Comparative Analysis of Green Hydrogen Policy Mixes of the EU and the US

Master Thesis

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Comparative Analysis of Green Hydrogen Policy Mixes of the EU and the US

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Engineering and Policy Analysis (EPA)**

Faculty of Technology, Policy, and Management

by

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To be defended in public on August 24, 2023

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Summary

Sustainable energy transition is the need of the hour, more so, because of the accelerated effects of climate change. This necessitates rapid, continuous, and persuasive political and technological approaches to enable an ecosystem of green alternatives for countries to support their net-zero ambitions. One such emerging technology approach is green hydrogen, which is hydrogen produced from renewable sources. Green hydrogen is considered as a versatile energy carrier to support transitioning of industries, energy systems and transport, towards sustainability. As such, globally, many countries have increasingly considered green hydrogen as a part of their decarbonisation plans.

Today, at least 26 countries have adopted hydrogen policy strategies and supporting policy instruments. However, mere adoption is not enough – a test of policy effectiveness is required to evaluate whether policies will be executed in keeping with their stated objectives, whether the various policy instruments/tools introduced to support overall strategies will be collaborative or may conflict with one another, and whether the policies will address issues systematically or ad hoc. It becomes important to understand whether policy strategies and instruments, the underlying processes, and their characteristics - collectively called a policy mix- could actually support policy goals, objectives, and ambitions of various countries.

The work of this thesis is, therefore, centred around the analysis of the policy mixes concerning green hydrogen for two cases of the EU and the US, using an analytical framework called the policy mixes framework. The policy mix framework is an analytical comprehensive framework that evaluates policy strategies, policy instruments, instrument interaction, policy processes and characterises them on four characteristics of consistency, coherence, credibility, and comprehensiveness.

The research question of the thesis explores and compares green hydrogen development in the EU and the US both individually and collectively. For each of the regions, their policy strategies, policy instruments and characteristics (consistency, credibility, and comprehensiveness) were determined through document analysis and semi-structured interviews.

Based on the analysis, it can be said that the US' strategic focus is on establishing a domestic environment of green hydrogen and ensuring its roll-out in a cost effective manner through R&D across various industries at scale, as a means of decarbonisation and achieving overall net-zero ambitions, with exports being a focus area in the long term. For the EU, strategic focus is on accelerating the development of a green hydrogen market through both domestic production and imports, while providing the supporting infrastructure, regulatory framework, skilling, and financial

mechanisms to achieve EU's decarbonisation and climate goals. The instruments in the US are mostly informational in nature covering skills, standards, alliances, and consortiums, supported by strong economic instruments such as the IRA, IIJA which are also regulatory in nature. The EU, on the other hand, has multiple instruments which are regulatory in nature such as the CBAM, AFIR, Delegated Acts etc., which cover the domains of end-use, infrastructure, terminologies, and definitions. These are also backed by economic instruments such as the upcoming EHB and existing financial mechanisms such as the InnovFund, CEF etc., and information tools such as the ECHA, CHP. The US policy mix is fairly consistent, while being somewhat credible and comprehensive to an extent. The EU policy mix, on the other hand, is less consistent, while being somewhat credible and comprehensive to an extent. Between the two regions, the US performs better on the characteristic of consistency, while the EU performs better on the characteristic of comprehensiveness, with both performing similarly on credibility.

Both the regions are in very similar stages of green hydrogen development because of the nascent nature of the field itself. Furthermore, both the regions appear to be equally committed towards the development of a green hydrogen market as strategies and instruments are present across the hydrogen supply chain, i.e., production, distribution and end-use. There seems to be a positive albeit reactionary approach to the initiation and further development of strategies and corresponding instruments concerning green hydrogen for both the regions. In a way, the US mirrors what the EU does, with a delay, and vice versa.

As recommendations to improve the policy mixes, for both the regions it is suggested to finalise their strategies and instruments soon. Additionally, for the US, it is recommended to introduce regulations for hydrogen infrastructure, permitting timelines for projects and carbon border mechanisms to better the policy mix. For the EU, it is suggested to speed up approvals of current draft regulations to ensure faster implementation, while having confirmed mandates to support end-use. For both regions, it is also recommended to develop certification standards and increase community engagement efforts.

The limitations of this study include the (high) level of analysis, which does not take into consideration state level initiatives and strategies, (possible) limited inputs because of (less) number of interviews conducted, and challenges associated with the operationalisation of the policy mix framework. For future research, it is suggested to increase scope and provide depth by including state level initiatives, enrich data through more interviews and expand policies to include those concerning renewable energy, industrial decarbonisation etc. as well to enable the placement of green hydrogen in the overall decarbonisation story.

Acknowledgements

As with any work which finds its way into fruition, this thesis is a culmination of the efforts of many people, beginning and continuing with the constant support and advice from my first supervisor, Nihit. Other Committee members –Kenneth (second supervisor) and Zofia (Chair) – provided much needed support with their valuable insights while also being accommodating of my timelines and change in methods for the thesis. I am also very thankful to all the interviewees across the US and the Netherlands who provided their inputs for my thesis.

I could not have done a lot of my work without the constant support of my family – my parents, my sister, and my nephew - who have been with me through thick and thin, endured my busy schedules and always lent an ear, come hell or high water. My friends and acquaintances in the Netherlands – Zeeshan, Ludovica, Maanav, Aditya, Nirupama, John, Anju, Cem, Jeroen, Alex, Sufiyan, Yaren, Aspasia, Dorukhan, Nicolo, Gerdus, Peter, Vaibhavi, Jeremy and Thomas, friends outside the Netherlands – Kanchana, Supriya, Priyanka, Arshvir, Shravan, Harshita, Pratik, Jivraj, Kaustubh and Triveni, my brother-in-law and my cousins – Vivek, Varun & Monisha, Purnima & Ram, have been there for me in ways I cannot describe, making life liveable, easier and each day worth looking forward to.

I cannot miss mentioning the wonderful and constant support provided by my supervisor at Ohmium – Rasool - for being empathetic, helping with connections for interviews, teaching me so much about green Hydrogen, and understanding the grit associated with this master's. I'm also grateful to the larger team at Ohmium for their continuous cooperation and understanding. It goes without saying that had it not been for Pashu, I would have never been introduced to the area of green Hydrogen – I am immensely thankful to you for many of my subsequent experiences.

I also express my gratitude to the faculty and international office at TU Delft and the faculty and academic services at CMU, US for their support, availability, and continuous learning. My time at the Hague and Delft have been wonderful and I take along with me many beautiful memories. I am greatly thankful to Haiko for being considerate, and easily approachable, and to Lillian for spreading happiness and charm. Lastly, I thank the beautiful country of the Netherlands for making it a relatively easy transition from India – I could not have asked for a better country to move to: a home away from home.

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1. Introduction

1.1 Background

Sustainable energy transition is the need of the hour. Latest studies and reports suggest an accelerated effect due to climate change (IPCC, 2022) and depict an urgency for international agreement between countries to achieve net-zero emissions and become carbon neutral by 2050. This requires immediate, sustained, and convincing technological and political approaches for transitioning towards greener alternatives. It is not only the energy system that needs to transition, but also other application areas of the industry and mobility. A solution, although not a panacea, to this problem, is seen in the deployment of 'Green Hydrogen' technologies, especially for sectors which are hard to electrify (IEA, 2022b).

Green Hydrogen, which is hydrogen produced from renewable sources, is considered as a versatile energy carrier to support transitioning of industries, energy systems and transport, towards sustainability. It is a subject of growing interest in politics, industry, and academia over the last couple of years. The advantage of green hydrogen is the zero carbon dioxide emission production process (Ejike, 2022) and its applicability to be used and leveraged across multiple sectors. As such, globally, many countries, notably the EU, US, Japan, Australia, China, and India, have increasingly considered hydrogen as a part of their decarbonisation plans (IEA, 2022b), and have announced goals for hydrogen production and hydrogen cost reduction.

1.2 The Need for Policies

There are concerns about markets meeting the goals set forth by various nations for green hydrogen. The uncertainty surrounding the supply of electrolysers for green hydrogen is regarded as a major issue (Odenweller, Ueckerdt, Nemet, Jensterle, & Luderer, 2022). Markets could, therefore, fail to follow through in terms of demand-supply economics and the fulfilment of the hydrogen supply chain. Policies designed to accelerate the deployment of gigawatt-scale electrolyzers in the coming years could help unlock significant innovation and scaling effects. These could act as a signal for industries to shift from manual to automated production and thus drive down costs, secure expectations and accelerate growth. In addition to supply constraints, the high costs associated with green hydrogen production (Ajanovic, Sayer, & Haas, 2022) act as an impediment for markets as well, since investments in a new sector are considered risky. Here too, policy interventions in the form of financial support could provide the necessary cushioning and help de-risk investments.

Globally, today, at least 26 countries have adopted hydrogen policy strategies and supporting policy instruments (IEA, 2022b). Multiple bilateral and multilateral partnerships are also signed for green hydrogen – examples include the Netherlands and UAE (FuelCellWorks, 2022), the EU and countries in North Africa (Ivanova, 2022), Australia and Japan (ARENA, 2022), the US and Chile (Dokso, 2022), etc.

However, mere adoption is not a reliable predictor of policy effectiveness. Several factors must be considered, including whether the policies exist only on paper, whether they will be implemented in accordance with their stated objectives, whether the various policy instruments/tools introduced to support overall strategies will be synergistic or may undermine one another, and whether the policies will address issues systematically or in an ad hoc manner. It, therefore, becomes imperative to understand whether policy strategies and instruments, the underlying processes and their characteristics - collectively called a policy mix (Rogge & Reichardt, 2016) - could actually support policy goals, objectives and ambitions of various countries.

While this thesis does not delve into an analysis of policy mixes for all the countries which have strategies today, it considers the cases: the European Union (EU) and the United States (US). These two regions have democratic institutions of governance, are large economies and are committed to be net-zero by 2050 (EC, 2023b; UNFCCC, 2021). Both these regions also have ambitious targets and have rolled out volume of incentives for green hydrogen and clean energy initiatives. Combined they have best technological expertise for green hydrogen and have the highest number of projects proposals (IEA, 2022c), along with policy initiatives to nurture technological development and market development on a large (MW) scale (Heid, Sator, Waardenburg, & Wilthaner, 2022).

The EU has the second highest electrolyzer manufacturing capacity in the world (IEA, 2022a). The US on the other hand is the pioneer of the technology of Proton Exchange Membrane (PEM) electrolysis, which was first used in the US Navy and space explorations with NASA back in 1950s and 1960s (Grubb & Niedrach, 1960). EU was among the first to launch a Hydrogen Strategy in 2020, third to only Japan (2017) and Australia (2019). The EU has the ambition of achieving 20 million metric tonnes (MMT) per annum of production of green hydrogen by 2030 (EC, 2022) , while the US has a similar goal of achieving 10 MMT annual production of green hydrogen with a goal of reducing the cost of clean hydrogen by $1/kg by 2031 (HFCTO, 2021). Additionally, these two regions have an international influence concerning decarbonisation goals of countries globally and establishing global markets for sustainable energy transition.

1.3 Research Objective and Research Approach

There is limited research conducted in both the EU and the US concerning green hydrogen policies. The literature review explained subsequently in Chapter 2 (Section 2.5) covers this premise. Additionally, research is scare in the area of comparative analysis to identify how similar or different hydrogen policies introduced by various countries are. The research objective of this paper, therefore, is to contribute to the existing limited green hydrogen policy literature and also sustainable energy transition studies by offering an in-depth cross-regional comparative analysis of the green hydrogen policy mixes of the US and the EU.

The paper considers a comparative case study approach to provide the required depth (Harrison, Birks, Franklin, & Mills, 2017) to analyse these two regions. Furthermore, to evaluate the policy mixes of the EU and the US, the policy mixes framework is used. The framework allows for clear analysis by providing an explanation and an evaluation of interactions between policy strategies, instruments, and processes. It is an analytical framework that organises the required terminology for policy mixes by providing sub-elements and characteristics of consistency, coherence, credibility and comprehensiveness to symbolise policies and processes (Rogge & Reichardt, 2016). These characteristics can be briefly described as – *consistency*: to determine the alignment between the instrument mix and instruments and strategic goals, *coherence*: to determine whether methods in which policy making and implementation are performed include stakeholders, actor interests etc., *credibility:* to determine how reliable the policy mix is, and finally *comprehensives:* to determine how exhaustive and extensive the instruments are and whether extensive decision-making takes place for policy processes. There is widespread agreement in academic literature that policy mixes are required to support processes of innovation and technological change (Kivimaa & Kern, 2016) and the use of this framework is warranted for innovative technologies.

Some instances of where the policy mixes framework are used, specifically in the realm of sustainable energy transition, include - a comparative analysis of carbon capture and utilisation for the US and the EU (Thielges et al., 2022), energy transition for the German industry (Kern et al., 2022), power-actor group analysis for renewable energy transition in Iran and Germany (Mohammadi & Khabbazan, 2022), carbon pricing for decarbonizing buildings in Germany (Braungardt, Bürger, & Köhler, 2021), among others. It has not yet been used for green hydrogen, and this paper would be the first to use it, especially in the context of a comparative analysis for the regions of the EU and the US.

The research question that this thesis explores is as follows–

How do the European Union (EU) and United States (US) green hydrogen policy mixes compare when it comes to the development of a green hydrogen market?

The sub-questions that follow the main research question and are explored as a part of this thesis are as below –

1. *What policy strategies and instruments are present in the EU and the US for green hydrogen development?*
2. *How do the EU and the US green hydrogen policy mixes perform individually across the characteristics of consistency, credibility, and comprehensiveness?*
3. *How do the green hydrogen policy mixes of the two regions compare systemically and across the three characteristics?*

1.4 EPA Relevance

Green hydrogen falls under the category of solutions that could be leveraged to support the decarbonisation and sustainable energy transition goals of countries. The need for such a transition is because of the accelerated effect of climate change (IPCC, 2022) and responsibility and commitment of regions globally to become net-zero or carbon-neutral by 2050 and beyond. These commitments have taken the form of policies through enactment of regulations and supporting financial mechanisms – this is seen in the context of green hydrogen as well. The relevance of this paper, therefore, is seen in the context of global sustainable energy transition, with a focus of two important regions (US and EU) that influence each other and the energy goals of countries globally.

Additionally, this thesis uses an analytical framework such as the policy mixes framework which evaluates policy mixes and helps determine the effectiveness of the mixes by drawing on how consistent, credible, coherent, and comprehensive they are. Based on the assessment of the policy mixes, recommendations to improve the policy mix are also provided. A combination of the grand challenge of accelerated climate change/sustainable energy transitions, use of analytical frameworks and concluding with policy advice, make this paper EPA relevant.

1.5 Outline

Chapter 2 introduces green hydrogen, existing policy instruments and the academic literature concerning green hydrogen policies, while Chapter 3 covers the research approach and methodology detailing the case study approach, policy mixes framework, data collection and analysis methods. Chapter 4 and 5 cover the policy mixes of the US and the EU respectively and characterises them using the policy mix framework. Chapter 6 provides the comparative analysis of these two mixes. The final chapter discusses the main findings, and provides actionable recommendations, limitations, and the way forward for future research.

2. Green Hydrogen

2.1 Introduction to Hydrogen

Hydrogen's usage in industry historically dates back to the early 1950s (Gregory, Ng, & Long, 1972). Global demand today of hydrogen is roughly 94 MMT and is expected to increase to 614 MMT by 2050 (IEA, 2022b). Predominantly seen in the chemicals, fertilizers and refineries industries, the production of hydrogen has been a carbon intensive process (IEA, 2006), with green/electrolytic hydrogen production constituting barely 0.1% of the overall production (IEA, 2019). Carbon intensive hydrogen is both because of the electricity input that is supplied to produce hydrogen (directly from the grid using coal-fired plants) and the conventional methods of steam methane reformation (SMR) and coal gasification, which produce carbon emissions. However, hydrogen can also be produced from other pathways such as the electrolysis of water and biomass gasification, resulting in relatively less carbon dioxide emissions (Chai et al., 2021; Jang et al., 2022) [Also see figure 1 below].

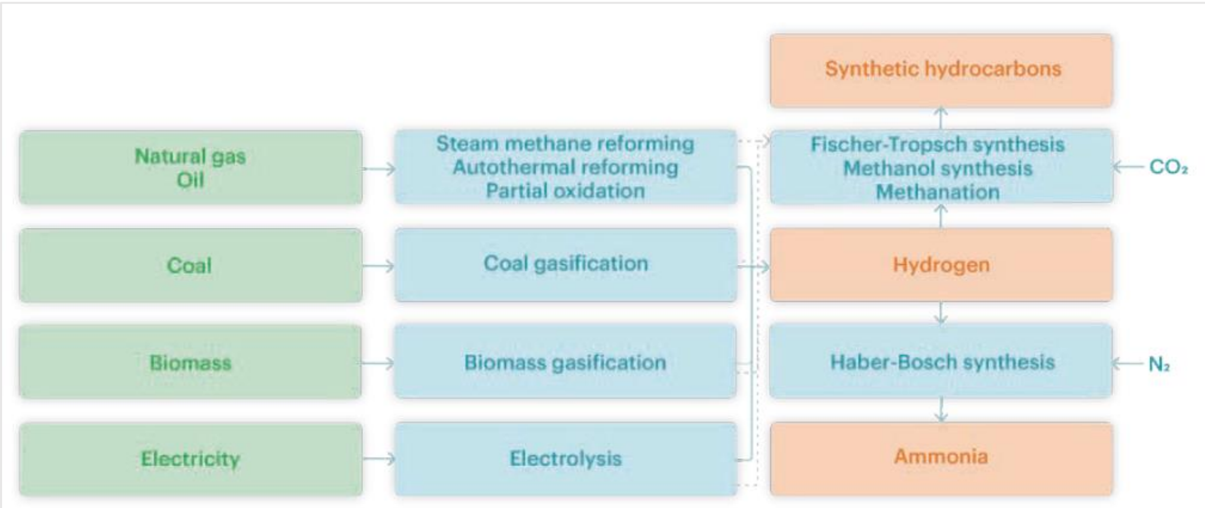

Figure 1: Production Pathways of Hydrogen (IEA, 2019)

Based on the production pathways, hydrogen can be categorised as grey (SMR), brown/black (coal gasification), blue (SMR with carbon capture, utilisation, and storage), and, green (electrolysis with renewable energy as input) (IEA, 2019).

2.2 Green Hydrogen

As mentioned above, green hydrogen is that hydrogen which is produced by a process which is considered as an end-to-end (from electricity supplied to final hydrogen produced) zero carbon dioxide process (Ejike, 2022). However, globally, there is no single definition for green hydrogen. It could take interpretations as below –

1. European Union - The EU does not have a definition of green hydrogen explicitly. However, it has the definition of renewable hydrogen which is as a part of Renewable Fuels of Non-biological origin (RFNBOs) under the Draft Delegated Act on Additionality (Commission, 2023) . It defines renewable hydrogen as "Hydrogen may be considered renewable only when the additionality requirement has been observed. Under this requirement, the

hydrogen must be produced by means of additional renewable electricity, produced at the same time and in the same area as the hydrogen."

2. United States of America – The US does not have a definition of green hydrogen but rather defines clean hydrogen, based on the value lifecycle greenhouse gas emissions rate - range of 0 kg CO_2e/kg H_2 to 4 kg CO_2e/kg H_2 - of the hydrogen produced (Congress.Gov, 2022). If we consider this range, green hydrogen will be the one which results in zero CO_2 emissions.
3. Australia – Australia defines green hydrogen as that which is carbon free, and is produced from renewable energy and non-fossil fuel sources (Council, 2021).
4. India – India does not have a concrete definition but as per the National Green Hydrogen Mission document, green hydrogen is considered as hydrogen produced through electrolysis of water or using biomass, using renewable energy as electricity input (Energy, 2023) .

For the purposes of this project, it is suggested to define green hydrogen as "*hydrogen which is produced from electrolysis using renewable energy sources, with the process of production being almost emissions free, and possibly including criteria such as additionality (of renewable energy), temporal correlation/time matching and geographical correlation/deliverability*." This enables us to align with the overall purpose of green hydrogen to support decarbonisation.

2.3 Ecosystem of Green Hydrogen

Having an initial sense of the production pathways of green hydrogen, a further understanding of the ecosystem of green hydrogen helps realize and breakdown policy interventions present globally. An early representation of a comprehensive green hydrogen ecosystem is shown in Figure 2.

The ecosystem can be broken down into 3 major parts – production, transportation & distribution (including storage) and end-use. A precursor to transportation could include conversion.

2.3.1 Production (or Supply) along with Transformation (if needed)

It can be seen that green hydrogen is produced through the process of electrolysis (only one pathway is present in the figure), with renewable energy as electricity input. It is further either transformed as a fuel (ammonia, synthetic fuels etc.), or it is used directly as input for an application.

