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Research article

Financing low-carbon hydrogen: The role of public policies and strategies in the EU, UK and USA

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Abstract: The goal of this study is twofold: first, to understand the rationales of public policies and possible outcomes on energy systems design behind supporting national hydrogen strategies in three major economic blocs (the EU, UK and USA) and possible outcomes on energy systems design; second, to identify differences in policy approaches to decarbonization through H_2 promotion. Large-scale expansion of low-carbon H_2 demands careful analysis and understanding of how public policies can be fundamental drivers of change. Our methodological approach was essentially economic, using the International Energy Agency (IEA) policy database as a main information source. First, we identified all regional policies and measures that include actions related to H_2, either directly or indirectly. Then, we reclassified policy types, sectors and technologies to conduct a comparative analysis which allowed us to reduce the high degree of economic ambiguity in the database. Finally, we composed a detailed discussion of our findings. While the EU pushed for renewable H_2, the UK immediately targeted low-carbon H_2 solutions, equally considering both blue and green alternatives. The USA pursues a clean H_2 economy based on both nuclear and CCS fossil technology. Although there is a general focus on fiscal and financing policy actions, distinct intensities were identified, and the EU presents a much stricter regulatory framework than the UK and USA. Another major difference between blocs concerns target sectors: While the EU shows a broad policy strategy, the UK is currently prioritizing the transport sector. The USA is focusing on H_2 production and supply as well as the power and heat sectors. In all cases, policy patterns and financing options seem to be in line with national hydrogen strategies, but policies' balances reflect diverse institutional frameworks and economic development models.

Keywords: hydrogen; public policies; energy strategy

JEL Codes: Q28, Q42, Q48

1. Introduction

1.1. Motivation

The major motivation of this study is to understand the rationales of public policies supporting national hydrogen strategies in three major economic blocs (the EU, UK and USA) and possible outcomes on energy systems design. Public policy choices regarding decarbonization and use of alternative energy sources can actively influence public financing as well as improve the economic/financial attractiveness to companies interested in scaling up hydrogen projects. In particular, highly energy-consuming industries are considered to be in the front row of potential interested companies. It is widely recognized that public policies can play a decisive role in innovation diffusion, namely, in innovative energy technologies. This is particularly – but not exclusively – true for developing countries (Surana and Anadon, 2015). Moreover, for less mature energy technologies, both institutional and utility investors have high aversion concerning non-regulated revenues, which is the case for green hydrogen and energy storage systems (Côté and Salm, 2022). Even institutional investors tend to show some kind of reluctance to invest in greenfield ventures. Consequently, reducing market risk becomes crucial.

The current performance of the energy sector is unsustainable, with about two thirds of the anthropogenic greenhouse gas emissions originating from this sector (Iribarren et al, 2020). Alongside application of other viable strategies to close the gap into a cleaner energy sector, hydrogen (H_2) seems a promising solution. Due to hydrogen's technical properties (high mass energy density, low weight and facile electrochemical conversion), it can be transported overseas or through long distances using pipelines, contributing to a diversity of functions (Oliveira, Beswick & Yan, 2021). In fact, H_2 can have a significant impact in optimizing grid balance, by storing the surplus renewable power when electricity demand is low, and in the decarbonization overall process, being an alternative solution in hard-to-electrify sectors (heavy industry or long-distance transport) and a zero-carbon feedstock in chemicals and fuel production (Van Renssen, 2020). It arises not only as an alternative but also as a complement to the large investment in renewable energy and global energy transition.

Currently, green H_2 production cost is still well above that of grey H_2 and even that of blue H_2 (natural gas-based H_2 production with carbon capture and storage), and major cost reductions depend on heavy investments in research and development (R&D) and large demonstration electrolyzer projects, as well as cheap renewable electricity supply. As Cammeraat et al., (2022) identify, even in countries strongly supporting clean transition, green H_2 competitiveness remains frustrating compared with fossil-fuel based alternatives. Those authors also recognize that firms are not primarily interested in innovation but rather oin commercialization as the recent increase of H_2 trademarks may suggest. This may be understood as an anticipation of a growing H_2 market pulled by government subsidies. Thus, national H_2 strategies seem to rely more on financial support for the deployment of large new electrolyzers than on direct support for innovation.

Despite the effort on new alternatives, there is still a lot of uncertainty about novel H_2 projects. Even countries most involved in energy transition present ambiguous strategies for renewable H_2 and low-carbon H_2 settlement, as well as insufficient information about emissions intensities (Chen et al., 2019). Stimulation seeking a low-carbon H_2 economy is dependent on several variables, namely, costs and technical efficiency, but policy measures are also crucial to promote a proper energy transition (Van de Graaf et al., 2020). Furthermore, it is essential for national institutions to participate in shifting the economy towards a long-term, strategic perspective to achieve the significant socio-technical transition. This shift requires a systemic change in policies and decision-making processes that prioritize building a sustainable future for future generations, rather than solely focusing on short-term economic gains (Falcone et al., 2018).

Meanwhile, in liberalized energy markets some factors may compromise new energy technologies' implementations: namely, low-carbon technologies. Their higher costs compared with mature technologies and a relatively low cost of CO_2 are the most important factors, among others (Krozer, 2019). As the Netherlands case study clearly shows, even strong industrial decarbonization support programs together with carbon levy are unable to turn green H_2 projects financially acceptable (Anderson et al., 2021). Acemoglu et al., (2012) also refer the "case of path dependency in favor of technological change", thus locking the economy into the use of a specific energy technology, namely, non-renewables. As for the renewable energy sector, green H_2 large-scale expansion demands a careful analysis and understanding the way(s) public policies can be a fundamental driver of clean H_2 promotion.

In the future, H_2 is expected to play a significant role alongside other renewable energy sources to establish a 100% sustainable economy; while renewable energy is expected to cover most areas where electrification is possible, there are still gaps in decarbonization that cannot be reached without a bridge (Oliveira et al., 2021). It has the potential to fill these gaps due to its flexibility, despite the current inefficiencies in its value chain. To achieve this, it is important to identify the role of public policies in stimulating the growth of H_2, considering that private financing for clean H_2 production technologies presents several risks. Thus, public financing will be necessary to reduce the risk associated with new technologies.

In this context, the role of the state and public entities will be crucial in reducing these risks. One key area for investigation is to identify similarities and differences in the types of public strategies used to incentivize the H_2 economy in the three analyzed regions. By better understanding the role of public policies and financing in this field, we can help accelerate the transition to a more sustainable energy future.

1.2. Core objective

The core objective of this study is to identify the following:

- Common and specific approaches of the proposed low-carbon H_2 economies
- Main similarities and differences regarding specific H_2 economy indicators
- Governmental financing initiatives towards low-carbon H_2 economies
- Coherence between low-carbon H_2 national goals and public policy support

Public policies will naturally influence the emergence of H_2-based economies, considering the high-risk profile of nascent projects, which generally have low technological maturity and are dependent on large investments with uncertain returns. Governmental programs, policies and overall access to credit have the potential to mitigate negative impacts against macroeconomic issues that can act against novel projects (da Silva César et al., 2019). Through instauration of environmental targets, regulations and application of economic/financial tools, governmental entities are determining factors in how sustainable paths may develop, based upon knowledge of economic structures (size of companies, weight of heavy industry in the country's GDP) and infrastructures.

1.3. Contribution

The major contribution of this paper is to present a systematic comparison and critical analysis of H_2 national strategies, public policy choices and their financing options. Building upon major recent literature on hydrogen's potential contribution to a low-carbon economy and national roadmaps, our focus is the role of public policies in financing new challenges put by riskier energy technologies.

1.4. Structure of the paper

This paper is structured as follows: Section 2 presents the literature review, focusing on different kinds of public policies involved in the energy transition process toward a low-carbon economy. Section 3 presents the methodological approach, while section 4 shows the main results concerning the EU, UK and USA H_2 roadmaps and their policy priorities. Section 5 discusses coherence between strategies adopted and policy priorities, with a section including the major financing options. Finally, section 6 summarizes the main conclusions.

2. Literature review

2.1. Public policies in energy and environment

Public policies are core tools to promote innovative clean energy. These can work by direct energy policy interventions or by environmental and even fiscal measures. While energy and environment are closely related, the energy transition requires a strong political and technological transformation, as well as social behavior changes, and it should focus on two main priorities: reducing both the carbon intensity of energy and GDP energy intensity (Fankhauser & Jotzo, 2018). Therefore, different kinds of policies and strategies must be involved in a holistic policy framework (IRENA, 2022). Decarbonization goals set by international organizations such as the United Nations (UN), the European Commission (EC) or even by national governments reflect the urgent need to address climate change negative consequences by reducing greenhouse gas emissions. Therefore, there is a need for providing effective public policies that promote the establishment of innovative technologies.

When properly applied, government incentives (tax credits, subsidies, grants) can reduce the overall associated costs of investing in disrupting technologies, making alternative strategies more accessible. Through regulation, fair competition is promoted in different economic sectors, giving market players equal opportunities, while ensuring consumer protection. However, the effectiveness and efficiency of government incentives and regulations in promoting innovation and competition is highly dependent on their design, their implementation method and their alignment with both market trends and consumer demands (Bersalli et al., 2020). Hence, policy designing requires extreme caution, thorough analysis and a comprehensive understanding of the complex interdependencies and challenges involved.

