

Scaling-up Green Hydrogen Development with Effective Policy Interventions

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Abstract

Discussions around hydrogen as a future energy source have taken center stage in the last few years. Countries have recognized the benefits of hydrogen as an effective energy carrier and consider it a promising transition pathway to achieve net-zero objectives. Several countries support the development of green hydrogen as part of a long-term strategy. Among various hydrogen generation options (Green, Blue, Grey), green hydrogen generated from renewable electricity and water electrolysis is considered sustainable and climate safe. However, green hydrogen development is still at a niche stage and faces various technical challenges and economic viability issues. This paper discusses how effective policy interventions focused on addressing technical and commercial challenges can help scale-up green hydrogen generation. The paper discussed policy interventions by countries like France, Germany, Japan, the UK, the US, and other EU nations leading green hydrogen development and proposed a push-pull policy model. The proposed policy model combines demand-side policy interventions with supply-side policies to scale-up green hydrogen development.

Keywords: demand-side, electrolyzer, green hydrogen, innovation, market, supply-side

1. Introduction

1.1 Background

The energy systems are going through a significant transition to reduce dependency on fossil fuels and achieve decarbonization targets aligned with the Paris agreement. As part of this transition, renewable electricity consumption from solar and wind has significantly increased in the last ten years while costs continue to decrease (IRENA, 2020). However, countries still face decarbonization challenges in hard-to-abate sectors like transportation and heavy industries, where energy needs can't be fulfilled with electrification (IRENA, 2018). Hydrogen as energy can play a critical role in hard-to-abate sectors where direct electrification is challenging, such as steel, chemicals, and long-haul transport (IRENA, 2020). Due to its physical properties and high energy intensity, hydrogen is an effective energy carrier and provides much more flexible storage management compared to electrical batteries. Because of such benefits, hydrogen can take a significant share in the overall energy mix by replacing natural gas and help achieve net-zero targets by decarbonizing hard-to-abate sectors. WEC (2021) suggested considering a scenario with higher climate ambition, when hydrogen will be used in the hard-to-abate sectors, the estimated green hydrogen demand could go above 600 million tons per annum by 2050. According to Eljack and Kazi (2021), green hydrogen production should increase ten folds from the current production capacity (around 70 million tons per annum) to achieve 2050 net-zero targets.

The hydrogen, depending upon carbon intensity involved in the manufacturing process, is identified with different color codes, namely, "green" hydrogen, "blue" hydrogen, and "grey" hydrogen. According to IRENA (2020), only "green" hydrogen produced from water electrolysis powered by renewable electricity sources (wind or solar) is considered sustainable and climate-safe, while "blue" hydrogen and "grey" hydrogen contribute to carbon emissions of varying levels. Blue hydrogen is produced by splitting natural gas into hydrogen and CO₂ (Carbon Dioxide) using steam or thermal reforming processes; the by-product CO₂ is captured and stored using Carbon Capture Usage and Storage (CCUS) technology. Although the produced CO₂ is captured in the blue hydrogen manufacturing process; yet, the process itself involves high carbon-intensive activity, so it can't be considered carbon-neutral. Blue hydrogen is viewed as an alternative to natural gas in the transport and heavy industry sectors. On the other hand, the grey hydrogen is produced from natural gas or methane reforming; the by-product CO₂ is

not captured as part of the manufacturing process and leads to significant emissions that make grey hydrogen least sustainable compared to green and blue hydrogen. In terms of capacity, storage, and distribution, blue hydrogen has better prospects to scale up quickly as many international oil and gas operators with hydrogen production experience are willing to invest in blue hydrogen development. In contrast, green hydrogen produced from water electrolysis is still in the novice stage due to lower production capacity and lack of storage and distribution infrastructure. Currently, around 96 % of total hydrogen production is fossil-fuel based manufactured from the methane reforming process, while only 4% is produced from water electrolysis (IRENA,2018). The OECD report on green hydrogen policy published by Cammeraat et al. (2022) recommends that blue hydrogen as an interim solution can fill in the hydrogen demand gap required for energy transition and climate actions until the green hydrogen technologies are matured and scaled up.

Green hydrogen upscaling faces several technical and commercial challenges; among them, the cost and availability of renewable electricity and the large-scale adoption of electrolysis technologies are significant (WEC, 2021). Currently, the production cost of green hydrogen is 2-3 times higher than blue hydrogen (produced from fossil fuels with carbon capture and storage), and cost reductions are needed to scale up green hydrogen production to support net-zero ambitions (IRENA, 2020). According to Eljack and Kazi (2021), the green hydrogen production via electrolysis (US\$10.3 per kg) is five times that of established technologies like reforming (US\$1.5–2.3 per kg). Green hydrogen production requires a reliable source of renewable electricity. The cost of renewable electricity is the largest component in green hydrogen production cost, which is location-dependent and varies significantly across the region. Therefore, the availability of low-cost renewable electricity is necessary to improve the cost competitiveness of green hydrogen (IRENA, 2020). The efficiency and cost of electrolysis units also influence green hydrogen production costs. Among available electrolysis technologies such as Alkaline (ALK) and Proton Exchange Membrane (PEM), the cost of hydrogen production depends on several factors like required power density & efficiency, module size/capacity, reliability of electricity sources, CAPEX & OPEX of plants, the output pressure of produced hydrogen. Economics of scale and optimization of CAPEX & OPEX with centralized units can help reduce the cost of electrolysis. Further, slow growth in hydrogen technology patents and new trademarks fails to bring down CAPEX & OPEX costs. Slow growth in patenting and trademarking suggests that the pace of innovation activity is not aligned with hydrogen ambitions to achieve net-zero (Cammeraat et al., 2022). Since electrolysis technologies are still evolving, achieving technology scale-up and cost reduction is the most critical challenge. Continued R&D support, innovations, and wider adoption of technologies are needed to improve electrolysis power density and efficiencies and reduce CAPEX & OPEX costs (IRENA, 2018).

