Capacity per Plant

The data on hydrogen production residual capacities reveal significant disparities among European countries. Lithuania leads by a substantial margin with a residual capacity of 61,623.76 tonnes per year, followed by Croatia and Bulgaria. In contrast, Western European nations such as Germany, France, and the UK display moderate capacities, ranging from approximately 3700 to 5400 tonnes per year. Scandinavian countries show varied results, with Norway having a notable capacity of 11,842.97 tonnes per year, while Sweden and Denmark have much lower capacities. Southern European countries like Italy and Spain have capacities slightly above 5000 tonnes per year, whereas Portugal's capacity is under 1000 tonnes per year. Estonia, Iceland, and Slovenia have minimal residual capacities. These differences highlight the varying levels of investment and infrastructure development in hydrogen production across Europe, with Eastern European countries generally leading in capacity. The disparities in hydrogen production capacities across European countries are striking and warrant a closer look to understand the underlying factors contributing to these differences.

Lithuania's leading position is particularly noteworthy. This significant capacity can be attributed to the country's strategic investments in hydrogen production infrastructure and technology. Lithuania has been proactive in adopting policies that support the development of renewable energy sources, including hydrogen. The country's focus on transitioning to a green economy has likely played a crucial role in establishing such a high residual capacity for hydrogen production. Croatia's substantial capacity indicates a strong commitment to developing its hydrogen production capabilities. The country has recognized the potential of hydrogen as a key component of its energy strategy, leading to investments in research, development, and infrastructure. Croatia's geographical location and natural resources also provide favourable conditions for hydrogen production, further boosting its capacity. Bulgaria's energy sector has been undergoing significant transformations, with an increasing emphasis on renewable energy sources. The government's support for hydrogen projects and collaborations with international partners have contributed to the development of the necessary infrastructure for hydrogen production. As a result, Bulgaria has been able to achieve a relatively high residual capacity, reflecting its commitment to sustainable energy solutions. Slovakia's capacity can be attributed to its strategic location in Central Europe and its well-developed industrial base. The country has been investing in hydrogen technologies as part of its efforts to diversify its energy mix and reduce GHG emissions. Similarly, Romania's capacity reflects its growing focus on renewable energy and hydrogen production. The country's abundant natural resources, such as water and wind, provide favourable conditions for hydrogen production, contributing to its high residual capacity. In contrast to the high capacities observed in Eastern European countries, Western Europe displays moderate capacities [47,48]. Germany has been a leader in renewable energy initiatives. However, its hydrogen production capacity may appear moderate compared to some Eastern European countries due to the mature state of its renewable energy sector and the diversified nature of its energy sources. Germany's focus on other renewable technologies, such as wind and solar power, might result in relatively lower residual capacities for hydrogen production. France's capacity is indicative of its commitment to hydrogen as part of its broader energy transition strategy. France has been investing in hydrogen technologies and infrastructure, with a particular focus on green hydrogen production. The country's emphasis on reducing carbon emissions and achieving energy independence aligns with its efforts to enhance hydrogen production capacities. The UK has also been making strides in hydrogen production; its government has set ambitious targets for hydrogen as part of its clean energy strategy, aiming to position the country as a leader in the global hydrogen economy. The moderate capacity observed in the UK reflects its ongoing efforts to develop hydrogen infrastructure and integrate hydrogen into its energy system. Scandinavian countries show varied results in hydrogen production capacities. Norway's substantial capacity can be attributed to its abundant renewable energy resources, particularly hydropower. The country has been leveraging its renewable energy potential to produce green hydrogen, contributing to its high residual capacity. Norway's commitment to sustainability and decarbonization further supports its hydrogen production efforts. Sweden and Denmark, on the other hand, have much lower capacities, reflecting different levels of investment and infrastructure development. While both countries have strong commitments to renewable energy, their focus may be on other technologies, such as wind and bioenergy, resulting in lower residual capacities for hydrogen production. Southern European countries like Italy and Spain have capacities slightly above 5000 tonnes per year, with a growing interest in hydrogen as part of their energy strategies. Both countries have been exploring hydrogen production to diversify their energy mix and reduce reliance on fossil fuels. The moderate capacities observed in Italy and Spain suggest ongoing efforts to develop the necessary infrastructure and technology for hydrogen production. Portugal has been focusing on renewable energy sources, particularly wind and solar power, which may explain its lower residual capacity for hydrogen production. However, the country has recognized the potential of hydrogen and is likely to increase its capacity in the future through targeted investments and policy support. Estonia's capacity is the lowest among the countries analysed. This minimal capacity may be due to limited investments in hydrogen infrastructure and a stronger focus on other energy sources. Estonia's energy strategy might prioritize sectors like oil shale and biomass. Iceland's unique energy landscape, dominated by geothermal and hydropower, might influence its hydrogen production capacity. While Iceland has significant renewable energy resources, its focus on utilizing these resources for electricity generation could result in lower residual capacities for hydrogen. Similarly, Slovenia's energy strategy and resource availability may contribute to its lower hydrogen production capacity.