Energy systems are composed of interrelated and diverse elements, lack a central authority and display self-organizing behavior that cannot be fully predicted through analysis of individual components alone (Bale et al., 2015). These characteristics present significant challenges and limitations in the development of new public policies aimed at promoting efficiency and security, economic growth and sustainability within the energy sector.

In the recent past, renewable energy integration is probably one of the most important examples where public policies played a pivotal role. The integration of renewable energy sources into the power system brings both economic and environmental benefits, but it also results in higher levels of variability and uncertainty due to the intermittent nature of these resources (Abujarad et al., 2017). Thus, an increased use of renewable generation needs more demand-side flexibility and storage to assure a stable energy mix (Lezama et al., 2018). Furthermore, market failures arise due to the design of the energy sector, which is primarily geared towards fossil fuel-based generation, as well as the unique characteristics of renewable energy technologies (Polzin et al., 2015). Additional operation and investment costs (integration costs) may be needed, which in turn may act as economic barriers, thus affecting the pace of energy transition (Hu et al., 2018). To reduce these problems, public policies can play a crucial role in addressing these challenges and promoting a smooth transition towards a renewable energy system. This can be achieved through various measures such as financial incentives, regulatory frameworks and technical assistance.

2.2. Fiscal policy and finance incentives in energy transition

Having distinct origins and objectives, the interaction between energy, climate and fiscal policies is becoming increasingly significant, and understanding their relations is mandatory for policy deployment (Hoogland et al., 2022). Despite limited analysis on policy effectiveness presented in the literature, some authors highlight the importance of direct subsidies and public intervention under a policy-driven context, instead of following market patterns (Marques & Fuinhas, 2012). Regarding the energy transition, there is a global trend of utilizing fiscal policy interventions as trials to facilitate low-carbon alternatives and enable their sustainability amidst the dominance of fossil fuel-based energy systems (Roy, Ghosh, Ghosh & Dasgupta, 2013). Additionally, incentives in the form of financial and monetary support play a main role in energy policies and have been utilized to speed up the development of renewable energy projects (Polzin et al., 2015).

Energy financial incentives and regulations are divided into price-based, such as feed-in tariffs (FIT) and feed-in premiums (FIP), aimed at offering stable and predictable returns on investment, and quantity-based policies, including targets for renewable energy integration and schemes like auctions or renewable portfolio standard (RPS) with flexibility mechanisms like green certificates (Bersalli et al., 2020). As for price-based mechanisms, FIT and FIP were largely implemented in Europe during the early 2000s, whereas in the United States, RPS programs have emerged as the most prevalent policy, experiencing a 4.2% increase from 2009 to 2019 (Greenstone & Nath, 2019). Tax credits and incentives to invest in new innovative projects were also used. However, according to Bersalli et al., (2020), there are very few cases where they represent the main support policy. Yet, there are contrasting results on the impacts of incentive policies. In consonance with a recent study in Jordan, adopting FITs and subsidy policies is expected to result in a high level of clean energy security by 2050, which will enhance energy capabilities and reduce global warming (Al-Refaie, & Lepkova, 2022). Other authors suggest that quantity-based renewable energy standards are a more effective way of promoting innovation and investment incentives among firms compared to R&D or price subsidies (Paulson & Khanna, 2022). Nevertheless, the effectiveness of policy tools can vary greatly based on the technology's stage of development and the unique design elements of each policy tool (Bersalli, Menanteau & El-Methni, 2020). In Europe, for example, it appears that price instruments positively influence policy outcomes rather than quantity-based measures (Haas et al., 2011; Faure et al., 2020; Willner & Perino, 2022). Empirical findings also show that grants, R&D, taxes, certification and policy support have a positive impact on renewable energy capacity, but direct investments, loans and net metering instruments have no stimulating effect on renewable energy deployment. These results suggest that regulations and direct investments can act as deterrents to the growth of renewable energy capacity (Bölük & Kaplan, 2022). Meanwhile, renewable energy policies need to be reviewed, reformed and strengthened, as was shown by the deficiencies in Iran's five-year National Development Plan: The lack of sufficient attention to renewable heat and fuel was one of the weaknesses detected (Dehhaghi et al., 2022). Moreover, when energy policies are customized to the local circumstances of each region, returns tend to be more efficient, helping to clarify which is the novel technology that is more appropriate to invest in (Hafeznia et al., 2017; Zahedi, Zahedi & Ahmadi, 2022).

As stated above, most econometric studies in the literature suggest that both financing and fiscal measures are effective in general, but further empirical evidence is needed to determine the differences between specific instruments. Regarding H_2 public policies, the academic literature offers limited empirical evidence on their effectiveness or appropriate design due to their novelty. Nevertheless, some authors (da Silva Veras et al., 2017; Shin et al., 2019; Jones et al., 2020; de las Nieves Camachoet al., 2022; Jafari et al., 2022; Park et al., 2022) have started to investigate this issue, with a particular focus on the transportation sector, highlighting the importance of fiscal policy as a significant tool to positively impact competitiveness in fuel-cell vehicles. There are also some studies with a broad spectrum of analysis on the "hydrogen economy" which highlight the importance of considering the interactions among the political, techno-economic, technical, market and social dimensions in future policy planning (Moore & Shabani, 2016; Bianco & Blanco, 2020; Chu, et al., 2022; Gordon et al., 2023). Another study stated that production tax credits and electricity incentives were more effective in promoting low-carbon hydrogen production than capital subsidies, steam methane reforming bans or higher carbon taxes and that a strategic deployment of policies over time was more effective than cumulative subsidies (Talebian et al., 2021). Regulatory frameworks at the national level play a crucial role in facilitating the transition towards a green economy through green hydrogen production, with studies highlighting the need for policy alignment and reform to support the growth of the H_2 market and accelerate the decarbonization process (Ballo et al., 2022; Rodríguez et al., 2022). On the other hand, experts also recognize the existence of several negative criticalities that may hinder energy transition projects when government policies include some uncertainty (Falcone & Sica, 2019; Howlett, 2022).

3. Methodology

Due to the early stage of hydrogen's role in energy systems, conducting a comprehensive analysis of hydrogen-related political measures is challenging. More importantly, it may be too soon to assess policy effectiveness. However, it is essential to identify differences among the three economic blocs in their political strategies to promote low carbon H_2 and to recognize both technologies and target sectors.

The study comprised two main parts, with the first part consisting of a descriptive analysis of the three blocs' official H_2 strategies and their main financing initiatives. The investigation was supported by official documents, academic literature and technical reports to better understand the core characteristics and assumptions by the three regions. In the second part, a policy categorization scheme was proposed.