One way to reduce the green hydrogen cost is to increase the market demand with effective demand-side policy interventions. Such demand-side policy initiatives not only improve the economics of scale but can also bring new investments in green hydrogen distribution and storage infrastructure, therefore, reducing the overall cost (Cammeraat et al., 2022). Another way to make green hydrogen more competitive against natural gas is to address market imperfections in the energy sector. In many countries, the cost of carbon emissions from natural gas is not internalized in the market price leading to market imperfections. Policymakers can address market imperfections by applying carbon prices or taxes on carbon-based fuels to make green hydrogen more competitive in the market (Baranzini et al., 2017). Technology push for green hydrogen could be another way to provide an impetus for green hydrogen development. As electrolysis technologies are still evolving, policy interventions on the supply side can provide a required technology push. As part of the supply-side initiative, the government can enact regulations to promote green hydrogen, provide R&D subsidies/incentives, and create a green hydrogen ecosystem (IRENA,2020). Policy interventions aimed at technology push will help consolidate a supply chain of electrolysis equipment, bring new technology providers, improve electrolysis performance, and reduce costs. Like any other green technologies in the past, governments with effective policy mix interventions can support the upscaling of green hydrogen development. Policymakers can use a mix of both supply-side and demand-side initiatives to create a technology push and demand-pull effect for green hydrogen upscaling.

In Europe, governments aiming to support green technologies have used a policy mix strategy to create balance and coherence between various technology push and market demand-pull policy instruments (Costantini et al., 2015). The main objective of a policy mix strategy in upscaling specific renewable technology is to have coherence between various policy instruments rather than applying individual policies in isolation leading to policy fragmentation. A policy mix strategy based on policy integration and learning approach can address the issue of fragmentation; however, scholars have cautioned that a policy mix strategy's success depends on its consistency, credibility, and comprehensiveness. Inconsistency and incoherence in the policy mix can be detrimental to achieving policy objectives (Rogge & Schleich, 2018). In complex social-technical transitions, such as energy transition, inconsistencies and incoherence are expected due to conflicting priorities and mutually exclusive

interests between the actors involved; therefore, policymakers should be aware of such interactions when applying policy mix (Rogge & Reichardt, 2016). Several countries leading green hydrogen developments, like France, Germany, Japan, the UK, the USA, and other EU nations, have implemented various policy measures on both supply and demand sides. The paper analyzes current policy interventions by countries leading green hydrogen pathways and discerns effective policy interventions to propose a push-pull model which can be followed by other countries striving to scale-up green hydrogen development.

1.2 Aim of the Paper

This paper aims to address technical and commercial barriers to upscaling green hydrogen development using effective policy interventions. The paper proposes a policy model based on technology push and market pull that can create a supportive environment to upscale green hydrogen development. We started in section 1 with a brief discussion on the role of green hydrogen in achieving energy transition and net-zero targets; we also briefly discussed technical and commercial challenges. Section 2 discusses the methodology used to underpin the proposed policy model. Section 3 discusses commercial and technical barriers in detail, including policy issues currently faced in green hydrogen development. In section 4, we analyzed green hydrogen policy by comparing and contrasting policy implementations by lead countries involved in green hydrogen development and identified key policy instruments on both supply and demand sides. In section 5, we proposed a technology push and market pull policy model for green hydrogen development that can be followed by countries striving to scale-up green hydrogen developments. Section 6 concludes the paper by highlighting key takeaways in the paper.

2. Materials and Method

A literature review was conducted on green hydrogen related articles published in the past two to three years. The literature review provided insight into technical and commercial barriers faced in green hydrogen upscaling. Sector status reports issued by international bodies like IRENA (International Renewable Energy Agency), WEC (World Energy Council), OECD (Organization for Economic Co-operation and Development), and EC (European Commission) were used as a secondary data source to gain insight into various policy interventions. In our analysis, we compared and contrasted policy implementations by lead countries like France, Germany, the UK, Japan, the USA, and other EU nations to identify and highlight key policy instruments on both supply and demand side of green hydrogen development.

3. Green Hydrogen as Transition Pathway

According to the world bank report 2020, green hydrogen, produced from water electrolysis powered by renewable electricity, can provide a potential energy transition pathway and support climate actions; green hydrogen could contribute to the net-zero objectives in heavy industry and transportation (ESMAP,2020). Green hydrogen will play a key role in decarbonizing the energy sector and help overcome challenges in achieving net-zero 2050 objectives in hard-to-abate industries (IRENA,2020; Cammeraat et al., 2020). However, in reality, the current green hydrogen production is way below the expected level to catch up with the energy transition pace required to achieve the net-zero 2050 target. Currently, around 4% of global hydrogen production can be categorized as green hydrogen, while 96% of hydrogen is produced from fossil sources (IRENA,2018). Despite low production, green hydrogen draws interest from governments in all regions. Over the next five years, evidence suggests that the transport and energy sector will drive hydrogen growth in developing countries as well (ESMAP, 2020).

