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"Green" Hydrogen Products and Their Economic End-Uses: A Statistical Perspective

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Abstract. *Mitigation of greenhouse gasses heightens attention on hydrogen as a crucial element in the global energy transition, while combating climate change. Building on previous analyses of hydrogen projects compiled by the International Energy Agency (IEA), this paper provides an updated and comprehensive analysis of this database while delving deeper into the intricacies of hydrogen products and their economic end-uses. Given the availability of alternative technologies in some sectors, it is crucial to understand the nuances of hydrogen projects, particularly in "hard-to-decarbonize" or "hard-to-abate" sectors such as iron and steelmaking, where the key benefit of using green hydrogen is to reduce greenhouse gas emissions from the process and energy use. Therefore, this paper's objective is to provide insights into the distribution, technologies, and trends of hydrogen projects produced with renewable power, while unraveling the diverse products of these projects and identify the sectors benefiting most from them. Employing a rigorous statistical data analysis, a dataset encompassing approximately 2000 hydrogen projects worldwide is scrutinized. These questions guide the investigation: a) What is the distribution of hydrogen projects across different countries globally? b) What are the key trends in technology choice over time? c) What are the key trends of hydrogen projects using renewable energy? d) What are the primary products of green hydrogen projects? e) Which end-use sectors are benefiting from the "green" hydrogen products the most? The findings reveal a spectrum of internationally pursued hydrogen-derived products, ranging from hydrogen to ammonia and beyond. Moreover, they provide insights into industries that stand to gain from innovation, including mobility, ammonia production and other industrial applications. This paper significantly contributes to the understanding of "green" hydrogen products, and their end-uses. Governments and businesses can leverage this knowledge to make informed policy and investment decisions in a rapidly evolving market.*

Keywords: green hydrogen production, green hydrogen products, renewable energy sources, climate change mitigation, energy transition.

Introduction

Since the international adoption of the Paris Agreement, researchers, governments, and businesses alike are seeking to find solutions, both technical, technological, and socio-economic in order to abide by it and keep the temperature rise to "*well below 2°C above pre-industrial levels*" while "*pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*" in order to limit the risks and the impact associated with climate change (United Nations, 2015).

To mitigate, i.e., reduce the man-made greenhouse gases, which are "*unequivocally*" causing climate change, and which have "*caused substantial damages, and increasingly irreversible losses*" (IPCC, 2022, p. 6), several mature and innovative solutions alike are available around the globe to be implemented at large scale.

Since the most problematic greenhouse gas is carbon dioxide (CO_2), reducing CO_2 emissions in various sectors of the economy is of paramount importance, including energy production and consumption not just in the power sector, but also transport, heating and cooling in buildings and industrial applications.

DOI: 10.2478/picbe-2024-0102

Among the technologies available to mitigate climate change, the International Panel on Climate Change (IPCC), which is the key global scientific authority on climate, acknowledges the role of renewable energy sources, such as solar and wind; energy efficiency technologies, including demand-side management; the electrification of end-use sectors which would otherwise consume other fuels; as well as better management of our land, including forests and crops; among others (IPCC, 2022).

Such technologies, their development, deployment, and cost performance over time, have been the subject of research. The International Renewable Energy Agency (IRENA) has been at the forefront of tracking the costs and deployment status of renewable energy sources around the world. In its report on renewable power generation costs, IRENA highlights that the total installed costs of solar photovoltaic energy and onshore wind energy have dropped between 2010-2022, by 83%, and respectively 42%, which is not negligible (IRENA, 2023a).

The cost reduction of these technologies, coupled with the increasingly higher new installed capacity of renewable energy sources around the world, make these technologies the cornerstone of the global energy transition (IRENA, 2023a). As such, in its World Energy Transitions Outlook 2023, IRENA includes the following elements as key components in a 1.5°C scenario (IRENA, 2023b): a) electrification with renewable energy, b) direct use of renewable energy in end-use applications and district heating, c) energy efficiency, d) electrification of economic sectors, e) carbon capture and storage and bioenergy with carbon capture and storage (BECCS), and f) hydrogen production and consumption – especially in industries that are considered "*hard-to-decarbonize*" such as iron- and steelmaking, cement and lime, aluminum, chemicals and petrochemicals or some segments of the transport sector like aviation, shipping or heavy-duty vehicles (IRENA, 2020a).

In this global policy context, governments around the world are developing strategies dedicated to hydrogen production, transport, and consumption, while government agencies are collaborating to create a global hydrogen market in the future, acknowledging that this energy vector will play a key role in various economic sectors, and especially when it comes to coupling the various economic sectors with each other, in addition to decarbonization efforts.

Since hydrogen is gaining momentum around the world, there will be more pressure put on businesses both from the public sector, but also from its shareholders and stakeholders to embark in a transition from the business-as-usual towards a more sustainable, low-carbon, net-zero-emissions-type of business. Therefore, analyzing the hydrogen project database compiled by the International Energy Agency (IEA) can reveal useful insights that inform strategic decisions for those businesses who wish to remain competitive in an ever-changing global competitive environment.

First, to obtain a better picture of the database and projects globally, a series of preliminary questions are being asked and answered to:

a) What is the distribution of hydrogen projects across different countries globally?
b) What are the key trends in technology choice over time?
c) What are the key trends of hydrogen projects using renewable energy?

Further, the fundamental research questions include:

d) What are the primary products of green hydrogen projects?
e) Which end-use sectors are benefiting from the green hydrogen products the most?

As such, this paper has two objectives: First, it aims to investigate the global distribution and the key trends in terms of technology choice and renewable energy source used in hydrogen projects as documented in the IEA database, with a focus on understanding their evolution over time. Second, the paper aims to conduct an analysis using the IEA hydrogen project database to explore the green hydrogen products and the end-use economic sectors that stand to benefit the most from these.

These objectives are aligned with the above-mentioned research questions and will guide the research paper in exploring the contribution of hydrogen in the global effort to mitigate climate change and materialize the energy transition, while highlighting its implications for strategic decision-making by governments and businesses alike.

To reply to the above-mentioned research questions, the following analyses are performed: a geographic analysis; a technology analysis; a renewable energy analysis; green hydrogen product analysis and an end-use sector analysis.

The paper is structured like this: the first chapter contains the introduction, the second contains the literature review, followed by the description of the methodology, after which the fourth chapter contains and discusses the results. Further, the fifth chapter contains the conclusion and the last chapter contains the references.

Literature review

Hydrogen strategies globally and their role in the energy transition

While the interest in hydrogen is not new, the scale and the pace of recent developments is unprecedented. The first strategies for hydrogen were established after the 1970s' oil crisis. Active countries in this field during that time included the United States of America, several European countries, and Canada.