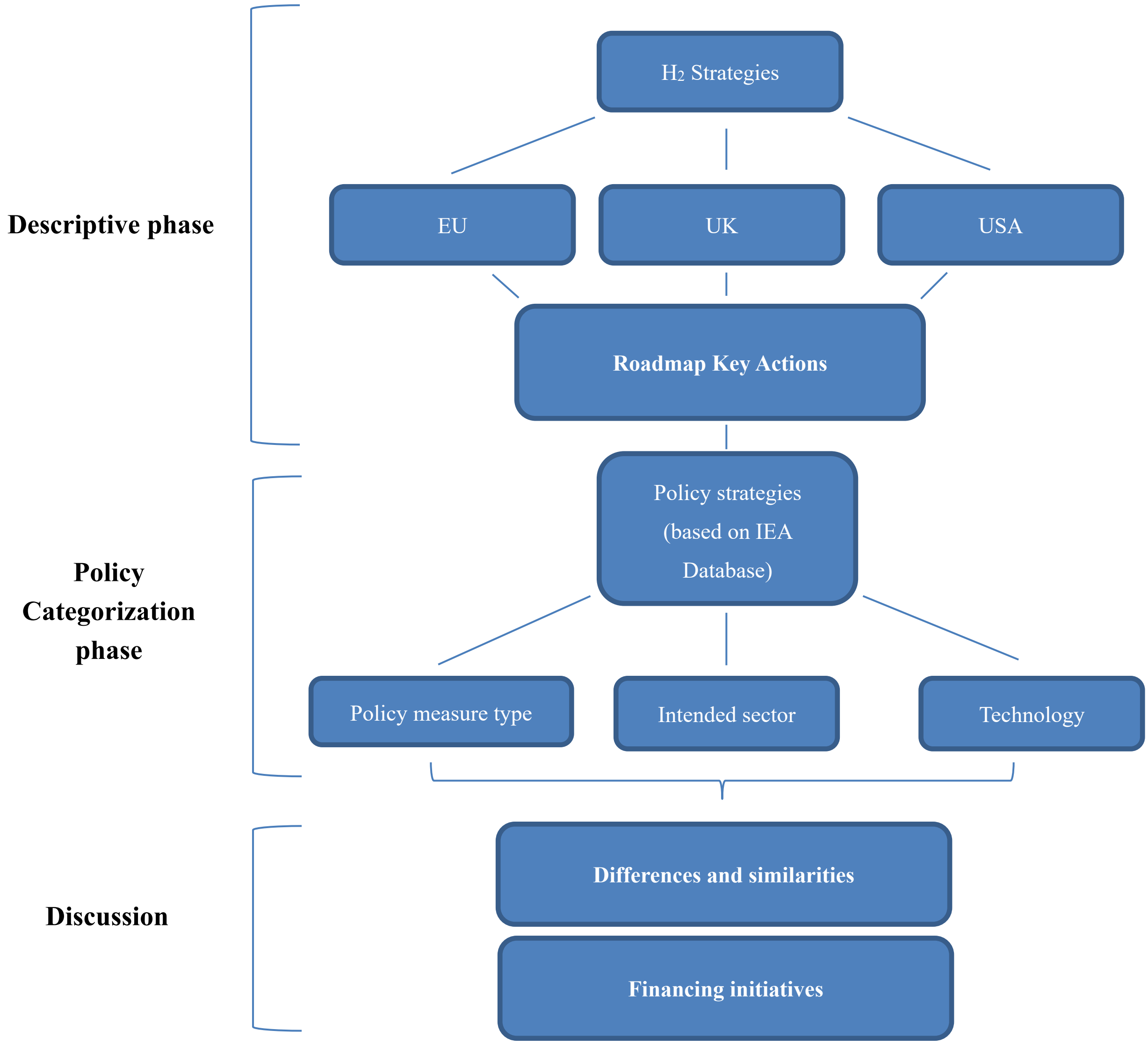

Figure 1. Methodology framework.

Our methodological approach remained essentially economic, while we used the IEA policy database as a main information source (IEA[2], 2022). It allowed access to a wide range of information on energy transition governmental actions, namely, the IEA/IRENA Renewable Energy Policies and Measures Database, the IEA Energy Efficiency Database, the Addressing Climate Change database, and the Building Energy Efficiency Policies (BEEP) database. Our methodological approach can be schematically presented as in Figure 1.

The first step in this process involved identifying all policies and measures of all regions that include actions related to H_2, either directly or indirectly. It considered factors such as policy, measure types, fiscal incentives or regulatory frameworks and other relevant factors to identify main similarities or differences among them. To collect information from the IEA database, we primarily verified the presence of the keyword "hydrogen" in the three regions, and then we organized the data by type of policy, target sector and technology.

In the second step, it was necessary to reclassify policy types, sectors and technologies to conduct a comparative analysis. Our proposal aggregated similar/equivalent typologies given by the IEA (Tables C.1, C.2 and C.3 - Appendix). This procedure reduced the high degree of ambiguity in the database when we assume an economic perspective, by creating a more specific and consistent classification system for hydrogen-related policies and measures for all regions. It is important to note that each one of the policies involved may have several associated categories, and our aim was to capture and maintain as much relevant information as possible. In the third step, we created comparative tables and graphics for the three regions. By assessing the frequency of each category, we can gain insight into the relationships between policy types, sectors and technologies in each region.

In the final stage, a detailed discussion was carried out. A comparative table aggregates the strategies and policies of all blocs by highlighting various proposed indicators. Additionally, a section was included to summarize the allocation of funds in the latest H_2 financing initiatives, providing a broader perspective on the overall funding landscape.

4. Results

Hydrogen roadmaps and national strategies reflect a government's vision and the fundamentals translated by public policies. These should include well-defined targets for deploying low-carbon production and create a new market environment to stimulate demand (IEA[1], 2021).

4.1. European Union

The European Hydrogen Roadmap (Hydrogen Strategy for a Climate Neutral Europe) strengthens the role of H_2 in the European Green Deal, establishes H_2 implementation marks until 2050 and reinforces investment priorities in the H_2 supply chain through initiatives such as the Next Generation EU or 2021–27 Multiannual Financial Framework plans (European Commission, 2020). Measures concerning the phasing out of coal and decarbonizing gas are already being deployed among several member states, while promoting a fully integrated, interconnected, digitalized and carbon-neutral energy market (EU Commission, 2019). In the long term, the interplay between different low-carbon technologies such as solar PV, wind energy and carbon-capture and storage (CCS) is expected to play a core role in energy supply sectors (Antenucci et al., 2019). The diversity of these technologies is essential to decarbonization, and their contribution is expected to reduce fossil fuel usage from 80% to 50% of total global energy in 2050 (Prăvălie & Bandoc, 2018). In addition, Europe already has the EU Emissions Trading System in force, a key tool used for tackling greenhouse gas emissions over the last years (since 2005), being the world's first major carbon market implemented (European Commission, 2022). Table 1 summarizes main actions considered in the EU H_2 Strategy:

Table 1. EU key actions.

Period	Production	Network	Use
2020–2024	Scaling up of large electrolyzers (up to 100 MW); Existing decarbonizing H_2 - 6 GW of renewable H_2 (1 million tons renewable H_2 installations)	Initial deployment close to demand centers	End-use applications adaptation for H_2; Planning of both transport and regulatory frameworks
2024–2030	40 GW of renewable H_2 (10 million tons renewable H_2)	Infrastructure expansion (new and repurposed from natural gas); Logistical infrastructure development (refueling points, storage facilities)	Research and innovation funding emphasized
2030 +	Large-scale deployment and demand	Mature H_2 network	Mature H_2 technologies

Source: Adapted from Erbach & Jensen, 2021.

The European H_2 strategy includes 20 key actions to promote sustainable H_2 development, supported by a chain of supportive programs (European Commission[2], 2022) (Table A.1 – Appendix A). The European Clean Hydrogen Alliance, a group formed by European member states, is the central pillar serving as an investment pipeline, ensuring adequate policy coordination and bringing together primary stakeholders, such as industry, public authorities and civil society (Erbach & Jensen, 2021). It will be supported by R&D provided by the Clean Hydrogen Partnership, the successor of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), having taken over its legacy portfolio and pursuing clean H_2 solutions (Clean Hydrogen Partnership, 2022). Since 2014, member states can also be involved in projects with strategic significance for achievement of future targets. Through the initiative "Important Projects of Common European Interest" (IPCEI), European countries contribute for the growth, employment and competitiveness of the European Union industry (European Commission[3], 2022). This will affect the new H_2 economy as well. The Innovation Fund is also one of the world's largest funding programs focusing on low-carbon technologies. Financed by the EU ETS, it is expected to assist EU innovative projects with €38 billion from 2020 to 2030, depending on the carbon cost (European Commission[4], 2022). Finally, REPowerEU is a recent program that consists of a plan to decrease energy dependency from Russia until 2030. This program intends to mitigate the rising energy prices to European consumers, to promote new gas storage measures every year and to optimize market design by diversifying energy supplies (European Commission[5], 2022). It includes a target of 10 million tons of domestic green renewable production per year complemented by another 10 million tons from imports in 2030, an updated ambition from the previous 6 million tons predicted by the revised Renewable Energy Directive (REPowerEU Plan, 2018).

In general, the EU strategy comprehends three phases towards a sustainable energy system (2020–2025, 2025–2030 and 2030–2050), recognizing the need for a gradual trajectory, initially including blue H_2 projects and moving towards a climate-neutral energy system mostly based on renewable electricity, where the nuclear option is still an open debate (Clifford, 2022; Maisonneuve, 2022). The

H_2 ecosystem was launched in the first phase, in which at least 6 GW of renewable H_2 electrolyzers were to be installed until 2025, to achieve one million tons of renewable H_2. The second stage (2025–2030) states a target of at least 40 GW of renewable H_2 electrolyzers, pushing the production and transportation of renewable H_2 to around 10 million tons. From 2030 onwards, renewable H_2 will be ready to be deployed at a large scale, covering most hard-to-decarbonize sectors (European Commission, 2020). Considering infrastructure, the EU goal is to inject H_2 into the gas grid in the immediate future, in which the percentages to be deployed depend on each member state's ambition.

4.2. United Kingdom

The UK Hydrogen Strategy, launched in August 2021, states that the UK has ideal conditions to rapidly build a low-carbon H_2 economy, due to its geography, geology, infrastructure and general expertise (UK Government, 2021). Table 2 presents the UK's main targets.

Table 2. UK key program targets.

Period	Production	Network	Use
2020–2024	Small-scale electrolytic production	Direct pipeline, co-location, trucked (non-pipeline) or onsite use	Some transport (buses, early HGV, rail & aviation trials); industry demonstrations; neighborhood heat trial
2025–2027	Large-scale CCUS-enabled production in at least one location; electrolytic production increasing in scale	Dedicated small-scale cluster pipeline network; expanded trucking & small-scale storage	Industry applications; transport (HGV, rail & shipping trials) village heat trial; blending (tbc)
2028–2030	Several large-scale CCUS-enabled projects & several large-scale electrolytic projects	Large cluster networks; large-scale storage; integration with gas networks	Wide use in industry; power generation & flexibility; transport (HGVs, shipping); heat pilot town (tbc)
2030 +	Increasing scale & range of production (nuclear, biomass)	Regional or national networks & large-scale storage integrated with CCUS, gas & electricity networks	Full range of end users incl. steel; power system; greater shipping & aviation; potential gas grid conversion

Source: Adapted from UK Government, 2021.