3.1 Current State of Development

Green hydrogen is about three times more expensive than grey or blue hydrogen (Cammeraat et al., 2022). If green hydrogen has to emerge as a realistic alternative in the next 10-15 years, a significant cost reduction in green hydrogen production is required. Also, the availability of low-cost renewable electricity is essential to make green hydrogen cost-competitive; the cost of renewable electricity should fall from an average of US\$53 per MWh to around US\$20 per MWh in the next 10-15 years (IRENA, 2020; Cammeraat et al.,2022). Currently, the green hydrogen market is negligible; with effective policies, countries must develop new markets to attract investments in the areas of electrolyzer manufacturing and distribution networks to scale up the production of green hydrogen (IRENA, 2020). Overall, the success of green hydrogen as a transition pathway crucially depends on cost reduction and improved efficiency of electrolyzes, the availability of cheap renewable electricity, the development of new markets, and private investments through effective policy interventions (Cammeraat et al.,2022).

Currently, green hydrogen is not economically viable without effective policy interventions. In order to design an effective policy model, it is therefore essential to understand the factors influencing the LCOH (Levelized Cost of Hydrogen) of green hydrogen. The Levelized cost of hydrogen (LCOH) is a cost metric that expresses the cost per energy unit of green hydrogen produced (£/MWh or US\$/kg); it covers all relevant costs faced by the green

hydrogen producer, including the capital, operating, electricity costs (BEIS, 2021). LCOH depends on several variables, such as selected electrolysis technology (ALK or PEM) and the load factor of renewable electricity (grid-connected or on-site). The lower load factor of renewable electricity results in higher LCOH as the electrolyzer capacity factor is reduced. The LCOH decreases with increasing load factor; the grid-connected renewable electricity can result in a 100% capacity factor for electrolyzer compared to on-site intermittent renewable electricity (Christensen, 2020; IRENA, 2018). The LCOH cost structure shown in table-1 highlights that the cost of green hydrogen is impacted by 1) CAPEX and OPEX of electrolysis units, 2) efficiency and capacity factor of the electrolysis process, and 3) availability of renewable electricity. According to BEIS (2021), LCOH is a production cost metric and does not include any costs associated with compression, storage, and delivery of the produced hydrogen. The delivery cost could be substantial depending on the availability of hydrogen distribution, transmission, and storage network. Therefore, it is essential to distinguish between LCOH and delivered hydrogen costs. The hydrogen delivery cost can often easily exceed the production cost, which includes costs associated with hydrogen transmission, storage, distribution, and dispensing (EC,2020). The hydrogen delivery cost can be reduced with demand-side interventions aimed at creating lead markets having decentralized and distributed delivery system allowing more consumers to get connected at a lower cost.

Table 1.

<i>Levelized Cost of Green hydrogen (LCOH) Metrics (BEIS,2021)</i>	
Capital Expenditure (CAPEX):	<ul style="list-style-type: none"> • Total investment expenditure (Including electrolyzer units and other equipment costs)
Operating Expenditure (OPEX):	<ul style="list-style-type: none"> • Fixed & Variable OPEX including maintenance • Renewable electricity costs used in electrolysis process • Water cost used in electrolysis process • Grid fee (when grid electricity used)
Elements impacting green hydrogen production	<ul style="list-style-type: none"> • Capacity utilization of plant • Renewable electricity load factor • Efficiency of electrolyzes
The Levelized Cost of Green hydrogen (LCOH)	$LCOH = \frac{\sum_t^n \frac{Total\ CAPAX + OPEX_n}{(1+r)^n}}{\sum_t^n (GRNHYD_n / (1+r)^n)}$ <p>CAPAX = Capital expenditures OPEX_n = Operations and maintenance cost in the year n, GRNHYD_n = Green Hydrogen production in the year n, r = Rate of return on investment, n = Lifetime of the plant.</p>

3.2 Supply Side Issues

At the beginning of the 19th century, ALK electrolyzers were used for non-energy purposes, especially in the chemical industry, for chlorine production from sodium chloride in water and to produce hydrogen as a by-product (IRENA,2020). Initially, ALK electrolyzers operated at low current densities due to the high internal ohmic resistance of diaphragms separating two electrodes. However, this issue was resolved with Zirfon material-made diaphragms, which provided low internal resistance and allowed higher current density. In mid of 19th century, PEM electrolyzers emerged. Using a polymer electrolyte membrane between electrodes, PEM allowed hydrogen ions selectively to move across the polymer membrane to the cathode while the electrons flow through an external circuit. PEM cells could be easily fed with pure water instead of caustic solutions required in ALK systems; this considerably reduces system complexity and footprint and provides higher efficiencies and power densities (IRENA,2020). SOEC (Solid Oxide Electrolyzer Cell) technology, which emerged in the last decade, provides a better promise of greater efficiencies than ALK and PEM. However, SOEC is a less mature technology, still at the laboratory stage without many demonstrations on a commercial scale (IRENA,2018). A comparison between ALK and PEM technologies is shown in table-2. Another technical issue is the non-availability of larger electrolyzer module sizes. Commercially available module sizes are in the 1 to 10 MW range; electrolyzer module size must

be scaled up to 100s of MW. However, manufacturers lack R&D support, engineering knowledge, and long-term business visibility to increase module size. The economies of scale with increased module size will help reduce CAPEX costs by around a third (Cammeraat et al.,2022).

If the green hydrogen price has to be around US\$ 1 per kg by 2050, electrolyzer KPIs must improve significantly, as per the below-mentioned expectations shown in table-3 (IERNA,2020). Innovations and R&D supports are crucial to achieving improvements in KPIs. Innovations in hydrogen production technologies will help reduce the production cost of green hydrogen (Cammeraat et al.,2020). Innovations and design improvements will help 1) reduce electrolyzer cost with standardization and simplified design; 2) improve efficiency and reduce the electricity consumption required to produce one unit of hydrogen; and 3) increase equipment lifetime (IERNA,2020).