In recent years, after the adoption of the Paris Agreement in 2015, 136 nations representing 90% of the global gross domestic product (GDP) and 85% of the global population have adopted a net-zero policy, i.e., a target aimed at reducing to below zero the difference between the greenhouse gases emitted and those absorbed from the atmosphere (Raman et al., 2022). More countries can be expected to follow suit after the adoption of the first Global Stocktake under the Paris Agreement (UNFCCC, 2023).

As such, more and more countries have elaborated a hydrogen strategy, among which France (2018), Australia (2019), Japan (2019), Chile (2020), Finland (2020), Germany (2020), Portugal (2020), Republic of Korea (2020), the Netherlands (2020), Spain (2020), Romania (2023) and even the European Union (2020) as a whole. Other countries also have strategic documents, which are not necessarily labelled as strategy, like roadmaps in Japan (2019), Republic of Korea (2019) or Russia (2020); vision documents in New Zealand (2018), Canada (2019) or Portugal (2020); and research and development (R&D) programs in China (2020) (IRENA, 2020b).

In addition to government policies at national/regional level, there are other international initiatives, either public, private or a combination of these, which seek to collaborate closely together with the purpose of eventually creating a global hydrogen market.

Major hydrogen themes in the scientific literature

These developments are well reflected in scientific literature, since a bibliometric analysis has shown – based on 642 articles between 2016-2021 from the Scopus database – that there are major themes emerging around hydrogen, i.e., storage, production, electrolysis and economy, while research clusters are also emerging including "*materials chemistry, hydrogen energy and cleaner production, applied energy, and fuel cells*" (Raman et al., 2022).

Similarly, based on 610 articles between 2000-2022, another research concluded that most publications have a "*multidisciplinary*" scope, including "*generation, storage, transportation, application, feasibility, and policy development*" (Sharma et al., 2023).

Status and outlook of hydrogen production

Hydrogen, the most abundant molecule in the universe, is not found in its pure form easily and in large quantities around the world, this being the reason for which it needs to be produced via various technologies to be further used in various applications.

Depending on the technological pathway used (e.g., electrolysis, pyrolysis, etc.) and the energy put into the process (e.g., fossil fuels or renewable energy sources), hydrogen is conventionally assigned a color, such as "*black*", "*brown*", "*grey*", "*blue*", "*turquoise*" and "*green*", among others. However, it has been argued in previous research by this author that such a color code does not accurately reflect the actual greenhouse gas emissions, and can, therefore, be misleading (Ocenic & Tantau, 2023).

While some researchers identify 14 hydrogen production technologies without assigning any color labels (Nikolaidis & Poullikkas, 2017), other researchers categorize hydrogen into three colors, namely "*grey*", "*blue*" and "*green*" (Patnaik et al., 2023). A widely-accepted and consistently-applied labelling framework does, however, not exist – for now.

Currently, the production of hydrogen around the world is around 0.7 million tons/year and it is projected to increase to 518 million tons/year by 2050 in a Paris-compliant scenario. For this to happen, the installed hydrogen electrolyser capacity needs to increase from 0.5 gigawatt (GW) today to 5722 GW by 2050. Concomitantly, the investments into the relevant infrastructure would need to increase from 1.1 USD billion/year to 170 USD billion/year (IRENA, 2023b).

Status and outlook of hydrogen consumption

In the 1.5°C scenario, IRENA estimates that the low-carbon hydrogen consumption of the industrial sectors would need to increase from 0.04 exajoule (EJ) to 40 EJ by 2050 (IRENA, 2023b), and it has a role to play in various end-uses (IRENA, 2020b) including industry, transport, heating, and power generation.

Analyses of hydrogen project databases

Given the novelty and importance of the topic for governments and businesses, hydrogen is gaining interest from researchers. In addition to the reports produced by international governmental organizations mentioned in the present work, there are some studies looking closer at the actual projects being implemented or developed by the private sector for hydrogen production.

Although data remains relatively scarce and often proprietary, the IEA has managed to compile and maintain a hydrogen database of projects with climate and energy objectives (IEA, 2024). Limited research has investigated this database, and the number of projects included in such publications reveals that the database is evolving rapidly.

While one article includes 789 projects from 61 countries between 1975-2038 from the IEA database (Pleshivtseva et al., 2023), another paper analyses an undefined number of projects in the 2000-2028 timeframe from the same source (James & Menzies, 2022). In contrast, the present paper contains an analysis of all 1997 projects as of retrieval date, 6 January 2024.

When it comes to the methods used by researchers previously, both exploratory and econometric analysis have been performed. Pleshivtseva et al. have applied a comparative analysis, including an analysis of the IEA database until October 2021 versus October 2022. James and

Menzies adopted mathematical and statistical methods to investigate the "*propagation and capacity of low-carbon hydrogen projects over the past two decades*" (e.g., regression, variance, correlation).

When it comes to the results obtained, Pleshivtseva et al. presented the key characteristics of the projects studies, out of which 65 have been completed at that point in time. Among key findings, they presented that most projects were using electrolysis as the preferred technology for hydrogen production, while the average installed capacity of projects was increasing 140 times by 2038. Asian and American countries were catching up with Europe, but Germany remained at the forefront with the highest number of electrolysis projects.

The results obtained by James and Menzies included an exponential growth rate in the capacity of green ("*zero carbon*") versus "*blue hydrogen*" (with carbon capture technologies). Their study confirmed that Europe was leading in terms of hydrogen projects, followed by Japan and North America, and – after some stagnation – a global penetration of hydrogen projects was observed.

Methodology

This paper contains an exploratory analysis, using data visualization of the IEA hydrogen production and infrastructure projects database (IEA, 2024), focusing on the hydrogen production projects dataset using the software Tableau 2023.1 and JupyterLite with the programming language Python. Exploratory analysis is useful to gain insights into the database, discover patterns, understand the structure, relationships, and characteristics of the data.

The exploratory analysis includes a geographic analysis; a technology analysis; a renewable energy analysis; green hydrogen product analysis and an end-use sector analysis. As such, the fourth chapter contains subsections with each of them detailing the results of the analyses mentioned above.

More specifically, the steps followed for the exploratory analysis are: 1. Download/retrieve the data in Microsoft Excel; 2. Format the database (e.g., remove lines/rows which were empty, i.e., contained no data about projects); 3. Add explicit country labels (e.g., "*Germany*" instead of "*DEU*"); 4. Encode the data about the products from categorical variables (e.g. "*ammonia*") into binary variables (e.g. "*ammonia* = 1" if applicable for the project, or "*ammonia* = 0" if not applicable); 5. Plug the database into Tableau and JupyterLite; 6. Analyze the data in several iterations; 7. Cluster the data; 8. Assess the results; 9. Present the results visually.