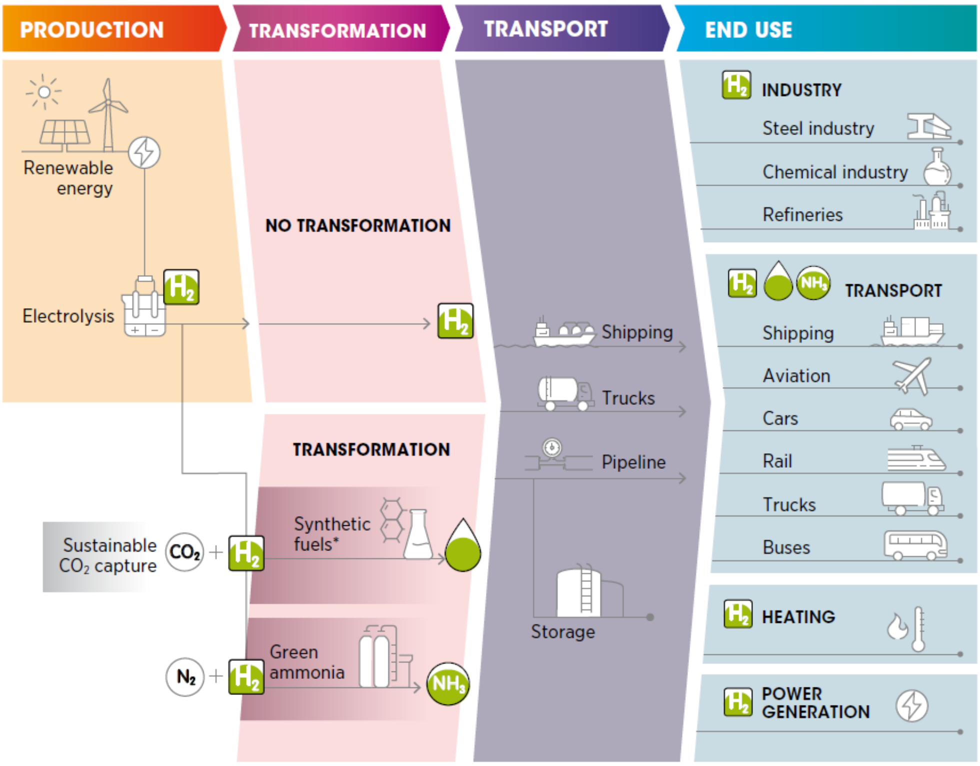

Figure 2: Green hydrogen ecosystem (IRENA, 2020)

2.3.2 Transportation & Distribution (or Infrastructure)

While hydrogen can be produced close to demand centres (decentralised production) thereby reducing the need for transportation and distribution, it could also have centralised production and be delivered to end-use sectors using shipping, pipeline, trucks, etc. Based on the method of transport, as well as the mode of storage, hydrogen can be compressed in tanks and distributed.

2.3.2 End-use/Application (or Demand)

As conveyed earlier, hydrogen can be used in diverse applications. This is also seen in the figure above, where hydrogen is used across industry – steel, chemicals, refineries etc., in transport, and for heating and power generation.

2.4 Policies to support the Green Hydrogen Ecosystem

The nascency of the green hydrogen market and possibility of market failures as discussed in the introduction provide an avenue for policies that could shape the development of green hydrogen. Policies afford initial support among others, through financial instruments for de-risking investments and reducing the costs of new and innovative technologies, and regulatory instruments to ensure minimum (demand) requirements for industry uptake and build infrastructure. Based on the representation of the green hydrogen ecosystem, policies can be grouped within the three parts of the supply chain. Globally, at least 26 countries have released hydrogen strategies and have accompanying policy instruments to facilitate the development of the green hydrogen ecosystem (IEA, 2022b). Table 1 below lists the examples of policy instruments across various dimensions of the ecosystem for some countries and regions. These are sourced from the webpages of EUR-Lex (EUR-Lex) for the EU, US Congress (Congress.Gov) for the US, Ministry of New and Renewable Energy (MNRE) for India and, Ministry of Economy, Trade and Industry (METI) for Japan. Furthermore, they are classified as *economic, regulatory* and *information* based on the policy mixes framework (Rogge & Reichardt, 2016), examples of which are expanded in Table 0 below.

	PRIMARY PURPOSE		
PRIMARY TYPE	**Technology Push**	**Demand Pull**	**Systemic**
Economic	RD&D grants and loans, tax incentives, state equity assistance	Subsidies, feed-in tariffs, trading systems, taxes, levies, deposit-refund-systems, public procurement, export credit guarantees	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulatory	Patent law, intellectual property rights	Technology/performance standards, prohibition of products/practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information	Professional training and qualification, entrepreneurship training, scientific workshops	Training on new technologies, rating and labelling programs, public information campaigns	Education system, thematic meetings, public debates, cooperative RD&D* programs, clusters

Table 0: Type-purpose instrument typology – Recreated Table 2(Rogge & Reichardt, 2016)

Dimension of the hydrogen ecosystem	Policy Details	Country
End-use	Regulatory - Mandatory quota for fertilizers and refineries sector to use green hydrogen (Proposed)	India
Production and End-use	Economic – (Domestic) Production Linked Incentive Scheme for Electrolyzer Manufacturing (Proposed)	India
End-use	Regulatory - Mandates for usage (of hydrogen) by 2030 (proposed) for industry and transport	EU

	Economic - Connecting Europe Facility (CEF) and CEF - Transport to support transition of the energy grid and transport towards sustainable alternatives	
Infrastructure (Systemic)	Regulatory – • EU Hydrogen and Gas Package for infrastructure development of hydrogen and gas networks • Alternate Fuel Infrastructure Regulation for mobility to have one Hydrogen Refueling Station (HRS) every 200 km across the Trans-European Transport Network corridor Economic instruments (some examples) – • Grants of EUR 200 million for hydrogen valleys (covers the whole supply chain) from the Clean Hydrogen Partnership • Innovation Fund – Budget of EUR 3 billion for R&D, large scale innovative projects • Loans to Member States to support RePowerEU targets through the Resilience and Recovery Plans • Carbon Border Adjustment Mechanism to prevent carbon leakage outside of EU EFTA Information • Net Zero Industry Academies to provide skilling and develop workforce capacity to drive the hydrogen economy	EU
Production	Regulatory (Inflation Reduction Act) driven financial instrument - Production tax incentives for clean hydrogen produced (maximum of $3 for every kg of H2 produced) and Investment tax incentives for clean hydrogen installations	US
End-use	Regulatory – • Targets for transport sector – o Fuel Cell Vehicles (FCVs) to 200,000 by 2025 and 800,000 by 2030, and construct HRS in 320 locations by 2025. • Strategic Energy Plan – o Introduction of co-firing (30% hydrogen, 70% natural gas) in gas-fired power plants and the construction of pure hydrogen-fired power plants by 2030	Japan

Supply	Economic instruments – Green Innovation Fund JPY 370 billion for hydrogen projects for 10 years beginning 2021	Japan

Table 1: Snapshot of policy tools across the green hydrogen ecosystem

2.5 Academic literature for Green Hydrogen

Following a systemic understanding of the green hydrogen ecosystem, the next step is to understand how green hydrogen policy features in academic research. For this, a literature review was performed for 'green hydrogen policy' using the SCOPUS database. The search resulted in approximately a hundred and fifty papers with relevant information. It was further categorised into generic (Raman, Nair, Prakash, Patwardhan, & Nedungadi, 2022; Velazquez Abad & Dodds, 2020), technical (Akhtar, Dickson, Niaz, Hwang, & Jay Liu, 2021; Deng et al., 2022), production pathways for green hydrogen (Bhattacharyya, Singh, Grover, & Bhanja, 2022; Ghaebi Panah, Cui, Bornapour, Hooshmand, & Guerrero, 2022; Juárez-Casildo, Cervantes, & González-Huerta, 2022), decarbonisation of sectors (Abdel-Wahab & Ali, 2013; Nurdiawati & Urban, 2022), countries (Hjeij, Biçer, & Koç, 2022; Pradhan et al., 2022) and regions (Kopytin & Popadko, 2021), market studies (Khan, Yamamoto, & Sato, 2021) and impact of green hydrogen on specific applications (Choi, Choi, & Park, 2022), and finally, policies.

Around thirty papers focused on green hydrogen policies, covering both policy design and policy evaluation. Since this project focuses only on the regions of the EU and the US, the literature review below cover papers about green hydrogen policy for these two regions specifically. The appendix has details for other regions.

2.5.1 Academic Research concerning green hydrogen policy in the EU

For the European Union, papers are divided between those that consider individual countries such as Poland and Germany and those that cover the EU in total. The paper on Poland (Bednarczyk, Brzozowska-Rup, & Luściński, 2022) employs a SWOT analysis to emphasise how it is important to make use of the existing support of EU regulations and funding incentives, the increasing price competitiveness of green hydrogen and the emergence of a cross border hydrogen market in Europe, to take advantage of hydrogen development within Poland. Two papers on Germany perform a review of the existing regulations present in Germany and at the EU level to provide recommendations that strengthen green hydrogen production. While both the papers provide similar policy initiatives, the methods used are different – one uses only secondary literature without a framework for analysis (Ringsgwandl, Schaffert, Brücken, Albus, & Görner, 2022), whereas and the other uses a multi criteria analysis framework on the literature obtained (Tholen et al., 2021). Policy suggestions include a combination of those targeted towards industry defossilisation and economic incentives beyond grid tariffs.

A paper on EU "carbon diplomacy" (Hancock & Wollersheim, 2021) analyses the recently proposed Carbon Border Adjustment Mechanism (CBAM) policy to understand the impact of it on hydrogen imports from Australia to Germany as a case study. The research uses a seven-dimension energy security-justice framework and explains how the CBAM's applicability will be counter-intuitive towards imports because of Australia's support towards fossil fuels and their possible inability to transition towards sustainable alternatives. This however will not limit the imports of Germany and could result in some sort of a gridlock. Another study by (Koneczna & Cader, 2021) analyses which EU member states have adopted the national hydrogen strategy and have developed their own polices for green hydrogen. The main policy initiatives proposed by such states are incentives to stimulate demand, and initiatives to develop a hydrogen market and supportive hydrogen infrastructure, as means to reduce carbon dioxide (CO2) emissions across various sectors while adding value to the economy.

2.5.2 Academic Research concerning green hydrogen policy in the US

For the US, there is very limited research and only one article (Ricks, Xu, & Jenkins, 2022) which analyses the impacts of the latest regulation – the Inflation Reduction Act, 2022 – on carbon dioxide emission reductions. This papers concludes that there is a need for hourly matching and geographical correlation (deliverability) so as to ensure minimum carbon dioxide emissions are possible and hydrogen producers could leverage the benefits of the financial incentives provided.

2.5.3 Academic Research concerning comparative analysis of hydrogen policies globally

Moving one step further and to understand the academic literature concerning comparative analysis studies for hydrogen development or hydrogen policies globally, a search in SCOPUS using the keywords "comparison" AND "hydrogen energy development" was performed. It was also tweaked to include "similarity and difference analysis" (instead of comparison), which resulted in only 1 paper (Pingkuo & Xue, 2022), which also showed up in the original search.

The first search resulted in exactly six papers, out of which only three were concerning comparison of hydrogen energy between countries and regions. The other three papers involved technology comparisons for hydrogen (Tarasenko, Kiseleva, & Popel, 2022; Xu et al., 2020)[1].

[1] The third paper was a paper (in Chinese) which did not have a translation in English and therefore, I did not cite it here.

For the papers comparing regions or countries, one of the papers (Pingkuo & Xue, 2022) compares the US, Germany, Japan and China using a novel multi-dimensional framework called IETB – Institutions, Economics, Technology and Behaviour. The paper highlights the similarities and differences among the approaches across these four areas for green hydrogen development. It concludes that these countries are still in the stage of quantitative change, and that through the market, policy can determine the strategic objectives and development trajectory of hydrogen energy in these four countries. Out of the remaining two papers, one of them uses the same IETB framework to compare BRICS (Brazil, Russia, India, China, South Africa) grouping and the US (Kakran, Sidhu, Kumar, Ben Youssef, & Lohan, 2023). The paper provides a conclusion that renewable hydrogen figures as a part of the long-term energy transition for these countries. Furthermore, they each have distinct underlying driving causes and advantages to have hydrogen as a part of their decarbonisation goals. The last paper (Park, 2013) compares the UK and South Korea and tries to understand underlying hydrogen policy developments of early 2000s, that has provided shape to the hydrogen economy of these countries. The paper uses the National Systems of Innovation (NSI) analytical framework for both the countries and concludes that there are varying development phenomena for hydrogen – the UK is driven by mobility and energy transition, whereas S. Korea is focused only on mobility and therefore, narrow policies are present here. Furthermore, academia and R&D agencies are responsible for innovation initiation in the UK, compared to governments and industry being responsible in S. Korea. However, for both countries, carbon dioxide emissions, sustainability, energy security and economic growth were underlying goals of the policy instruments for innovation.

2.5.4 Literature Summary

Based on the overall literature review, it can be concluded that there is only a small body of academic literature so far that offers insights into how different countries and regions individually design and evaluate green hydrogen policy mixes. Furthermore, papers that analyse interaction between instruments for green hydrogen are not present. Additionally, comparative analysis concerning green hydrogen policy, which could provide an insight into the characteristics of policies (and policy mixes) designed and implemented by countries/regions to drive (or not) green hydrogen development, is limited. This type of comparison is useful for understanding how current policy efforts can foster support for green hydrogen development and how they can be adapted and replicated within countries/regions to accelerate green hydrogen transition. Alternatively, it may shed light on which policies may work against overall green hydrogen market development objectives.

This paper aims to contribute to the limited green hydrogen policy literature in general, with a focus on understanding the interactions within instruments and between instruments and strategies. It also intends to contribute to the literature on comparative studies for green hydrogen policies by providing an in-depth cross-regional comparative analysis of green hydrogen policy mixes in the US and the EU.

3. Research Design

This paper uses a (comparative) case study approach to answer the main research question. To specifically answer the sub-questions, the paper incorporates the policy mixes framework developed and used for sustainable energy transition studies. The framework helps in an analysis and assessment of the policy mixes of the EU and the US for green hydrogen market development.

3.1 Case Selection

For this paper, this particular definition of a case study fits well – "a case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident…[and] relies on multiple sources of evidence" (Yin, 1989). Case studies help answer different types of research questions of a descriptive nature and can be used as an approach to provide information for studies where quantitative data is relatively newer and the topic is contemporary (Yin, 1989). Furthermore, this approach provides an in-depth exploration (Crowe et al., 2011) of real-life scenarios and can support cross-comparative considerations.

An important element of a case study is the unit of analysis (Harrison et al., 2017). For this paper, the unit of analysis considered is the policy mix of each of the regions of the EU and the US. Accordingly, US-federal level and EU-level (governance level) strategies and instruments are covered as a part of the comparative study. The reason for selecting these two regions is based on the similarities of democratic institutions, well-funded budgets, strength of innovation for new technology development, and state support for the growth of new and emerging technologies such as green hydrogen. Additionally, the EU and the US have an international influence concerning decarbonisation goals of countries globally and establishing global markets for sustainable energy transition technologies.

However, it is important to note that there is a dynamic nature associated with the policy mixes of these two regions because of ongoing discussions and deliberations on various strategies and instruments for green hydrogen. Furthermore, the field of green hydrogen is in a nascent stage. Therefore, time as a dimension to the mix becomes significant for analysis. For this paper, desk research data is restricted (documents for strategies, instruments etc.) to the period of January 2020-April 2023.

The limitation of the case study approach is that there is no specific structure or guidelines regarding methods (Yin, 1989) for conducting a case study. While on one hand, it could be criticised for becoming too focused and lacking the ability to generalise (Crowe et al., 2011), on the other hand, the lack of structure makes it a free form of research (Maoz, 2002). I address this explicitly through the use of an analytical framework to guide and structure the case studies.

3.2 Policy Mix Framework – Conceptualisation and Limitations

There is widespread agreement in academic literature that policy mixes are required to support processes of innovation and technological change (Kivimaa & Kern, 2016). These policy mixes also need to be evaluated to determine their effectiveness, i.e., whether they will be implemented in accordance with their stated objectives, whether the various policy instruments/tools introduced to support overall strategies will be synergistic or may undermine one another, and whether the policies will address issues systematically or ad hoc. As a result, it is critical to understand whether policy strategies and instruments, as well as the underlying processes and features - together referred to as a policy mix (Rogge & Reichardt, 2016) - can genuinely support countries' policy goals, objectives, and ambitions.

The policy mixes framework is an analytical framework to evaluate policy mixes for a unit(s) in the field of sustainable energy transition. It is concerned with analysing how multiple and complex policies can coexist and must be studied or evaluated (Lindberg, Markard, & Andersen, 2019). Furthermore, it lays a special emphasis on the interactions among instruments and between instruments and strategies. The structure of the framework, as described subsequently, necessitates the discussion of many blocks and assessment criteria that are found not only in its own area but also, for example, in the policy coherence, integration, and coordination debate (Cejudo & Michel, 2017) . The use of this framework, therefore, for an emerging technology such as green hydrogen, is both well-grounded and applicable.

The policy framework (Rogge & Reichardt, 2016) consists of three building blocks covered in Table 2 below.

Building Blocks	Definitions
Elements	
Policy Strategy	Policy strategy is defined as a combination of policy objectives and principal plans to achieve them.
Policy instruments/tools	Policies/Programs/Measures which help translate principal strategic plans to strategic goals
Instrument Type	Regulatory, Economic and Information (Refer Table 0)
Instrument Purpose	Technology Push, Demand Pull and Systemic Concerns (Refer Table 0)

Instrument Design	Instrument design can be categorised into descriptive and abstract features/ Descriptive features include the legal form, target actors and duration of the instrument Abstract features are not fixed but include the below 6 - Stringency - Refers to the ambition level of an instrument and refers to the goals, actors or technologies that the instrument covers (relevant for regulatory and economic instruments) Level of Support - Captures the quantum of positive incentives provided by an instrument (relevant for economic instruments) Predictability -Captures the degree of certainty associated with an instrument's current and future development and include the details about the duration, rules and direction that the instrument intends to take Flexibility - Captures the degree to which innovators are allowed to choose their preferred way of achieving compliance with an instrument Depth - Refers to the range of innovation incentives offered by an instrument in terms of potential solutions to help achieve net zero emissions Differentiation - Captures the differentiation associated with an instrument such as the sector covered, size of the plant, geographical location etc.
Instrument Mix	Captures the interaction between instruments, analysing the influence of one instrument on another and how they co-exist
Processes	Processes include both policy making and implementation. Together, these help to determine the elements of the policy mix and how they change over time as they help build and shape the instruments to achieve strategic goals.
Characteristics	There are four characteristics to describe a policy mix - Consistency, Coherence, Credibility and Comprehensiveness
Consistency	Consistency (of elements) concerns the overall consistency of the policy instruments and the strategy, as well as the alignment of instruments, when it comes to achieving the objectives/goals of the strategy. It also looks at the interaction between the instruments to determine whether they have conflicting or cooperative goals.
Coherence	Coherence of processes determines how policy making, and implementation are performed - whether there is stakeholder participation, dedicated implementation agencies etc., in the development of these processes are considered.

Credibility	Credibility determines whether instruments and processes can be considered as reliable. It is supplemented by a clean commitment from the political leadership. Consistency of instruments and coherence of processes, in some form also support credibility.
Comprehensiveness	Comprehensiveness governs how exhaustive and extensive the instruments are and whether extensive decision-making takes place for policy processes.

Table 2: Building Blocks of the Policy Mix Framework

To determine the effectiveness of the policy toolbox (instruments and processes) for a technological change, an evaluation of the characteristics of the policy mix across the spectrum of consistency (of elements), coherence (of processes), credibility (of the policy mix), and comprehensiveness (of the policy mix) is performed. For this paper, only three characteristics were considered – *consistency, credibility, and comprehensiveness.* The fourth characteristic of *coherence* was not considered since policy processes were not covered in the scope of this paper because of limited time.

A challenge of the policy mix framework is the boundary or scope that needs to be set to determine the complexity of the policy set and to examine its impact. This could both broaden and limit the instruments that are considered and the analysis that would be conducted and therefore, needs to be defined early on. To overcome this limitation, a scope for data collection is defined as discussed in section 3.2.

3.1.2 Alternatives to the Policy Mix Framework and why Policy Mix is the choice

There are alternative frameworks available for policy evaluation of energy policies or sustainable energy transition polices such as (few are quoted below) –

- Multi-criteria analysis framework (Tholen et al., 2021) – Analysis of policy instruments against pre-determined multiple criteria/challenges such as cost, sustainability, market development etc., to understand which of the policy instruments are able to counteract the barriers and ultimately provide a ranking of supportive policy instruments.
- IETB framework (Liu, Pengbo, & Chen, 2021) – Analysis of barriers of energy transition against four areas of Institution - institutional policies, development planning and strategy; Economics- financial investments both public and private; Technology-infrastructure, available technology and scaling up, systemic issues; Behaviour – conflicts between various levels of government, between government and industry etc.
- National system of innovation framework (Park, 2013) – Analysis of a particular innovative technology across multiple factors and characteristics such as policies, vision and expectations, social aspects among others.

Among all the frameworks, the policy mixes framework stands out since it considers the entire toolbox – policy instruments and processes – for analysis. This is a limitation of other frameworks (MCA) that mostly focus on policy instruments and not the underlying processes. The policy mixes framework further helps analyse interactions among instruments and between strategy goals and instrument goals and reflect on their characteristics, which is not the focus of any of the other frameworks.