Table 2.

<i>Comparison between ALK & PEM Electrolyzer (IRENA,2018)</i>		
H2: Hydrogen		
<i>Key parameters</i>	<i>ALK</i>	<i>PEM</i>
Unit footprint	Large	Relatively smaller
Electrolyzer stack lifetime	80,000 hrs	40,000 hrs
H2 producing cell pressure [bar]	Atm. to <30 bars	> 30 bars
Flexibility in operation	Not flexible to demand changes	Flexible to demand changes
Stand-by mode	Not possible	Possible
Startup time	1-10 minutes	1-5 seconds
Ramp up / ramp down	0.2 to 20% per seconds	100% per seconds
Shutdown	1-10 minutes	1-5 seconds
CAPEX total system (US\$/KW)	750	1,200
Maintenance	Regular	low
Electricity Efficiency [kWh consumption /Kg of H2]	51	58

Table 3.

<i>Key Performance Indicators (KPIs) (IRENA,2020)</i>				
H2: Hydrogen				
<i>Electrolyzer KPIs</i>	<i>As of 2020</i>		<i>Expectation by 2050</i>	
Technology	ALK	PEM	ALK	PEM
H2 producing cell pressure [bar]	< 30	<70	>70	>70
Efficiency (system) [kWh consumption /Kg of H2]	50-78	50-83	<45	<45
Electrolyzer Lifetime [thousand hours]	80	50-80	100	120
Capital costs estimate for stack-only, > 1 MW [US\$/kW]	270	400	<100	<100
Capital cost range estimate for the entire system, >10MW [US\$/kW]	500-1000	700-1400	<200	<200

The current pace of innovations in hydrogen production technologies is not aligned with the global hydrogen ambition for climate action. According to Cammeraat et al. (2020), hydrogen-related patenting and trademarks doubled from 2014 to 2018; however, it only represented 2.7% of all climate-related trademarks and 5.9% of all

climate-related patents in this period. The low rate of patenting and trade marking is due to the relatively low degree of maturity of hydrogen technologies, where manufacturers are still focused on R&D activities than on commercialization (Cammeraat et al., 2020). Demonstration projects related to green hydrogen development can help promote innovations and disseminate best practices within the sector. Not all hydrogen producers are familiar with green hydrogen technologies. Government support is needed to deploy demonstration projects that could act as a bridge between lab and commercial scale and showcase techno-economical applications which can be replicated in different regions (IERNA,2020).

The large-scale deployment of green hydrogen production units depends on the availability of low-cost renewable electricity (Cammeraat et al., 2022). Renewable electricity is the most significant cost component in the green hydrogen LCOH. A lower cost of renewable electricity is necessary to make green hydrogen more competitive in the market; this creates an opportunity to produce green hydrogen at locations around the world that can generate high volume and low cost of renewable electricity (solar or wind) (IERNA,2020). Countries with high solar potential in North Africa, the Mediterranean region, the Middle East, and Southeast Asia and Countries with high wind potential in the Nordic region, North America and West Europe are well placed to produce competitive green hydrogen. With solar and onshore wind electricity prices falling below US\$25 per MWh in some countries like Chile, Portugal, Saudi Arabia, and the United States, electrolyzer companies are able to quote green hydrogen production costs below US\$3.50 per kg (ESMAP, 2020). However, region-specific low-cost renewable electricity does not reflect the overall global scenario. Still, vast amounts of renewable electricity are required to produce green hydrogen needed to reach net-zero by 2050. IEA estimates an installed global electrolyzer capacity of 3585 GW by 2050 (IRENA, 2021, Cammeraat et al., 2022). The electricity demand due to electrolyzer capacity corresponds to about 20% of the world's electricity supply in 2050, more than the total global renewable electricity capacity of around 2800 GW in 2020 (IRENA, 2021, Cammeraat et al., 2022). Besides adding new capacity for green hydrogen development, policymakers without a clear guideline face accounting problems for existing renewable electricity used in the electrolysis process. Several countries have planned decarbonization of the electricity sector with the rapid deployment of renewable electricity sources but diverting grid electricity to hydrogen generation could lead to policy conflict. Renewable energy directive in EU recognizes double counting issue in renewable sources. It specifies that when one energy vector (electricity) is transformed into another vector (green hydrogen), renewable energy use shall be considered only once for accounting purposes. The additionality concept, which emerged in the EU, necessitates policymakers to develop a mechanism to recognize that renewable electricity sources used in green hydrogen production are different from those required to meet the renewable electricity penetration target for electricity sector decarbonization (Pototschnig, 2021).

3.3 Demand Side Issues

Currently, green hydrogen demand and consumption are minimal without clearly delineating the green hydrogen market. There is a need to develop lead markets to increase the demand and consumption of green hydrogen and associated technologies. European Commission (2020) identified two lead markets, 1) industrial application and 2) transportation which can help to create demand for green hydrogen in the next 5-10 years. The transport sector fuel remains largely fossil-based with minimal use of biomethane and electric batteries. The hydrogen fuel-cell driven EVs have a near-term potential in heavy-duty vehicle transports (trucks and buses), where hydrogen and fuel cells are expected to play an important role and have a clear advantage over other fuels (IRENA,2020). Hydrogen is a promising opportunity in the transport sector, where electrification is more difficult. Early adoption of hydrogen can create new demand in commercial fleets or local city buses where electrification is not feasible (EC,2020).