These differences in residual capacities across European countries highlight the varying levels of investment and infrastructure development in hydrogen production. Eastern European countries generally lead, reflecting their proactive approach to renewable energy and hydrogen technologies. In contrast, Western European countries display moderate capacities, possibly due to their diversified energy strategies and focus on other renewable technologies. Scandinavian countries show a mix of high and low capacities, influenced by their renewable energy resources and strategic priorities [49,50]. Southern European countries exhibit moderate capacities, with ongoing efforts to integrate hydrogen into their energy systems. Estonia, Iceland, and Slovenia have minimal capacities, possibly due to different energy priorities and resource availability (see Figure 7).

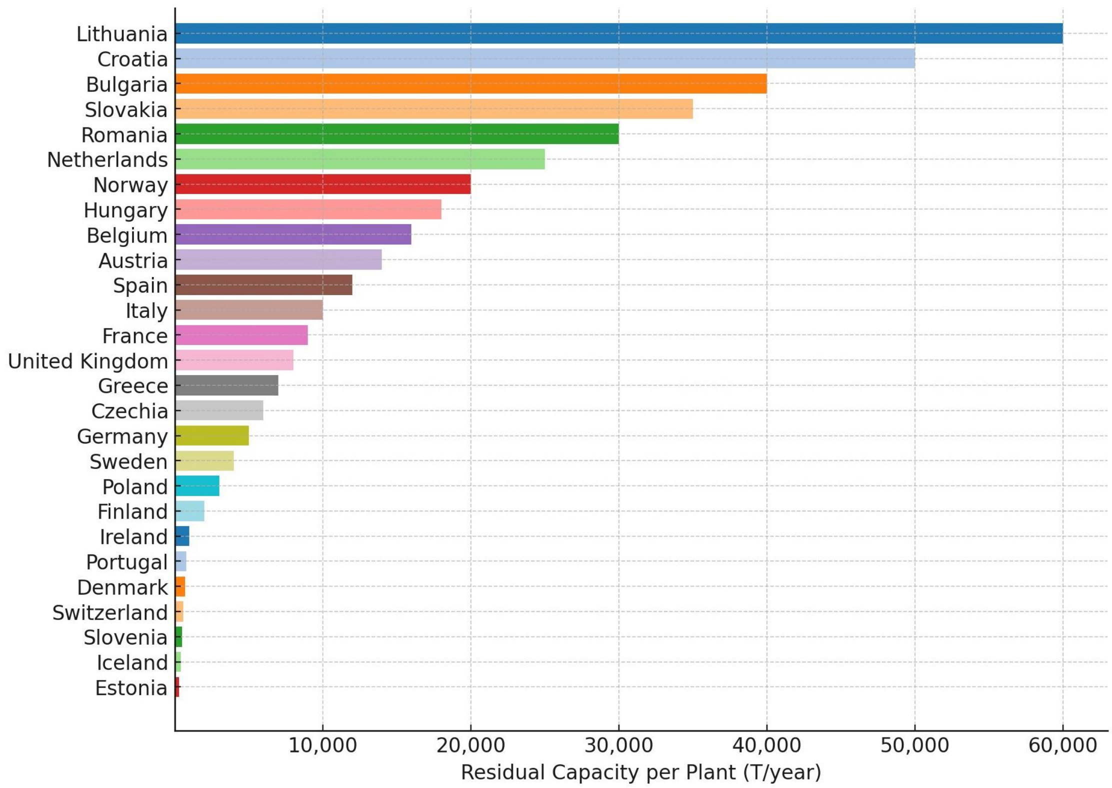

Figure 7. Residual capacity per plant (2022). Source: European Hydrogen Observatory, https://observatory.clean-hydrogen.europa.eu/ (accessed on 15 June 2024).

4. Correlation Analysis

In examining the correlation matrix, we aim to understand the relationships between the variables in the dataset, which includes information about the number of plants, production capacity, output, differences between production capacity and output, production per plant, output per plant, and residual capacity per plant across different countries (see Figure 8).