The IETB and NSI framework are more comprehensive in nature that look at both policies and the market, and since the focus of this paper is only on examining the policy (mixes), these frameworks were not chosen.

3.2 Data collection

To gather the relevant data for sub-question 1 which concerns the details of the policy mixes for the EU and the US, the top-down approach (Ossenbrink, Finnsson, Bening, & Hoffmann, 2019), was applied to identify and list the elements of the policy mix with the strategic intent of 'development of a green hydrogen market'. This ensured that the process to gather relevant policy mix elements would be narrowed down to only those strategies and instruments which directly affect the market for green hydrogen development. This paper, therefore, analysed a smaller set of instruments and supporting literature.

Two key data sources were used – desk research and semi-structured interviews.

3.2.1 Documents

The first step of the desk research included a web search on policy strategies for hydrogen in the EU and the US, using the keywords of "strategy", "hydrogen", "goals", "targets", "actions", "plans" for both the regions. For the EU, the database used is the Eur-Lex (EUR-Lex). For the US, the US-Congress (Congress.Gov) and US DOE (HFCTO, 2021) websites were searched.

Furthermore, to find data for policy instruments, reports by external organisations such as the IEA, IRENA, Hydrogen Council (see appendix for details) which provide information about important policy instruments that could drive a hydrogen market, were analysed, and noted down. Based on the analysis, the following instruments were considered - regulations or directives for infrastructure, mandates and market development (local and international), definitions for green hydrogen, financing mechanisms such as contracts-for-difference, grants, loans, tax subsidies or credits, cross-border tax adjustments, green premium, certifications or standards for green hydrogen and safety, skill development and training programs and workshops, and research and development initiatives. Based on this list, specific instruments for the EU and the US were searched first in the policy strategy documents of these two regions. This was complemented by going through the Hydrogen Funding Compass

(EC, 2021c) for economic incentives and, Eur-Lex for regulations/directives, for the EU. For the US, the US-Congress and US DOE websites were searched to provide information about instruments. Search terms of "hydrogen" and "funding", "legislations", "directives", "regulations" were considered. To further expand the list of instruments, keywords of "programs", "initiatives", "measures" were also used in DOE sites.

3.2.1 Semi-structured Interviews

The purpose of semi-structured interviews for this paper was to supplement document analysis and also provide inputs for the assessment categories of credibility and comprehensiveness. Semi-structured interviews provide the flexibility of focus through close-ended questions, while allowing for further exploration and clarification through follow-up open-ended questions (Adams, 2015).

To determine who could be interviewed, stakeholders of the green hydrogen market were considered. A stakeholder network consisting of 42 different categories (pg.32) (Schlund, Schulte, & Sprenger, 2021) was used as the first step. From this broad list, stakeholders only from 7 categories could be approached through my network. The 7 categories were – R&D (universities), Associations, Project developers, RES plant developers, Politics, Consultants, Hydrogen technology providers and Electricity utilities.

As the purpose of the interviews was to support document analysis, a ballpark figure of 5 interviewees spanning any of the 7 categories for each of the two regions was considered. For the EU, seven people were approached, out of which three people confirmed for interviews (response rate of 42%). While for the US, six people were approached, out of which four people confirmed for interviews (response rate of 67%). The stakeholder categories covered for interviews were R&D(universities), Associations, Project developers, RES plant developers and Consultants.

The 30 minute semi-structured interviews were held online, with a short questionnaire of six questions. The questions were designed in a manner to understand the relevance of green hydrogen in the overall sustainable energy transition segueing into the focus areas of discussing the policy mixes for each of the regions. Emphasis was placed on determining the performance of policy mixes to support the operationalisation of the characteristics of credibility and comprehensiveness, particularly focusing on the positives and negatives of the strategies and instruments for each of the regions. Furthermore, the questions were designed to include what was needed to improve the policy mix. The questions asked are as below –

Themes covered	Questions
Relevance of green hydrogen in net-zero conversations	a. What is your opinion about the role of green hydrogen for sustainable energy transition/decarbonisation efforts?
Why policies are needed/where markets fail	b. What, according to you, are the most urgent barriers for the development of a hydrogen market? How do you think policies should aim to address current barriers?
Characteristics of Comprehensiveness & Credibility	c. Are the current policies in line with your (sector's) expectations? Are they supportive of a development of a green hydrogen market/ supportive of achieving the intended targets or goals of the policy strategies? d. What, according to you, would be the immediate implications of the current policies? e. What do you think should be changed/improved in current policies? f. What do you think should be the focus policy area (of the EU/US)?

A summary of the interviews conducted for the US and the EU is covered in the appendix of this paper.

3.2.3 Data analysis – Operationalisation of the Policy Mix Framework

For all the policy strategy and instrument documents obtained, a priori coding (Burkholder, Cox, Crawford, Hitchcock, & Patton, 2020) or closed coding, using Atlas.ti software, was used to specifically identify the goal or objectives (and quantified targets), plans or actions, instrument type and objective, thereby, operationalising the 'elements' building block of the policy analysis framework (Rogge & Reichardt, 2016). Table 2 below presents operational criteria for the 'elements' building block based on the inputs provided by Rogge & Reichardt (2016), and also my own interpretation of the framework.

Building Block (Elements)	Definition & Operationalisation	Source	Operationalisation (Coding) with examples
Policy strategy	Focused on Strategic intent. Combination of objectives and actions.	(Ossenbrink et al., 2019) (Rogge & Reichardt, 2016)	Combination of "objectives/goals/targets" and "actions/activities" (described subsequently)

Objectives/ Goals (for strategies and instruments)	Long term targets with quantified ambition levels. Broad purposes of government activity in a field.	(Rogge & Reichardt, 2016) (Hogwood & Gunn, 1984)	Quantified/non-quantified targets/objectives/goals. For e.g., for the US – 'DOE aims to increase clean hydrogen production from nearly zero today to 10 MMT per year by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050.'
Actions	General path to attain objectives through framework conventions, guidelines, strategic action plans and roadmaps. Action verbs for simplification	(Rogge & Reichardt, 2016) Self-interpretation	Activities/actions/plans/strategic plans. For e.g., for the US – 'Target strategic, high-impact uses', 'Reduce the cost of clean hydrogen', 'Focus on regional networks'
Instruments	Tools to achieve objectives by translating actions. Introduced by a governing body. Alternate terms - Policies, programs, implementing measures. Type of instruments – economic, regulatory and information	(Rogge & Reichardt, 2016), Gray literature/ Reports of IEA, IRENA covered in appendix	Regulations or directives for infrastructure, mandates and market development (local and international), definitions for green hydrogen, financing mechanisms such as contracts-for-difference, grants, loans, tax subsidies or credits, cross-border tax adjustments, green premium, certifications or standards for green hydrogen and safety, skill development and training programs and workshops, and research and development initiatives. For e.g., for the US – 'Hydrogen Shot is one of DOE's flagship initiatives to drive down the cost of clean hydrogen, in concert with accelerating deployment and scale, such as through

			hydrogen', 'the IRA, signed into law in August 2022 provides a Hydrogen Production Tax Credit (PTC)'

Table 3: Operationalisation of Policy Mix Framework – Elements and Processes

To answer sub-question 2, the third building block of the policy mix framework, i.e., the categories or characteristics of the policy mix - consistency, credibility, and comprehensiveness, was operationalised. An assessment of the instruments, and strategies of the EU and the US, against the three categories, was performed. The operationalisation of these criteria is derived from the approaches taken by existing research for sustainable energy transition, using the policy mixes framework (Deligrozev, 2022; Rogge & Dütschke, 2018; Rogge & Reichardt, 2016; Thielges et al., 2022), and are covered below in a simplified manner.

1. Consistency

As mentioned in Section 3.2, consistency of elements refers to concerns the overall consistency of the policy instruments and the strategy, as well as the alignment of instruments, when it comes to achieving the objectives/goals of the strategy. It also looks at the interaction between the instruments to determine whether they have conflicting or cooperative goals which could determine whether the instruments could collectively support the achievement of strategies goals (Rogge & Reichardt, 2016).

To understand whether the elements are consistent, certain operational conditions were tested. Each of these conditions helped sequentially to determine this characteristic, however only the test conditions in **bold** were considered to determine the consistency of the mix –

Test condition	Source	Expected response
What are the instruments or action items – types, purpose, and design, which are present in strategies or obtained through web search.		Details of the instrument, including type, purpose, and design type (Howlett & Rayner, 2007; Rogge & Reichardt, 2016)
Do these instruments help achieve the	Rogge & Reichardt (2016)	Visualisation of relationships between instruments and strategic goals using a simple tabular representation. If there is a

goal/target of the policy strategy? How?		disagreement/misalignment between the instrument and strategic goals, the cell is coloured in 'red'.
Whether instruments reinforce or undermine each other to achieve overall strategic objectives?	Rogge & Reichardt (2016)	Visualisation of relationships within the instrument mix. If there is a disagreement/misalignment between instruments, it will be represented with a 'not equal to' sign (≠).
Whether objectives of the policy strategies can be achieved simultaneously without any trade-offs? How?	Rogge & Reichardt (2016)	Visualisation of relationships among policy strategies, Explanation based on whether objectives/goals can be achieved without any trade-offs. Any disagreement/misalignment is represented with a 'not equal to' sign (≠).

Table 4: Operationalisation of Policy Mix Framework – Characteristic: Consistency

- If there is an instance of misalignment/disagreement among instruments/between instruments and strategic goals or among the objectives of the policy strategy, the elements are considered to be less or not consistent. To determine where the elements lie on the spectrum of consistency, a measure of the instances of disagreement present (more than half can be considered as shifting towards inconsistency) and how deeply they impact the achievement of strategic goals, i.e., based on lack of foreseeable possibilities of handling trade-offs between strategic objectives (if trade-offs cannot be managed, it would be difficult to achieve consistency), were factored in. A combined consistency is determined as below –

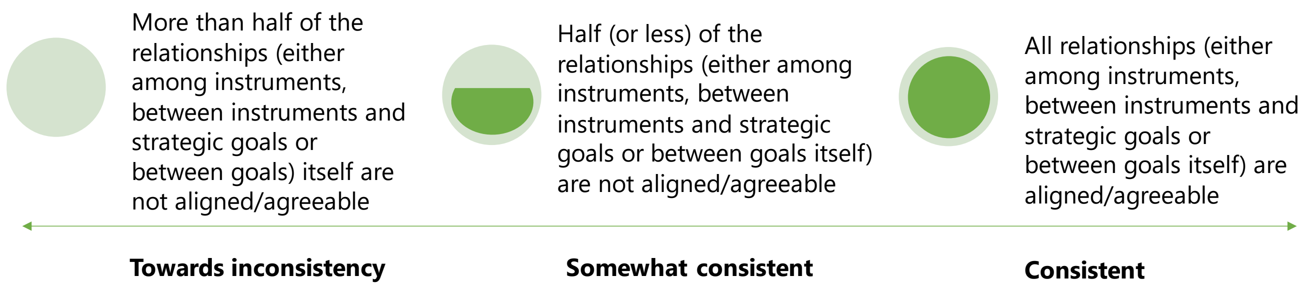

Figure 3: Consistency of the policy mix

2. Credibility

As mentioned in Section 3.2, credibility determines whether the policy mix, including the elements and processes can be considered as believable and reliable. It is supplemented by a clean commitment from the political leadership, which can be attributed to the clear and explicit mention of green hydrogen in any of the strategies or public procurement guidelines (Thielges et al., 2022) of the region. Furthermore, the stage of the instrument – draft, revision or complete - would contribute to credibility. In the sense, it would suggest that efforts are still required in building/confirming instruments (Thielges et al., 2022). Draft/revision stages of instruments suggest that there is a possibility that the instrument may not be passed legislatively ultimately, or the instrument may not be passed in the manner in which it is explained in this paper. Consistency of instruments and coherence of processes, in some form also support credibility. Finally, in the case of this thesis, inputs from interviewees who are a part of green hydrogen stakeholder network were also considered as their perception would help analyse whether the policy mix is believable in its current form (Rogge & Dütschke, 2018).

To understand whether the elements are credible, certain operational conditions were tested. Each of these questions helped sequentially to determine this characteristic, however only the test conditions in **bold** were considered for determining whether the mix is credible or not –

Test condition	Source	Expected response
Whether 'green (clean or renewable) hydrogen' is explicitly mentioned in any of the strategy documents of the regions or public procurement guidelines	Thielges et al. (2022)	Details of mention of green hydrogen in strategies and/or public procurement guidelines
Whether instruments are fully defined or still in process of being defined. What is the stage of instrument - draft vs complete vs revision stages, with supporting details.	Thielges et al. (2022)	Instruments' and their stage of completion along with details
Perceived credibility of the policy mix based on interviews with relevant stakeholders	Rogge & Dütschke (2018)	Positive or negative or mixed perceptions of the policy mix with possible

		recommendations for current barriers

Table 5: Operationalisation of Policy Mix Framework – Characteristic: Credibility

- Based on the stage of the instruments' definition, the credibility of the mix will differ. A score of '0' for 'draft' or 'revision' stage, '1' for final/complete stage, will help score the credibility index. '1' means it is credible, whereas '0' would suggest that it is not credible (yet). Even if one of the instruments is in a draft stage, the score will be defaulted to '0' as caution. Although the expectation of a fully defined mix may not be well-founded because of the nascency of the initiatives, it will be used to simplify the measure of credibility.

- Positive or negative or mixed perceptions of the policy mix will be scored on a '0 (negative)' or '1 (positive)' or '0.5 (positive with areas of improvement), score, and credibility will be established on a 0 to 1 scale (less to more credible) for semi-structured interviews. Perceptions of the policy mix directly concern responses provided to questions 4 & 6 in the interview question list "Are the current policies in line with your (sector's) expectations? Are they supportive of a development of a green hydrogen market/ supportive of achieving the intended targets or goals of the policy strategies?" and "What do you think should be changed/improved in current policies?" If the interviewer responds as –
    a. Yes, it is supportive without seeing any scope of improvement - the perception is scored as '1',
    b. Yes, there is scope of improvement with examples – the perception is scored as '0.5',
    c. No, it is not supportive, the perception is scored as '0'

  Across interviews, the overall perception was based on how many of the interviewees provided a 1,0.5 or 0 response. If there were more 1s than 0.5s or 0s, overall perception was considered as 1, if more 0.5s than 1s and 0s, overall perception was considered as 0.5, otherwise 0.

- Combined 'credibility' scale (below)

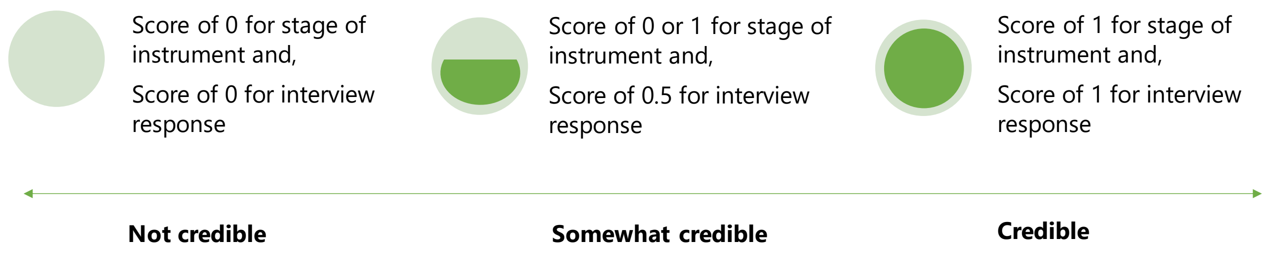

Figure 4: Credibility of the policy mix

3. Comprehensiveness

As mentioned in Section 3.2, comprehensiveness governs how exhaustive and extensive the instruments are and whether extensive decision-making takes place for policy processes. For this thesis, since processes were not considered for operationalisation, comprehensives of the policy mix was equated to the comprehensiveness of the elements. Rogge & Reichardt (2016) suggest that a comprehensive elemental mix would include a policy strategy with objectives and primary plans and at least one instrument in the instrument mix that operationalizes the policy strategy. Furthermore, the instrument mix would address all market, system, and institutional failures, including impediments and bottlenecks, and finally, the instrument mix would cover all three purposes of demand pull, technology push and systemic concerns.

To understand whether the elements are comprehensive, certain operational conditions were tested. Each of these questions helped sequentially to determine this characteristic, however only the test conditions in **bold** were considered for determining whether the mix is comprehensive or not –

Comprehensiveness of the instrument mix

Test condition	Source	Expected response
Whether instruments (at least one type of instrument) exist along with the strategy, with supporting details	Rogge & Reichardt (2016)	Details of instruments (if any) that help achieve strategic goals
Does the instrument mix address all the market, system, and institutional failures, including barriers and bottlenecks? If yes, how? If not, how?	Rogge & Reichardt (2016)	Analysis of the instrument mix systemically – both document analysis and interview responses (to questions covering this characteristic highlighted

		in Section 3.2) were considered
Whether the policy instruments/tools cover the array of purposes (technology push, demand pull and systemic concerns). * How?	Rogge & Reichardt (2016)	Details of the purpose of instruments/tools

Table 6: Operationalisation of Policy Mix Framework – Characteristic: Comprehensiveness

- If the instrument mix addresses all market, system, and institutional failures, including barriers and bottlenecks, it was considered to be comprehensive, otherwise it would be considered less or not comprehensive at all.
- If the policy mix addresses all the three purposes, it was considered to be comprehensive, otherwise it would be considered less or not comprehensive at all.
- Combined 'comprehensiveness' scale (below)

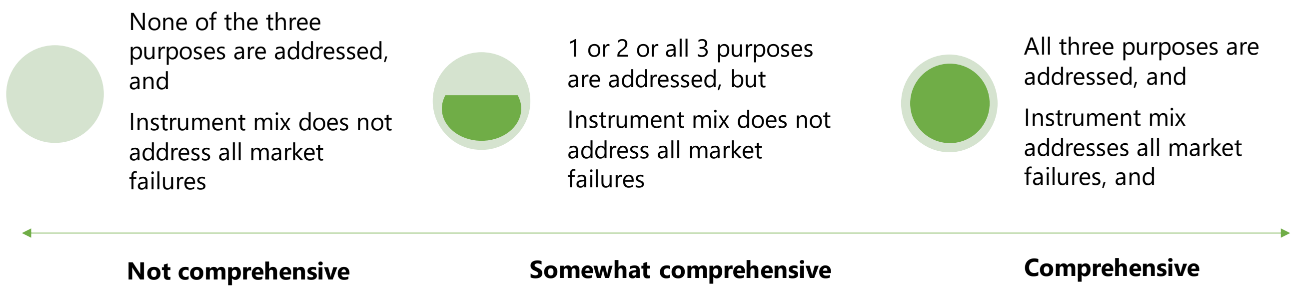

Figure 5: Comprehensiveness of the policy mix

* Technology-push instruments aim to increase the supply of technologies by providing incentives that reduce the costs of their development, such as direct research and development subsidies (Nemet, 2009). Demand-pull instruments, on the other hand, promote technological change by stimulating demand, for e.g., through regulation, financial incentives, or information campaigns (Peters, Schneider, Griesshaber, & Hoffmann, 2012). Systemic purpose instruments include those that provide support at a system level, for e.g., supporting infrastructure, market design reforms (Rogge & Reichardt, 2016) .

3.2.4 Data analysis – Comparative analysis of the two cases

The results of the operationalisation of the policy framework provided an explanation of the elements of US and EU policy mixes and an understanding of where the policy mixes lay on the spectrum of consistency, credibility, and comprehensiveness. An examination of this assessment offered an understanding of the similarities and differences of the policy mixes. Additionally, placement of the instrument mix (production, end-use and infrastructure), gave an idea of where the policy mix of each region was present or lacking. This was supplemented by inputs from the interviews. Interviewees provided areas of improvement in terms of what they considered were challenges for each of the policy mixes. These challenges were analysed to determine which parts of the hydrogen ecosystem they belonged to and were highlighted in the systemic diagrams (figure 10 and 11) for each of the regions.

The assessment and placement combined provided the direction towards drafting policy recommendations that could improve the current policy mixes for green hydrogen for the EU and the US and support the market development for both of these regions. Additionally, it added value in terms of learning opportunities, both in terms of what the two regions could learn from each other and what could be learnt overall as an application for countries that wish to develop and further ramp up their green hydrogen markets. This ultimately helped answer the main research question.

4. US Policy Mix on Green Hydrogen

4.1 General Approach

For the analysis, five documents were considered - Draft National Clean Hydrogen Strategy, legislations such as Inflation Reduction Act, Infrastructure and Investment Jobs Act, guidelines such as the Clean Hydrogen Production Standard and Executive Order to expand legislations such as the Defense Production Act. Additionally, information pertaining to programs supporting green hydrogen was gathered from the (respective) websites of the program. As discussed in Chapter 3, a priori coding (Burkholder et al., 2020) using Atlats.ti software was performed on the documents to specifically identify the strategy goal or objectives, plans or actions, instrument goal, type and purpose, implementing agencies and their programs, to operationalise the policy analysis framework (Rogge & Reichardt, 2016).