Another challenge is the lack of green hydrogen delivery systems comprising compression, liquefaction, transmission, and distribution components, including high-pressure pipeline access to cities and towns. According to European Commission (2020), the green hydrogen delivery infrastructure is insufficient to deal with the volumes of hydrogen required to meet net-zero objects in Europe. Immediate actions are required to retrofit existing natural gas infrastructure with hydrogen carrying capability; in parallel, a new dedicated hydrogen delivery infrastructure must be developed. From a supply chain perspective, green hydrogen production can only be scaled up when an established sink is available to absorb the produced quantity. Without dedicated hydrogen gas grids, until the green hydrogen market is fully developed, green hydrogen off-takers must be allowed to inject gas into existing natural gas grids with proper product labeling, origin tracking, certification, and compensation (IRENA,2020).

According to Goldman Sachs, an investment bank, hydrogen market investments could be worth US\$11.7 trillion by 2050 across Asia, the U.S, and Europe; mobilizing private funding is critical for green hydrogen market development (WEC,2021). The private sector holds a key position in bringing new market and infrastructure development investments when they have long-term revenue visibility. Establishing regulations and designing

markets, including setting deployment targets, tax incentives, and mandatory market quotas will guarantee revenue visibility for the private sector to invest in green hydrogen (IRENA,2020). Public and private partnerships across the entire value chain are essential to building a dynamic green hydrogen ecosystem that will help attract mass investments to drive green hydrogen deployment (European Commission,2020). Demand-side policies present a very different set of challenges related to market development and monetary & tax incentives; therefore, a more integrated and collaborative approach is required through industry engagements.

As the economic viability of the green hydrogen business case depends on several spatial factors, such as access to desalinized water, availability, and connectivity to renewable electricity and distribution systems, policymakers must recognize these factors while developing demand-side policies. Governments can identify and develop industrial clusters as part of their strategy to scale-up demands for green hydrogen and simultaneously bring down the overall cost (IRENA,2020). Such industrial clustering will help consolidate the entire green hydrogen value chain covering market and infrastructure angles, including research and innovation, which will eventually create an enabling environment to scale up hydrogen supply and demand (European Commission,2020).

4. Green Hydrogen Policy Analysis

Having understood current challenges, both on the supply and demand side, in this section, we aim to carry out a green hydrogen policy analysis of countries leading green hydrogen development. Over the last decade, policymakers in many developed countries have actively shaped and defined mission-oriented policies to address complex social-technical challenges such as energy transition (Boon & Edler, 2018). The policy approach to energy transition has shifted from supporting niche technologies with subsidies and grants to creating comprehensive and long-term policies to make niche technologies economically viable and self-sustaining. In the energy transition context, initially, policy instruments were mainly focused on the supply side; however, recently, the role of demand-side policies has gained attention (Edler & Fagerberg, 2017). Demand-side innovation policies emerged in Europe when countries found it difficult to convert research patents into commercially viable technologies using just supply-side policy supports. When effectively implemented, demand-side policies can act as an innovation driver and enable firms to gain better returns on investments in technology development which they have done on the supply side (Cunningham, 2009). Under the new policy approach, EU policymakers proactively develop new markets and address market imperfections to support niche technologies (Borrás & Edler, 2020). As part of the energy transition, EU countries have successfully implemented demand-side policies focused on the commercialization and diffusion of renewable technologies by overcoming market structural barriers and addressing market imperfections. According to Edler and Georghiou (2007), demand-side policies include (1) increasing market demand, (2) defining product specifications, and (3) articulating demands for specific technologies to address social needs. Demand-side policies also help create an experimental space and develop demonstration projects in collaboration with private sectors (Borrás & Edler, 2020). In efforts to shape effective demand-side policies, governments play the roles of gatekeeper, promoter, lead user, and enabler of specific technology or product (Cunningham, 2009). However, it is worth noting that demand-side policies cannot be implemented in isolation; instead, they are typically used as complementary to supply-side policy instruments. Policy experts suggest that market pull created by demand-side policies should be supported by technology push generated by supply-side policies in the case of niche technologies (Boon & Edler, 2018). Counterbalancing demand-side policy instruments with supply-side policies are strategically more effective in addressing complex systemic transitions (Cunningham, 2009).

Over the last few years, many countries have developed green hydrogen policies; however, their scope and scale differ significantly. According to (IRENA, 2020), these policies vary in scope (ranging from energy mix of both green and blue hydrogen to only focusing on green hydrogen) and scale (ranging from no specific targets to very ambitious, quantified green hydrogen targets). Although many countries have come up with an ambitious green hydrogen target, without clear policy commitments and visible actions, it is unlikely that hydrogen will emerge as an economically viable energy transition pathway (Cammeraat et al.,2022). To select a country for the policy analysis, we used three criteria 1) the number of hydrogen-related patents and trademarks owned, 2) public spending on RD&D (Research Development & Demonstration), and 3) planned hydrogen capacity (refer to tables- 4,5 & 6).

Table 4.

<i>Patent and Trademark Ownership</i> (OECD report by Cammeraat et al., 2022)		
<i>Countries</i>	<i>Patents ownership (in numbers) of hydrogen technologies (Including storage and fuel cells)</i>	<i>Trademark ownership shares (%) in global hydrogen trademark count</i>
Japan	2000+	45%
United States	1000+	15%
Germany	900+	10%
South Korea	500+	1%
France	300+	2.5%
United Kingdom	300+	2%
China	300+	5%
Netherlands	300+	0.5%
Australia	100+	0.5%

Table 5.