The ambition to become one of the "global leaders" in H_2 by 2030 is set through the aggregation of the UK Hydrogen Strategy objectives with other synergizing programs (Sixth Carbon Budget, 2020 Energy White Paper, Industrial Decarbonization Strategy, Net Zero Strategy) focusing on both economic and environmental concerns. Previously, the UK had already strengthened its goal to promote a Green Industrial Revolution when it presented its Ten Point Plan to pursue a new, competitive low-carbon H_2 industry as one of its priority sectors (UK Government, 2020). Besides including £500 million to develop low-carbon H_2, the government guarantees full support for carbon capture technologies' scaling-up in the main industrial clusters (Baker, 2022). It was also in this document that targets were set for low-carbon H_2 production, initially with 1 GW of production capacity by 2025 and 5 GW production capacity by 2030. More recently, the British Energy Security Strategy highlighted the importance of the low-carbon H_2 economy considering both energy security supply and decarbonization urgency, influencing a new decision by the government that doubled the UK's ambition to up to 10 GW production capacity by 2030, with half coming from electrolytic H_2 (UK Government, 2022).

4.3. USA

Under the Biden administration, the US assumed ambitious objectives such as a net-zero-emissions economy by 2050 (with 50–52% reduction by 2030) or a 100% carbon-pollution-free electric sector by 2035. More recently, the US Department of Energy (DOE) announced a $62 billion allocation in the framework of the Infrastructure Investment and Jobs Act, known as the Bipartisan Infrastructure Law (BIL), which will enable around $9.5 billion for clean H_2 development (DOE, 2022). With the BIL, a new Office of Clean Energy Demonstrations (OCED) was established to fill a critical innovation gap, allowing novel technologies to reach real world market conditions (DOE, 2021).

The US government assumes that the country is perfectly positioned to seek a "world leading" H_2 economy, claiming a lot of abundant, low-cost primary energy sources and a large industrial sector capable of scaling of a hydrogen economy (McQueen et al., 2020). The first draft of the US H_2 strategy, published in September 2022, focused on three main priorities: (1) strategic targeting of high-impact uses for clean H_2, recognizing that H_2 brings benefits in hard-to-decarbonize sectors (heavy industry, heavy-duty transport and energy storage), especially in early stages of development; (2) reduction of low-carbon/clean H_2 associated costs, through ambitious programs such as a Hydrogen Energy Earthshot (Hydrogen Shot); and (3) regional network development, promoting clean H_2 production and its use in proximity, enabling a "critical mass infrastructure" to support future scaling-up and market growth (DOE, 2022). On the same document, the US government committed to execute planned actions across the near term (until 2025), midterm (2026–2029) and longer term (2030–2035). These included a National Strategy and Roadmap constant updating every three years, work on a Clean Hydrogen Standard within five years, selection and development of four regional clean H_2 hubs; a focus on electrolyzer R&D and achieving a $ 2/kg target for green H_2 production, and a focus on additional manufacturing (of clean H_2 equipment) and recycling R&D.

The Department of Energy foresees three different phases towards a hydrogen economy, mainly based on estimated break-even and the relative attractiveness as a decarbonization solution (DOE, 2022). This gradual development will affect heavy industry clusters (refining, ammonia production) and heavy transports in the first phase. For the second phase, it is expected that wider ranges of both industry (fuel, steelmaking and feedstock) and transportation solutions will be included, as well as energy storage and power generation using H_2. The last phase will include a massive scaling-up of H_2 uses in energy, industrial and transportation sectors. Surprisingly, H_2 blending into natural gas infrastructure is only present at this phase (Table B.1 – Appendix B).

Finally, it is important to note the US will continue to rely on fossil-fuel resources and nuclear power plants to support future H_2 development that, together with the lack of a nationwide coal phasing-out timeline or carbon pricing, can potentially contribute to a lagged renewable H_2 market development due to competitiveness disadvantages (Cheng & Lee, 2022).

4.4. Policy categorization

In total, we considered 14 policies in the EU, 28 in the UK and 16 in the USA. The main criterion for evaluating the policies was their inclusion of hydrogen-focused measures. Based on the analysis of IEA's policy database, it is notable that the UK stands out in comparison to the other two blocs, with almost twice as many mentions of "hydrogen" in its policy strategies as the two other economic blocs. Tables 3, 4 and 5 present the considered policies and measures for each one (EU, UK and USA, respectively).

Table 3. EU policies and measures.

European Union	Type	Sector	Technology	Year	Status
Co-operation Agreement Signed with the USA on Energy Research	IC	MS	-	2001	In force
Clean Urban Transport for Europe (CUTE) - Hydrogen and Fuel Cell Buses	F	H2PS; T; FP	T	2001	Ended
Seventh Framework Program for Research and Technological Development (FP7)	F	PH; FP; MS	PH	2007	Ended
Central European Green Corridors: Implementing a fast-charging network for EVs in Central Europe.	F	T	T	2014	Ended
Hydrogen Strategy	SP; R; TFL	H2PS; FP; MS	HE	2020	In force
EU Strategy for Energy System Integration	F; SP; R; TFL	MS	-	2020	In force
Funding for innovative projects for decarbonization	SP; TFL	MS	-	2021	In force
EIB investments for climate action and clean energy, sustainable transport, communications	F	MS	-	2021	In force
Proposal on the regulation for the deployment of alternative fuels infrastructure (repealing EU Directive 2014/94/EU)	R	T	T	2021	Announced
European Raw Materials Alliance	F; IC	M	IP	2021	In force
Cross-border energy infrastructure, new rules for TEN-E	SP; R; TFL	PH; TR; FP; MS	HE; T; ES; FP	2021	In force
Approval of the IPCEI project Hy2Use	F	H2PS; FP; TR	-	2022	In force
RePowerEU Plan: Joint European action on renewable energy and energy efficiency	TFL; F; R	PH; I; MS	HP	2022	In force
RePowerEU Plan: Joint European action on gas supply security	TFL; F; R	PH; I; MS	HE; I	2022	In force

Policy types: F – Fiscal and finance, SP – Strategic Plan, TFL – Targets and framework legislation, R – Regulation.

Policy target sector: H2 Production and Supply – H2PS, Power and Heat – PH, Fuel Processing – FP; Transport – T, Transmission – TR, Industry – I; Buildings – B, Mining – M, Multi-sector – MS.

Policy technology sector: Hydrogen production (not specified) – HP, Hydrogen electrolysis – HE, Carbon Capture Systems – CCS, Transport – T, Infrastructure – I, Energy Storage – ES, Power and Heat – PH, Fuel Processing – FP, Industrial Processing – IP, Nuclear – N.

Table 4. UK policies and measures.

United Kingdom	Type	Sector	Technology	Year	Status
The Green Fuels Challenge	SP;	MS	-	2001	Ended
Environmental Transformation Fund (ETF)	F	PH; MS	PH	2007	Ended
Ultra low emission trucks scheme	F; R	T	T	2017	In force
Hy4Heat: Hydrogen for Heating Demonstration Program	F	H2PS;	PH; Fuel	2017	In force
Ten Point Plan for a Green Industrial Revolution - Point 2: Low Carbon Hydrogen	F; TFL	H2PS; FP	HE; CCS; IP; T; ES;	2020	In force
Ten Point Plan for a Green Industrial Revolution - Point 3: New and Advanced Nuclear Power	F; TFL;	PH; MS	N	2020	In force
Ten Point Plan for a Green Industrial Revolution - Point 4: Zero emissions vehicles	SP; TFL; F	T	T	2020	In force
Ten Point Plan for a Green Industrial Revolution - Point 6: Jet Zero and Green Ships	SP; TFL: F	T	T	2020	In force
Ten Point Plan for a Green Industrial Revolution - Point 8: Carbon capture, usage and storage	F	I	-	2020	In force
Ten Point Plan for a Green Industrial Revolution - Point 10: Green Finance and Innovation	F; TFL	MS	T; N; ES; HP	2020	In force
Subsidies to support green economic recovery in automotive sector	SP;	T	T	2020	In force
Jet Zero Council - Emissions Reduction in the Heavy Industry	SP;	H2PS; I	CCS	2020	In force
Package to Reduce Emissions in Heavy Industry and Drive Economic Recovery (Including Jet Zero Council)	F; TFL	T; I; B	CCS	2020	In force
North Sea Transition Deal - Hydrogen Production	SP; F	H2PS;	T; CCS; HE	2021	In force
Net Zero Strategy: Build Back Greener	SP;	MS	CCS; FP	2021	In force
Net Zero Strategy - Industrial Decarbonization and Hydrogen Revenue	F	I	HE	2021	In force
Investments in Green Technology	SP;	MS	-	2021	In force
Hydrogen storage project	TFL	PH;	-	2021	Announ
Green Aviation R&D	R; F	T	T	2021	In force
Industrial Decarbonisation Strategy	TFL	B; FP	T; CCS	2021	In force
North Sea Transition Deal - renewable energy	F	PH	IP	2021	In force
North Sea Transition Deal - CCUS	F	FP	CCS; T	2021	In force
UK Green Distilleries	F; TFL	PH	HP	2021	In force
Government funding for electric trucks and hydrogen-powered buses	F	T	T	2021	In force
North Sea Transition Deal - employment in more sustainable energy sectors and emissions reduction	SP; TFL	FP	-	2021	In force
Funding for EV Supply Chain RDD	F; TFL	T	T	2021	In force
Hydrogen BECCS Innovation Program	F	H2PS	CCS	2022	In force
Industrial Hydrogen Accelerator Program	F	I	HP	2022	In force

Policy types: F – Fiscal and finance, SP – Strategic Plan, TFL – Targets and framework legislation, R – Regulation.