For interviews, since the focus was on understanding the positives and negatives as well as the improvement areas for the US policy mix, responses to such questions were noted and included in the overall systemic representation of the US policy mix.

This chapter is broken down to cover the elements – strategies and policy instruments, and characteristics of the US policy mix using the operationalisation of the policy mix framework covered in section 3.2.3.

4.2 Strategies of the US

The US approach towards clean hydrogen has been gradual, as seen in the figure 6 below. Hydrogen featured in US strategies and regulations early on (DOE, 2020) with a Hydrogen Energy Roadmap being released in 2002. Inclusion of hydrogen in the

Energy Policy Act of 2005, however, was a turning point in legislation since it was an effort towards promoting development and commercialisation of hydrogen and fuel cell technology with industry support, specifically for the transportation sector. These programs and initiatives did not have a clear mention of hydrogen as clean or green or low carbon. In 2020, however, considering hydrogen as a low or zero carbon energy carrier across applications was seen as a part of the 'Hydrogen Strategy: Enabling a low carbon economy.' This strategy described the various R&D efforts that would be taken by the Office of Fossil Energy under the DOE to transition towards low carbon hydrogen.

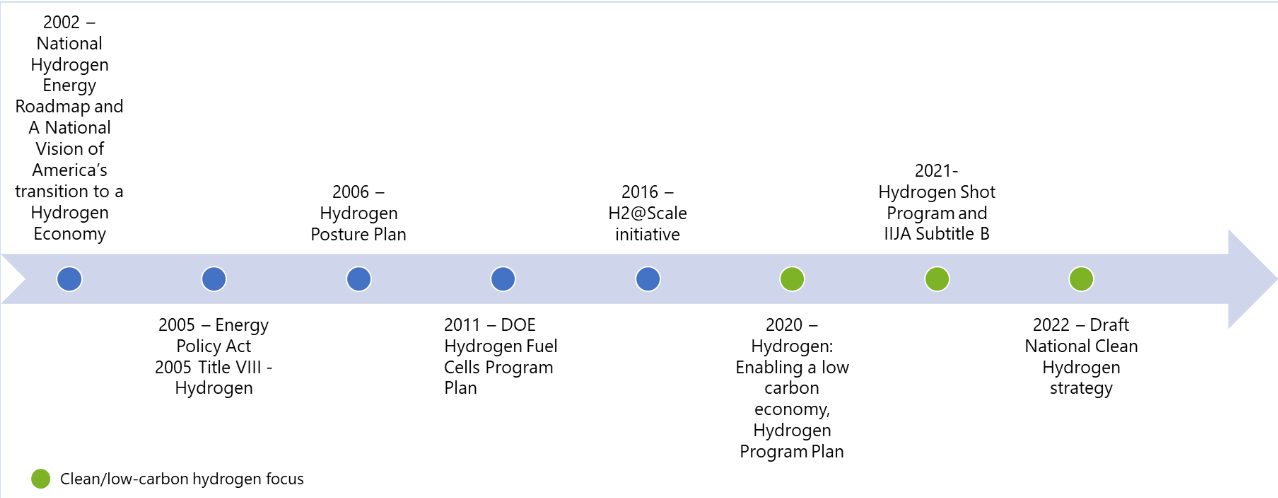

Figure 6: US Hydrogen Development

In September 2022, the DOE released the draft 'DOE Clean Hydrogen Strategy and Roadmap' (DOE, 2022b). Long-term annual production targets were specified for 2030 – 10MMT, 2040 – 20MMT and 2050- 50MMT for green hydrogen. A total GHG emission reduction by 10% (from 2005 levels) is also envisaged to be achieved by 2050. The goals of the strategy document are four fold:

- Leveraging hydrogen's use across multiple sectors, both domestic and exports.
- Finding ways to stimulate private investments.
- Including communities by ensuring an environmentally just and inclusive society is provided.
- Supporting the net-zero ambitions of the administration.

The action plans to achieve these goals include -

- Co-ordinating with state and federal agencies relevant to various parts of the ecosystem of hydrogen to accelerate progress and attain market lift-off.
- Targeting strategic end-uses for hydrogen. As of 2021, the maximum consumption of conventional hydrogen has been in refining (55%), ammonia

and methanol (35%) sectors. These sectors are the natural entrants and strategic choices to transition to green hydrogen.

- Reducing the cost of green hydrogen to catalyse innovation and scale up electrolyzer capacity and green hydrogen projects.
- Focusing on development of regional networks to enable large scale production and end-use proximity of green hydrogen through hubs/valleys.
- Focusing on development of requisite infrastructure, storage, and delivery of green hydrogen.

Apart from the goals and actions of the strategy document, one of the strategies of the US is also to have clean hydrogen research and development. This is covered in the amendment to the Energy Policy Act 2005 released in 2021. The goals detailed as per this program include advance research and development for demonstration and commercialisation of green hydrogen across various applications and demonstrating standards of green hydrogen by 2040. The goals are envisaged to be followed through safe and efficient delivery of green hydrogen and hydrogen carrier fuels, use of green hydrogen across various sectors and applications and also reducing the cost of green hydrogen.

Based on the strategies covered for the US, it can be gathered that the focus of the US is on establishing a domestic environment of green hydrogen and ensuring its roll-out in a cost effective manner through R&D across various industries at scale, as a means of decarbonisation and achieving US overall net-zero ambitions, with possibility of exports in the long term.

4.3 Instruments of the US

Instruments/tools of the US for green hydrogen are categorised based on the type, purpose and design features as defined in the policy mixes framework (Rogge & Reichardt, 2016) and table 7 below provides the details.

Policy/Program Instrument Name	**Primary Type**	**Primary Purpose (Refer Table 0)**	**Primary Design Features (Refer Table 2)**
Inflation Reduction Act (IRA) – Section 45V and Section 48 (a) (15)	Economic and Regulatory	Technology Push, Demand Pull	Stringency, Flexibility, Level of support
Infrastructure Investment and Job Act (IIJA) – Section B – Hydrogen	Economic and Regulatory	Systemic Concerns Technology Push (Secondary Purpose)	Stringency, Predictability, Level of support, Depth

Research and Development			
Clean Hydrogen Production Standard (CHPS)	Information	Systemic Concerns	Stringency, Flexibility
Defense Production Act - section 303(a)(7)(B)	Regulatory	Demand Pull	Stringency
Hydrogen Shot	Economic Information	Systemic Concerns	Depth
HyBlend initiative	Information	Technology Push	Differentiation
H2 Matchmaker Portal	Information	Systemic concerns	Cannot be classified
Super Truck 3	Economic	Demand pull	Differentiation
Sustainable Aviation Fuel (SAF) Grand Challenge	Economic	Demand pull Technology Push	Differentiation
H2NEW, HydroGEN, HyMARC, H-Mat, Electrocat	Information	Technology Push	Flexibility, Stringency
H2EDGE	Information	Systemic Concerns	Cannot be classified

Table 7: List of instruments, their purpose, type, and design features for the US policy mix

- IRA - Section 45V and Section 48 (a) (15) (Congress.Gov, 2022): The IRA, although is a regulatory form of instrument, specifically provides economic/financial incentives for various industries. For production of green hydrogen, the IRA in August 2022, established a production tax credit (PTC) incentive program under Section 45V. The tax credit provides ~$3 of a credit per kg of Hydrogen produced which is green (<0.45kgCO_2e/kgH_2). $3 is the maximum credit that can be provided, and this is subject to the fulfilment of prevailing wage and apprenticeship requirements. The IRA also extended the application of Section 48 in the form of investment tax credits for investments made in clean hydrogen. Similar to the PTC, the level of tax credits provided is also subject to the quantum of carbon dioxide emissions that are abated. Because of the level of carbon dioxide emissions that needs to be abated and the wage conditions that need to be met, this instrument is typically stringent in nature. The credit is a 10 year credit which can be claimed till 2032, for projects beginning construction after December 31, 2022 – this also ensures a significant level of support is provided. It is also flexible because both transferability of tax credits and direct pay options are available to obtain the tax credits. Where the instrument lacks is in the methodology of calculation of carbon dioxide emissions and therefore, this could be troubling for the stakeholders and makes it unpredictable in nature. The primary purpose of this instrument is to ensure there is a supply created for new technology of green hydrogen which acts as a sustainable substitute and carrier for various applications, where conventional hydrogen is already used and for other applications which are hard-to-decarbonise.

- IIJA – Subtitle B (Congress.Gov, 2021): The IIJA, similar to the IRA is a regulatory form of instrument. A new subtitle B for 'Hydrogen Research and Development' under the act includes provisions to amend the Energy Policy Act, 2005 and include the programs of Clean Hydrogen Research and Development, Regional Clean Hydrogen Hubs, Clean Hydrogen Manufacturing and Recycling and Clean Hydrogen Electrolysis as a means for commercialisation of green hydrogen. For each of the programs, there is dedicated funding -$1 billion for a Clean Hydrogen Electrolysis Program, $500 million for Clean Hydrogen Manufacturing and Recycling, RDD&D Activities and $8 billion for Regional Clean Hydrogen Hubs from 2022-26. The Clean Hydrogen Electrolysis Program provides funding across the hydrogen ecosystem - from research, development, and demonstration to commercialization and deployment ensuring a cost reduction of production of hydrogen by 2026. The Clean Hydrogen Manufacturing and Recycling is a way to ensure domestic manufacturing of equipment used for hydrogen, and encourages technology development in the U.S. This is also supported by the Clean Hydrogen Research and Development Program. Finally, the Regional Clean Hydrogen Hubs is systemically designed to support development of networks of producers, distributors, and end-users of hydrogen in a concentrated hub or valley, with necessary infrastructure. Because of the fixed timeline and quantum of funding available, the instrument's design is stringent and predictable, with a good level of support. The variety of programs available for green hydrogen also provides depth to the IIJA, as it covers systemic support through hubs and hydrogen electrolysis program, while providing the technology push through the hydrogen manufacturing and recycling program.

- CHPS (DOE, 2022a) : The CHPS features as a part of the IIJA. However, it is an external informational instrument that provides a guideline to stakeholders in the hydrogen ecosystem about the qualifications for green hydrogen required for the programs that are funded by IIJA. The CHPS explains a typical system boundary that acts as a reference to assess lifecycle emissions. The carbon dioxide emissions considered to define clean hydrogen range from <0.45 $kgCO_2e/kgH_2$ to $4kgCO_2e/kgH_2$. Since the CHPS provides a guide for the entire supply chain, its' purpose is systemic in nature. Furthermore, it is stringent in design (fixed range of carbon dioxide emissions), while also being flexible because of the way to achieve lifecycle emissions is not fixed.

- The Defense Production Act (DPA) – section 303(a)(5) was invoked in June 2022 (Energy.gov, 2022) to encourage domestic manufacturing of electrolyzers within the US. As such, its purpose is demand driven. Through an executive order, public procurement of electrolyzers was ensured and authorisation on expenditure of $50 million was waived off. The DPA is stringent in nature because it is limited only to public procurement of electrolyzers and also that electrolyzers are to be manufactured locally in the US.

- Hydrogen Shot (Energy.gov, 2021) program was launched by DOE in 2021, with a goal to reduce the cost of hydrogen production to $1/kg in one decade (2031). This program establishes a foundation for clean hydrogen deployment in the America Jobs Plan, through support for demonstration projects and is therefore, economic in nature. Through workshops and fellowship programs, this program is informative in nature as well. As a part of the program as well, the DOE considered stakeholder inputs through requests for information to identify locations and methods for reducing the cost of green hydrogen. This instrument provides depth because of the range of initiatives covered (trainings, workshops, fellowships) and is systemic in nature. The shot was followed by the IIJA.

- H2 Matchmaker Online Portal (DOE, 2022b) is an information instrument which was launched in 2022 to connect players in the hydrogen ecosystem with each other. Because of the broad range of stakeholders that the portal can connect, it is systemic in nature.

- HyBlend initiative (DOE, 2022b) is an information instrument that was launched in 2020 to address information gaps in blending of hydrogen with natural gas, by bringing together labs, industry, and academia. R&D efforts are led by the National Renewable Energy Laboratory (NREL). This initiative is a collaboration of DOE with the Office of Fossil Energy and Carbon Management, the Industrial Efficiency and Decarbonization Office, the Building Technologies Office, and other relevant offices and agencies. Through this initiative, tools that assess risks associated with blending to a pipeline system, evaluate opportunities and costs of blending and calculate lifecycle emissions of blending with other pathways, will be developed. The R&D efforts of this initiative from 2021-23 provide the technology push that could encourage green hydrogen use in natural gas as a cleaner method. Because this initiative is only focused on natural gas sector, it is differentiated from the other initiatives.

- Super Truck 3 program (DOE, 2022b), the most recent (2021) iteration of the existing Super Truck program, is an initiative of the DOE to demonstrate medium and heavy-duty hydrogen fuel cell trucks under real-world operating conditions. It is a demand pull instrument with a focus only on the transportation sector and is therefore differentiated. Because it provides funding to companies to ideate and provide solutions to reduce emissions in trucks, it is an economic instrument.

- Similar to the Super Truck 3 program, the Sustainable Aviation Fuel (SAF) Grand Challenge (DOE, 2022b) is an economic instrument that was launched in 2021 along with Department of Transportation and Department of Agriculture to reduce the cost, improve sustainability, and expand the production and use of SAFs with a 50% reduction in lifecycle GHG emissions compared to conventional fuels. The goal of this challenge is to scale up the production of SAF to 35 billion gallons per year by 2050, with a near-term goal of 3 billion gallons per year by 2030. It is a coordinated effort between DOE, Department of Transportation, Department of Agriculture, and other agencies and is focused only on the aviation sector. Therefore, it is differentiated, while its purpose is to create a demand and also push for technological developments in the aviation sector to make it green. Green hydrogen is one of the options to produce SAF among others, and therefore, this is not a dedicated instrument.

- H2NEW (Hydrogen from Nextgeneration Electrolyzers of Water) (DOE, 2022b; Energy.gov, 2023), a consortium of nine DOE national labs, industry, and academia, launched in 2020, focused on making large-scale electrolyzers, through R&D to overcome technical and cost barriers – Hydrogen production target < $2/kg by 2025. Since it is an instrument that leverages R&D efforts, its purpose its technology driven and since it consists of a cluster of labs, it is an information instrument. Additionally, it is stringent in nature because there are a set of electrolyzer feature goals that are targeted to be achieved by 2025. However, it is flexible, because it considers both low and high temperature electrolyzers and R&D for both these types to achieve the goals. Instruments similar to H2NEW are Hy-MARC (Hydrogen Materials Advanced Research Consortium) which is a consortium comprising of seven national labs focused on R&D for advancement of solid-state storage materials, HydroGEN which is a consortium of six DOE labs that aims to accelerate the RDD of advanced water splitting technologies for clean, sustainable hydrogen production, H-Mat (Hydrogen Materials Compatibility Consortium) which is a consortium of five labs working closely with industry and academic to pursue R&D efforts focused on the effects of hydrogen on performance of polymers and metals used in hydrogen infrastructure and storage, and ElectroCat (Electrocatalysis) Consortium, a DOE funded consortium, which is focused on increasing the competitiveness of the US in manufacturing fuel cells and electrolyzers

- H2EDGE (Hydrogen Education for a Decarbonised Global Economy) (U. DOE, 2021) is a project by the US DOE to enhance workforce readiness through training and education activities. Since H2EDGE includes skilling workshops, content etc., across the hydrogen supply chain, it is an information instrument with the purpose of being systemic. Furthermore, the timeline of this instrument is from 2021 to 2024.

4.4 Interaction between instruments and across instruments and strategies

The instrument mix covers the interactions among the instruments described above. Overall alignment of the instruments with policy strategy goals can be seen in figure 7. From the figure, it can be concluded that there is an alignment between instruments and policy strategy goals.

Between the instruments, a variation is seen in the dimension of time for implementation, with the IIJA being available for the time-period of 2022-2026, while the IRA is available from 2022-2032. Since they both have their own individual goals, different time dimensions do not impede the possibility of achievement of overall policy strategy goals. However, in the case of time dimension of target achievement, there is a slight mismatch between the strategy of demonstrating a standard of green hydrogen production by 2040 and reaching a quantity target of 10MMT annually by 2030. While quantity targets can be achieved without a developing a standard for green hydrogen, a confirmed standard can ensure that projects which claim to be producing green hydrogen are indeed producing green hydrogen through certification or other means, rather than adhering to project/tender specific requirements. Nonetheless, a time mismatch between these two is not considered as a major impediment to the development of a green hydrogen market.

The one common thing seen amongst all the instruments are the policy goals of ensuring ‘Green H2 use across sectors’ and ‘Support net-zero transition’. These two policy goals also interact with each other, since green hydrogen is defined as that which has least/zero emissions, and this would support the goal of a net-zero transition. Furthermore, an increase in 'Green H2 use across sectors' will also support the 'quantity targets' of annual production of Green H2.

While the instruments on their own are not seen as interacting with each other, they do interact with the overall strategy goals and targets.

- IRA Section 45V and Section 48 (a) (15) – For the policy instrument of IRA, the main instrument goals are 'production incentivisation' and 'reduction in cost of green H2 produced' since a $3/kg tax credit is provided. This also helps to 'stimulate private investments' since private sector companies are provided a relief for the investment costs that they undertake, while also, guaranteeing their intent because it is a 10 year long tax credit. It is also known that to achieve the credit, a certain carbon dioxide emission level needs to be met, and therefore, this 'supports the net-zero transition' goal of the policy strategy. By providing incentives for production of green hydrogen, the instrument also encourages the final 'end-use of hydrogen in various sectors'. The other instrument goal of 'Adhere to wage and apprenticeship requirements' directly links to the policy goal of 'community inclusion' since the instrument ensures that to obtain the tax credit, companies producing green hydrogen need to make sure companies provide the minimum prevailing wage and fulfil apprenticeship requirements.
- IIJA Subtitle B– For the program on Regional Clean Hydrogen Hubs, there are two main goals – 'target specific end-use sectors' and 'co-location of demand and supply'. The goal of targeting specific end-use sectors will support policy goals of 'Green H2 use across sectors.' This will also help to achieve quantity targets detailed out in the strategy. Co-location of demand and supply will ensure that more than anything, the 'quantity targets' of the policy strategy are met, while also supporting 'Green H2 use across sectors' and also help 'build hydrogen infrastructure and delivery.' The program on Clean Hydrogen Electrolysis Program has a goal to 'reduce the cost of hydrogen produced' to below $2/kg by 2026. Finally, the goal of the program on Clean Hydrogen Manufacturing and Recycling is to advance clean hydrogen across the value chain, while also 'reducing the cost of producing hydrogen' through recycling, while the program on Clean Hydrogen Research and Development will 'accelerate R&D efforts.'
- CHPS – The goal of the CHPS is to 'aid in project selection'. This will result in 'Green H2 use across sectors', while also 'supporting net-zero transition' and also help to 'demonstrate the standards of green H2' while achieving 'quantity targets.' The support to clean transition is because the standard ensures that a

certain level of carbon dioxide emissions is met so that the projects can qualify for funding under the IIJA programs.

- DPA 303(a)(5) – The goal of invoking the section of the DPA is to ensure that there is 'domestic manufacturing of electrolyzers' through public procurement. Electrolyzers' presence connects to the overall goal of deployment of 'Green H2 use across sectors.'

- The programs of HyBlend, Super Truck 3, SAF Grand Challenge, all have the larger policy goal of 'supporting net-zero transition.' Each of these individual programs as explained before, are geared towards green H2 use for reducing the carbon footprint of each of sector they are focused on – HyBlend for natural gas, Super Truck for transportation and SAF for aviation and therefore also support the goal of 'Green H2 use across sectors.' 2021 Data from the US Environmental Protection Agency (EPA) suggests that sectoral GHG emissions are highest for transportation (28%), followed by power (25%), and industry (23%). These specific programs in a way are supporting the overall decarbonisation of the most carbon intensive sectors (EPA, 2021) . The HyBlend initiative also supports 'accelerating R&D efforts' so that blending of hydrogen with natural gas is achieved.

- H2Matchmaker specifically acts as a program to 'connect producers with end-users' and therefore, through this effort, would help achieve the 'quantity targets' envisaged in the policy strategy, while also encouraging 'Green H2 use across sectors.' The Hydrogen Shot program was particularly launched as a way to 'reduce the cost of hydrogen produced' through 'R&D initiatives' and was further followed by the programs within the IRA and IIJA. Similar to the Hydrogen Shot program, the H2NEW, HydroGEN, H-Mat, HyMARC, ElectroCat instruments, being technical R&D focused, have as their goals the 'reduction of cost of green H2' and also 'advancing R&D efforts' which will also help 'demonstrate the standards of green H2.'

- H2Edge is focused on providing training and education activities to build hydrogen-ready workforces and therefore, supports the strategic goal of 'workforce capacity and skilling.'