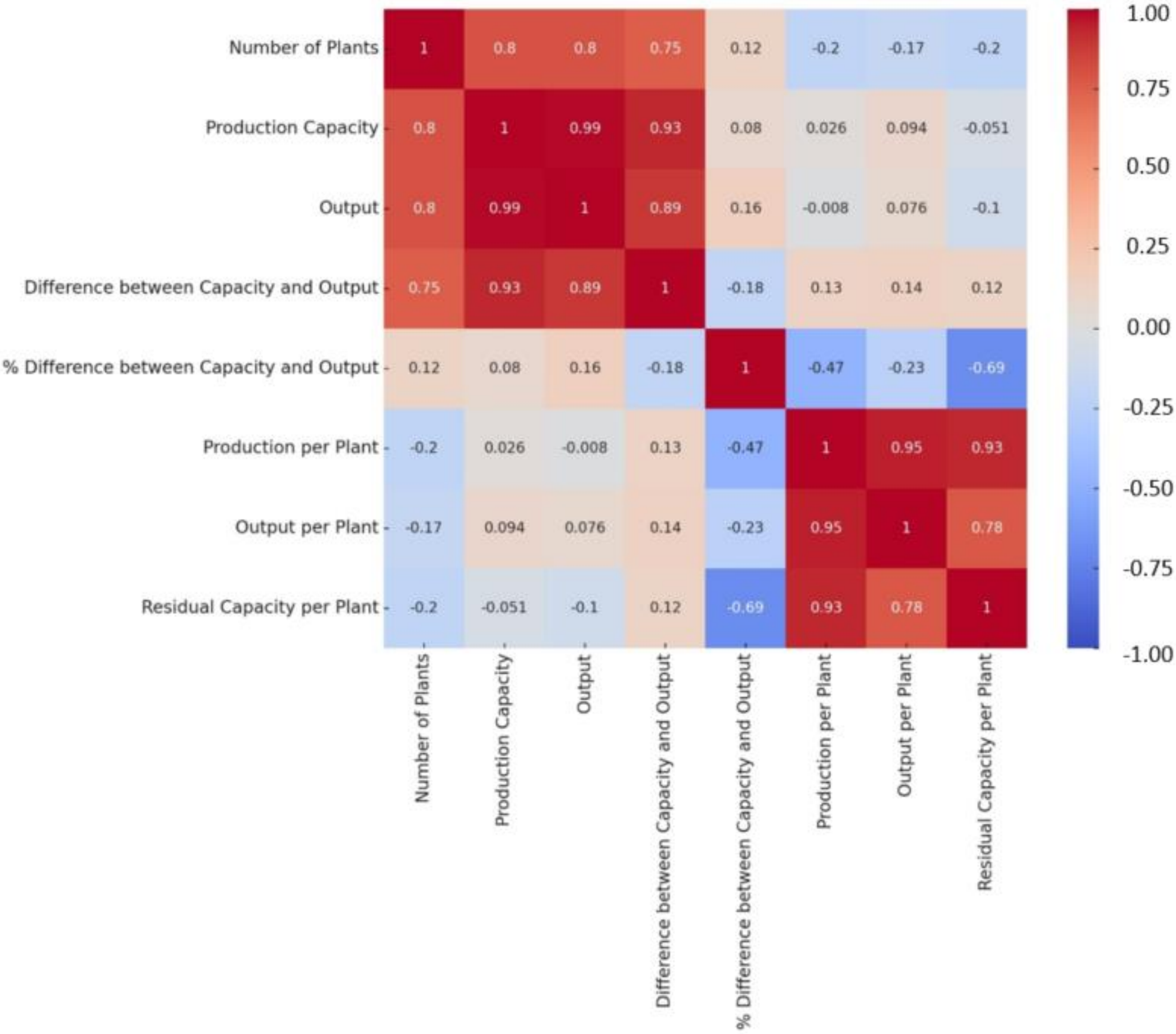

Figure 8. Correlation matrix.

The correlation between production capacity (in T/year) and output (in T/year) is equal to 0.994, which indicates a strong linear association, suggesting that countries with higher production capacities tend to have higher outputs. This is quite reasonable since production capacity sets the upper limit for output. The correlation between output per plant and production per plant (0.952) shows that countries with higher output per plant also have higher production per plant, implying that the efficiency or scale of individual plants influences both metrics similarly. Additionally, the correlation between the difference between production capacity and output and production capacity (0.938) suggests that countries with greater production capacities also experience larger discrepancies between their production capacity and actual output, possibly pointing to inefficiencies or other limiting factors in high-capacity countries. Similarly, the correlation between the difference between production capacity and output and output (0.894) indicates that as output increases, the difference between production capacity and output also tends to grow, highlighting the gap between potential and actual production. Furthermore, the correlation between production per plant and residual capacity per plant (0.936) suggests that countries with higher production per plant tend to have higher residual capacities per plant, which means that more efficient plants can ramp up production if needed.

These correlation coefficients collectively underscore the importance of efficiency and scalability in production processes. High production capacity is often accompanied by significant output, but it also brings the challenge of minimizing the gap between potential and actual production. Countries aiming to improve their production metrics should focus on optimizing plant efficiency and addressing any bottlenecks that prevent full utilization of their production capacities. Efficient plants not only contribute to higher production and output per plant but also maintain higher residual capacities, allowing for increased production flexibility. Addressing inefficiencies in high-capacity countries can lead to better alignment between production capacity and output, ultimately enhancing overall production performance. This comprehensive understanding of the correlations among these variables can guide strategic decisions to boost productivity and efficiency in the manufacturing sector.

Additionally, the correlation between the number of plants and production capacity (0.801) indicates that countries with more plants tend to have higher overall production capacities. This makes sense since more plants contribute to a higher cumulative capacity. The correlation between the number of plants and output (0.771) suggests that more plants generally lead to higher overall outputs. However, this correlation is slightly lower, indicating some variability in how effectively each plant operates. The correlation between output per plant and output (0.791) suggests that countries with higher output per plant also tend to have higher total outputs, but the relationship is not as strong as with production capacity [51].