Policy target sector: H2 Production and Supply – H2PS, Power and Heat – PH, Fuel Processing – FP; Transport – T, Transmission – TR, Industry – I; Buildings – B, Mining – M, Multi-sector – MS.

Policy technology sector: Hydrogen production*(not specified) – HP, Hydrogen electrolysis – HE, Carbon Capture Systems – CCS, Transport – T, Infrastructure – I, Energy Storage – ES, Power and Heat – PH, Fuel Processing – FP, Industrial Processing – IP, Nuclear – N.

Table 5. USA policies and measures.

United States of America	Type	Sector	Technology	Year	Status
Hydrogen and Fuel Cells Program	SP; TFL; F	H2PS; FP; T; PH; MS	T; PH; I; HP	2004	In force
National Fuel Cell Bus Technology Development Program (NFCBP)	F	T	T; I	2005	Ended
Section 1703/1705 Loan Guarantee Program	F	PH; I; MS	-	2006	In force
Alternative Fuel Infrastructure Tax Credit	F	T; I	T; IP	2006	Ended
American Recovery and Reinvestment Act of 2009: Tax-Based Provisions	F	T; PH; MS	T	2009	In force
Federal Funding for RDD in Energy	F	MS	PH; N	2021	Planned
Energy awards for clean hydrogen	F	H2PS; FP	HE	2021	In force
Climate Innovation Research Opportunity investment program	F; TFL	H2PS; PH; T; B; I; FP; MS	T; PH; CCS; HP	2021	In force
Aviation Climate Action Plan	SP; TFL;	T	T; FP; HE; I	2021	In force
University Hydrogen Turbine System	F	PH	PH; HP	2021	In force
Funding for fossil-based hydrogen production, transport, storage, and utilization coupled with	F	H2PS; FP	CCS; ES; FP	2021	In force
Funding to Advance Integrating Hydrogen and	F	H2PS; PH; FP	N; PH; HE	2021	In force
Carbon Negative Shot	TFL	I; MS	CCS	2021	In force
Infrastructure and Jobs act: clean hydrogen initiatives	F	I; PH; H2PS	HE	2022	In force
Inflation Reduction Act 2022: Sec. 50143 Domestic Manufacturing Conversion Grants	F	I	IP	2022	In force

Policy types: F – Fiscal and finance, SP – Strategic Plan, TFL – Targets and framework legislation, R – Regulation.

Policy target sector: H2 Production and Supply – H2PS, Power and Heat – PH, Fuel Processing – FP; Transport – T, Transmission – TR, Industry – I; Buildings – B, Mining – M, Multi-sector – MS.

Policy technology sector: Hydrogen production*(not specified) – HP, Hydrogen electrolysis – HE, Carbon Capture Systems – CCS, Transport – T, Infrastructure – I, Energy Storage – ES, Power and Heat – PH, Fuel Processing – FP, Industrial Processing – IP, Nuclear – N.

The UK places a significantly greater emphasis on fiscal and financing policies (23) and target framework legislation (16) when compared to both the EU and USA. EU has 9 identified fiscal and financing actions and 6 actions related to targets and framework legislation, whereas the USA has 14 and 4, respectively. In terms of regulation policy, the EU surpasses the other regions (6), while the UK and USA have lower values on regulation policy (2 and 0, respectively). This may suggest that these regions are still in the process of developing and implementing these types of policies. The rest of overall policy types in the three regions are quite similar, indicating a shared commitment to addressing climate change.

Considering the target sector, all regions present a high value on the "multi-sector" category, related to the "economy-wide" applications of certain adopted policies. "Fuel processing" is also similar across all regions, but there are also some differences worth noting. Considering "H_2 production and supply," it is more prominent in the UK (6) and USA (7) compared to the EU (3), having a similar pattern with the "Power and Heat" category: USA (7), compared to the UK (5) and EU (4). Another difference lies with the “Transport” and “Industry” categories, which are emphasized in the UK (8/5) and USA (6/6), in contrast to the EU (3/2). Considering “Buildings” category, the UK gives it a lot more attention compared to both the USA (1) and EU (0). The “Mining” category was only found in the EU (1), indicating a higher level of concern about the scarcity of resources and materials needed for hydrogen production and infrastructure.

The technology categorization of policies showed clear differences between the blocs. Despite “Hydrogen Electrolysis” being similarly taken in all three regions – EU (3), UK (3), USA (5) - “CCS” is only present in the UK (8) and USA (3), with no mentions within the EU policy strategy (0). The “Transport” technology focus is massive in the UK (12), followed by the USA (6) and EU (4). “Infrastructure” related technologies are more targeted in the USA (3) followed by the EU (1) and UK (0). “Power and Heat” is more focused on in the USA (5), followed by the UK (3) and EU (1). “Nuclear” is absent in Europe (0), with the UK (2) and USA (2) having some emphasis.

Figures 2, 3, and 4 present visual data on the analyzed policies categorized by type, target sector and technology. Through analysis of these graphs, the policy focus of each region becomes clearer. The EU shows a strong commitment through regulatory policy actions, while the UK and USA prefer a fiscal and financing approach to promote H_2 economies. In terms of the intended sector, the EU is creating a “wide-H_2-application” scenario by primarily focusing on the “Multi-sector” category, which is less specific when comparing with the other two regions. While the UK is prioritizing transport sectors, the USA’s policies are meant to improve H_2 production and supply efforts, as well as power and heat sectors. When analyzing the technology focus by policy, a common pattern is found: all three blocs are deploying dominant measures towards transport.

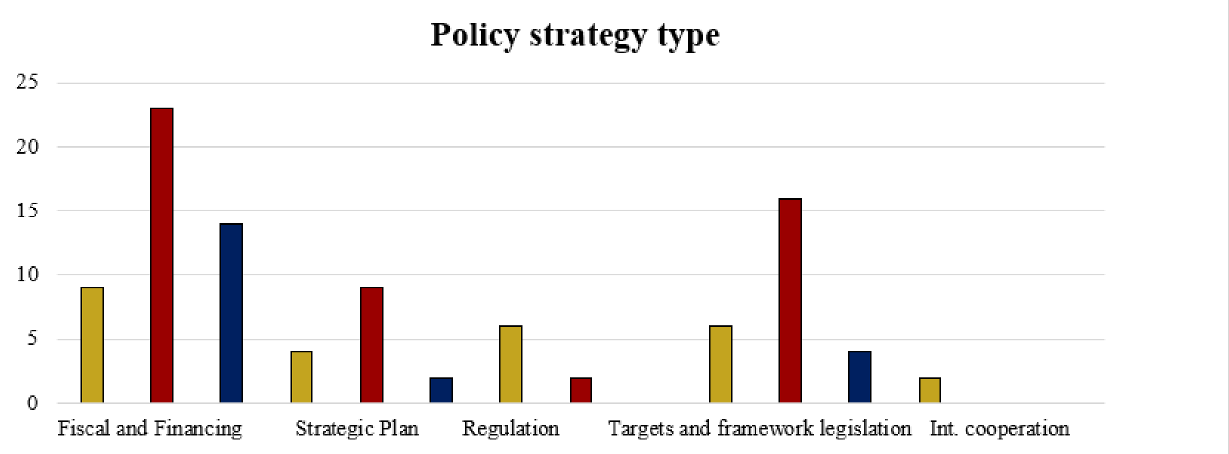

Figure 2. EU – Yellow; UK – Red; USA – Blue.

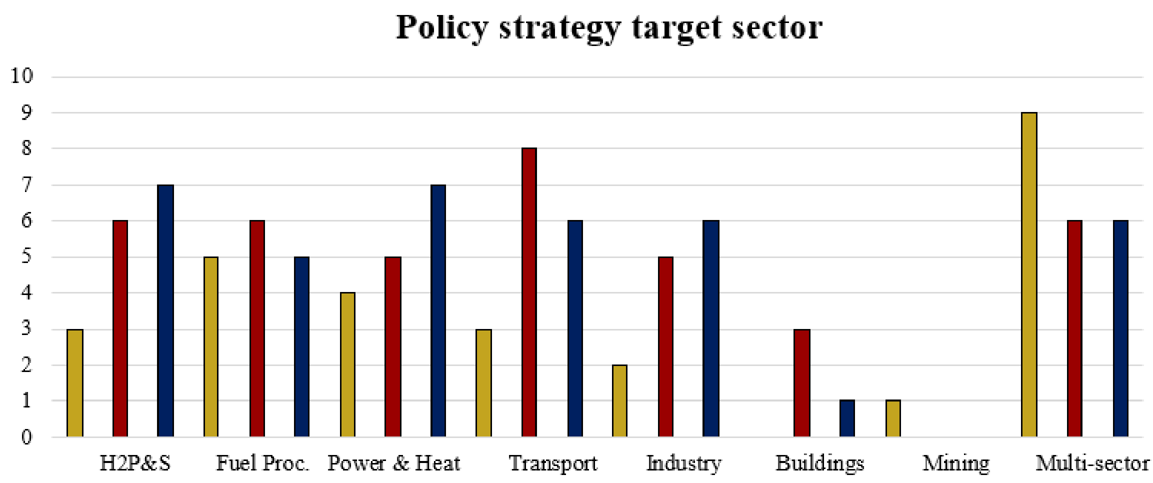

Figure 3. EU – Yellow; UK – Red; USA – Blue. H2P&S – H2 Production and Supply. Fuel Proc. – Fuel processing.