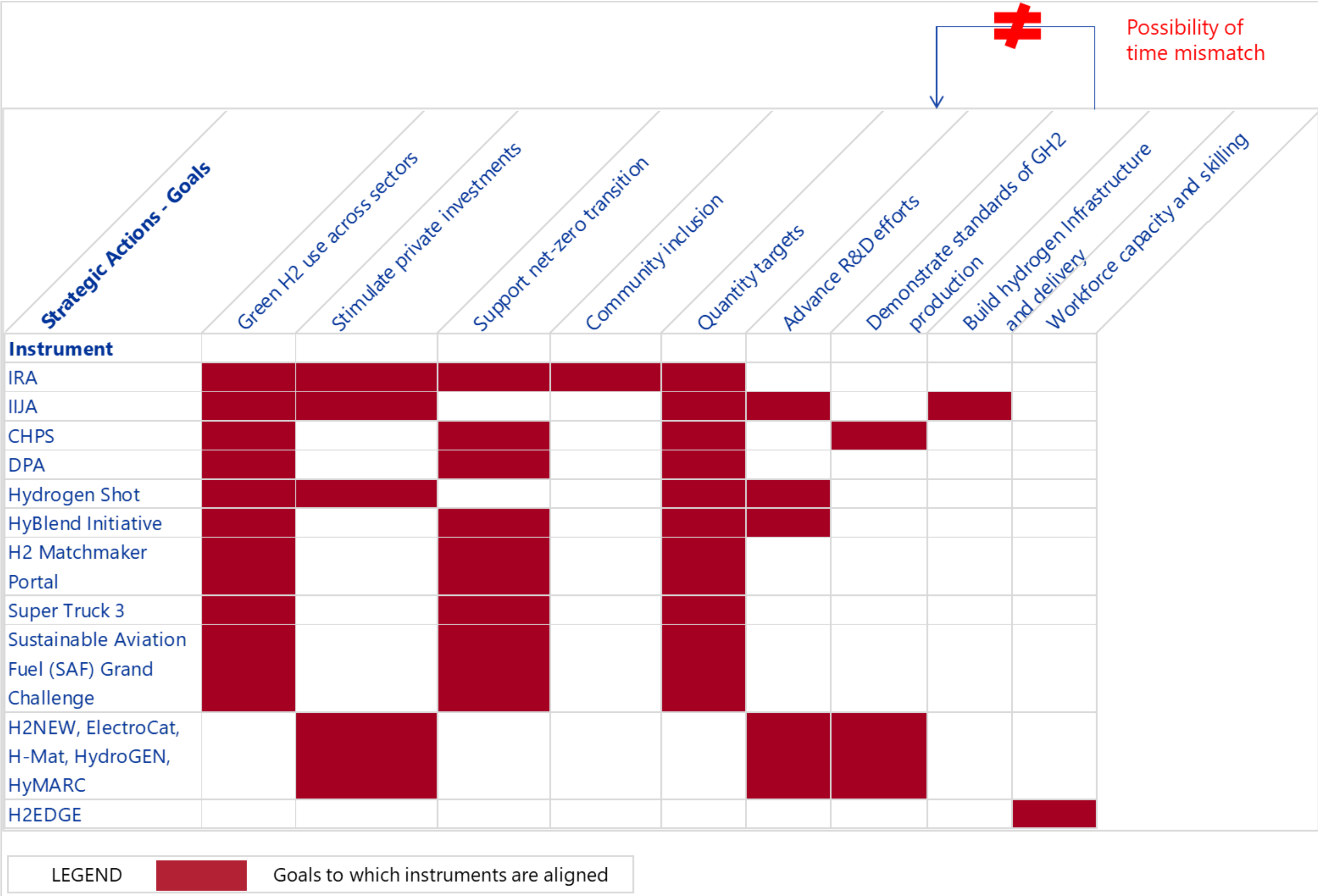

Figure 7: Relationship establishment between instruments and strategic goals

4.5 Characteristics of the Policy Mix

For the three characteristics of the policy mix, this paper analysed the policy mix elements and processes and based on the operationalisation detailed in section 3.2.3, the results are discussed subsequently.

4.5.1 Consistency of elements

For the test conditions mentioned below, the answers will help determine where the US policy mix stands with respect to consistency.

Test condition	Response	Section reference
What are the instruments or action items – types, purpose, and design, which are present in strategies or obtained through web search. **Do these instruments help achieve the goal/target of the policy strategy?**	The US has a combination of regulatory (DPA, IRA, IIJA), information (CHPS, HyBlend, SAF Grand Challenge, H2NEW, etc.) and economic instruments (IRA, IIJA), which cover the purposes of technology push, systemic concerns and demand pull through their design. While some of these instruments such as the IIJA, CHPS, Super Truck etc., find explicit mention in the Draft strategy document, others are programs and initiatives which were obtained from DOE's website. Furthermore, from figure 7, it can be concluded that all the instruments are aligned to/in agreement with larger policy strategic goals. Section 4.4 provides a detailed breakdown of the relationship between instruments and goals and further, how the instruments could help achieve overall strategic goals through their own interim instrument goals. Therefore, it can be said that existing instruments can help achieve the goals of the strategy.	4.3, 4.4, Figure 7
Whether instruments reinforce or undermine each other to achieve overall strategic objectives?	Based on the analysis from figure 7, none of the instruments are seen to be conflicting in nature. In fact, they appear to be working in tandem to help translate strategic actions and goals.	4.4, Figure

Whether objectives of the policy strategies can be achieved simultaneously without any trade-offs?	While there is alignment between instruments and between instruments and strategies, there appears to be a slight time mismatch between strategic goals. One of the goals of the strategies of the US is to demonstrate clean hydrogen production standards in line with CHPS by 2040. However, given the near-term quantity targets of 10MMT annual production of green hydrogen by 2030, the delayed demonstration (10 years) may cause an inconsistency in goal achievement. While quantity targets can be met without developing a green hydrogen standard, a confirmed standard can ensure that projects claiming to produce green hydrogen do so through certification or other means, rather than adhering to project/tender specific requirements. Nonetheless, the time difference between these two is not regarded as a significant hindrance to the creation of a green hydrogen market.	4.4

Based on the responses and the operationalisation covered in Section 3.2.3, we can say that the elements of the US policy mix are fairly consistent with caution about the slight time mismatch for the strategic goals of the US.

4.6.2 Credibility

For the test conditions mentioned below, the answers helped to determine where the US policy mix stands with respect to credibility.

Test condition	Response	Score (NA = Not applicable, 0= Draft/revision stage, 1 = Complete stage, 0 – negative perception, 1 – positive,	Section reference

		0.5 – positive with improvements)	
Whether 'green (clean or renewable) hydrogen' is explicitly mentioned in any of the strategy documents of the regions, public procurement guidelines	Both the Draft Clean Hydrogen Strategy and the IIJA which cover policy strategies explicitly mention clean/green hydrogen. On the other hand, the DPA which encourage public procurement of electrolyzers indirectly supports the green hydrogen market. This suggests a clear commitment from political leadership.	NA	4.3
Whether instruments are fully defined or still in process of being defined. What is the stage of instrument - draft vs complete vs revision stages	The instruments for the US are a combination of draft and complete stages, with none belonging to the revision stage. Amongst the tools, only the CHPS is in the draft stage. Furthermore, the main strategy (although not an instrument) is also in the draft stage. Other instruments such as the IRA, IIJA, DPA and various programs, consortiums are in the complete stage. This suggests that there is still work required to build the policy mix from its current form.	Combination of draft and complete stages. Precautionary, score of 0 (draft) is given	4.3
Perceived credibility of the policy mix based on interviews with relevant stakeholders	Based on the interviews conducted for the US, it can be concluded that there is a general sense of positivity regarding the policy instruments that the US has shaped for the green hydrogen market. For instance, the interviewees considered the financial incentives provided by the IRA as revolutionising in a way to support	0.5	Summary of interviews for the US

	the US' market oriented initiatives for green hydrogen. However, in addition to the positive views, areas of improvement were suggested. These included the lack of regulations for hydrogen infrastructure, lack of clarity about permitting reforms for projects, possibility of less availability of renewable energy capacity, missing carbon border mechanisms, need for community engagement for hydrogen and lack of a clear definition for green hydrogen. The perception of current policy mix is, therefore, considered to be positive with possible areas of improvement.		

Based on the responses to the conditions and the operationalisation covered in Section 3.2.3, it can be concluded that the policy mix is somewhat credible as instruments are present in the draft stage, while there are areas of improvement suggested by interviewees.

4.6.4 Comprehensiveness

For the test conditions mentioned below, the answers helped to determine where the US policy mix stands with respect to comprehensiveness.

Test condition	**Response**	**Section reference**
Whether instruments (at least one type of instrument) exist along with the strategy	All three instrument types – economic, regulatory and information – are found in the current green hydrogen policy mix of the US. Economic instruments such as the IRA, regulatory instruments such as the DPA and information instruments such as CHPS, H2NEW, Hy-Marc etc. are present. The instrument mix is therefore comprehensive in its type.	4.3

Does the instrument mix address all the market, system, and institutional failures, including barriers and bottlenecks?	Based on figure 11, it can be said that the instrument mix covers all the three areas of the hydrogen ecosystem, i.e., production, distribution and end-use. For instance, instruments H2NEW, HydroGEN, IRA are a part of the production area, programs such as the Hydrogen Shot and IIJA form a part of the infrastructure area, whereas instruments such as SAF, Super Truck 3 are aligned to support the end-use area. Furthermore, programs such as HyBlend, Super Truck 3 and SAF Grand Challenge are focused to decarbonise specific sectors of energy (natural gas blending), and transportation. Based on 2021 Data from the US Environmental Protection Agency (EPA) sectoral GHG emissions are highest for transportation (28%), followed by power (25%), and industry (23%). These specific programs therefore, support, overall decarbonisation of the most carbon intensive sectors (EPA, 2021) present in the US. However, based on the interviews conducted, systemic challenges are noted. The lack of regulations for hydrogen infrastructure and lack of clarity about permitting reforms for projects affects the infrastructure sub-part of the supply chain. Missing carbon border mechanisms affect end-use, and the need for community engagement for hydrogen and lack of a clear definition for green hydrogen concern the overall hydrogen ecosystem. Therefore, it can be said that the instrument mix is its current form does not fully address all institutional and market barriers.	4.3, Figure 11, Summary of Interviews for the US
Whether the policy instruments/tools	The US instrument mix has instruments which cover all three purposes, i.e., technology push (HyBlend, IRA, IIJA, H2NEW, HydroGEN etc.),	4.3

cover the array of purposes (technology push, demand pull and systemic concerns)	demand pull (IRA, DPA, Super Truck 3, SAF) and systemic concerns (H2EDGE, IIJA, H2Matchmaker). The instrument mix is therefore comprehensive with regard to purpose.	

Overall based on the operationalisation covered in Section 3.2.3, it can be said that the policy mix is somewhat comprehensive since there are certain market and institutional barriers that are not fully addressed by the current instrument mix.

Overall, the US policy mix can be considered to be *consistent with caution, being somewhat credible and comprehensive to an extent*.

5. EU Policy Mix on Green Hydrogen

5.1 General Approach

For the analysis, 10 documents were considered – EU Hydrogen Strategy, REPowerEU Plan, EU Green Deal Industrial Plan, Draft Delegated Acts on Additionality and GHG, Hydrogen and Decarbonised Gas Market Package, "Fit for 55" Plan, Net zero Industry Act, European Hydrogen Bank, PFAs ban directive. Additionally, information pertaining to regulations within the Fit for 55 plan and other programs were gathered from the (respective) website of the plan and programs.

As discussed in Chapter 3, a priori coding (Burkholder et al., 2020) using Atlats.ti software was performed on the documents to specifically identify the strategy goal or objectives, plans or actions, instrument goal, type and purpose, implementing agencies and their programs, to operationalise the policy analysis framework (Rogge & Reichardt, 2016).

For interviews, since the focus was on understanding the positives and negatives as well as the improvement areas for the EU policy mix, responses to such questions were noted and included in the overall systemic representation of the EU policy mix.

This chapter is broken down to cover the elements – strategies and policy instruments, and characteristics of the EU policy mix using the operationalisation of the policy mix framework covered in section 3.2.3.

5.2 Strategies of the EU

The EU's approach towards green hydrogen have been continuous in the timeframe of 2019-2023, as seen in the figure 8. Hydrogen's mention as a low carbon carrier/clean energy option was first made in the EU Green Deal of 2019, post the COVID-19 pandemic. As a part of this, green hydrogen was considered as a focus area of breakthrough technologies for commercialisation through R&D efforts under the Horizon Europe program (EC, 2023b)

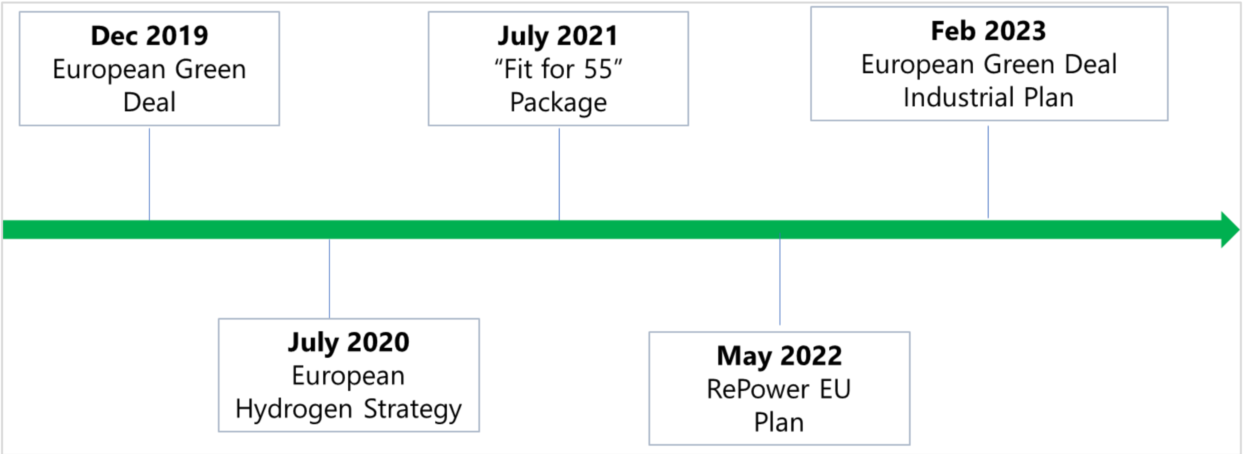

Figure 8: EU Hydrogen Development

The release of the European Hydrogen Strategy in 2020 (EC, 2023b) set out the first set of action plans to include green hydrogen for sustainable energy transitions of the EU to achieve climate neutrality by 2050. The objectives of the strategy document are divided into three phases to ensure that the EU develops –

- 6GW of electrolyzer capacity and green hydrogen production of up to 1MMT by 2024 while expanding it to,
- 40 GW and green hydrogen production of up to 10MMT by 2030 and,
- Mature green hydrogen technologies that are deployed at large scale to reach all hard-to-decarbonise sectors between 2030 and 2050.

The actions to achieve these goals are as below –

- Boosting demand of end-use sectors and scaling up production through mandates, pilots, demonstration projects etc.
- Supporting strategic investments in green hydrogen
- Encouraging R&I efforts under various existing and new programs in the EU
- Building infrastructure for hydrogen transportation and distribution
- Designing enabling market rules and building international collaboration and trade
- Introducing a comprehensive terminology for certification of green hydrogen and developing a common standard for promotion of green hydrogen.

In continuation with EU Hydrogen strategy, a follow-up policy strategy was the Fit for 55 package introduced in July 2021 (EC, 2021b). The overall goal of this package was in line with EU's climate goal of reducing emissions by 55% by 2030. This package provided a set of legislative proposals to support the development of the hydrogen strategy. These included introducing new and revising existing legislative proposals dedicated towards green hydrogen. New instruments such as Carbon Border Adjustment Mechanism, Hydrogen and Decarbonised Gas Market package, Alternate Fuel Infrastructure Regulation, FuelEU Maritime and ReFuelEU Aviation, and revision of the Renewable Energy Directive II with binding sectoral targets for the consumption of renewable hydrogen in industry and transport- Industry target of reaching 50% of Renewable Fuels of Non-biological Origin (RFNBOs) by 2030 and 75% by 2035, 5.7% target for RFNBOs in the transport sector by 2030, a sub-target of at least 1.2% RFNBOs by 2030 in the maritime sector (ITRE, 2022) were introduced as a part of this plan.

The war in Ukraine in March 2022 provided much impetus to the EU to increase their efforts towards greener alternatives and move away from their gas dependence on Russia. The strategic plan introduced was the RePowerEU plan (EC, 2022), with the objective of accelerating green hydrogen ambitions to 20MMT by 2030 through domestic production of 10MMT and import of another 10MMT. Following the hydrogen strategy in 2020, the actions of RePowerEU focused on diversifying energy imports and deploying hydrogen infrastructure for producing, supporting, importing, and transporting green hydrogen. RePowerEU also directed efforts towards supplementing existing financial mechanisms to ramp up the production of green hydrogen, while also encouraging private investment, focusing on skilling initiatives to support the hydrogen economy, pushing for mandates of uptake of industry for green hydrogen, working on joint purchasing of hydrogen and reporting of hydrogen use in hard-to-abate industries along with Member States.

The final piece of policy strategy of the EU was the Green Deal Industrial Plan released in February 2023 (EC, 2023b). The main objective of this plan was to have hydrogen infrastructure and manufacturing capacity in place by developing a predictable and simplified regulatory environment, providing faster access to sufficient funding, skilling, and developing open trade for resilient supply chains.

Based on these strategies, it can be said that the focus of the EU is to accelerate the development of a green hydrogen market through both domestic production and imports, while providing the supporting infrastructure, skills, regulatory framework, market ease and financial mechanisms to achieve EU's decarbonisation and climate goals.

5.3 Instruments of the EU

Instruments/tools of the EU for green hydrogen are categorised based on the type, purpose and design features as defined in the policy mixes framework (Rogge & Reichardt, 2016) and table 8 below provides the details.

Policy/Program Instrument Name	Primary Type	Primary Purpose	Primary Design Features
Carbon Border Adjustment Mechanism	Economic And Regulatory	Demand Pull	Stringency, Predictability
Alternative Fuel Infrastructure Regulation	Regulatory	Systemic Concerns	Stringency, Predictability, Differentiation
Delegated Act on Additionality	Regulatory	Technology Push	Stringency, Predictability
Delegated Act on GHG emissions	Regulatory	Systemic Concerns	Stringency, Predictability
ReFuelEU Aviation	Regulatory	Demand Pull	Stringency, Predictability, Differentiation
FuelEU Maritime	Regulatory	Demand Pull	Stringency, Predictability, Differentiation
Hydrogen and Decarbonised Gas Market package	Regulatory	Systemic Concerns	Stringency, Level of support
European Hydrogen Bank	Economic	Demand pull Technology Push	Level of support, Predictability
Net Zero Industry Act	Regulatory	Technology Push	Stringency
Net Zero Industry Academies	Information	Systemic Concerns	Cannot be classified
Temporary Crisis and Transition Framework	Economic	Systemic Concerns	Level of support
Existing financial mechanisms, expanded to include green hydrogen - Innovation Fund, Horizon Europe, Just Transition Fund, Cohesion Fund, Connecting Europe Facility	Economic	Technology Push, Systemic concerns, Demand pull	Level of support, Depth

(CEF), LIFE Programme, InvestEU Programme, Recovery and Resilience Facilities			
Clean Hydrogen Partnership	Economic	Technology Push Demand Pull	Level of support
European Clean Hydrogen Alliance	Information	Systemic Concerns	Depth
Europe Energy Platform	Information	Systemic Concerns	Cannot be classified
PFA Ban Directive	Regulatory	Technology Push (Not)	Stringent

Table 8: List of instruments, their purpose, type, and design features for the EU policy mix

- Carbon Border Adjustment Mechanism (CBAM) (Consilium, 2023b) – The CBAM is an economic instrument introduced as a part of the Fit for 55 package in 2021, which creates incentives for non-EU producers to reduce emissions. It is an instrument to counter carbon leakage that happens outside the EU and specifically applies to EU importers. Under the CBAM, importers have to purchase CBAM certificates based on the amount of carbon dioxide emissions that is produced, paying the carbon price that is prevalent in the EU corresponding the sector. CBAM is applicable from October 2023 and will replace the existing Emissions Trading System (ETS) by 2034. Hydrogen production features as one of the sector on which CBAM is applicable. This, therefore, becomes an indirect instrument to encourage green hydrogen production and is therefore, a demand pull instrument. Because of its design, it is stringent, while it is predictable since the timeline and sectors covered are already determined.

- Alternative Fuel Infrastructure Regulation (AFIR) (Consilium, 2023a) -AFIR is a regulatory instrument, once again part of the Fit for 55 package. It sets concrete targets for deploying such alternate fuel refuelling stations and supporting infrastructure to achieve EU's climate ambitions – it is, therefore, systemic in form. For hydrogen specifically, the regulations aims to have hydrogen refueling stations (HRS) at least every 200km on main roads by 2030, at least one HRS on every urban node (part of the TEN-T network). Because of the fixed targets, the AFIR is stringent and predictable in nature. Furthermore, it is focused only on the road transport sector and therefore, it is differentiated.