Results and discussions

Geographic distribution of hydrogen projects

Globally, there are 1997 hydrogen projects in 92 countries. Among these, 7 projects have no country allotted and 7 are multi-country projects. Among the 10 leading countries with the highest number of projects, are Germany (198), United States of America (164), Australia (147), Spain (143), France (126), United Kingdom (111), the Netherlands (89), China (81), India (79), Denmark (61) (Figure 1).

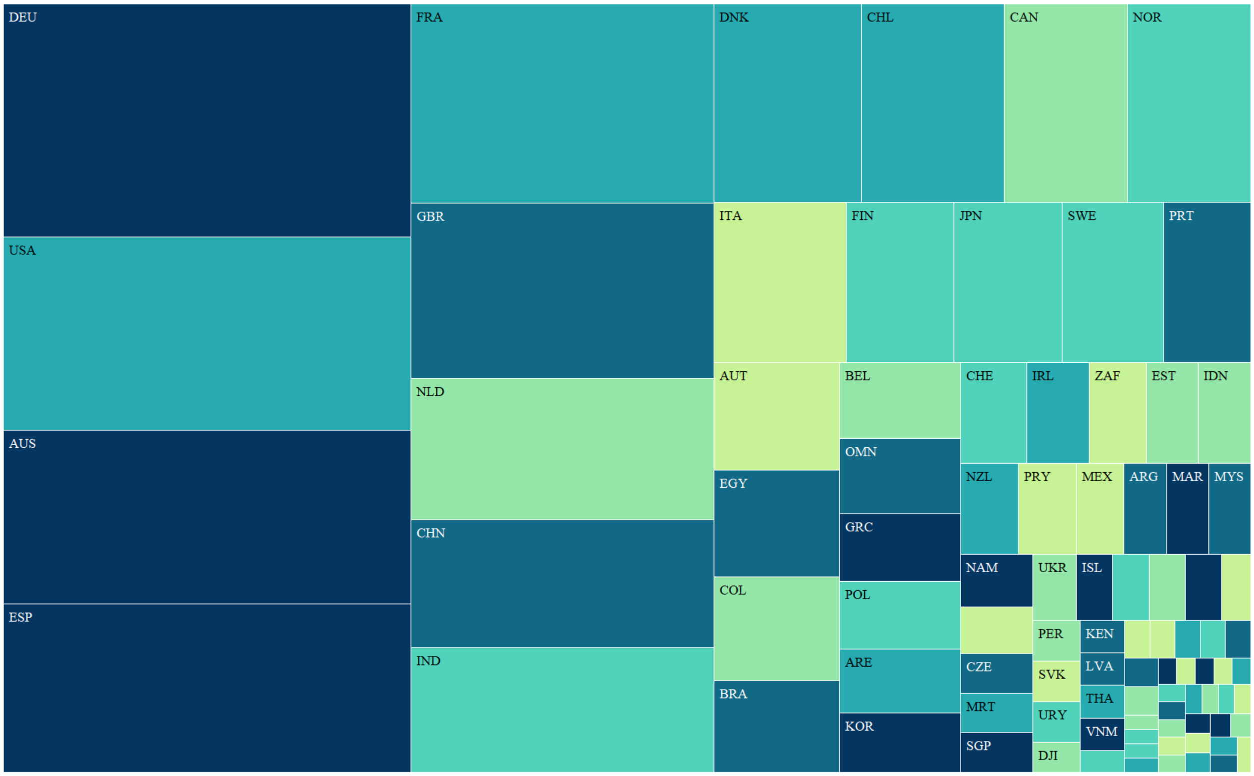

Figure 1. Distribution of all projects per countries

Source: Authors' own research results based on IEA, 2024.

Note: Country codes are presented as per ISO Alpha-3 code, a three-letter code representing country names in a representative manner. E.g. DEU = Germany.

Another way to look at the data would be to analyze the geographical distribution for the operational projects only, which would give an insight into the actual state of play in terms of hydrogen production around the globe. As such, some noteworthy differences are visible, compared to the previous figure. While Germany is still leading in terms of absolute number of operational hydrogen projects around the world, represented with a larger black circle on the map, the total electricity capacity associated with the hydrogen plants, expressed in megawatt-hours (MW) reveals some insights into the scale of the projects around the world.

If measured by the sum of installed power expressed in MW of all operational hydrogen plants, China (including Taiwan) is leading with 603 MW, which represents 54% of the total installed capacity around the globe. China is followed by Germany with 77 MW, United States of America with 39 MW, Spain with 36 MW and Peru with 25 MW (Figure 2).