<i>Spending on Research Development & Demonstration Supports</i> (OECD report by Cammeraat et al., 2022)			
<i>Countries</i>	<i>Spending in 2016 (€ million)</i>	<i>Spending in 2019 (€ million)</i>	<i>Average annual growth in spending during 2016-19</i>
Japan	116.47	254.91	+30%
Germany	16.49	45.98	+41%
France	31.02	38.74	+8%
United Kingdom	17.06	32.21	+24%
United States	95.30	106.64	+4%
South Korea	31.85	28.97	-3%
Netherlands	1.00	14.68	+145%
Australia	2.55	10.85	+62%

Table 6.

<i>Planned Hydrogen Capacity Until 2040</i> (OECD report by Cammeraat et al., 2022)		
<i>Countries</i>	<i>Capacity (Million cubic meters of hydrogen per hours)</i>	<i>Hydrogen Color</i>
France	7.7	Green
United Kingdom	6.2	Green and Blue
Australia	5.9	
Netherlands	3.9	Green and Blue
Germany	3.0	Green
China	1.78	
Canada	1.86	Green and Blue
United States	0.9	
Japan	3400 (cubic meters per hours)	

Table 7.

<i>Country-wise Positioning on Selection Criteria for Policy Analysis</i>			
<i>Countries</i>	<i>Patents and Trademarks Criteria</i>	<i>RD&D Support Criteria</i>	<i>Planned Hydrogen Capacity Criteria</i>
Germany	High	High	High
Japan	High	High	Low
United States	High	High	Low
France	Medium	Medium	High
United Kingdom	Medium	Medium	High
China	Medium	Data not available	Medium
Australia	Low	Low	High
Netherlands	Low	Low	Medium
South Korea	Medium	Low	Data not available

Based on the set criteria, Germany ranked high in all three categories. On the other Japan and US scored high in hydrogen production technology patenting & trademarking and RD&D spending, while there is no major plan for hydrogen capacity expansion. France and the UK scored medium in technology patenting & trademarking and RD&D spending but ranked high in hydrogen capacity planning. Australia and Netherlands ranked low in technology patenting & trademarking and RD&D spending; however, they ranked high and medium in hydrogen capacity planning. Asian countries, China and South Korea, ranked medium in hydrogen patenting & trademarking; China ranked medium in the capacity plan, and South Korea ranked low in RD&D spending. The country-wise position in table-7 suggests that Japan and US have a strong focus on innovation and technology push; in contrast, Australia and Netherlands broadly focused on the demand side. While France, Germany, and the UK have focused on the entire hydrogen value chain. Since this paper aims to propose a push-pull policy model which complements technology push supports with market pull policy instruments. Therefore, we selected Germany, the UK, and France for policy analysis who are focusing on the complete hydrogen value chain and have policy actions to support RD&D, attract new investments, increase market demands and develop a delivery system.

4.1 Germany

The national hydrogen strategy in Germany aims to promote only green hydrogen and its rapid market development by strengthening the complete value chain; therefore, the federal policymakers have taken a systemic approach to connect the supply side to market demand (BMW,2020). Germany plans to deploy up to 5 GW of green hydrogen-producing electrolyzers by 2030 and 10 GW by 2035-2040 (IRENA, 2020). Between 2006 and 2016, the German federal government funded €700 million under the National Innovation Programme on hydrogen and fuel cell technologies and committed a total of €1.4 billion of funding between 2016 and 2026 (BMW,2020). Additionally, between 2020 and 2023, the federal government plans to provide €310 million for practice-based research on green hydrogen under the energy and climate fund, and there are plans to offer an additional €200 million during this period to strengthen practice-oriented energy research on hydrogen technology (BMW,2020). Under the decarbonization scheme, between 2020 and 2023, the federal government will fund more than €1 billion to attract new green hydrogen investments in large-scale industrial facilities; also, they will offer a package of €7 billion for speeding up the market rollout of hydrogen technology in Germany (BMW,2020). To improve renewable electricity availability at a lower cost for green hydrogen production, Germany identified offshore wind as attractive renewable technology to supply electricity that can meet full load requirements. German government developed a framework to attract new investments in offshore winds with green hydrogen production in mind (BMW,2020).

To create an incentive for green hydrogen production technologies and address emissions in the transport sector, the federal government aims to develop new regulations permitting the use of green hydrogen in transport fuel production (BMW,2020). To create new market demand for hydrogen-powered vehicles, including heavy-duty vehicles and public transport federal government pledged purchase grants of €3.6 billion for such vehicles (BMW,2020). Additionally, to strengthen hydrogen refueling infrastructure for vehicles, including heavy-duty vehicles and public transport, a combined grant of €3.4 billion is considered (BMW,2020).

As part of the national hydrogen strategy, Germany supports switching over hydrogen as a base fuel, particularly in the heavy industries, and developed fund schemes for decarbonizing the industrial sector. German government recognizes the international competitive environment and does not want to pass on the cost of zero-carbon technologies to the customer; therefore, it launched several fund schemes during 2020-2024 to reward the switchover from fossil-fuel-based technologies to industrial processes hydrogen-based technologies (BMWI,2020). Germany also implemented an innovative market-driven policy instrument called CCfD (Carbon Contract for Difference) on a pilot basis. To attract new investors into green hydrogen technologies and decrease green hydrogen price uncertainty, Germany implemented CCfD, a forward contract on the price of abated greenhouse gases, and pledged €500 million until 2023 (Cammeraat et al., 2022). Under the CCfD scheme, the government will guarantee funds amounting to the difference between the contractually agreed cost of avoiding emissions and the ETS (Emission Trading System) prices; in case the ETS price rise above the contractually agreed carbon price, companies would be bound to pay back the difference to the government (BMWI,2020).