- Delegated Act on Additionality and GHG Methodology (Commission, 2023) – As a part of the revision to the Renewable Energy Directive II (REDII), there were two delegated acts/regulatory instruments that were introduced in 2021, one to provide a definition to what constitutes green hydrogen (under the larger definition of renewable fuels of non-biological origin or RFNBOs) and the other to provide a methodology assessing greenhouse gas emissions savings from green hydrogen. The DA on additionality helps define green hydrogen as one that adheres to the three pillars of additionality, temporal and geographical correlation. Because of the strict conditions for additionality and the fixed methods of emission calculations, these instruments are stringent and predictable by design.

- ReFuelEU Aviation and FuelEU Maritime (Consilium, 2023d) – Similar to the DAs introduced previously, the ReFuelEU Aviation and FuelEU Maritime are regulatory instruments that were introduced as a part of the Fit for 55 package to push for sustainable transport fuels in both aviation and maritime sectors as they are heavily dependent on fossil fuels only. Both these regulations are designed to have a gradual increase in the deployment of sustainable aviation fuels (SAFs) (green hydrogen derived) and green hydrogen in maritime transport, beginning 2025 (2% for aviation) till 2050 (70% for aviation). Aside from a phased increase in fuels, the instruments are designed to provide the requisite infrastructure at airports and ports to support the transition. They are therefore differentiated in design, while also being stringent (fixed share of SAFs) and predictable (fixed timeline of 2025 to 2050).

- Hydrogen and Decarbonised Gas Market package (Consilium, 2023c)- This package is a part of the Fit for 55 plan and is a regulatory instrument which is systemic in nature and focused on building an EU wide hydrogen market through facilitating domestic and international trade rules and infrastructure to support the ambitions of having 10MMT of green hydrogen by 2030. It also considers an integration of green hydrogen into the existing gas grid, establishing a 2049 deadline to long-term fossil gas contracts. Furthermore, this instrument supports the process of consumer shifting to greener alternatives, while also focusing on increasing the security of supply and cooperation between Member states in the EU. As such, it is stringent in nature. Additionally, because of the span of initiatives and focus area it covers, it provides a good level of support to foster green hydrogen transition in the EU.

- European Hydrogen Bank (EHB) (EC, 2023c) - The EHB while first introduced during the RePowerEU as a concept, found traction and concretisation in the

Green Industrial Plan. It is an economic instrument, in which a subsidy in the form of a fixed (green) premium/kg of hydrogen produced will be awarded to hydrogen producers for a maximum of 10 years of operation. The first pilot auction of €800 million in Autumn of 2023 will support the production of green hydrogen. This instrument is designed to bridge the cost gap and increase revenue stability, thus ensuring bankability of projects. The current design of this instrument is for a period of three years and therefore, it is predictable in nature. Furthermore, since there is a significant volume of finance being provided, there is a good level of support given by EHB.

- Net Zero Industry Act (EC, 2023d) – This act is a part of the Green Deal Industrial Plan and is dedicated to ensuring that there manufacturing capacity of electrolyzers is present to support the ambitions of 10MMT of domestic green hydrogen production in the EU by 2030. The instrument is regulatory in nature, while being technology focused and stringent and covers expediting permitting timelines for plants that are either newly engaging in manufacturing electrolyzers or are expanding their capacity. Electrolyzers and fuel-cells are part of the set of strategic projects which require even faster permitting timelines (9 months instead of 12) than other net-zero technology projects.

- Net Zero Industry Academies (EC, 2023b) – This is an information instrument introduced as a part of the Green Deal Industrial Plan whose main purpose is to provide skills and prepare the workforce to be ready to support transition to green hydrogen technologies.

- Temporary Crisis and Transition Framework (TCTF) (EC, 2023b) – The TCTF was extended as a part of the Green Deal Industrial Plan to simplify State Aid rules for green hydrogen technologies and also increase the threshold of State Aid for green hydrogen projects. It, therefore, functions as both a technology push and demand pull instrument and provides a level of support for green hydrogen.

- Existing Financial Instruments (EC, 2020a, 2022, 2023a) – Many of the existing financial instruments of the EU were expanded in scope to include green hydrogen technologies and projects. While funds such as the Innovation Fund and Horizon Europe programme drive research and innovation, pilot and demonstration projects, other funds such as CEF are focused on providing infrastructure support for transport and energy sectors. Funds such as the Modernisation Fund, Cohesion Fund and Just Transition Mechanism are geared to assist specific regions (low income or socio-economic challenging) with transitioning towards greener alternatives, while the LIFE fund supports clean energy transition programmes. The InvestEU constitutes the EIB, EBRD and EIF and help boost net-zero investments within and outside the EU. Another important financing mechanism is the recovery and resilient facilities, which are grants and loans provided by the EU to Member States post COVID to support their efforts towards decarbonisation. As each of these instruments target various sectors and areas of hydrogen innovation, they are considered to provide a significant level of support and depth.

- Clean Hydrogen Partnership(CHP)(CHP, 2023) - The Clean Hydrogen Partnership is a unique public private partnership supporting research and innovation activities in hydrogen technologies in the EU. It falls under the Horizon Europe programme, and it supplemented with both budgetary allocation from the EU and private investment to support research activities. It is therefore economic in nature, with a focus on technology push offering a level of support.

- European Clean Hydrogen Alliance (EC, 2020b) – The Alliance was formed in 2020 to facilitate the large-scale deployment of clean hydrogen technology by 2030. It combines renewable and low-carbon hydrogen generation, demand in industry, transportation, and other sectors, as well as hydrogen transmission and distribution. It aims to promote investments and stimulate hydrogen production and use through summits, working groups and reports. As such it is an information instrument with a systemic focus. Because of the various focus areas (barriers and challenges, project pipelines, electrolyzer manufacturing, permitting reforms etc.) of the alliance, it provides depth in its design.

- Europe Energy Platform (EC, 2022) – The energy platform (online) introduced as a part of the RePowerEU Plan is designed for voluntary common purchase of hydrogen and also to form a dedicated work stream with Member States on joint purchasing of hydrogen. This will enable demand aggregation, import, storage and transmission gas infrastructure and international outreach.

- PFAs (Per- and polyfluoroalkyl substances) Ban Directive (ECHA, 2023) – The proposed PFAs ban introduced by the European Chemicals Agency initiates a restriction on the use of PFAs across the EU, affecting the energy sectors, particularly electrolyzers and fuel cells that make use of PFAs. The report is an effort towards amending the REACH regulation to include the PFAs ban and has a tentative timeline of implementation beginning 2026 (if passed). Because it would amend a regulation, this instrument is regulatory in nature and affects technological advancement. Furthermore, since it deals with banning substances, it is stringent in nature.

5.4 Interaction between instruments and across instruments and strategies

The instrument mix covers the interactions among the instruments described above Overall (mis) alignment/ (dis)agreement of the instruments with policy strategy goals can be seen in figure 8. From the figure, it can be concluded that there is a misalignment/disagreement between instruments and policy strategy goals.

Most of the new instruments introduced in the EU for green hydrogen, at the time of writing of this paper, are in the draft stage. The timelines of most of the instruments are designed keeping in mind the overall strategic plan that they are a part of, oscillating between and including both 2030 and 2050. There is, therefore, no limitations seen with respect to timelines for various instruments.

Furthermore, some of the instruments such as the European Hydrogen Bank and the Clean Hydrogen Partnership have their funding (partly or entirely) derived from some of the existing financial instruments. For example, the EHB is funded entirely by the Innovation Fund, while the CHP is a part of Horizon Europe. There is an interaction seen between the instruments for the EU.

Overall, the instruments of the EU cover the breadth of the hydrogen ecosystem and since green hydrogen is considered as a means to achieve emission reduction, any instrument that supports or is designed to 'boost green hydrogen end-use' is geared towards achieving a 'reduction in GHG emissions'. These two strategic actions/goals interact with each other and along with the action/goal of 'increasing manufacturing capacity of electrolyzers', also help achieve the 'quantity ambitions' of the EU. For each of the instruments, their (mis)alignment is explained subsequently.

- Carbon Border Adjustment Mechanism (CBAM) – The goal of the CBAM is to 'reduce emissions' and since it is particularly applicable to EU importers, in one way it affects 'international trade and collaboration.'

- Alternative Fuel Infrastructure Regulation (AFIR) – The AFIR is focused on development of 'hydrogen infrastructure', and since it makes use of alternative fuels for transportation, it also helps 'boost demand of end-use sectors', helping 'reduce emissions'.

- Delegated Act on Additionality and GHG Methodology – Both the DAs are designed to provide a 'terminology for green hydrogen', while also helping to 'reduce emissions' since they both increase the deployment of green hydrogen and renewable energy (additionality DA) and provide a methodology for calculation for GHG emissions (GHG DA).

- ReFuelEU Aviation and FuelEU Maritime – Both these instruments support the end goal of 'reducing emissions', while also helping 'boost demand of end-use sectors', because they have specific targets for use of SAFs (aviation) and green hydrogen in maritime sectors from 2025 to 2050.

- Hydrogen and Decarbonised Gas Market package – The package is specifically designed to 'build hydrogen infrastructure', by including hydrogen to the existing gas infrastructure and also developing new infrastructure and networks to support a green hydrogen market. Furthermore, the instrument also helps 'design enabling market rules' by having common rules for transport, supply and storage, and discounting tariffs for hydrogen distribution, also focuses on 'international trade and collaboration' by considering hydrogen interconnected with third countries.

- European Hydrogen Bank (EHB) – The primary goal of the EHB is to 'reduce cost gaps' by supporting projects that are producing green hydrogen, and therefore helps 'boost demand of end-use sectors/accelerate GH2 production.'

- Net Zero Industry Act - The main goals of the Act are to 'increase manufacturing capacity of electrolyzers' by categorising them as strategic projects and reducing permitting timelines for such projects, thereby, 'designing enabling market rules.'

- Net Zero Industry Academies – The academies are an initiative towards providing required skills to support a green hydrogen market and therefore, builds 'workforce capacity.'

- Temporary Crisis and Transition Framework – TCTF is designed to 'support strategic investments' through increasing State Aid for green hydrogen projects, while also simplifying the rules for providing aid and helps 'enabling market rules.'

- Existing Financial Instruments – While each financial instrument has different goals, they are all aligned to 'support strategic investments/reduce cost gaps.' Furthermore, instruments such as the Innovation Fund, Horizon Europe are specialised instruments for R&D/I projects in emerging technologies, and therefore, ‘encourages R&D/I efforts.’ Also, instruments such as CEF are designed to ‘boost demand of end-use sectors’, and also focusing on ‘building hydrogen infrastructure.’ The Cohesion Fund, LIFE Programme, Just Transition Mechanism and Recovery and Resilience Facilities, exclusively support green/sustainable energy transition projects and help ‘reduce GHG emissions.’ Lastly, InvestEU in addition to ‘boosting demand of end-use sectors’, also supports ‘international trade and collaboration.’

- Clean Hydrogen Partnership (CHP) – The main goal of the CHP is to ‘support strategic investments’ by ‘encouraging R&D/I efforts.’

- European Clean Hydrogen Alliance – Based on the activities of the ECHA, their goals are multi-fold: ‘boosting demand in end-use sectors’, ‘supporting strategic investments’ and also ‘building hydrogen infrastructure.’

- Europe Energy Platform – The Energy Platform by connecting players in the hydrogen ecosystem will help ‘boost demand in end-use sectors’, and also support ‘international trade and collaboration.’

- PFAs Ban Directive – Since the goal of PFAs ban is to ensure that devices that make use of PFA are not deployed in the EU, and these include PEM electrolyzers which is one of the technologies that performs electrolysis and produces hydrogen, this instrument goal’s is against the goal of ‘increasing manufacturing of electrolysers’ and indirectly to the goal of ‘quantity ambitions’, relating to the capacity development associated with electrolyzers. However, it does support the goal of ‘reduction in GHG emissions’ since the main reason of the proposed ban is to reduce the negative effects of PFAs against the environment.

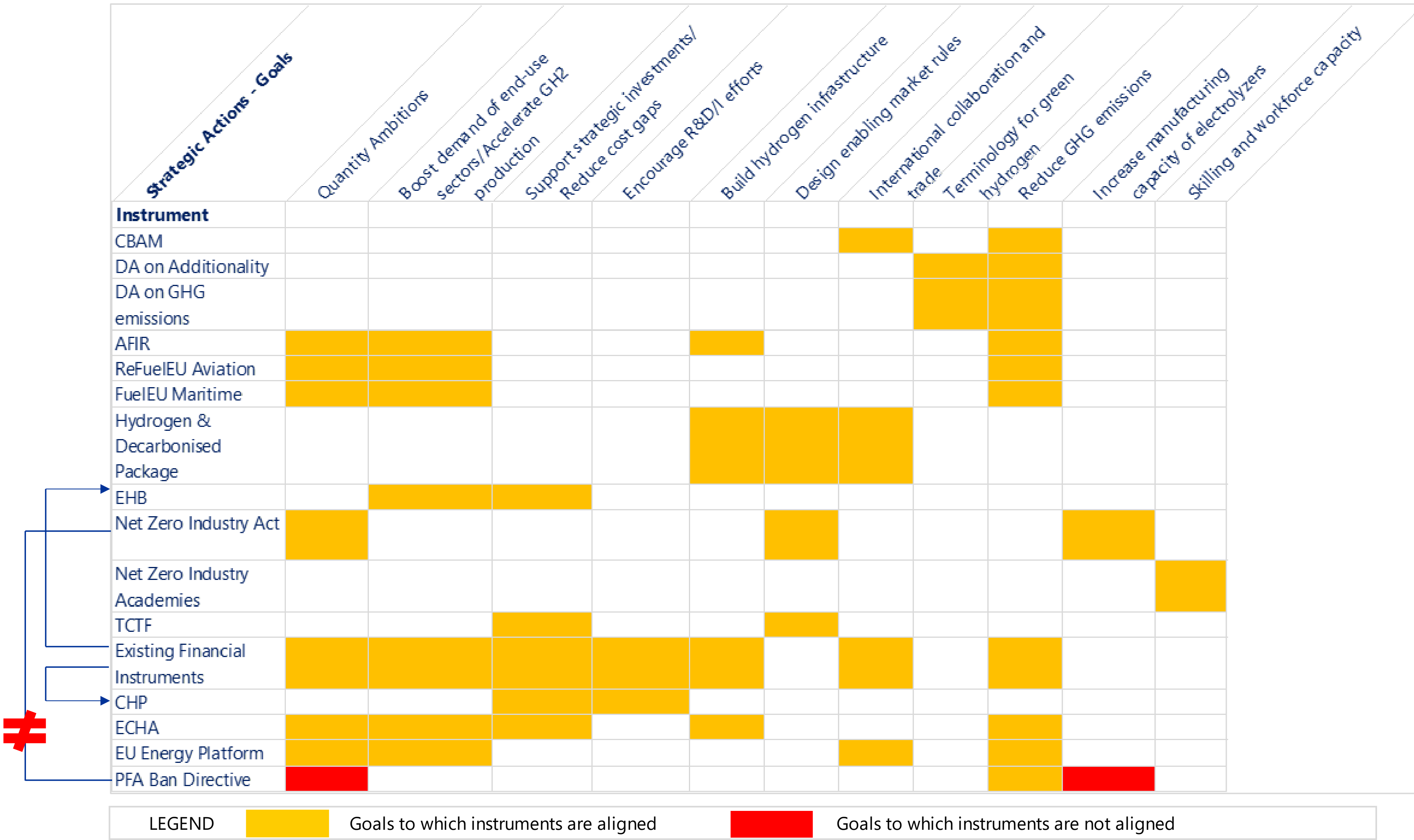

Figure 9: Relationship establishment between instruments and strategic goals

5.5 Characteristics of the Policy Mix

For the three characteristics of the policy mix, this paper analysed the policy mix and based on the operationalisation detailed in section 3.2.3, the results as below are presented.

5.5.1 Consistency of elements

For the test conditions mentioned below, the answers will help determine where the EU policy mix stands with respect to consistency.

Test condition	**Response**	**Section reference**
What are the instruments or action items – types, purpose, and design, which are present in strategies or obtained through web search. **Do these instruments help achieve the goal/target of the policy strategy?**	The EU has a combination of regulatory (AFIR, CBAM, ReFuelEU Aviation, FuelEU Maritime etc.), information (ECHA, Net Zero Academies etc.) and economic instruments (EHB, Existing financial instruments, CHP etc.), which cover the purposes of technology push, systemic concerns and demand pull through their design. Almost all the instruments (CBAM, AFIR, EHB for instance) find mention in the strategies of the EU, however existing instruments such as InnovFund, CEF etc., were discovered and explained from websites such as CINEA. From figure 9, it can be concluded that all but one instrument - PFAs ban directive – are in agreement with the strategic goals of the EU. The proposed PFA ban while supports the goal of reducing GHG emissions, goes against the goals of increasing manufacturing capacity of electrolysers and indirectly, against the quantity ambitions concerning electrolyser capacity for the EU. This instrument, therefore, presents itself as a challenge concerning the consistency of the elements of the policy mix.	5.3, 5.4
Whether instruments reinforce or	Based on the analysis from figure 9, the proposed PFAs ban directive seems to be	5.4, Figure 9

undermine each other to achieve overall strategic objectives?	conflicting the effects of the Net Zero Industry Act which is responsible for increasing electrolyzer manufacturing capacity. Furthermore, there is a dependency seen between existing financial instruments and the EHB (InnovFund specifically) and CHP (Horizon Europe specifically). In a way if there is more or less budgetary allocation to the existing financial instruments, there could be an indirect impact on the EHB and CHP. From the current relationship, it can be said that the existing financial instruments, EHB and CHP are reinforcing in nature to achieve strategic goals, whereas the PFAs ban, and the Net Zero Industry Act are opposing in nature resulting in possible conflict to achieve strategic goals.	
Whether objectives of the policy strategies can be achieved simultaneously without any trade-offs?	From figure 9, because of the negative association of the instrument - PFA bans directive –with two of the strategic goals (directly with electrolyzer capacity and indirectly with quantity ambitions) but a positive association with one of the strategic goals (reducing GHG emissions), it appears to be difficult to achieve all the objectives of the strategies simultaneously without a trade-off.	5.4

Based on the responses and the operationalisation covered in Section 5.5.1, it can be concluded that the elements of the EU policy mix are less consistent, since one of the instruments – PFAs ban directive – is not in complete agreement with all the strategic goals and it may be difficult to simultaneously achieve the objectives of the strategies of the EU for green hydrogen without a possible trade-off. This also presents a conflict within the instrument mix.

5.5.2 Credibility

For the test conditions mentioned below, the answers helped to determine where the EU policy mix stands with respect to credibility.

Test condition	Response	Score (NA = Not applicable,0= Draft/revision stage, 1 = Complete stage)	Section reference
Whether 'green (clean or renewable) hydrogen' is explicitly mentioned in any of the strategy documents of the regions, public procurement guidelines	The EU Hydrogen Strategy, RePowerEU plan, Fit-for-55 package cover green hydrogen explicitly. This suggests a clear commitment from political leadership.	NA	5.3
Whether instruments are fully defined or still in process of being defined. What is the stage of instrument - draft vs complete vs revision stages	The instruments for the EU are a combination of draft, complete and revision stages. Amongst the tools, EHB, Hydrogen and Gas Decarbonised Package, AFIR, Net Zero Industry Act, DA on Additionality and GHG Methodology, TCTF, ReFuelEU Aviation, FuelEU Maritime, PFA Bans directive are in the draft stage, whereas the CBAM, CHP, ECHA, Energy Platform are in the complete stage. Existing financial Instruments which are budget based, are in the revision stage. This suggests that there is still work required to build the policy mix from its current form.	Combination of draft, complete and revision stages. Therefore, precautionary score of 0 (draft/revision) is given.	5.3

Perceived credibility of the policy mix based on interviews with relevant stakeholders	Based on the interviews conducted for the EU, it can be concluded that there is a general sense of positivity regarding the policy instruments that the EU has shaped for the green hydrogen market. The interviewees provided confidence in the current policy mix noting that the EU has a robust system to provide bankability of green hydrogen through policy mandates. In addition to the positive views, areas of improvement were suggested. These include a need to speed up the finalisation and implementation of instruments, the need for confirmed off-take agreements, possible constraints on water availability for electrolysis, and the need for development of certification standards. The perception of the current policy mix is, therefore, considered to be positive with possible areas of improvement.	0.5	Summary of Interviews for the EU

Based on the responses to the conditions and the operationalisation covered in Section 5.5.2, the EU policy mix is considered to be somewhat credible as instruments are present in both draft and revision stage, while there are areas of improvement suggested by interviewees.

5.5.3 Comprehensiveness

For the test conditions mentioned below, the answers helped to determine where the EU policy mix stands with respect to comprehensiveness.