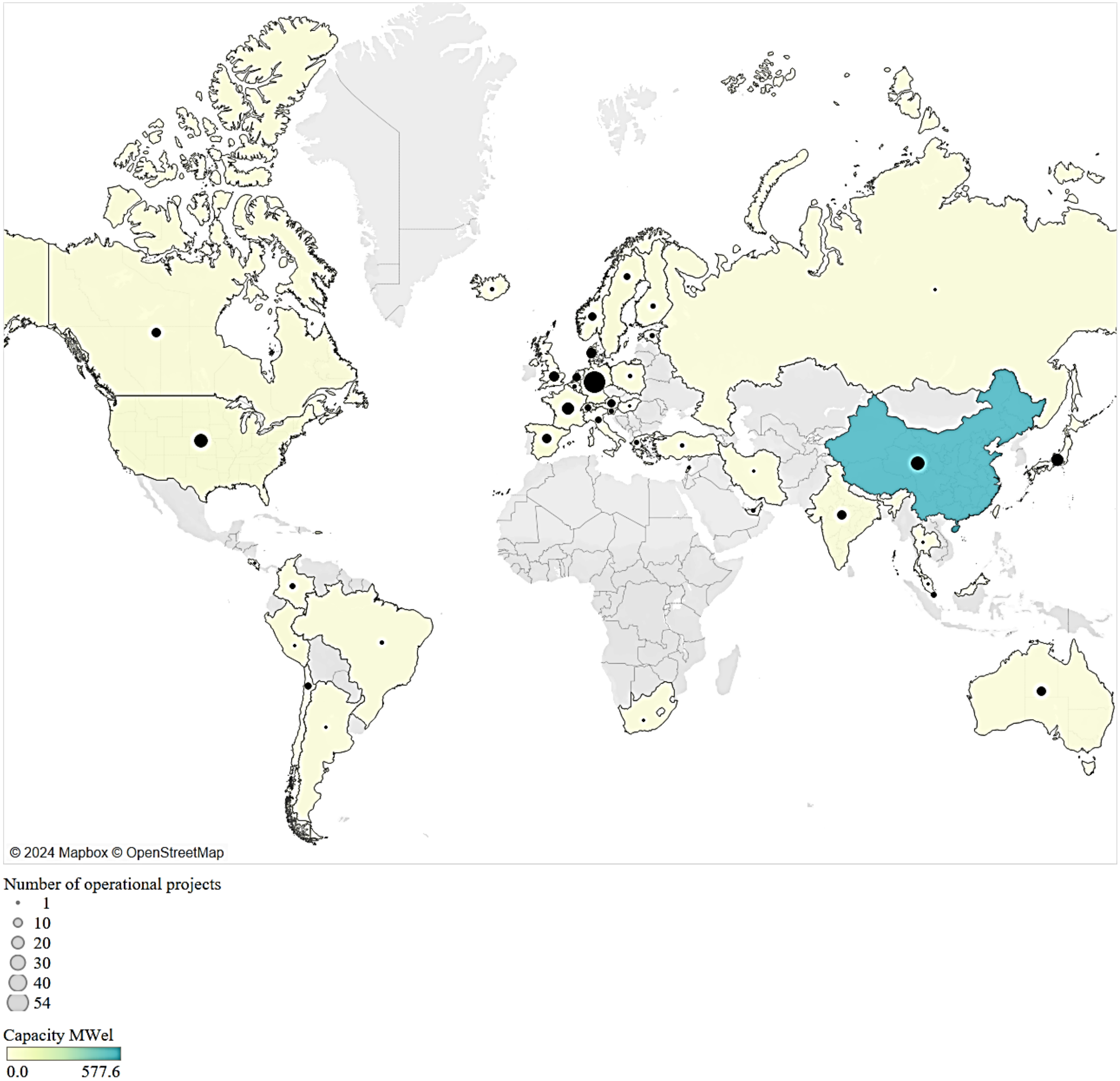

Figure 2. Geographical distribution of operational hydrogen projects with installed electricity capacity (MW)

Source: Authors' own research results based on IEA, 2024.

Technology analysis of hydrogen projects

Understanding the technology employed is of research interest, since not all technologies have the same degree of technological maturity, nor the same technological efficiency or the same level of emitted greenhouse gases. Further, a renewable energy analysis can only be performed after a technology analysis has been conducted, since only a fraction of all available technologies are employing less polluting energy sources, while other technologies are inherently linked to greenhouse gas emitting fossil fuels.

To what extent a given technology can be considered "*green*" or not (i.e., employing other color labels) is of interest for the author and needs further investigation with respect to the carbon dioxide emitted in the hydrogen production process to ensure that the labels used are compliant with commitments taken at the highest international level in terms of climate change mitigation (Ocenic and Tantau, 2023). Simply put, technologies using renewable energy in electrolysis processes to produce hydrogen emit less greenhouse gasses than methods employing fossil fuels.

Among the hydrogen production technologies included in the database, are: 1) water electrolysis technologies, like alkaline electrolysis (ALK), proton exchange membrane electrolysis (PEM) and solid oxide electrolysis cells (SOEC); 2) fossil fuels with carbon capture, like hydrogen production from coal gasification (all types of coals and derivatives) coupled with carbon capture, utilization and storage ("*coal w CCUS*"), hydrogen production from natural gas reforming (steam reforming, autothermal reforming or other advanced reforming technologies) coupled with carbon capture, utilization and storage ("*NG w CCUS*") and hydrogen production from oil-based processes (reforming, cracking or gasification of oil products) coupled with carbon capture, utilization and storage ("*Oil w CCUS*"), and 3) biomass-based hydrogen, i.e., biomass-based technologies such as biomass or waste gasification, biogas pyrolysis, biogas reforming or membrane separation. "*Other electrolysis*" refers to undisclosed electrolysis technology, while "*Other*" refers to several different technologies different from those previously described, such as membrane separation from industrial residual gaseous streams.

By looking at these technologies and their evolution over time, some interesting insights can be drawn. Between 1975 and the early 2020s, the two main electrolyser technologies employed were alkaline and proton exchange membrane, after this date, a high number of projects was announced, but their technology is mostly not revealed, although established technologies seem to be continued (Figure 3).

Assessing closely the projects by considering their technologies employed, but also the project status gives an indication of the current market status and future trends. While only 14% of the projects included in the database were operational at the time of analysis, the remaining were either undergoing a feasibility study (37%), still a concept (26%), or under demonstration (10%) with 226 projects under construction (11%) and with the remaining being either decommissioned (0.4%) or other/unknown.

Further, among those operational projects around the world, 113 were using proton exchange membrane electrolysis technology, 85 alkaline electrolysis, 58 other electrolysis and 8 natural gas with carbon capture utilization and storage, among other technologies. However, when looking at the projects under development, the analysis confirms the previous presented results, indicating that – although many projects have been announced, there is not yet a clear technological leader, in the sense that most of the technologies behind the projects are not disclosed, although we know that these will be electricity-based, i.e., electrolysis technology.