The correlation between production capacity and production per plant (0.852) indicates that higher overall production capacity tends to correlate with higher production per plant, suggesting larger or more efficient plants. Similarly, the correlation between output and production per plant (0.844) indicates that higher total outputs correlate with higher production per plant. The correlation between the % difference between production capacity and output and the difference between production capacity and output (0.753) shows that countries with larger absolute differences between production capacity and output also tend to have higher percentage differences, which is intuitive. Finally, the correlation between the % difference between production capacity and output and production capacity (0.686) suggests that higher production capacities often correspond to higher percentage differences between capacity and output, indicating potential inefficiencies or underutilization in high-capacity countries.

The correlation between the number of plants and output per plant (0.395) suggests a positive relationship, although not very strong, indicating that simply having more plants does not significantly increase the output per plant. The correlation between production capacity and residual capacity per plant (0.492) shows a moderate relationship, suggesting that higher production capacities tend to have higher residual capacities per plant; however, other factors might influence residual capacities as well. On the other hand, the negative correlation between the number of plants and production per plant (−0.171) indicates that having more plants slightly correlates with lower production per plant, potentially pointing to diminishing returns or inefficiencies in scaling up the number of plants.

Insights from strong correlations provide a valuable understanding of how certain metrics move together. For instance, countries with high production capacities generally achieve high outputs, although they also show larger differences between potential and actual production, which could point to inefficiencies or external factors limiting production. The strong correlation between production per plant and output per plant highlights the importance of individual plant efficiency, suggesting that countries focusing on maximizing production per plant tend to see higher outputs per plant. This underscores the need to optimize plant operations and address any inefficiencies that might hinder the achievement of the full potential of production capacities.

Countries with high production capacities but also high differences between capacity and output may benefit from investigating the causes of underutilization. This could involve addressing bottlenecks in production processes, enhancing supply chain logistics, or investing in technology to increase plant efficiency. The moderate correlation between the number of plants and overall output suggests that simply increasing the number of plants is not guaranteed to boost production. The focus should also be on optimizing the performance of existing plants and ensuring that new plants are brought online efficiently. For countries with lower production per plant, investments in technology, training, and process improvements could yield significant benefits. Enhancing individual plant performance can lead to overall increases in output. Countries with high residual capacities per plant should assess their market demand and strategic reserves. Achieving a balance between having enough capacity for future demand spikes and efficiently utilizing existing capacity is crucial for optimal performance. By understanding these relationships, countries can make informed decisions to optimize their production processes, enhance plant efficiency, and address any gaps between capacity and output. Continuous monitoring and targeted interventions based on these insights can lead to significant improvements in overall production performance and economic benefits [52].

5. Clusterization with the K-Means Algorithm

In the following analysis, we report the results from the k-means algorithm optimized with the silhouette coefficient. According to the silhouette coefficient, the optimal number of clusters is 3 (see Figure 9).

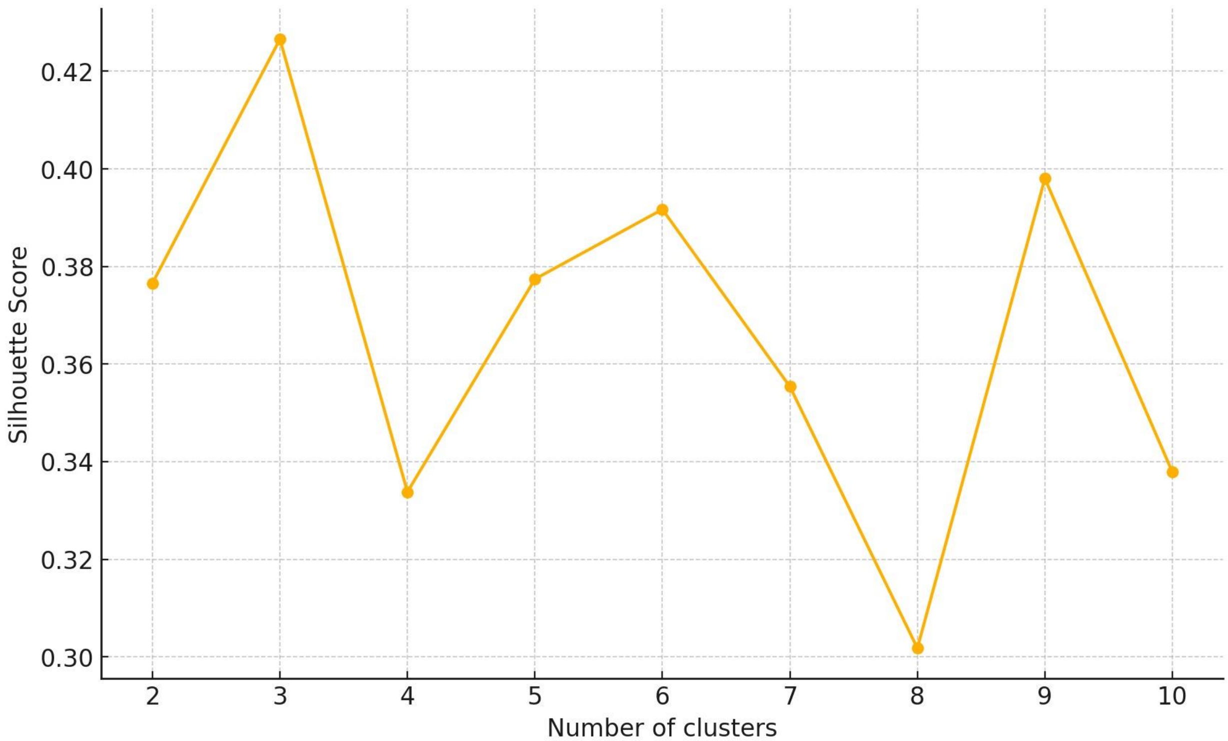

Figure 9. Silhouette coefficient for k from 2 to 10.