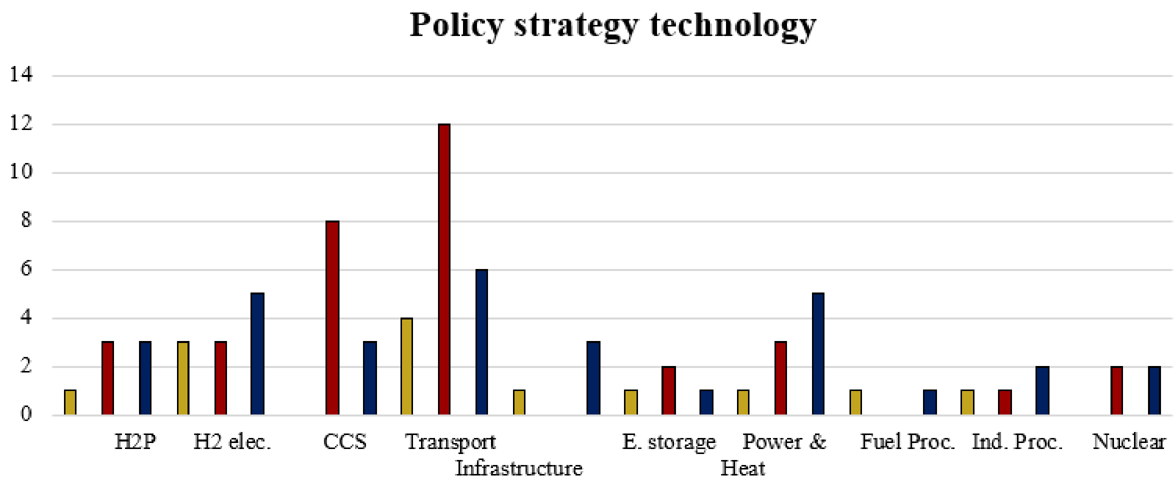

Figure 4. EU – Yellow; UK – Red; USA – Blue. H2P – Hydrogen production (not specific). H2 elec. – Hydrogen electrolysis. CCS – Carbon Capture Systems. E. storage – Energy storage. Fuel Proc. – Fuel processing.

5. Discussion

5.1. Differences and similarities between the 3 economic blocs

In terms of general structure, the three analyzed blocs showed different approaches to promote a new H_2 economy. The EU pushed for renewable H_2 (using mainly wind and solar energy), while recognizing the need on opting for low-carbon H_2 (fossil origin coupled with CCS technologies) in the short term (European Commission, 2020). The UK immediately targeted low-carbon H_2 solutions due to its geographical context, with available fossil-based resources, good storage potential for CO_2 emissions and decarbonization goals at medium term (Holloway et al., 2006; UK Government, 2021). The USA released its first official draft on national H_2 strategy very recently, and it became clear it does pursue a strong will for a new clean H_2 economy, based on both nuclear and fossil fuels, the latter coupled with CCS production (DOE, 2022).

As presented in the previous section, the USA quickly stands out with technical targets, having a strong commitment to maximize cost reductions at the same time electrolysis technology develops through R&D efforts. There are no H_2 production targets or even H_2 production capacities over different periods, as the EU and UK strategies do. Through the commitment of refining and updating analyses across the H_2 value chain, the USA government does not exclude the possibility of scaling-up renewable solutions at later stages, being dependent on R&D results. Renewable H_2 production potential is still under investigation, by the time the EU and UK are already deploying small and medium scale green projects over their own regions. Both the UK and EU acknowledge the importance of starting to act now towards sustainable options, forcing an early penetration of renewable H_2 production in the short-term (European Commission, 2020; UK Government, 2021). Production emission standards for "low carbon" hydrogen production are also being developed and present similar values between the three regions, ranging from 2.4 kg CO_2eq per kg H_2 (UK) to 4 kg CO_2eq/kg H_2 (USA) (European Commission[7], 2022; UK Government[2], 2022; EERE, 2022).

In terms of end-use priorities, the UK gives an unprecedented priority to domestic heating using H_2, easily confirmed by several demonstration projects already ongoing, while the EU and USA do not emphasize this option at early stages (still debating the viability of this application). Aside from this, all three regions share a similar pathway in which hard-to-abate sectors are the priority. Heavy industries' hubs will be the starting point to develop H_2 economies, where H_2 production can significantly influence local necessities and stimulate future infrastructure development into complex systems. Uses in transport are also similar. All regions expect to deploy fuel cell technologies on heavy-duty vehicles (aviation, shipping, passenger transports) or other easy-to-apply solutions.

The importance of early planning of the future infrastructure is also a priority. Blending and repurposing of natural gas structures is a common approach, shared by all blocs, with differences in implementation timings: While the EU and the UK expect to proceed with early blends, the USA states that costs must decline considerably for this option to be economically viable. Notwithstanding, the US government also recognizes that H_2 blending can start at first stages in local networks (DOE, 2020). The UK assured blending H_2 into the gas grid from 2023 onwards through prototype projects, after the government agreed with the Energy Networks Association (ENA) suggestion to increase the production target to 10 GW by 2030 (S&P Global Commodity insights, 2022).

Table 6 presents a comparison between the three blocs according to 13 indicators:

Table 6. Final comparison of main indicators.

	EU	UK	US
Official national strategy	Yes	Yes	Yes (draft)
Production type	Renewable and fossil CCS	Fossil CCS, Renewable and nuclear	Nuclear, Fossil CCS, renewable
H_2 Emission Standard	3 kg CO_2eq / kg H_2	2.4 kg CO_2eq / kg H_2 *	4 kg CO_2eq / kg H_2
End-uses	Industry hubs; power, heating (?), transport (heavy duty).	Industry hubs; heating power, transport (heavy duty), exports (due to doubled efforts).	Transport, industry hubs; power; exports
Infrastructure	5 to 20% Blending	20% Blending	5 to 15% Blending?
Main Targets	2024: 6GWS 2030: 40 GWS (only renewable H2)	2030: 10 GWS (half green)	Clean H2 cost reduction by 80%, to $1 per 1 kilogram in one decade
Critical resources acknowledgment	Yes	Yes	Yes
R&D Projects	719	90	114
H_2 Green Projects (Dedicated Renewables)	414	43	34
H_2 Related Policies (IEA database)	14	28	16
Dominant H_2 Policy Type	Fiscal/Finance	Fiscal/Finance	Fiscal/Finance
Dominant H_2 Policy Target Sector	Multi-sector	Transport	H2 Production and Supply / Power and Heat
Dominant H_2 Policy Technology focus	Transport	Transport	Transport

Source: The authors' own elaboration. European Commission, 2020; European Commission[7], 2022; UK Government, 2021; UK Government[2], 2022; DOE, 2022). *Conversion unit: H_2 LHV = 120 MJ/kg.

All authorities acknowledge resource scarcity problems concerning electrolyzer construction. Materials such as nickel, copper, steel, platinum and titanium will be needed in large scale, increasing pressure on demand of future global markets (Parkes[2], 2022). The EU will consider this problem under the Critical Raw Materials Action Plan combined with the new Circular Economy Action Plan, while the USA will focus R&D actions to tackle this risk (DOE, 2022; European Commission, 2020). The UK government claims that it will work with academia and several industry stakeholders to assess associated risks in the availability of rare materials and the essential H_2 supply chain (UK Government, 2021).

In terms of R&D deployment, the EU currently leads the R&D initiatives by far. IEA data confirms the great effort on seeking renewable solutions for H_2 production by European members, emphasizing the importance of innovative actions to deploy this kind of technology in an effective way (IEA, 2022). The same dataset allows us to compare the H_2 electrolytic production capacity until 2020, with EU leading the way with about 94 MWel (EU-27), followed by the UK with 4.5 MWel and finally the USA with only 13 MWel. By 2030 and considering current projected capacities, it is expected that the USA will experience the largest increase in comparison to other blocs, with about 10 872 MWel to reach. The UK capacity will raise slightly, until 5896 MWel, and the EU-27 will remain with the largest capacity overall, with 130 358 MWel (IEA, 2022).

The categorization process based on the IEA's Policy Database has provided valuable information considering design patterns related to the type, the target sector and the technologies involved in all identified policies. All blocs are already implementing several proposals related to H_2 promotion but with different approaches.