German policymakers recognize that the need for delivery infrastructure for reliable hydrogen supply will be vital to the future hydrogen market development; therefore, they plan to retrofit existing infrastructure for hydrogen delivery and construct new elements of the supply infrastructure (BMWI,2020). The federal government aims to develop a regulatory framework to integrate the electricity, heat, and gas infrastructure to improve the cost-effectiveness of the entire hydrogen value chain (BMWI,2020)

As part of the European Clean Hydrogen Alliance to fulfill European strategic interest in hydrogen development, Germany committed an investment of €1.5 billion during 2021-2026 through IPCEI (Important Project of Common European Interest) (Cammeraat et al.,2022).

4.2 France

Alike Germany, the French government, also selected green hydrogen as a transition pathway and aimed to strengthen the entire green hydrogen value chain. According to the French govt (2022), synchronizing policy supports on the supply and demand sides will enable green hydrogen development. France plans to install a 6.5 GW green hydrogen capacity using electrolysis by 2030 and aims to accelerate the growth by committing a €7.0 billion investment (French govt, 2022). As part of the short-term plan 2020-2023, France allocated €3.4 billion support fund to three priority areas a) research and innovation (19% allocation), b) hydrogen-based transport (27% allocation), and c) decarbonization of heavy industry (54% allocation).

To scale up green hydrogen deployment, France allocated € 275 million until 2023 to develop regional hydrogen hubs by bringing regional authorities and industrial solution providers together and creating regional ecosystems combining different industrial and transport users (French govt, 2022). France allocated €350 million until 2023 to fund demonstration projects related to new solutions and systems in green hydrogen production and distribution (French govt, 2022). Additionally, France allocated €65 million until 2023 to fund research and development of green hydrogen technologies.

France plans policy instruments (regulations, taxes, GOs, and compensation mechanisms) to improve the scale of economics and increase the adoption of electrolyzes in the industry (French govt, 2022). As part of the European Clean Hydrogen Alliance, France set aside a financial allocation of €1.5 billion to support IPCEI (French govt, 2022).

Although France plans to scale up green hydrogen demand in the industry and transport sector, the current policy outline does not elaborate much on improving delivery infrastructure. There are no clear policy outlines to develop a hydrogen gas grid or to connect industrial consumers with the supply side. According to FCH (2020), France is considering using its existing methane infrastructure for hydrogen distribution; converting the networks to a dedicated hydrogen grid would be a longer-term consideration. Also, there is no clear policy outline on dedicated renewable electricity sources. There is no clarity on how renewable electricity sources will be scaled-up to match green hydrogen production. The use of nuclear energy for green hydrogen generation aimed at addressing climate change is a debatable issue. However, France's sizeable nuclear power generation capacity presents an opportunity for rapid deployment of green hydrogen as the cost of nuclear power is very low; also, unlike intermittent electricity sources, nuclear power can provide a full load for hydrogen production (FCH,2020).

4.3 United Kingdom

In contrast to France and Germany selecting the green hydrogen pathway, the UK's national hydrogen strategy is based on a mix of green and blue hydrogen. The UK aims to set up 10 GW of low-carbon hydrogen production by 2030 using a twin-track approach, meaning projects will get capital support under two schemes, HBM (Hydrogen Business Model) and NZHF (Net Zero Hydrogen Fund) (BIES, 2022a). To achieve the 10GW hydrogen

production target, the UK aims to attract £9 billion of private investments by 2030 by showcasing economic opportunities and growth potential (BIES,2022a). The UK aims to support multiple technologies for low-carbon hydrogen using LCHS (Low Carbon Hydrogen Standard), which promotes technology neutrality and allows a range of production routes to deliver low-carbon hydrogen (BIES, 2022a). To support hydrogen development through CCUS technology and water electrolysis, the UK allocated £ 240 million from Net Zero Hydrogen Fund (NZHF) until 2025. Beyond 2025, the UK also plans to implement HBM, where the revenue stream will be derived from levy funding without relying on government subsidies (BIES,2022a). Using £1 billion under the net-zero innovation portfolio, the UK set out a road map to support hydrogen related innovation (BIES,2022a).

Under the HBM scheme, the UK plans to implement CfD (Contract for Difference) market-driven instrument to incentivize producers, reduce investment risk, and provide long-term revenue visibility. According to (BEIS; 2022b), the past success of CfD schemes in renewable electricity growth has demonstrated that business models based on CfD can provide long-term certainty to private investors and projects. Under the HBM, the UK allowed volume scaling and long duration (10-15 years) of CfD contracts to make the hydrogen business more profitable. The HBM being a producer-focused scheme, could be a faster and simpler way to support the deployment of low carbon hydrogen plants. The HBM schemes will apply to only hydrogen-producing technologies that adhere to LCHS (BIES,2022b). The gaps in the carbon price regime are the major cause of energy market imperfections; the present UK ETS is limited to energy intensive industries, the power generation sector. The UK policymakers recognized this gap and plan to extend UK ETS coverage to other sectors like transport, certain industrial emissions, and the built environment to make HBM more effective and incentivize users to switch to low carbon hydrogen (BEIS,2022a).