Figure 10 shows the obtained clusters based on a principal component analysis (PCA), with k = 3.

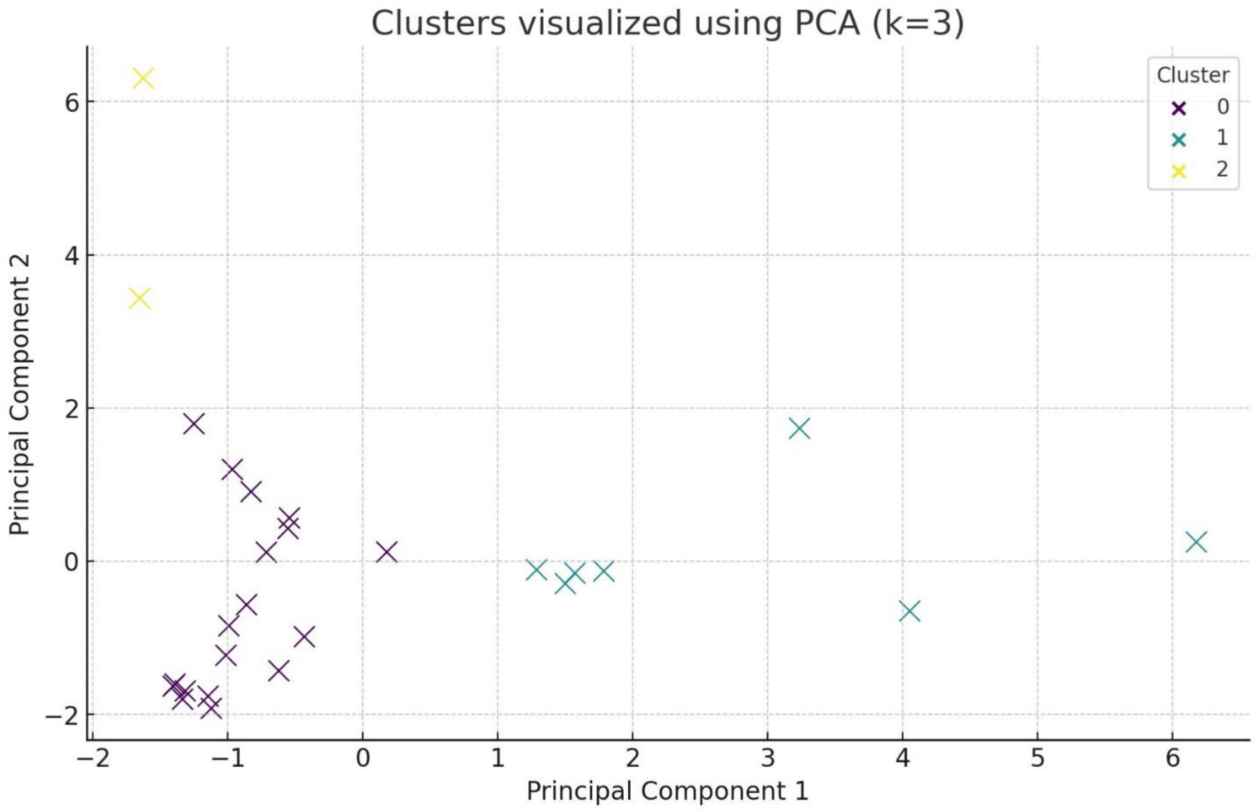

Figure 10. Cluster visualization.

The results of the clusterization can be summarized as follows:

- Cluster 0: This cluster includes Belgium, Bulgaria, France, Germany, Greece, Hungary, Italy, the Netherlands, Poland, Romania, Slovakia, Spain, and the UK. These countries represent some of Europe's most advanced and industrialized nations, characterized by robust infrastructure and significant investment in hydrogen production technologies. The relatively high hydrogen production and production capacity observed in these countries can be attributed to several factors, including strong governmental policies supporting renewable energy, advanced R&D facilities, and substantial financial investments in green technologies. Belgium and the Netherlands, for instance, have strategically positioned themselves as hydrogen hubs, leveraging their advanced port facilities and industrial complexes to foster large-scale hydrogen production. Both countries have implemented comprehensive national hydrogen strategies to reduce carbon emissions and achieve energy transition goals. These nations' high numbers of plants reflect their commitment to becoming central players in the European hydrogen market. France and Germany, with their long-standing industrial histories, have also made significant strides in hydrogen production. France's extensive nuclear power infrastructure provides a reliable source of low-carbon electricity, which is crucial for producing green hydrogen through electrolysis. Germany, on the other hand, has been a pioneer in renewable energy adoption, with significant investments in wind and solar power that complement its hydrogen production efforts. The substantial production capacity in these countries ensures they are well-prepared to meet both domestic and international hydrogen demand. Greece, Hungary, Poland, Romania, and Slovakia, while not traditionally seen as leaders in renewable energy, have made notable progress in recent years. These countries have recognized the potential economic and environmental benefits of hydrogen production and have taken steps to modernize their energy sectors. For example, Greece has leveraged its abundant solar and wind resources to establish new hydrogen production facilities, while Poland and Hungary have focused on utilizing their existing industrial bases to transition to hydrogen as a cleaner energy source. Italy and Spain, with their favourable climatic conditions and strong industrial bases, have also emerged as key players in the hydrogen sector. Italy's extensive natural gas infrastructure is being adapted to accommodate hydrogen, and Spain's significant investments in solar power are driving its green hydrogen production capabilities [53]. These countries' strategic initiatives ensure that they maintain high production capacities while progressively increasing their output to meet the growing demand for hydrogen [54,55]. With its ambitious net-zero targets, the UK has heavily invested in hydrogen production as part of its broader energy transition strategy. The UK government's hydrogen strategy outlines plans for developing low-carbon hydrogen production capacity, supported by substantial funding and policy incentives. The country's commitment to hydrogen is evident in its numerous pilot projects and collaborations with private-sector stakeholders to scale production. The difference between production capacity and actual output in these countries can be attributed to various factors, including the nascent stage of the hydrogen market, infrastructural challenges, and the need for further technological advancements. However, the higher residual capacity per plant observed in these nations indicates a readiness to increase production as demand increases and technological efficiencies improve. This surplus capacity serves as a buffer, ensuring that these countries can meet future hydrogen demands without significant delays [56,57].

- Cluster 1: This cluster includes Austria, Croatia, Denmark, Finland, Iceland, Ireland, Lithuania, Norway, Portugal, Slovenia, Sweden, and Switzerland. These nations have carved out a niche in the hydrogen production landscape, characterized by moderate production levels and capacities compared to the high-output countries in Cluster 0. What sets Cluster 1 apart is its strategic focus on balancing production capacity with actual output, resulting in a more efficient utilization of resources and a lower residual capacity per plant. Austria and Switzerland, known for their strong environmental policies and commitment to sustainability, have leveraged their advanced technological infrastructures to develop hydrogen production facilities that are both efficient and environmentally friendly. Austria's approach includes integrating hydrogen production with its well-developed renewable energy sector, particularly hydropower, which provides a steady and reliable source of green energy for hydrogen production. Switzerland, with its strong emphasis on technological innovation, has focused on pilot projects and research initiatives to optimize hydrogen production and utilization, particularly in the transport sector. The Nordic countries, including Denmark, Finland, Norway, and Sweden, have made significant strides in hydrogen production, driven by their abundant renewable energy resources and robust policy frameworks. Denmark, a leader in wind energy, has utilized its offshore wind farms to power electrolysis processes for hydrogen production, positioning itself as a key player in the green hydrogen market. Finland's strategy includes leveraging its extensive biomass resources to produce hydrogen through sustainable means. Norway, with its rich hydroelectric resources, has focused on producing blue hydrogen and green hydrogen, capitalizing on its expertise in natural gas and renewable energy. Sweden's comprehensive approach includes investments in both green hydrogen and innovative storage solutions, ensuring a steady supply of hydrogen to meet its industrial and transport needs. Portugal and Iceland have unique advantages that they are harnessing for hydrogen production. Portugal's sunny climate makes it an ideal location for solar-powered hydrogen production, with several large-scale projects underway to produce green hydrogen for domestic use and export. Iceland, with its abundant geothermal energy, has focused on using this renewable resource to produce hydrogen, supporting its goal of becoming a carbon-neutral nation. The country's commitment to renewable energy has facilitated the development of hydrogen infrastructure that is both efficient and sustainable. In the Baltics and Eastern Europe, countries like Lithuania, Slovenia, and

Croatia are emerging players in the hydrogen sector. Lithuania has made significant investments in renewable energy sources, which it is now integrating with hydrogen production technologies. Slovenia and Croatia, with their growing focus on energy diversification, have initiated projects aimed at utilizing their natural resources and existing industrial capabilities to produce hydrogen efficiently. Ireland, with its strong wind energy potential, has embarked on ambitious plans to develop a hydrogen economy, leveraging its renewable energy resources to produce green hydrogen. The country's strategic location also positions it as a potential exporter of hydrogen to other European nations, supporting the broader EU hydrogen strategy. Cluster 1 countries, with their moderate hydrogen production capacities, have strategically focused on optimizing the balance between production and output. This balance reflects a more mature approach to resource utilization, minimizing waste and ensuring that production capabilities are aligned with demand. The lower number of plants in these countries does not imply a lack of ambition but rather a calculated approach to scaling production in a sustainable and efficient manner. By investing in advanced technologies and integrating hydrogen production with existing renewable energy infrastructures, these nations are setting a benchmark for efficient and sustainable hydrogen production. This strategic approach not only supports their domestic energy needs but also positions them as key contributors to the global hydrogen economy, driving innovation and sustainability in the energy sector [58–60].