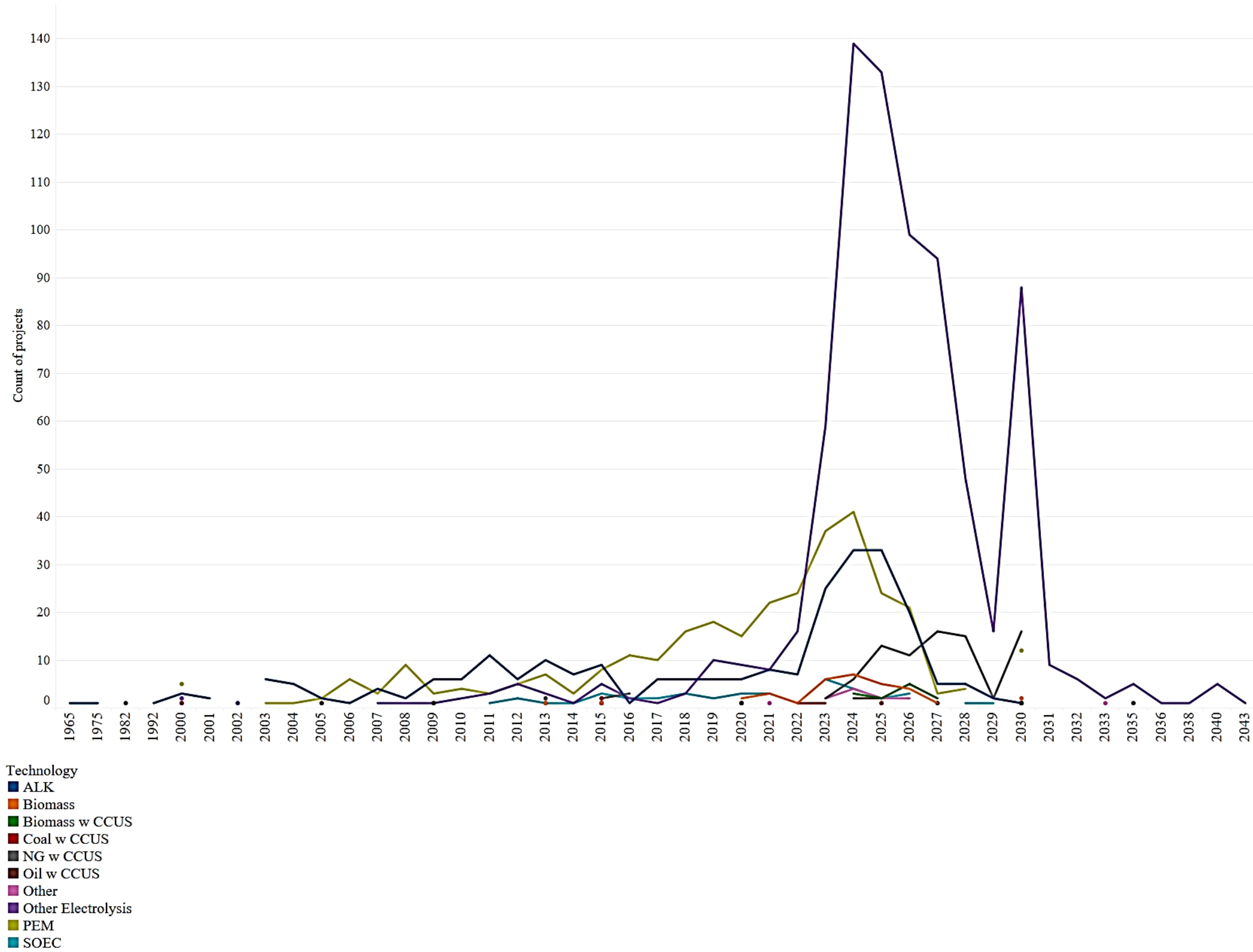

Figure 3. Evolution of hydrogen projects per technology

Source: Authors' own research results based on IEA, 2024.

Diving deeper into the data, the scatter plot presented in Figure 4 shows the individual projects with their respective technologies employed, over time, i.e., by the year of (planned) construction, while considering the logarithm of the installed electricity capacity (log10). This scatter plot shows that, while alkaline electrolysers have been dominant over time, proton exchange membrane electrolysers are gaining field around the world. Moreover, solid oxide electrolysis cells are emerging as a new technology. However, undefined "*other*" electrolysis technologies seem to gain even more field, which could, in fact, hide the previously mentioned technologies – in the sense that these are undisclosed by project promoters for the sake of confidentiality. For a better illustration of the technological trends over time, trends lines are presented in Figure 5, highlighting the trajectory of capacity growth for each technology.

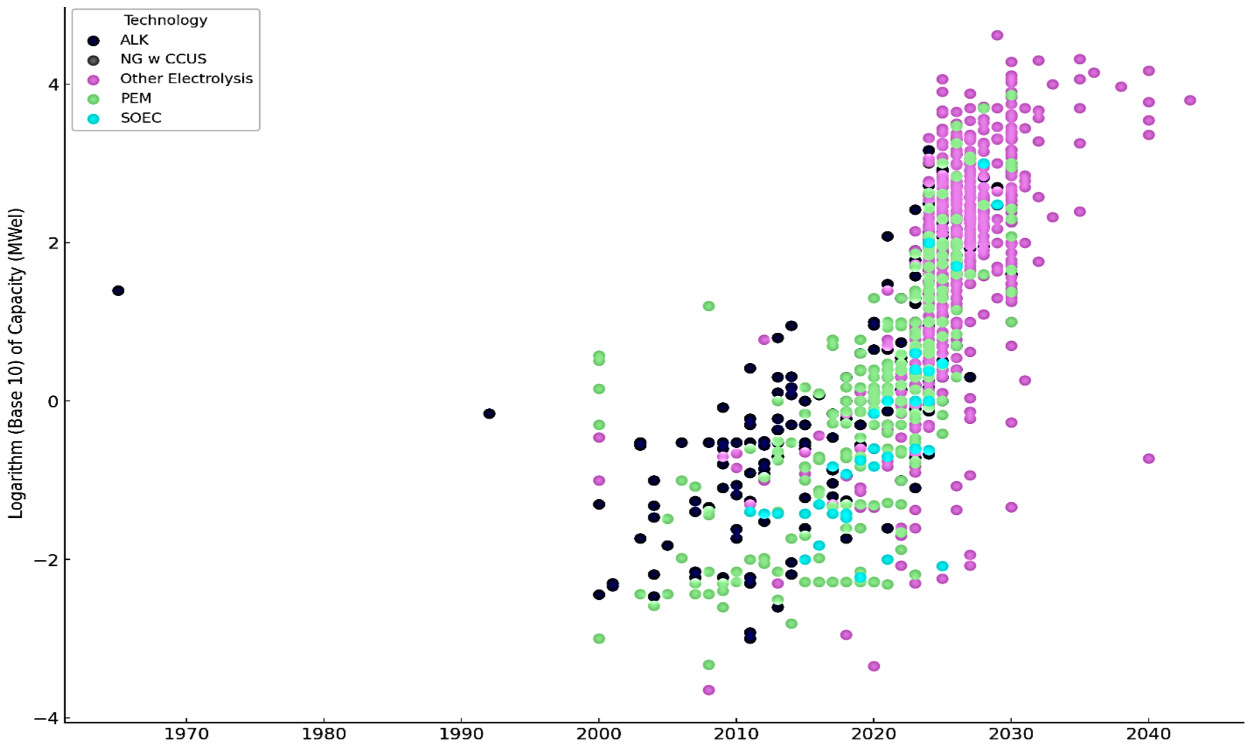

Figure 4. Logarithm of capacity vs. year of construction per technology

Source: Authors' own research results based on IEA, 2024.