The UK has more identified policies than the EU and USA, probably related to their national urgency on energy transition coupled with a deep economic crisis (OECD, 2023). Although all blocs are prioritizing fiscal and finance policy initiatives, the EU has already deployed several regulation proposals, showing a more developed stage towards the H_2 market integration efforts. The UK also shows a great commitment for "targets and framework legislation" actions, when compared to their European and American counterparts. Lower values presented by the EU might be related to the fact that the European Commission is limited in promoting incentives and tax policies through directives, which require subsequent ratification at the national level, limiting their ability to take broader effective action. The USA's strong focus on fiscal and financial policy measures may reflect their need for R&D initiatives toward a clean H_2 economy before the deployment of targets or regulation measures. The significant technical advancements required to unlock the potential of H_2 demand a consistent and extensive investment roadmap.

There are some noteworthy differences between the UK and the EU regarding their approaches to target sectors for H_2 applications. The UK appears to be committed to pursuing H_2 domestic heating applications, as evidenced by three of their policies dedicated to this end. On the other hand, the EU has taken a unique approach by including policies that address the issue of resource and material scarcity, particularly in the mining sector. This is likely due to the need to acquire sufficient resources for the new H_2 value chain, specifically for electrolyzers, since the greater focus is on green H_2 production. Despite this, the EU has fewer policy initiatives than the USA and UK toward general H_2 production and supply sectors, transportation and industry applications. In fact, the European bloc presents a lot of ambiguity when considering the final intended sector of policies, which could explain some major differences to the UK and USA.

When categorizing policies based on technologies, there are significant differences between the EU, the UK and the USA. Specifically, policies related to CCS and nuclear technologies appear to be absent in the EU compared to the UK and the USA. These two blocs, on the other hand, have more robust initiatives, which are linked to their greater availability of fossil natural sources. All regions are placing a strong emphasis on transport technologies, but the UK stands out with a notably higher level of commitment compared to both the EU and the USA, exhibiting a high level of determination. This is particularly evident in its emphasis on fuel-cell vehicles, which is consistent with its official roadmap document for H_2.

5.2. Financing hydrogen

To assess how governments are supporting their own strategies, a comparison among financing initiatives was carried out based on official statements. High ambition of the EU is accompanied by strong financing support toward a sustainable H_2 economy. While proposing a gradual plan, the EU Commission expects to deliver between 320 and 458 billion euros until 2030, to support new H_2 production facilities and infrastructure, followed by a scaling-up process after this period (with an additional 180 to 470 billion euros of projected investment) (Table 7).

Table 7. EU Investor roadmap (gross investment).

2020–2030	€	Goal
Electrolyzers	24–42 billion	Green H_2 production
Scaling up RES	220–340 billion	Solar and wind production/connection
CCS technologies	11 billion	Retrofitting half of existing plants
H_2 transport, distribution and storage, refueling stations	65 billion	H_2 general infrastructure
2020–2050	€	Goal
Production capacity	180–470 billion	Scaling up H_2 production

Source: (European Commission, 2020).

The EU plan has well-defined targets over different periods, with announced investment amounts for the short, medium and long terms. Deployment of funds is being conducted through several programs. The Clean Hydrogen Partnership, focusing on the renewable H_2 value chain (from production to storage, distribution and transport), has €10 billion of funding to be applied, matched with at least the same amount of investment by member states over the next decades (Clean Hydrogen Partnership, 2022). From the total amount, €1 billion will be allocated annually for the period 2021-2027 (with another €1 B being provided by EU partners) (European Commission[6], 2022). The first call for proposals started in March 2022, with a budget of €300 million to promote green H_2 production. Later, in May, a reinforcement of €200 M was announced to be deployed for the Clean Hydrogen Partnership, due to execution of the REPowerEU plan. In fact, 2022 has been a year with several supporting initiatives. Through the Innovation Fund, the Commission announced support for three new H_2 projects, of a total €1.8 B fund to be used until 2030 (HyResource, 2022). Under different names, the strategic forum of the IPCEI has already taken some initiatives towards low-carbon technologies, with open rounds since the beginning of 2022: IPCEI "Hy2Tech" and IPCEI "Hy2Use," providing €5.4 and €5.2 billion of public funding, respectively (European Commission[3], 2022). In September 2022, the EU announced the foundation of a European Hydrogen Bank (EHB) to foster the future H_2 market. It would consist of €3 billion, supported by the Innovation Fund, guaranteeing purchases to help create demand for a future H_2 economy (Parkes, 2022). Unfortunately, there are few details how this bank will support H_2 projects. Table 8 summarizes recent European financial support.

Table 8. EU financial supportive initiatives.

EU	Program	Value	Period	Focus
	Clean Hydrogen Partnership	€1B	2021 - 2027	Renewable H_2 production and storage
	Innovation Fund	€1.8B	2020 - 2030	Low-carbon technologies
	IPCEI Hy2Tech	€5.4B	2022 - 2036	Renewable and low-carbon H_2 production, storage and transport; R&D
	IPCEI Hy2Use	€5.2B	2022 - 2036	Low-carbon H_2 production, storage and transport; R&D
	European Hydrogen Bank	€3B	?	Hydrogen market
	REPowerEU	€200M	2030	Clean Hydrogen Alliance (Horizon Europe Program)

Sources: Clean Hydrogen Partnership, 2022; European Commission[3], 2022; HyResource, 2022; Parkes, 2022.

By analyzing financing values of supporting programs, it seems clear that, despite the focus on green hydrogen development, European leaders are also investing in low-carbon technologies. Higher values of IPCEI initiatives can be an indicator of European leaders' acknowledgment of blue hydrogen, despite the preferred focus on green hydrogen alternatives.

Coupled with support measures provided by the Net Zero Fund (including £1 billion to be distributed by novel programs), the UK government seeks to decrease costs of decarbonization while pushing for a cleaner energy sector. From the total amount, £240 M is exclusively dedicated to the H_2 economy and will be delivered between 2022 and 2025 (Net Zero Hydrogen Fund), supporting all forms of H_2 production (including nuclear energy) (Donoghue et al., 2022). Despite not presenting investment values for both medium and long term, recent history showed frequent calls for competing programs. More details about supportive programs are summarized in Table 9. The UK government, through all previous support programs, reflects a strong will and commitment for a new H_2 economy establishment, clearly focusing on low-carbon technologies over renewable solutions in the short run. Doubling renewable production targets for 2030 (from 5 GW production capacity to 10 GW), the UK recently opened the 2022 Electrolytic Allocation Round (under the Hydrogen Business Model), to secure that at least 50% of all low-carbon H_2 produced by then comes from offshore wind, other renewables and nuclear (Chakrabarty, 2022).

Table 9. UK financial supportive initiatives.

UK	Program	Value	Period	Focus
	Net Zero Hydrogen Fund	£240M	2022–2025	Low-carbon H_2 production projects
	Hydrogen Business Model (2022 Electrolytic Allocation Round)	£100M	2022–2030	Novel electrolytic projects
	Industrial Decarbonization and Hydrogen Revenue Support (IDHRS)	£140M	2021–2024	New H_2 and industrial carbon capture business models
	Low-Carbon Hydrogen Supply 2 Competition	£60M	2021–2025	Novel low-carbon H_2 production projects
	Industrial Hydrogen Accelerator (IHA)	£26M	2022–2030	Design and implementation of H_2 systems for industry
	Hydrogen BECCS Innovation Program	£5M	2022–2024	H_2 production using bioenergy with carbon capture and storage
	Industrial Fuel Switching Competition	£22.2M	2021–2025	Industry switch to lower carbon fuels

Sources: Chakrabarty, 2022; UK Government[2-5], 2021; UK Government[2,3], 2022.

After ratification of the American Infrastructure Investment and Jobs Act, investment by the US in H_2 has become clearer. Development of clean H_2 will be supported by $9.5 B, with focuses on electrolysis ($1 B) and RD&D of manufacturing/recycling of electrolyzer components ($500 M), as well as settlement of first H_2 hubs across the country ($8 B) (Table 10) (DOE, 2022).

Table 10. USA investor roadmap (gross investment).

Focus	$ (2022–2026)	Goal
Hydrogen hubs development	$8b	Enable large-scale clean H_2 production and end use in proximity
Electrolysis R&D	$1b	Improve the efficiency and cost-effectiveness of electrolysis technologies
Manufacturing & Recycling R&D	$500M	Manufacturing of clean H_2 equipment; support projects that improve efficiency and cost-effectiveness; support domestic supply chains for key components

Source: DOE, 2022.

Financial assistance has been deployed through open funding opportunities applications (FOAs). Most of them are aligned with H2@Scale initiative (2016) and the Hydrogen Shot (2021) objectives. Based on recent official announcements, it is evident that significant efforts are being made in terms of R&D initiatives and demonstrations focused on clean H_2 production, cost reduction and other several end-uses, including fossil-CCS and high-temperature electrolysis methods (Table 11). Recognizing the importance of securing rare materials for the future H_2 supply chain, the USA strategy is unique in dedicating a separate fund to deal with this problem (DOE, 2022).

Table 11. USA financial supportive initiatives.