- Cluster 2: This cluster consists of Czechia and Estonia. These countries are in the early stages of hydrogen production development and currently exhibit significantly lower production levels and capacities compared to other European nations. Their minimal numbers of plants underscore the nascent nature of their hydrogen sectors. However, the limited production capacity and actual output are closely aligned, resulting in a small difference between the two metrics and reflecting a more contained and efficient production per plant. Czechia's hydrogen production is part of a broader energy strategy that aims to diversify its energy sources and reduce dependence on fossil fuels. The country has been gradually integrating renewable energy into its energy mix, and hydrogen production is seen as a complementary component of this transition. Czechia has focused on small-scale pilot projects and research initiatives to explore the potential of hydrogen as a clean energy source. These projects often involve collaborations between government agencies, research institutions, and private companies, creating a foundation for future expansion. The country's industrial base, particularly in the automotive and manufacturing sectors, provides a potential market for hydrogen applications, such as fuel-cell vehicles and industrial processes. Estonia, on the other hand, has made strides in digital innovation and technology, but its hydrogen production capabilities remain limited. The country has begun to explore hydrogen as part of its commitment to the EU's green energy targets and climate goals. Estonia's approach to hydrogen production is characterized by its focus on leveraging its existing energy infrastructure and resources. For instance, Estonia has explored the use of its oil shale industry for producing hydrogen as a transitional measure while expanding its renewable energy capacity. The Estonian government has shown interest in developing hydrogen technologies, with initiatives to foster innovation and attract investment in this sector. The small number of hydrogen plants in both Czechia and Estonia can be attributed to several factors, including limited financial resources, infrastructural challenges, and the need for further technological advancements. However, the production capacities of these plants are designed to match their outputs closely, ensuring that the production processes are efficient and that there is minimal waste. This alignment indicates a cautious and measured approach to scaling hydrogen production, focusing on optimizing current capabilities before embarking on larger-scale expansions. Despite their current limitations, Czechia and Estonia have the potential to grow their hydrogen production capacities in the coming years. Both countries have recognized the strategic importance of hydrogen in achieving energy security and sustainability. As part of the EU, they have access to funding, expertise, and collaborative opportunities that can accelerate the development of their hydrogen sectors. Investments in R&D, infrastructure, and regulatory frameworks will be crucial to unlocking this potential. Furthermore, Czechia and Estonia can benefit from regional collaborations with neighbouring countries with more advanced hydrogen infrastructures. By integrating into regional hydrogen networks and participating in cross-border projects, these countries can enhance their production capabilities and market reach. Such collaborations can also provide valuable knowledge transfer and technical support, facilitating the growth of their hydrogen industries [61–63].

6. Policy Implications

The strategic development of hydrogen production in Europe holds profound implications for national and regional policy frameworks. As hydrogen becomes a cornerstone of the EU's energy strategy, policymakers must navigate a complex landscape to maximize the benefits of hydrogen while mitigating associated challenges. These policy implications span environmental regulation, energy security, economic growth, technological innovation, and international cooperation. One of the primary policy implications of hydrogen production is its alignment with Europe's climate goals. Hydrogen, especially green hydrogen from renewable energy sources, offers a pathway to decarbonize several sectors, including industry, transportation, and energy. Policymakers must create robust regulatory frameworks that incentivize the production and use of green hydrogen. This includes setting clear targets for hydrogen production, implementing carbon pricing mechanisms, and providing subsidies or tax incentives for renewable energy projects. Additionally, regulatory standards must ensure that hydrogen production does not inadvertently lead to environmental degradation or overuse of water resources. Hydrogen production has significant implications for Europe's energy security and independence. By investing in domestic hydrogen production, European countries can reduce their reliance on imported fossil fuels, thereby enhancing energy security. Policymakers need to develop strategies that support the diversification of energy sources. This includes facilitating the integration of hydrogen production with existing renewable energy infrastructures and ensuring a stable supply chain for hydrogen production inputs. The development of a trans-European hydrogen network, encompassing production sites, storage facilities, and distribution networks, is essential. Such infrastructure will not only stabilize supply but also enable cross-border trade of hydrogen, enhancing energy resilience across the continent. The hydrogen economy presents substantial opportunities for economic growth and job creation. Policies that support the development of hydrogen technologies can stimulate innovation, attract investments, and create high-skilled jobs. Governments must prioritize funding for R&D in hydrogen technologies, including electrolysis, fuel cells, and hydrogen storage solutions [64,65]. Furthermore, policies should promote public–private partnerships to leverage private-sector expertise and investment. Vocational training and education programs focused on hydrogen technology will be crucial to equip the workforce with the necessary skills, ensuring a smooth transition and sustained economic benefits. Hydrogen production requires significant advancements in technology and infrastructure. Policymakers must focus on fostering an environment conducive to technological innovation. This includes funding for R&D, support for pilot projects, and the creation of innovation hubs that bring together academia, industry, and government. Developing a comprehensive hydrogen infrastructure is equally important. Policies should facilitate the construction of hydrogen production plants, refuelling stations, and storage facilities. Standardizing regulations across the EU will help streamline the deployment of hydrogen infrastructure, ensuring interoperability and efficiency. Creating a competitive hydrogen market is vital for the sustainable growth of the hydrogen economy. Policymakers must develop regulations that promote market transparency, prevent monopolistic practices, and encourage competition. Establishing certification schemes for green hydrogen can help differentiate it from other types of hydrogen, thereby creating market incentives for producers to invest in renewable energy sources. Additionally, international trade policies must be designed to support the export and import of hydrogen, ensuring that European hydrogen producers can compete on the global stage. The transition to a hydrogen economy also has significant social implications. Public acceptance of hydrogen technologies is crucial for their widespread adoption. Policymakers must engage with communities to build awareness and acceptance of hydrogen as a safe and sustainable energy source. This includes transparent communication about the benefits and potential risks of hydrogen production and use [66]. Policies should also address any environmental justice concerns, ensuring that the development of hydrogen infrastructure does not disproportionately impact disadvantaged communities.