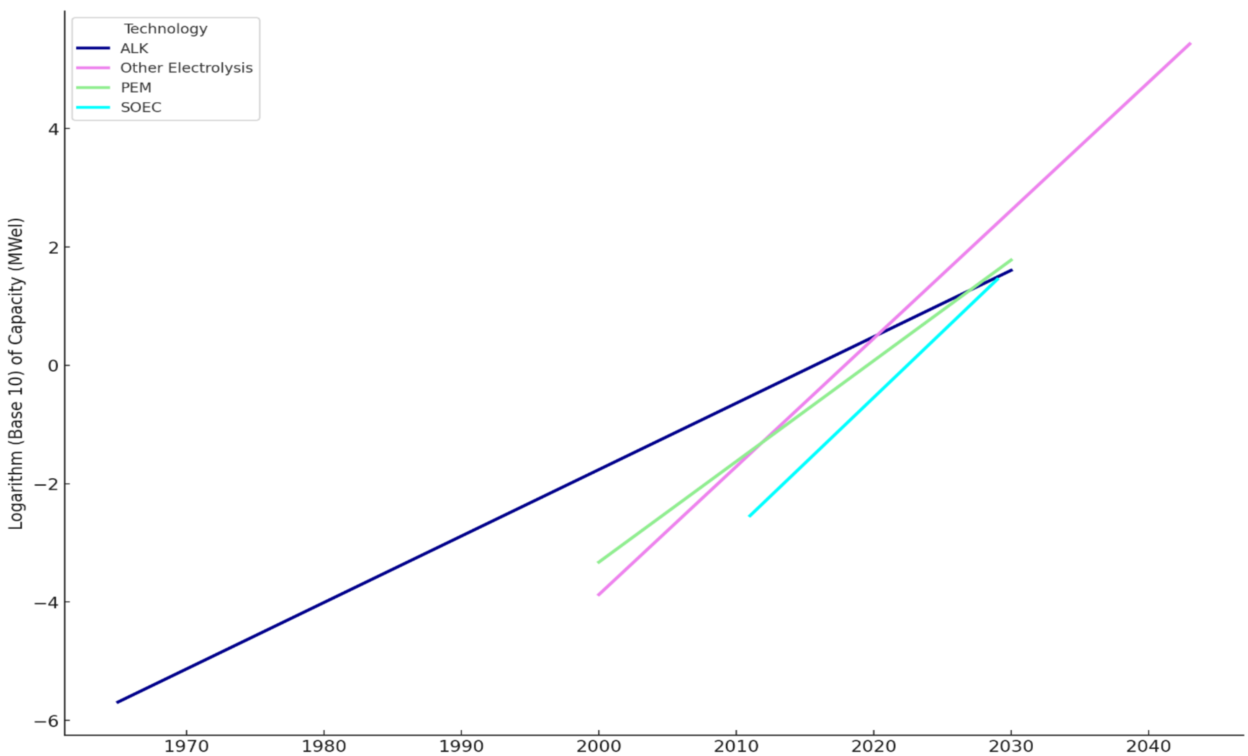

Figure 5. Installed capacity trend lines by year and technology

Source: Authors' own research results based on IEA, 2024.

Renewable energy analysis of hydrogen projects

If societies and economies are to abide by the Paris Agreement, then an important question is whether the hydrogen projects are contributing to the reduction of emitted greenhouse gases from current and future planned activities by increasingly employing renewable energy sources. So, to what extent are these helping mitigate climate change?

Most countries with electrolysis projects, are having dedicated renewable energy sources for the hydrogen production facilities, while some are planning to use the excess renewable energy injected into the national grid in times of abundant solar and wind power generation, while some others are planning to use electricity from the grid or nuclear energy.

Spain, Australia and Germany are the countries with the highest number of dedicated renewable energy projects for hydrogen production, while Chile, India and Spain are leading in terms of number of projects using renewable electricity in times of abundance ("*grid+renewables*"), and eventually France, Germany and Finland are leading when it comes to projects using electricity from the grid. Finally, the United States, the Republic of Korea and eventually China are leading with the highest number of projects using nuclear power, as specified in the database. However, it could be argued that France is also using a significant amount of nuclear power since the electricity from the grid is powered by nuclear energy.

Diving further into the question whether project promoters are seeking to reduce greenhouse gas emissions, looking at the source of renewable energy employed in hydrogen projects can be of great value. When it comes to all the projects contained in the IEA database that are having a dedicated renewable energy plant associated with the hydrogen production facility, most of the projects have undisclosed energy sources ("*other/various*" and "*unknown*").

To obtain a better understanding of the projects using renewable energy sources, it is important to include in the analysis the installed capacity of these projects (MW). As such, Figure 6 shows that globally there are 98.977 MW of solar photovoltaic (PV) energy, followed by 67.288 MW of dedicated offshore wind projects for hydrogen production in the database, further followed by 41.384 MW of onshore wind, and eventually followed by hydropower with 9.714 MW.

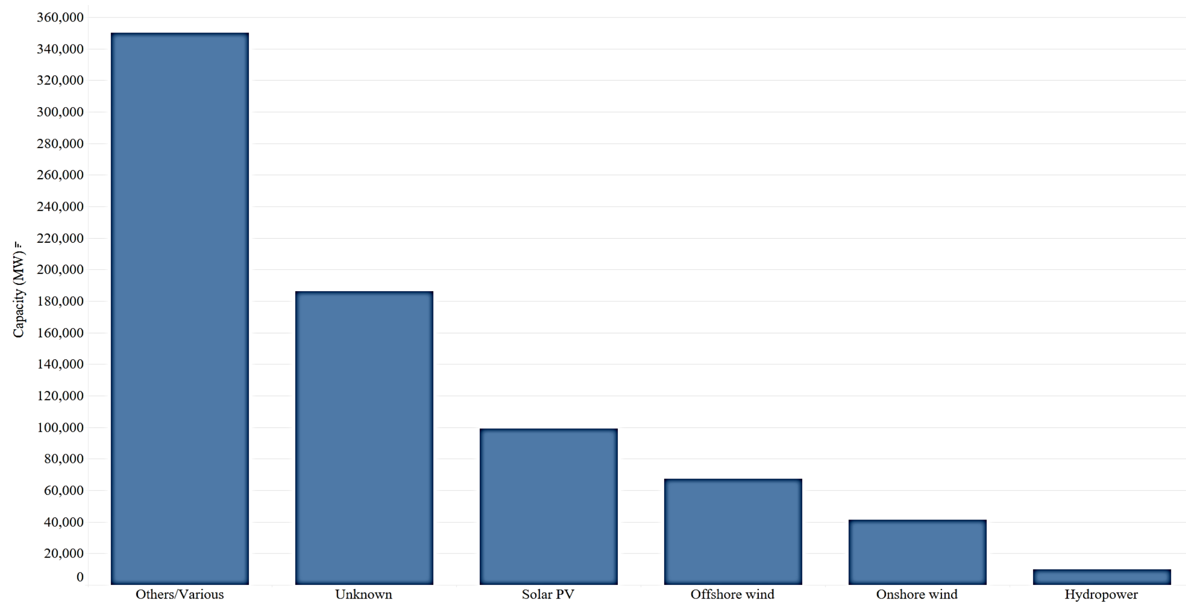

Figure 6. Type of renewable electricity for electrolysis projects

Source: Authors' own research results based on IEA, 2024.