Test condition	Response	Section reference
Whether instruments (at least one type of instrument) exist along with the strategy	All three instrument types – economic, regulatory and information – are found in the green hydrogen policy mix of the EU. Economic instruments such as the EHB and existing financial instruments, regulatory instruments such as the AFIR, CBAM, Delegated Acts etc., and information instruments such as ECHA are present. The instrument mix is therefore comprehensive in its type.	5.3
Does the instrument mix address all the market, system, and institutional failures, including barriers and bottlenecks?	Based on figure 10, it can be said that the instrument mix covers all the three areas of the hydrogen ecosystem, i.e., production, distribution and end-use. For instance, instruments EHB, Net Zero Industry Act are a part of the production area, tools such as the AFIR and Hydrogen and Decarbonised Gas Packaged form a part of the infrastructure area, whereas instruments such as CBAM, ReFuelEU Aviation, FuelEU Maritime are aligned to support the end-use area. Furthermore, instruments such as the ReFuelEU Aviation, FuelEU Maritime, and specific sectoral financial instruments such as the CEF-Transport, CEF (for Energy) are focused on decarbonisation of specific sectors of transportation and energy respectively. Based on data from Eurostat for 2022, transportation has one of the highest emissions, followed by electricity (Eurostat, 2023). Furthermore, transportation has seen the highest growth in emissions year-on-year from 2021 to 2022. These specific instruments, therefore, support, overall decarbonisation of some of the most carbon intensive sectors present in the EU.	5.3, Figure 10, Summary of Interviews for the EU

	However, based on the interviews conducted, systemic challenges were noted. The need for confirmed mandates for end-use sectors affects the end-use sub-part of the ecosystem. Lack of speedy finalisation and implementation of draft regulations as well as no harmonised certification standards concern the overall hydrogen ecosystem. Therefore, it can be said that the instrument mix is its current form does not address all institutional and market barriers.	
What are the purposes (technology push, demand pull and systemic concerns) that the policy mix is trying to address	The EU instrument mix has instruments which cover all three purposes, i.e., technology push (Existing financial instruments, Net Zero Industry Act, EHB, CHP etc.), demand pull (ReFuelEU Aviation, FuelEU Maritime, EHB, CHP) and systemic concerns (EEP, ECHA, TCTF, Existing financial instruments etc.). The instrument mix is therefore comprehensive with regard to purpose.	5.3

Overall based on the operationalisation covered in Section 3.2.3, it can be said that the policy mix is somewhat comprehensive since there are certain market and institutional barriers that are not fully addressed by the current instrument mix.

Overall, the EU policy mix can be considered to be *less consistent, being somewhat credible and comprehensive to an extent*.

6. Comparative Analysis of the two policy mixes

6.1 General Approach

Following chapters 5 and 6 that described the US and the EU policy mix respectively using the policy mixes framework, this chapter provides a comparison of the two mixes. It begins with an overview of the comparison of the two mixes followed by detailed breakdown of the comparison - a systemic comparison of the US and the EU, comparison between the elements and characteristics of each of the policy mixes.

6.2 Overall comparison of the two mixes

Both the regions are in very similar stages of green hydrogen development because of the nascent nature of the field itself. However, strategies and instruments for the EU and the US are either already implemented or being finalised and implemented - there is more to be seen in the future.

Based on interview inputs and desk research performed, the US is considered to be more market and technology oriented through rapid financial incentives such as the IRA introduced in 2022 to enable cost reduction on a large scale and many information instruments that are R&D focused (H2NEW, Electrocat, HydroGEN etc..). Although the US main strategy is not formalised and published, policy instruments that are present are considered to be revolutionising, since they cover one of the most pressing issues of green hydrogen development concerning the high production costs of green hydrogen, while also focusing on large scale demand through formation of hubs. However, there are still concerning areas where policy instruments are seen to be less represented such as regulations to support hydrogen infrastructure and to reduce carbon intensive hydrogen entering the US, which in the EU's case is much better since it is has dedicated instruments such as the Hydrogen and Gas Decarbonised Package for infrastructure, Net Zero Industry Act to speed up permitting timelines, and the CBAM to handle carbon leakage.

In comparison, the EU is considered to be more ecosystem focused, attempting to build a thorough policy framework covering all the sub-parts of the green hydrogen ecosystem, while focusing on technology as well. There are many existing financial instruments that are revised to include green hydrogen spanning R&D, demonstration, small scale & large scale projects and support energy transition of socio-economic challenged regions. However, a real game changing instrument such as the incentives provided by the IRA, are yet to see the light of day through the EHB (expected in Autumn 2023). Also, as conveyed from interviews, there are areas within the EU policy mix that need further representation such as confirmed mandates for end-use and systemic efforts of certification standards. However, EU's regulatory instruments to ensure green hydrogen deployment in each of the sectors such as aviation, transportation, maritime sectors, displays commitment in sector decarbonisation. There are no similar regulatory instruments seen on a federal level in the US.

Comparing the policy mixes across the characteristics, US policy mix performs better on consistency, while EU's mix performs better on comprehensiveness, with both the mixes performing similarly on credibility.

6.3 Systemic (Hydrogen ecosystem) of the US and the EU

Looking at figures 10 and 11, a commonality is present that there are instruments that cover all the areas – production, distribution and end-use – of the green hydrogen ecosystem for both the EU and the US.. A difference is seen however in the overall timeline of green hydrogen initiatives, where the EU has a head start with earlier strategies in 2020, while the US initiated direction in 2021 through the IIJA. Furthermore, for both the regions, strategies and instruments are in the draft stage and are yet to published and finalised.

	PRODUCTION (Supply)	TRANSPORTATION AND DISTRIBUTION (Infrastructure)	END-USE (Demand)
Constraints on water availability			
	DA on Additionality*	AFIR*, Hydrogen and Decarbonised Package*	CBAM
	DA on GHG*		
	Existing Financial Instruments, TCTF		
	PFA Ban Directive*		FuelEU Maritime*
	Net-zero Industry Act*		ReFuelEU Aviation*
	Net-zero Academies*, ECHA, EEP		
	EHB*, CHP		EHB*, CHP
			Need for confirmed mandates for sectors, committed offtakers
	Need for quicker finalisation on draft regulations, certification standards for green hydrogen		

LEGEND		
Type of Instrument		
Economic	*Information*	*Regulatory*
Inconsistent instrument		
** In draft stages*		
Challenges based on interview inputs		

Figure 10: EU Policy Mix in the Hydrogen Ecosystem

	PRODUCTION (Supply)	TRANSPORTATION AND DISTRIBUTION (Infrastructure)	END-USE (Demand)
Capacity constraints for additional renewable energy			
	IRA		IRA
	IIJA		
	CHPS, H2MatchMaker, H2EDGE		
	HyBlend Initiative		DPA
	Hydrogen Shot		
	H2NEW, HydroGEN		SAF
	HyMARC, H-Mat		SuperTruck 3
	Electrocat		
		Lack of interconnection and transmission (pipeline) infrastructure	*Lack of carbon border mechanisms*
		Clear permitting reforms for infrastructure	
	Need for more community engagement about hydrogen, clear definition of green hydrogen		

LEGEND		
Type of Instrument		
Economic	*Information*	*Regulatory*
Challenges conveyed by interviewees		

Figure 11: US Policy Mix in the Hydrogen Ecosystem

6.4 Elemental Comparison of the EU and the US

For both the regions, green hydrogen features in dedicated strategies and there are both existing and new instruments present to provide fruition for specific actions of strategies, helping translate larger goals and ambitions of the EU and the US.

6.4.1 Comparison of strategies

While the EU's first initiatives for green hydrogen were seen in 2020 with the release of EU Hydrogen Strategy, in the US, strategic shape was seen in 2021 from an R&D perspective with the Clean Hydrogen Research and Development Program within the IIJA. Furthermore, it was only in September 2022 that a Draft National Clean Hydrogen Strategy was released which provided information about the goals and actions that the US intends to take regarding green hydrogen.

Overall, for each of the regions, there is a similarity in their strategic actions and goals as highlighted in figure 12. For both the regions, green hydrogen's use across sectors as a means to support net-zero transitions or reduce carbon emission is key. Reducing the cost of green hydrogen through stimulating private investments is also a common action /goal of the EU and the US. Skilling, R&D and building hydrogen infrastructure are also shared focus areas of these two regions. However, there are also differences seen.

For instance, in the US, one of the strategic goals is including communities in the overall efforts concerning green hydrogen which is explicitly not present in the EU. Another goal is to demonstrate the standards of GH2 production through various projects, which is also not seen for the EU. The closest action/goal of the EU is to have defined terminologies for green hydrogen in the EU to kickstart green hydrogen projects. In the EU, on the other hand, strategic actions, and goals of international collaboration and trade, increase in manufacturing capacity of electrolyzers and designing enabling market rules are not mentioned explicitly for the US. However, instruments such as the IRA and DPA are geared towards increasing the manufacturing capacity of electrolyzers, while the CHPS helps provide a terminology for GH2. What is missing however is a mention of international trade and collaboration in the strategies of the US. While sectoral use of GH2 is considered for both domestic and export markets in the US, trade does not feature in the strategy of the US. The same can be said about designing enabling market rules, which will help harmonise green hydrogen development in the market in the US.

Lastly, there are quantitative differences in the goals/ambitions of the US/EU. The US has a goal of reaching 10MMT annual production of green hydrogen by 2030, while the EU has an ambition of 20MMT annual production (both domestic & imports) of green hydrogen by 2030.

6.4.2 Comparison of policy instruments

If we compare figure 10 for the EU and figure 11 for the US, it can be concluded that based on the document research and analysis performed for the thesis, the EU has a greater number of instruments (15 including bundled existing economic instruments) covering green hydrogen, compared to the US (11 including bundled R&D instruments). Furthermore, it can be said that the US has greater number of information instruments focused on R&D (H2NEW, HyMARC, among others), skill (H2EDGE), and standards (CHPS) as a part of their policy mix. The EU on the other hand, has a higher number of regulatory instruments that cover sectoral ambitions and decarbonisation efforts (FuelEUMaritime, ReFuelEU Aviation, PFAs ban directive), carbon leakage (CBAM), definitions of green hydrogen (DA on Additionality) and GHG calculations (DA on GHG), infrastructure (AFIR, Hydrogen and Gas Decarbonised package) and manufacturing ramp up (Net-zero Industry Act). However, in the EU, most of the regulatory instruments are in the draft stage and yet to be agreed upon and published, at the time of writing of this paper.

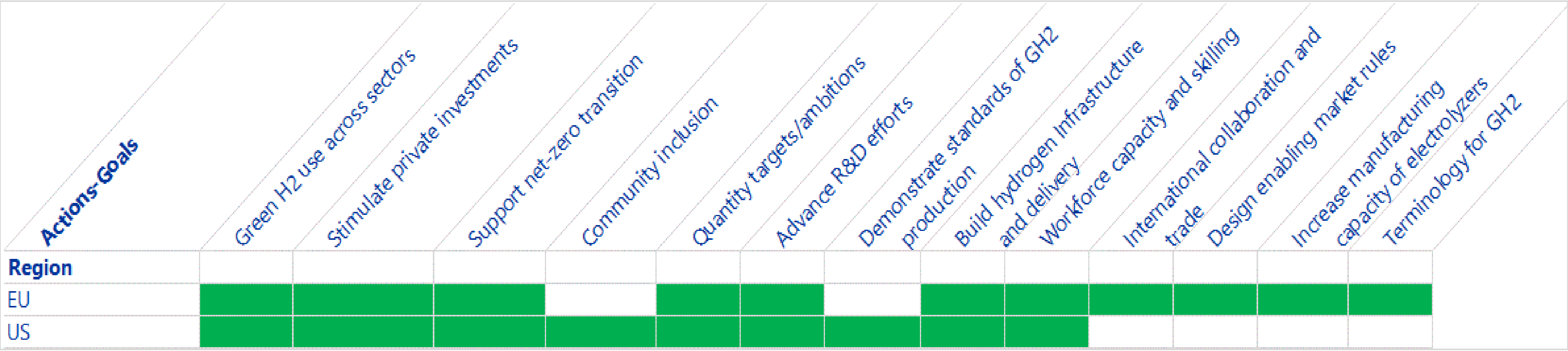

Figure 12: Comparison of strategic goals and actions for the two regions

For both the regions, economic instruments are present which help reduce cost gaps of projects (InnovFund & EHB in the EU, IRA in the US), increase demand for hydrogen hubs (CHP in the EU, IIJA in the US), accelerate R&D developments (Horizon Europe in the EU, IIJA in the US) and provide specific sectoral funding (CEF in the EU, SAF in the US).

6.4.3 Comparison of characteristics

6.4.3.1. Consistency of elements

For the US, as discussed in section 4.5.1, there is a slight time mismatch seen in the two of strategic actions/goals, i.e., to demonstrate standards of green hydrogen by 2040, with quantity targets set by 2030. This time difference, however, is not considered as a major hindrance to the efforts of the US towards green hydrogen. Furthermore, the instrument mix, interaction between instruments and strategic goals and the strategic goals in themselves are well aligned without any challenges, and the US can be considered to have a *consistent* policy mix overall. However, for the EU, since one of the instruments – PFAs ban directive- is in conflict with one of the strategic goals (and indirectly with another) while being aligned to reduce GHG emissions, overall consistency is seen as challenging. Furthermore, instruments PFA bans directive and Net Zero Industry Act are seen as conflicting in nature, and a trade-off to achieve goals simultaneously is foreseen. The EU policy mix is, therefore, considered to be *less consistent*. *Between both the regions, the US can be said to be performing better on the characteristic of consistency compared to the EU.*

6.4.3.3. Credibility of the policy mix

Both the EU and the US have expressed clear commitments for green hydrogen as a part of the decarbonisation efforts through the explicit mention of green hydrogen in their strategies. For the US, since the main strategy (National Clean Hydrogen Strategy) is in the draft stage, it cannot be said with certainty whether the strategic goals and actions will see the light at the end of the day, in the way presented in this paper or whether they will differ. Furthermore, one of the instruments (CHPS) is also in the draft stage, while all the other instruments are in the complete stage. It is a similar case for the EU since important regulatory instruments concerning the overall system (ReFuelEU Aviation, FuelEU Maritime, EHB, DAs, TCTF, Net Zero Industry Act, Hydrogen and Decarbonised Gas Market package etc.) are in the draft state, while other tools are in the complete or revision stage.

Additionally, from interviews conducted, it can be concluded that there are areas where both the policy mixes need further representation, although there is an overall, positive perception of the policy mixes. For the US particularly, since permitting reforms and regulatory clarity for hydrogen distribution were seen as lacking, one of the main parts of the ecosystem was seen as less represented in the instrument mix.

Furthermore, interviewees suggested that along with efforts to support domestic green hydrogen production, there was a need to reduce carbon leakage across sectors in the US through efforts such as the carbon border mechanism present in the EU. For the EU on the other hand, the delay in finalisation and procedural delay after finalisation towards implementation, along with a lack of confirmed offtake and mandates for sectors, was concerning. Between the two regions, it is hard to determine if one or the other mix is more credible, since from document analysis, the US seems to be more credible (as fewer elements are in the draft stage). However, based on the interviews, the EU can be said to be more credible since fewer areas of improvement are suggested compared to the US. *Therefore, both the policy mixes can be said to be somewhat credible*.

6.4.3.3. Comprehensiveness of policy mix

Both the EU and the US have more than one instrument which helps translate strategic actions to goals and they belong to all three types (of instruments) suggested by Rogge & Reichardt (2016), i.e., information, regulatory and economic. Furthermore, instruments present also support all three purposes of comprehensive policy mix, i.e., systemic concerns, technology push and demand pull. However, if we take into account whether the policy mixes can help overcome market and institutional barriers, there are certain limitations noted for each of the regions, based on the interviews conducted.

For the US, under infrastructure, end-use and also, on a systemic level, instruments are seen to be less present. For e.g., on an infrastructure level, regulatory mechanisms concerning transmission infrastructure are currently not present in the policy mix. For the EU, there is a possibility of better representation of instruments under end-use through confirmed mandates, and also on a systemic level, in terms of certification standards. The EU can overall be considered to be better than the US, as possible areas of improvement are limited to only one of the sub-parts of the ecosystem (end-use), instead of two (end-use and infrastructure), for the US. *Therefore, between the regions, the EU can be said to be performing better on the characteristic of comprehensiveness compared to the EU.*

7. Discussion and Conclusion

This chapter begins by summarising the findings presented in the previous chapter, and moving on to interpreting and discussing them, followed by providing some actionable recommendations for each of the regions. Subsequently, a discussion of the position of this paper and its contribution to the larger academic literature on policy mixes framework, green hydrogen and comparative studies is provided. Finally, the limitations and future research areas are suggested.

7.1 Summary of findings

1. *What policy strategies and instruments are present in the EU and the US for green hydrogen development?*

   In the US, current strategic focus appears to be placed on establishing a domestic environment of green hydrogen and ensuring its roll-out in a cost effective manner through R&D efforts across various industries at scale. This is considered as a means of decarbonisation to achieve overall net-zero ambitions while having exports as a focus area in the long term. For the EU, on the other hand, strategic focus appears to be placed on accelerating the development of a green hydrogen market for decarbonisation through both domestic production and imports by providing the necessary infrastructure, regulatory framework, skilling efforts, and financial mechanisms.

   For both the regions, instruments are present across the hydrogen ecosystem, i.e., production, distribution and end-use. Currently, the instruments in the US are mostly informational in nature covering skills, standards, alliances, and consortiums, supported by strong economic instruments such as the IRA, IIJA which are also regulatory in nature. The EU, on the other hand, has multiple instruments which are regulatory in nature such as the CBAM, AFIR, ReFuelEU Aviation, FuelEU Maritime, Delegated Acts, Hydrogen and Gas Decarbonised Package etc., which cover the domains of end-use, infrastructure, terminologies, and definitions. These are also backed by economic instruments such as the upcoming EHB and existing financial mechanisms such as the InnovFund, CEF etc., and information tools such as the ECHA, CHP.

2. *How do the EU and the US green hydrogen policy mixes perform individually across the characteristics of consistency, credibility, and comprehensiveness?*

   The elements of the US policy mix are *fairly consistent* with caution about the slight time mismatch for two of the strategic goals (demonstrate standards of green Hydrogen by 2040 and quantity targets by 2030) of the US. Furthermore, the policy mix is *somewhat credible* as there are few elements (main strategy document and Clean Hydrogen Production Standard instrument) present in the draft stage, while also there are areas of improvement (need for permitting reforms, carbon border adjustment mechanisms and community engagement) suggested by interviewees. Finally, it can be said that the policy mix is *somewhat comprehensive* since there are certain market and institutional barriers concerning infrastructure and end-use that are not fully addressed by the current instrument mix, while, however, the instruments of the policy mix are of all three types - information, regulatory and economic - and fulfil all the three purposes of demand pull, technology push and systemic concerns.

On the other hand, the elements of the EU policy mix are *less consistent*, since one of the instruments – PFAs ban directive – is not in complete agreement with all the strategic goals concerning green hydrogen and it may be difficult to simultaneously achieve the objectives of the strategies of the EU for green hydrogen without a possible trade-off. This also presents a conflict within the instrument mix. Furthermore, the EU policy mix is considered to be *somewhat credible* as most regulatory instruments (ReFuelEU Aviation, FuelEU Maritime, EHB, DAs, TCTF, Net Zero Industry Act etc.) are present in the draft stage, while there are areas of improvement (delay in finalisation and procedural delay towards implementation, lack of confirmed offtake and mandates for sectors) suggested by interviewees. Finally, the EU policy mix is *somewhat comprehensive*, since there are certain market and institutional barriers concerning end-use that are not fully addressed by the current instrument mix, while, however, the instruments of the policy mix are of all three types - information, regulatory and economic - and fulfil all the three purposes of demand pull, technology push and systemic concerns.

3. *How do the green hydrogen policy mixes of the two regions compare systemically and across the three characteristics?*
   Systemically, the policy mixes of both the regions cover the three main parts of the green hydrogen ecosystem, i.e., production, distribution and end-use. Furthermore, policy strategies of the US and the EU have many common actions and goals (green hydrogen use across sectors, reducing GHG emissions, increasing manufacturing capacity of electrolyzers etc.), with some differences. There is also a difference in ambitions/targets present for both the regions, with the EU having a larger ambition (20MMT pa) compared to the US (10MMT pa).
   Regarding instruments, the EU has a greater number of regulatory instruments focusing on sectoral decarbonisation, infrastructure development, ramping up manufacturing capacity and harmonising market rules, while the US has a greater number of information instruments focused on R&D, alliance, and coalition building. Both the regions have similar economic instruments to reduce cost gaps and encourage development of hydrogen hubs to build demand for the market. However, the sheer number of instruments in the EU is more. While many of the regulatory instruments for the EU are in the draft stage, the US' main strategy and one of its instruments (CHPS) is in the draft stage. Between the two regions, there is instrument interaction seen in the EU (between PFA bans and Net Zero Industry Act, and between existing financial instruments and EHB and CHP). There are no interactions seen between the instruments for the US.

As explained in the response to the previous question, the US policy mix is *fairly consistent*, while being *somewhat credible* and *comprehensive to an extent*. The EU policy mix, on the other hand, is *less consistent*, while being *somewhat credible* and *comprehensive to an extent*. Between the two regions, *the US performs better on the characteristic of consistency, while the EU performs better on the characteristic of comprehensiveness, with both performing similarly on credibility*

7.2 Interpretation of findings

Both regions are in very similar stages of green hydrogen development because of the nascent nature of the field itself. Furthermore, both regions appear to be equally committed towards the development of a green hydrogen market as strategies and instruments are present across the hydrogen supply chain. Across the characteristics, the policy mixes perform similarly on the category of credibility, while, however, the EU policy mix can be said to be more comprehensive, and the US policy mix can be said to be more consistent.