Hydrogen production is not confined to national borders; it requires international cooperation. European policymakers must work with global partners to develop common standards and regulatory frameworks for hydrogen production, transportation, and use. This includes collaboration on R&D initiatives, sharing best practices, and harmonizing safety and environmental standards. International cooperation will also be essential for establishing global hydrogen trade routes, enabling Europe to export surplus hydrogen and import it when necessary. The transition to a hydrogen economy requires substantial financial investment. Policymakers must design financial support mechanisms that de-risk investments in hydrogen technologies. This includes grants, low-interest loans, and guarantees for hydrogen projects. Public funding should be used strategically to leverage private investments, ensuring a multiplier effect. Additionally, policies should promote the development of green finance instruments, such as green bonds, to raise capital for hydrogen projects. As hydrogen technology evolves, regulatory frameworks must be flexible enough to adapt to new developments. Policymakers should adopt a dynamic approach to regulation, allowing for iterative improvements based on technological advancements and market feedback. This includes implementing regulatory sandboxes that enable testing and scaling of innovative hydrogen solutions in a controlled environment. Finally, the development of hydrogen production must be guided by a long-term strategic vision. Policymakers need to articulate a clear roadmap that outlines the steps towards a fully integrated hydrogen economy. This vision should be aligned with broader climate and energy goals, providing a coherent framework for action. Regular monitoring and evaluation of progress toward this vision will be essential to ensure that policies remain effective and responsive to changing circumstances [67].

7. Conclusions

Hydrogen production in Europe is at a pivotal moment, with varying levels of development across different countries. This comprehensive analysis highlights the disparities in hydrogen production capacities, outputs, and efficiencies, emphasizing the strategic importance of hydrogen as a key component in the transition to sustainable energy systems. The findings underscore several critical insights and policy implications essential for driving the hydrogen economy forward.

Countries such as Belgium, Bulgaria, France, Germany, Greece, Hungary, Italy, the Netherlands, Poland, Romania, Slovakia, Spain, and the UK are at the forefront of hydrogen production. These nations benefit from strong governmental policies, advanced R&D facilities, and substantial financial investments in green technologies. However, despite their high production capacities, these countries face challenges in fully utilizing their potential due to infrastructural and technological constraints. Addressing these inefficiencies through targeted investments and technological upgrades could significantly enhance their hydrogen outputs, aligning production more closely with capacity and supporting their ambitious energy transition goals.

Furthermore, Austria, Croatia, Lithuania, Portugal, Slovenia, Sweden, Denmark, Finland, Ireland, Norway, Iceland, and Switzerland represent countries with moderate hydrogen production levels. These nations have strategically focused on balancing production capacity with actual output, resulting in more efficient resource utilization. By investing in advanced technologies and integrating hydrogen production with existing renewable energy infrastructures, these countries are setting a benchmark for efficient and sustainable hydrogen production. Continued investment and further integration of hydrogen production into their energy systems will be crucial for scaling up hydrogen capabilities sustainably.

Czechia and Estonia, with significantly lower hydrogen production levels and minimal plant numbers, are in the early stages of developing their hydrogen sectors. Despite their limited capacities, these countries exhibit efficient production processes with minimal waste. Their cautious and measured approach focuses on optimizing current capabilities before expanding on a larger scale. Leveraging EU funding, expertise, and regional collaborations can enhance their hydrogen production capacities, contributing to a diversified and resilient energy future.

The study also reveals a common trend of underutilization of production capacities across most European countries, attributed to infrastructural bottlenecks, operational inefficiencies, and regulatory hurdles. Addressing these challenges through targeted investments, technological advancements, and supportive policies can significantly boost hydrogen output, helping Europe meet its decarbonization targets, enhance energy security, and stimulate economic growth. In conclusion, hydrogen production in Europe presents a varied landscape, reflecting different levels of industrial development, resource availability, and policy support. Leading countries with substantial capacities must focus on optimizing efficiency, while emerging players need to invest in infrastructure and technology to scale up production. Continued international collaboration, research and development, and supportive regulatory frameworks are essential to realizing the full potential of hydrogen as a sustainable energy source. The concerted efforts across European nations will ensure that hydrogen plays a pivotal role in the continent's transition to a low-carbon future, providing environmental, economic, and social benefits.

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