DOI: 10.2478/picbe-2024-0102, pp. 1197-1211, ISSN 2558-9652 |
Proceedings of the 18th International Conference on Business Excellence 2024

Diving deeper into the data, the scatter plot presented in Figure 7 shows the individual projects with their respective dedicated renewable energy source, over time, i.e., by the year of (planned) construction, while considering the logarithm of the installed electricity capacity (log10). This scatter plot shows that, while the very first hydrogen production facilities were using hydropower, onshore wind powered many hydrogen facilities in the early 2010s. However, interestingly, – although it can be considered a late bloomer –, solar photovoltaic energy is emerging at a rapid pace over time, with higher capacities being planned to be installed in the future. Another emerging renewable source to power hydrogen production is offshore wind. For a better illustration of these renewable energy trends over time, trend lines are presented in figure no. 8, highlighting the trajectory of capacity growth for renewable energy sources.

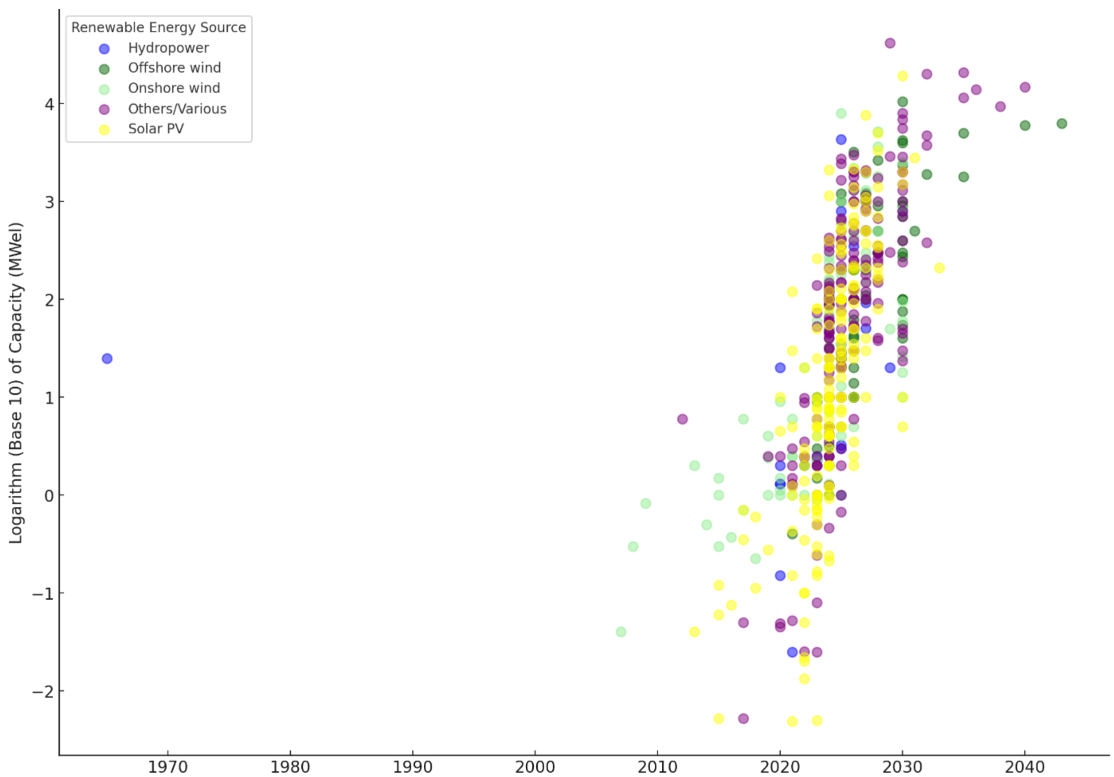

Figure 7. Logarithm of capacity vs. year of construction per renewable energy source

Source: Authors' own research results based on IEA, 2024.

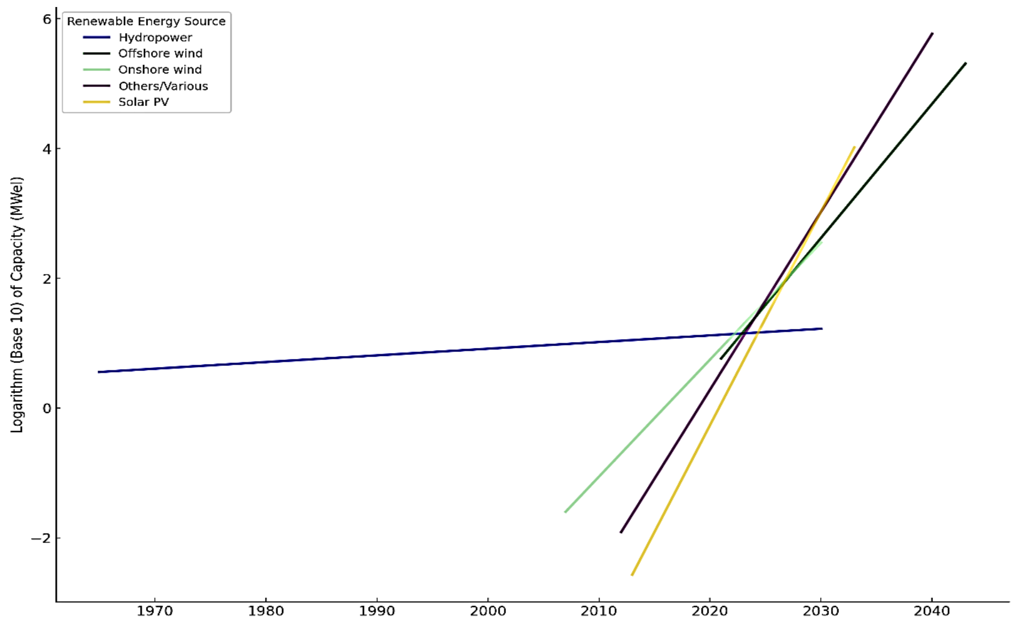

Figure 8. Installed capacity trend lines by year and renewable energy source

Source: Authors' own research results based on IEA, 2024.

Green hydrogen product analysis

As shown in Figure 9, the number of green hydrogen projects contained in the database refer to the production of hydrogen itself with an overwhelming majority (73%), while the remaining share is split between ammonia production (16%), methanol (4%), synfuels (3%) and methane (2%) with the rest being various or unspecified products. Therefore, based on the available data, at this point it can be concluded that most green hydrogen products are aimed to produce hydrogen itself, rather than its derivatives.