Overall, there is a good chance that the policy mixes are likely to be effective, even though one may be performing less on a particular characteristic. Since the policy mixes are fairly comprehensive, they are designed keeping in mind the overall hydrogen ecosystem and the sub-parts present. Furthermore, in the EU's case, there is still room for revision as many of the instruments, including the proposed (conflicting instrument) PFA bans' directive, are under discussion and there may be a possibility of achieving strategic objectives simultaneously without trade-offs, in the future. The same can be said about US strategy for Clean Hydrogen. This thesis takes on an optimistic view of the efforts of both regions. This can be attributed to supporting data presented in subsequent paragraphs.

In the EU, explicit climate commitments to become carbon neutral/net-zero by 2050 through the Climate Law in 2021 (EC, 2021a), provide confidence that technologies that support sustainable energy transitions, such as green hydrogen, can see the light at the end of the day and will have concrete deployment. In the US, the current administration's efforts to rejoin the Paris Agreement in 2021 restores the commitment of the US to become net-zero by 2050 (House, 2021). However, because of political changes on the federal level, it might be difficult to ascertain whether sustainable technologies will continue to be in the long run. Based on the inputs provided by interviewees, however, bipartisan support appears to be present for the US regarding green hydrogen because of the technology's ability to support decarbonisation of many sectors without possibly affecting their traditional bases. Furthermore, financial commitments such as the IRA, may be the strong signal of the commitment of clean initiatives of the US.

Additionally, there seems to be a positive albeit reactionary approach to the initiation and further development of strategies and corresponding instruments concerning green hydrogen across both regions. In a way, the US mirrors what the EU does, with a delay, and vice versa. For e.g., the US caught up with a late release of the National Clean Hydrogen Strategy in 2022, following the strides made by the EU during the period of 2020-2022 with the EU Hydrogen Strategy, Fit for 55 package, RePowerEU plan etc. The same can be said about the much delayed cost reducing policy instrument such as the EHB of the EU announced in early 2023 (yet to be implemented), as a response to the unexpected but transforming tool of the IRA of the US in 2022.

Finally, considering the approaches taken by individual regions, the US approach towards green hydrogen development appears to be market oriented targeting cost reduction through their policies while the EU's appears to be ecosystem driven, ensuring there are regulations designed to support each part of the hydrogen supply chain. They are, therefore, two different models aimed at reaching the ultimate objective of having green hydrogen as a part of their decarbonisation goals.

7.3 Limitations

One of the main limitations of this thesis is the level of analysis, i.e., the regional level of comparison of the US and the EU. In the US, there is a broader federal structure of governance and legislative process and making, and each state has powers to take decisions that support the growth of the individual state, much rather than the whole country. Because of this, a federal level analysis is limiting as many state-specific nuances regarding green hydrogen are not captured. While federal rules and regulations provide much needed guidance and also provide benefits for the growth of a green hydrogen market, states can form their own instruments and strategies to support green hydrogen initiatives across the state-specific hydrogen supply chain. For e.g., the state of California has already considered green hydrogen in transition of many mobility applications (EERE, 2023), while the state of New York is examining the role of green hydrogen as a part of their climate ambitions (NYSERDA, 2023). In the EU as well, while member states' consensus and agreement is required for many of the regulations, each member state can design and determine supporting instruments, either financial, regulatory or information, to guide green hydrogen development. Member states can also form strategic partnerships with third countries for trade and initiatives, while also releasing their own ambitions for green hydrogen production. For e.g., Germany has an ambition of reaching 5GW of electrolyzer capacity by 2030 (BMWK, 2023) and has instruments such as the H2Global Mechanism to reduce price gaps for green hydrogen (BMWK, 2023). Similarly, Spain has its own national hydrogen strategy and ambitions of 4GW of electrolyzer capacity by 2030 (MITECO, 2020). Many of these ambitions and initiatives also support overall EU goals. This paper has not considered such differences and additional tools which could support or hinder green hydrogen development.

Secondly, since the paper uses a top-down approach focusing on the strategic intent (Ossenbrink et al., 2019) of the 'development of a green hydrogen market', strategies or policy instruments apart from those that specifically concern green hydrogen were not considered. For e.g., renewable energy policies, larger industrial decarbonisation policies or strategies, climate ambitions and agreements. Therefore, only a much narrower set of elements were considered, which limits analysis concerning how green hydrogen could fit into overall decarbonisation strategies, and whether renewable energy policies are designed to support additional renewable energy capacities for green hydrogen development.

Thirdly, the limitation of the policy mixes framework is noted as operationalisation of the framework was challenging for emerging fields where strategies and instruments are still in draft stages, and much of the literature does not provide a thorough understanding of how to operationalise this framework using a specific template. This paper has attempted to combine the abstract approaches taken by others using the framework and develop an analytical 'test-conditions based template' to simplify the application of the framework for characteristics, specifically. The validity of this template has not been performed and is therefore, open to feedback and criticism.

Fourthly, because of the limited number of interviews conducted, inputs considered to support the analysis of the characteristics of credibility and comprehensiveness, have to be considered cautiously.

Finally, the analysis and conclusions drawn are not validated through expert interviews or peer reviews, which questions the credibility of the paper. The claims made in this paper are based on my understanding and application of the framework and there are inherent biases and limitations associated with it, which need to be taken into account.

7.4 Actionable recommendations – general and based on cross-learnings

Based on the findings and their interpretation, the examination of the EU and US green hydrogen policy mixes reveals that plans, actions and policy tools are in place across the supply chain of green hydrogen,. The policy mixes are, therefore, likely to be effective, even though there is scope for improvement possible. These subsequent paragraphs provide recommendations based on the assessment and limitations of the study, taking into account cross-regional learning possibilities as well as the potential to improve the consistency, credibility, and comprehensiveness of the policy mixes.

One of the first things which is recommended for the US is to finalise the draft strategy for green hydrogen and the clean hydrogen production standard. This may increase overall credibility and concretise the direction and intention of the US concerning green hydrogen, and also provide a definite definition of green hydrogen in the US. Secondly, a better representation of regulatory instruments within the policy mix to support hydrogen infrastructure could enable and provide clarity to hydrogen players about transportation and distribution of green hydrogen using pipelines or other modes. Thirdly, the inclusion of a comparable carbon leakage instrument such as the CBAM in the EU to the US policy mix may ensure that overall decarbonisation goals and commitments of the US are met with respect to trade and imports. While international trade and collaboration are not explicitly present in the strategic goals of the US, it is well known that US has trade relations with many countries. Therefore, including trade as a strategic action and goal, short or long term, is recommended to ensure that, in a way, carbon leakage instruments can also work in tandem with trade. As discussed in Section 7.3, as states are not considered in the current analysis, it is noted that the recommendations provided above are for a federal level and could possibly act as guidelines for state strategies and initiatives.

For the EU, it is recommended to speed up consultations regarding regulatory instruments which are in draft stages, build consensus and ensure they are finalised and officially published – this is also suggested for game changing financial instruments such as the EHB. This could support the credibility of the policy mix. A significant impediment of the instrument mix in its current form is the conflicting nature of the policy instrument, PFAs ban directive's, with another instrument, Net Zero Industry Act. While the ban is directed towards reducing GHG emissions and enables efforts towards net-zero emissions, it undermines efforts concerning scaling up of manufacturing of electrolyzers, which could ultimately affect the supply of green hydrogen and indirectly possibly, reduce chances of achieving the quantity ambitions of the EU. Recommendations such as delaying the PFAs ban for electrolyzer and fuel cell industries till industries are able to find alternatives but within pre-defined timelines, could possibly support sustainable changes and enable the growth of the green hydrogen market in the EU, i.e., help achieve strategic goals simultaneously without trade-offs. This could make the policy mix consistent. Finally, to improve the comprehensiveness of the EU policy mix, it is suggested to confirm mandates for end-use sectors as a way to ensure consistent demand for green hydrogen.

For both regions, it is also suggested to develop certification of standards as a means to harmonise green hydrogen production and trade. Furthermore, having community engagement programs can alleviate any apprehensions concerning new technologies such as green hydrogen and provide relevant information to help the development of a green hydrogen market.

7.5 Contribution to academic literature – green hydrogen, policy mixes framework and comparison studies

The thesis has made the attempt to study nascent, emerging, green, and rapidly expanding technologies such as green hydrogen and the role that policies can play or are playing to shape the development of newer sustainable industries. Given the limited academic literature covering green hydrogen as discussed in section 2.5, this paper is an effort to add to the existing literature on green hydrogen policies, for each of the regions of the EU and the US individually and overall, for comparative analysis studies of green hydrogen policies globally. *Additionally, this thesis is the first to make use of the policy mixes framework for green hydrogen.* As such, this paper can be considered as the basis for research covering green hydrogen policy mix efforts in the EU and the US, i.e., to understand the effectiveness of these mixes in their current form and the interaction between existing instruments and how they affect overall strategic efforts.

The paper's approach of placing policies along the ecosystem of green hydrogen brings out a holistic approach of viewing polices from a systemic level. Making use of the policy mixes framework for innovative technologies, this paper has tried to analyse the US and EU green hydrogen policy mixes and determine the elements (strategies, instruments, and interaction of the instrument mix) as well as their important defining characteristics and understand where it stands as of today and what can be the way ahead to improve the policy mixes. Additionally, this paper is the first to have made an attempt of operationalising the policy mixes framework using an analytical 'test-conditions based template,' which could be used in the future to apply the policy mixes framework for emerging technologies where policy instruments are not fully shaped and actual effectiveness can possibly be ascertained in the future.

Furthermore, this study has tried to look at two regions such as the US and the EU, instead of comparing countries, as seen in much of the current literature. By considering a regional level perspective, the comparison is done on a higher and much larger scale. Since the US and the EU are two of the most aggressive contenders for innovation and emerging technologies, a comparison between the two helped to understand their approaches and also focus areas. Furthermore, as seen in section 7.3, a comparative analysis also provided much need cross learnings which could better shape policy mixes for both the regions and possibly, others globally. Comparative analysis also helped to understand collectively where both policy mixes could improve.

7.6 Future research

For future research, it is suggested to expand the scope of geography by also including examples of states within the US and the EU and bring out the nuances associated with green hydrogen policy mixes as seen on national/state level. This could provide much depth to existing federal/regional level studies and expand the scope of analysis, introducing more interactions and possibly determine whether states are aligned with federal/regional level strategies or not. Secondly, widening the scope of the instruments considered by having a bottom up approach (Ossenbrink et al., 2019) to focus on the impact domain (green hydrogen economy/development) is considered. Such an approach will cover a much larger set of instruments such as decarbonisation roadmaps for industries, renewable energy policies, climate goals, international trade policies etc., which could fit the green hydrogen story within the overall dimension of sustainable energy transition/emission reducing efforts.

Comparative studies such as these can also be made more interesting by including other regions/countries, such as comparing developed and emerging economies as one instance. The EU and the US are similar regions in terms of governance and economic growth and may have the advantage to roll out multiple policies to support sustainable energy transitions. This may not the be the case with other regions/countries with limited resources or other strategic goals, but nonetheless are a part of global decarbonisation efforts. On a data front, current data can be made richer by including more interviews. Finally, a similar project can be carried out 5-10 years from now once instruments are implemented and possibly, the green hydrogen market has reached a certain level of maturity to understand where the policy mixes stand and whether they have been effective.

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Appendix

Detailed Literature Review of countries other than the US and the EU

Note: References for the papers referred in this section are not included

India

Research that looks at the possibility of developing a green hydrogen economy in India (Ghosal & Kumar, 2022; Singh et al., 2022) concludes that a combination of financial policies such as duty waiver for electrolysers, GST waiver for green hydrogen production and public funds for R&D, industry mandates such as mandatory blending of natural gas with hydrogen, technical initiatives such as technology transfer partnerships with other countries and standards on green hydrogen production and demand incentives such as government procurements will act as levers to support the development of a hydrogen economy. A similar set of policies using the energy modelling and scenario framework, is proposed for the ASEAN countries (Phoumin et al., 2021).

South Korea

Chu et al. (2022) suggest that a hydrogen policy that could work for South Korea should include an import model because of the limited renewable energy development and low levels of technological development for green hydrogen production within the country.

China

Two interesting papers covering China make use of System Dynamics (SD) as a way of forecasting the demand and supply of a green hydrogen market in China (Huang et al., 2022) and evaluating the impact of subsidy policies on green hydrogen in China (Li et al., 2022). In the former paper, existing hydrogen policies that are in place in China since 2020 for transportation, industry, and storage, are included into and varied within the SD model, to determine the development of the hydrogen market. In the latter, subsidy policies for investment, production, hydrogen-production electricity price and income tax rate were varied to design and evaluate the development of the green hydrogen industry. Both the papers provide interesting results suggesting the optimum combination of policies required to develop a hydrogen market. Another paper (Y. Li et al., 2022) on China uses roadmapping techniques to provide a list of policies that could support a hydrogen economy. These include seed funding, R&D support through demonstration projects, exploration of hydrogen for priority applications such as sector coupling and public transport, and regulatory support for safety standards for hydrogen.

Africa

For Africa, four papers cover policy initiatives. AbouSeada & Hatem (2022) emphasise that within Africa, policies that bring out alliance & coalition building of the local hydrogen industry, and technical & financial partnerships with countries in the EU, would support hydrogen transition. Another paper that focuses on MENA (Razi & Dincer, 2022), uses the 3S concept entailing 'source, system, and service' to provide an understanding of the initiatives needed to have clean hydrogen in the region. Splitting the policy recommendations between near-term, mid-term and long-term goals, the paper highlights that, large investments for hydrogen production, infrastructural modifications, and choice of priority applications to support hydrogen deployment are key. The papers covering ECOWAS (Ballo et al., 2022) and Southern Africa (Imasiku et al., 2021) use a qualitative literature or desk research method to provide an analysis of existing policies and the recommendations for a policy framework. It is suggested that a combination of targets for sectors for hydrogen deployment, infrastructural changes and collaboration, R&D support, and financial support for electrolysis will work towards reducing the barriers associated with developing a hydrogen economy in these regions.

Brazil

Research done in Brazil (Chantre et al., 2022) on the development of a hydrogen economy uses a survey-based approach and provides policy recommendations such as tax exemption for hydrogen production, encouragement of infrastructural expansion, R&D for innovation in hydrogen production, economic incentives for fossil fuel substitution and definition of a waste policy targeting renewable hydrogen production.

UK

Research done in the UK (Joy & Al-Zaili, 2021) takes a quantitative approach using economic evaluation to understand whether existing hydrogen policy instruments would help projects be financially viable for hydrogen producers. Based on the analysis, the paper explains how contracts-for-difference as a policy instrument could serve as a good mechanism for revenue stabilisation for hydrogen producers because it helps bridge the gap (much better that other options) associated with higher costs of hydrogen production.

Relevant Reports for Information about Instruments

Name of Publication	**Author/Organisation (Year of Publication)**
The Future of Hydrogen	IEA (2019)
Green Hydrogen: A guide to policy making	IRENA (2020)

Hydrogen Insights	McKinsey & Hydrogen Council (2021, 2022)
National Hydrogen Strategies (Working Paper)	World Energy Council (2021)
Regional Insights into Low-Carbon Hydrogen Scale-up (Working Paper)	World Energy Council (2022)
Geopolitics of the Energy Transformation: The Hydrogen Factor	IRENA (2022)

List of stakeholders for hydrogen network

Table B.5: Centrality indicators of stakeholder network (BC' = Betweenness of centrality ; DC' = Degree of centrality)

No.	Stakeholder group	BC'	No.	Stakeholder group	DC'
1	R&D	0.1147	1	R&D	0.8293
2	Hydrogen technolygy providers	0.0997	2	Hydrogen technolygy providers	0.8293
3	Electricity utilities	0.0875	3	Electricity utilities	0.7317
4	Public companies	0.0494	4	Heavy-duty transport	0.6585
5	Muncipal utilities	0.0466	5	Muncipal utilities	0.6585
6	Heavy-duty transport	0.0466	6	Associations	0.6341
7	Project developers	0.0465	7	Public companies	0.6098
8	RES plant operator	0.0313	8	ESCOs	0.5854
9	Associations	0.0295	9	Vehicle manufacturers & OEMs	0.5610
10	ESCOs	0.0268	10	Project developers	0.5610
11	Petroleum industry	0.0243	11	Industrial gas companies	0.5122
12	Gas TSOs	0.0204	12	Gas TSOs	0.5122
13	Vehicle manufacturers & OEMs	0.0147	13	Industrial sector	0.4878
14	Politics	0.0139	14	Chemical industry	0.4878
15	Industrial sector	0.0101	15	Petroleum industry	0.4878
16	Industrial gas companies	0.0086	16	Politics	0.4634
17	Chemical industry	0.0081	17	RES plant operator	0.4390
18	Gas industry	0.0059	18	Gas industry	0.4390
19	NGOs	0.0043	19	NGOs	0.3902
20	Heating system manufacturers	0.0030	20	Storage operators	0.3415
21	Consultants	0.0027	21	Rail transport	0.3171
22	Gas DSOs	0.0018	22	Consultants	0.3171
23	Storage operators	0.0013	23	Electricity TSOs	0.2927
24	Transport sector	0.0012	24	Aviation	0.2927
25	Electricity TSOs	0.0011	25	Transport sector	0.2927
26	Water resource management	0.0008	26	Water resource management	0.2683
27	Rail transport	0.0006	27	Heating system manufacturers	0.2683
28	Other commercial vehicles	0.0005	28	Gas DSOs	0.2683
29	Aviation	0.0003	29	Steel industry	0.2683
30	Steel industry	0.0002	30	Seaports	0.2195
31	ICT industry	0.0002	31	ICT industry	0.2195
32	Electricity DSOs	0	32	Cement industry	0.1951
33	Energy cooperatives	0	33	Other commercial vehicles	0.1707
34	Agriculture & Forestry	0	34	Electricity DSOs	0.1463
35	Refineries	0	35	Buses	0.1463
36	Seaports	0	36	Intra logistics	0.1463
37	Buses	0	37	Refilling station operators	0.1463
38	Intra logistics	0	38	Building sector	0.1220
39	Building sector	0	39	Institutional investors	0.0732
40	Cement industry	0	40	Energy cooperatives	0.0488
41	Refilling station operators	0	41	Refineries	0.0488
42	Institutional investors	0	42	Agriculture & Forestry	0.0244

Figure 12: Stakeholder Network (Schlund et al., 2021)

Summary of Interviews

US

The interviews for the regions of the US included stakeholders from R&D(universities), project developers, RES plant operators and associations. The general perception about green hydrogen policies in the US was positive. Interviewees value the inclusion of green hydrogen in the overall conversation concerning sustainable energy transition as one of the ways to decarbonise those sectors that cannot be electrified easily and also for greening the grid. They provided the following responses concerning the existing instruments and strategies of the US for green hydrogen–

Positives

- Significant financial support through mechanisms such as the IRA's tax credits and IIJA's dedicated funding for R&D, manufacturing and recycling, hydrogen hubs etc.
- Supporting instruments such as the Hydrogen Shot provide the necessary signalling concerning cost reduction targets of the US ($1/kg by 2031)
- Focus on end-use sectors, hydrogen hubs/valleys is supportive to build demand
- Domestic manufacturing of equipment through IIJA is a strength to develop the market
- Sustainable and inclusive practices are encouraged and in a way forced because of the economic benefits accrued from instruments such as the IRA
- (Outside of instruments but still affects) - Overall political support for green hydrogen is present because there are multiple production pathways which supports traditional sectors such as oil and gas

Areas of improvement

- Lacking regulatory framework for hydrogen infrastructure (pipelines, refueling stations etc.)
- Need for permitting reforms concerning green hydrogen projects, to avoid delays in overall project timelines
- Lacking carbon border mechanisms to avoid carbon intensive products from entering the US
- Lacking clear definition for green hydrogen, with three pillars of additionality, time correlation and deliverability
- Need for balancing and having dedicated authorities for infrastructure – regional interconnection may be helpful here
- (Outside of hydrogen ecosystem but still affects) – Possible shortage of renewable energy capacity/grid constraints to support additional green hydrogen production, Need for communities to be engaged to understand the benefits of green hydrogen

EU

The interviews for the regions of the EU included stakeholders consulting organisations. The general perception about green hydrogen policies in the EU was positive. Similar to the US, interviewees strongly consider green hydrogen in the net-zero approach of the EU as one of the methods to decarbonise sectors that cannot be electrified easily and also as an electricity source. The nascency of green hydrogen technologies was emphasised as well. They provided the following responses concerning the existing instruments and strategies of the EU for green hydrogen -

Positives

- Robust system to provide bankability of green hydrogen based on policy mandates and enforcements to decarbonise such as CBAM/phasing out of ETS free allowances, ReFuelEU Aviation, FuelEU Maritime
- Systematic approach to develop the right set of regulations and initiatives from infrastructure development – Hydrogen and Decarbonised Gas Market package, AFIR, to market update (RED II/III mandates)
- Right kind of signalling to ecosystem participants by setting up mandatory obligations

Areas of improvement

- Delayed finalisation and implementation of policies
- Need for certification standards to support international trade and collaboration
- (Outside of hydrogen ecosystem but still affects) – Water constraints in the future for green hydrogen production