USA	Program	Value	Period	Focus
	RD&D activities under H2@Scale (EERE)	$64 M	2020	Funding for 18 projects that will support the H2@Scale vision
	Hydrogen and Fuel Cell R&D and the H2@Scale Vision (EERE)	$33 M	2020	H_2 and fuel cell R&D, infrastructure supply chain development and validation, and cost analysis activities
	Accelerate Progress in Clean Hydrogen (EERE and FECM)	$52.5 M	2021	Funding 31 projects regarding clean H_2 technologies R&D, focusing cost reduction and sector breakthroughs
	National Laboratory H2@Scale Projects (EERE)	$8 M	2021	H_2 technologies integration in future energy systems (energy storage, safety and risk mitigation)
	Clean hydrogen from nuclear power (DOE)	$20 M	2021	Demonstration technology to produce clean H_2 from nuclear power
	R&D and front-end engineering design (FEED) projects (FECM)	$28 M	2022	Use of clean H_2 (CCS) in transportation, industrial use and electricity production
	Next-Generation Energy Storage Technologies (FECM)	$2.4 M	2022	Novel thermal and H_2 energy storage technologies
	Hydrogen Turbine Performance and Reducing Hydrogen-based Energy Costs (FECM)	$4 M	2022	Development of ceramic-based materials to improve the efficiency of H_2-fueled turbines
	Advanced Clean Hydrogen Technologies for Electricity Generation (FECM)	$24.9 M	2022	Improve electricity generation efficiency using H_2 produced with CCS
	Advanced Clean Energy Storage project in Utah (DOE – Loan)	$504.4 M	2022	Loan guarantee for construction of the largest clean H_2 storage facility in the world
	Funding Opportunity in Support of the Hydrogen Shot and a University Research Consortium on Grid Resilience (EERE)	$60 M	2022 – 2026	Development and deployment of clean H_2 technologies. Implement grid resilience programs and achieve decarbonization
	Hydrogen Shot Incubator Prize (EERE)	$2.6 M	2022 - 2026	Identify, develop, and test disruptive technologies that reduce the cost of clean H_2 production
	Nuclear-Coupled Hydrogen Production and Use (DOE)	$250 M	2022 – 2026	Development of nuclear plant thermal integration
	Regional Clean Hydrogen Hubs (H2Hubs)	$8 B	2022 - 2026	Development of at least four H2Hubs

Sources: DOE, 2020; EERE, 2020; DOE[3], 2021; EERE, 2021; DOE[2], 2021; FECM, 2022; FECM[2], 2022; DOE[2-4], 2022.

While the EU and UK are quickly developing the first green or blue H_2 small scale projects, the USA is still working towards an ambitious R&D environment to achieve satisfactory technical targets in several H_2 crucial areas. From all financial support initiatives, there was only one totally dedicated to developing the first H_2 clusters: the Regional Clean Hydrogen Hubs (H2Hubs) program.

5. Conclusions

The EU, UK and USA envision a gradual transition to low-carbon H_2, be it by focusing on renewable H_2 (EU and partially UK) or through CCS technologies (UK and USA). H_2 will play a significant role in the decarbonization of their economies in the medium term, although the USA opts for further R&D support to achieve lower costs. Contrasting with IEA recommendations and both EU and UK approaches, the US government is still debating costs and performance targets to enable the adoption of H_2 technologies, to reduce market barriers and other complications across multiple applications and sectors (IEA[2], 2021).

The US strategy is unfocused on renewable (green) H_2, raising a lot of uncertainty about its role. This fact might be related to the widespread availability of nuclear and fossil fuels, specifically natural gas, contributing for a slow-paced transition due to low carbon content of this resource and its effect on energy security issues. Also, lacking a proper carbon price mechanism at a national level, the USA is behind the commitment level of both European and UK H_2 plans. This is also reflected in current H_2 emission standards, with the USA presenting the highest value admitted for low-carbon production (4 kg CO_2eq/kg H_2) in comparison with both EU (3 kgCO_2eq/kgH_2) and UK (2,4 kgCO_2eq/kgH_2). For the EU and UK, leaders seek a very different approach. Both regions show good geographic conditions to explore fossil or nuclear-based fuels, but decarbonization urgency and energy security issues seem to ask for urgent policy choices regarding H_2. Recent events related to the Russian invasion of Ukraine contributed to a certain level of disruption of the EU energy sector, which in turn has the potential to trigger alternate solutions and innovative technologies, including a solid H_2 economy establishment in the short and medium term. Due to strong investments of renewable energy in the last years, the EU presents significant potential regarding self-sufficiency and security of supply through hydrogen-based power, aligned with green H_2 imports (Sasanpour et al., 2021). These could help to understand early European and UK interest in H_2 solutions.

In terms of H_2 applications, all regions show similar patterns, with several commitments in heavy-industry and heavy-transportation sectors, power generation and heating. However, differences are also found considering priority end-uses. The UK follows a strategy where domestic heating is present at early stages, contrasting with the other two blocs that recognize the need for more evidence to start deploying it. In Europe, the changing of former "Fuel Cell and Hydrogen Joint Undertaking" into "Clean Hydrogen Alliance" reflected a shift in priority by European leaders, moving from a transportation focus to "less controversial no regret applications," as energy experts explained in a recent interview (Kurmayer, 2021).

Future infrastructure is also being planned in similar ways across the analyzed regions. In short, all regions are following a pragmatic approach of using the existing natural gas infrastructure to begin blending at first stages, adapt specific operational requisites as needed and slowly increase H_2 amounts over time to reach a 100% H_2 composed gas (Mahajan et al., 2022). Differences exist in the timing and in the percentages of H_2 injected into the existing natural gas system, ranging between 5% and a maximum of 20% at first stages, due to technical and safety issues (Abbas et al., 2021). Considering this point, the USA highly contrasts with both European and UK strategies, leaving blending pipeline projects to the last phase of implementation.

Public policy deployment is still in the early phases, but it is possible to distinguish different approaches to promote H_2 economies. All regions show a strong commitment towards fiscal and financing actions, but the EU presents a stricter regulation environment. The EU's strong focus on regulatory frameworks may reflect their need to deploy a proper market and infrastructure so that all member states can benefit from a low-carbon H_2 economy. Due to the different stages of governance (national vs. international), it is understandable that significant work is required to address both technical and market risks. However, it is difficult to predict whether this rigidity will ultimately boost or hinder H_2 development. The USA's high focus on production and supply of the H_2 sector coupled with power and heat applications probably reflects their urgency to complete their robust H_2 technical objectives included in their strategy. It can also suggest a greener stage considering H_2 production when comparing with Europe and the UK, since these two regions seem to be ahead in terms of H_2 production capacity considering electrolysis (IEA, 2022). Nevertheless, transportation technologies are the preferred focus of all three regions. This urgency may be attributed to the need to establish viable fuel cell technologies as soon as possible, as heavy-duty applications are expected to be adopted in the short term. Overall, all blocs' policy patterns seem to be in accordance with their official roadmaps, with particular attention given to the mentioned absence of CCS and nuclear technologies in the EU's policy portfolio.

Financing options in all cases seem to be in line with both national hydrogen strategies and policy focus. Due to European and UK continued efforts on hydrogen supply chain R&D, new small-scale H_2 projects are rapidly emerging, to achieve 2025 and 2030 announced targets, while the USA is clearly behind this rhythm. Having recently announced a massive support package to H_2 R&D promotion after the BIL ratification, the American government opts for a longer-term scenario to deploy H_2 effectively, in which nuclear (high-temperature electrolysis) and fossil-based fuels (with CCUS) will be dominant over renewable ones. This seems to be in accordance with ongoing R&D projects, when the ratio between dedicated renewable projects and total projects equals 29.8%, contrasting with the 57.6% from Europe and 47.8% from the UK (IEA, 2022).

Finally, it is important to state some limitations of this study. The main objective of this study was to understand major differences regarding H_2 low-carbon economy promotion between the three chosen blocs while identifying particular policy measures. This work combines an analysis of the official H_2 strategies with a reclassified policy database originally proposed by the IEA. The categorization process was carried out by retaining original information as much as possible. Notwithstanding, it was impossible to disassociate some categories, which will naturally influence the quality of the analysis. This is due to the low specification on IEA's category definition. For example, considering the policy strategy type, the "Payments, finance and taxation" IEA category contains different types of economic tools, and it is impossible to assess which one is, in fact, associated with a certain policy. Another example includes the "Tax" category, which has 4 other similar types described: "Taxes, fees and charges," "Tax credits and exemptions," "Taxes and charges" or just "Taxes." Since no detailed, normalized description is available, similar categories were aggregated in order to avoid errors and possible misinterpretations, resulting in the five categories proposed – Fiscal and Finance, Strategic Plans, Regulation, Targets and framework legislation, International cooperation.

Second, it should be noted that the categorization process did not evaluate the maturity or effectiveness of specific policies. While this approach enhances our understanding of policy strategy choices in relation to their primary objectives, it is important not to draw conclusions regarding their suitability. As H_2 policy designing and deployment is currently underway, future work should aim to investigate the impact of public policies on the establishment of H_2 as an alternative pathway, thus enabling the adoption of a proper decarbonization route where it plays a complementary, yet crucial role.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Authors declare no conflicts of interest in this paper.

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