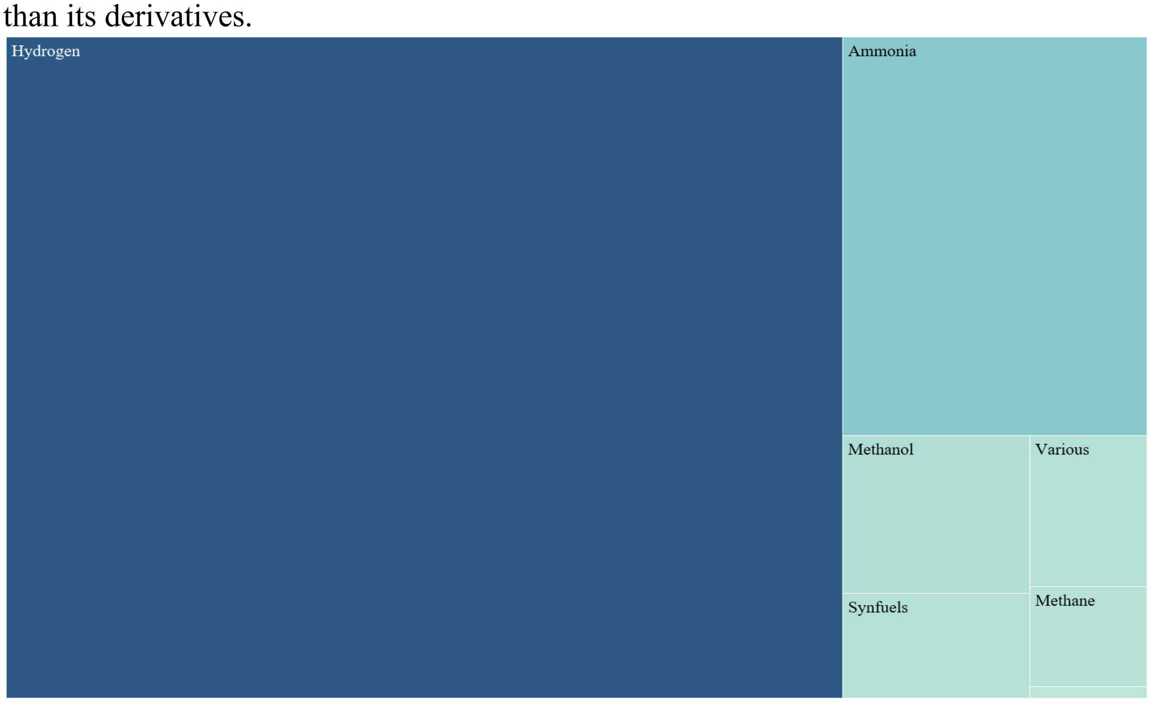

Figure 9. Distribution of "green" hydrogen products, including hydrogen itself

Source: Authors' own research results based on IEA, 2024.

End-use sector analysis

Figure 10 shows that the end-use economic sector that is positioned to benefit the most from green hydrogen production projects globally is by far the mobility sector, followed by ammonia production, other industrial applications, and eventually followed by uses in the power sector, grid injection and others.

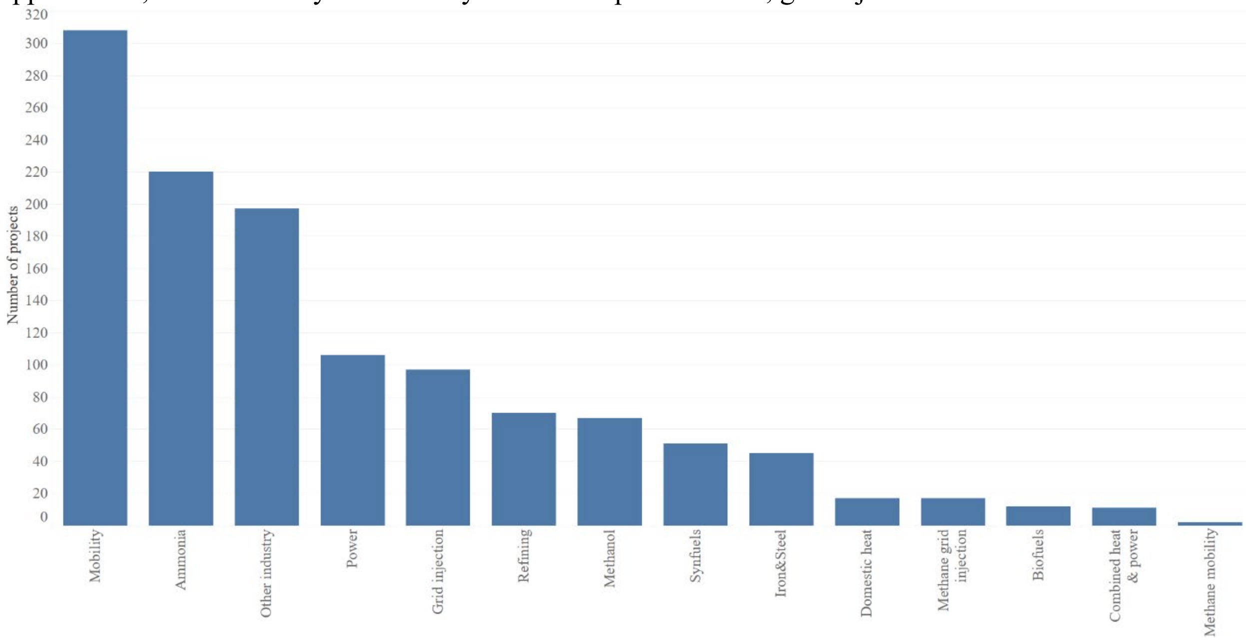

Figure 10. Number of "green" hydrogen projects per economic end-use sectors

Source: Authors' own research results based on IEA, 2024.

Conclusion

In conclusion, this paper has explored the growing significance of hydrogen as a crucial global vector in the energy transition. With the aim of mitigating climate change and materializing the Paris Agreement, governments and businesses around the world are increasingly investing in hydrogen projects.

The analysis of the IEA hydrogen project database has provided valuable insights into the geographic distribution of projects, revealing the leadership of countries like Germany, the United States of America and Australia. Additionally, an increasing number of projects under development is observed over time, indicating the growing momentum for hydrogen.

While the main electrolyser technologies employed were alkaline and proton exchange membrane until the early 2020s, after this period, a high number of projects announced have undisclosed technologies, probably for proprietary reasons. Further, although most hydrogen production projects with dedicated renewable energy sources do not disclose their energy source either, globally, solar photovoltaic energy powers (or is planned to power) most hydrogen projects, followed by offshore wind energy, onshore wind energy and eventually hydropower – to a lesser extent.

These findings emphasize the importance of hydrogen as a clean energy solution and provide useful information for stakeholders making strategic decisions in this evolving and nascent field. As the world continues to transition towards a sustainable, low-carbon future, hydrogen will play a crucial role in decarbonizing various sectors and achieving climate goals.

Subsequent analysis would be beneficial if they were to dive deeper into individual economic end-uses and their derivatives (e.g. hydrogen applications in the mobility sector). As such, this is a limitation of the present paper. Another limitation is the lack of validation from experts in the hydrogen industry which could benefit future assessments greatly.

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