The LCHS sets out a threshold limit of 20gCO₂e/MJ(LHV) of hydrogen at the production point, which means technologies with carbon emissions within the threshold limit can be qualified under LCHS (BEIS,2022c). To ensure electricity is used in hydrogen production from renewable sources, under LCHS, the UK aims to use market-based mechanisms like Renewable Energy Guarantees of Origin (REGOs) and Power Purchase Agreements (PPAs) (BEIS,2022c). Such market-based measures will assure that hydrogen production electricity is from renewable sources. UK policymakers outline the additionality principle to address the additionality problem. Under the additionality principle, the hydrogen producers demonstrating they have built or funded new low carbon generation or are utilizing curtailed electricity will be eligible for support under HBM and NZHF schemes (BEIS,2022c). Also, the additionality evaluation criterion will help producers improve their overall rating to get recognized under LCHS (BEIS, 2022c).

Like Germany and France, the UK also targeted heavy industries and the transport sector to create demand for hydrogen. As part of demand-side policy initiatives, the UK plans to develop large industrial clusters during the 2020s to create early demand and foster an initial hydrogen market; the UK also planned to fund a range of fuel switch demonstration projects in heavy industries (BEIS,2022a). The UK recognized the transport sector as an early market and identified that public transport buses and heavy goods vehicles could play an important role in the scale-up of hydrogen demand (BEIS,2022a). UK plans to introduce Renewable Transport Fuel Obligation (RTFO) through consultation to promote the use of low carbon hydrogen as fuel in the transport sector (BEIS,2022a). UK aims to target a policy decision by 2023 on the feasibility of 20% hydrogen blending in the UK's gas networks (BEIS,2022a). With international collaboration and partnership in mind, the UK plans to set up a hydrogen certification scheme by 2025 to capitalize on low carbon hydrogen opportunities and support future international trade (BEIS,2022c).

5. Discussion

This paper aims to identify critical policy interventions to overcome technical and commercial barriers to green hydrogen upscaling and propose a technology push and demand-pull policy model. In section 4, we analyzed the hydrogen policies of countries leading green hydrogen development. France and Germany selected green hydrogen pathways; in contrast, the UK used technology-neutral policies aimed at a mixed pathway (green and blue) with water electrolysis and low carbon CCUS technology. We selected three countries, France, Germany, and the UK, for policy analysis since they have developed policy interventions to strengthen the complete hydrogen value chain from supporting technology push to market demand creation. In contrast, Japan and USA policy interventions are mainly concentrated on the supply side with a high number of technology patents & trademarks and substantial RD&D funding but no visible actions on the demand side. Australia has set an ambitious target to increase hydrogen production; however, their policy actions on the supply side for technology push are ineptive. In the EU, Netherland is another country with an ambitious plan to increase hydrogen production without much focus on supporting technological development. China and South Korea have the aspiration to develop hydrogen

capabilities as part of their national strategy; however, their policy actions to create a hydrogen value chain are still ineptive.

The high cost of green hydrogen is a major concern, and electrolyzer technologies are still evolving. The policy action on the supply side should aim to reduce CAPX and OPEX costs and improve electrolyzer efficiency. Therefore, supply-side policies should focus on developing cost-effective and efficient electrolysis units, increasing capacities from MW to GW scale, and making renewable electricity accessible to green hydrogen units. In our analysis, we observed that as part of the technology push policy, France, Germany, and the UK have set up innovation funds to support R&D activities and supported demonstration projects to improve economies of scale and replicate the knowledge through project-based learning.

Renewable electricity availability and price are significant contributors in the green hydrogen LCOH and act as a barrier to up-scale green hydrogen production. Interestingly, three countries responded differently to this issue. Germany identified offshore wind potential and developed a framework to create new assets to support green hydrogen production; It also plans to reduce renewable electricity costs by abolishing the EEG surcharge on electricity intended for green hydrogen production. Considering the lower cost and without intermittency issues, France plans to utilize excess nuclear power capacity to support the rapid deployment of water electrolysis units. On the other hand, the UK took a diverse approach by defining the additionality principle for renewable electricity intended to be used for hydrogen generation. Under the additionality principle, the hydrogen producer to get benefits of HBM must demonstrate that utilized renewable electricity is a result of curtailment or sourced from new renewable electricity assets built exclusively for hydrogen generation. The UK also plans to use market-based instruments like REGOs and Power Purchase Agreements (PPAs) to increase the diffusion of low-cost renewable electricity for hydrogen generation.

France, Germany, and the UK committed to financial support for the technology push as part of a short-term plan from 2020 to 2025. However, by 2030, these countries expect hydrogen production costs to come down, and the hydrogen business will become profitable without relying on government funds and subsidies. This expectation aligns with the idea that governments should gradually curtail subsidies and public funds on renewable energy technologies and apply effective demand-side policy interventions to make renewable energy economically viable and self-sustaining. This move not only helps the government to control tax money used on subsidies but also helps renewable energy technologies to mature. Although technology push policies on the supply side have been successful in technology development. Nevertheless, with countries moving away from subsidies and public funds, policymakers are shifting their focus to demand-side interventions. When complementing supply-side policies, demand-side policies are more effective in stimulating innovations and incentivizing innovators. According to Hansen et al. (2017), demand-side policies can remove market uncertainties and attract new investments; therefore, policymakers should adopt a systemic approach to creating technology push and demand-pull policies. By having a systemic view of the complete value chain, policymakers can apply the choice of policy instruments to support the generation and diffusion of innovations and the creation of future market demands (Edler & Fagerberg, 2017). Complementing supply-side policies with demand-side policy instruments is strategically more effective in addressing complex systemic transitions such as energy transition, where the interconnection of technology and market-related issues cannot be overlooked (Cunningham, 2009)

During analysis, it was observed that all three countries, France, Germany, and the UK, identified areas for early demand creation, especially in the heavy industries and transport sector. As part of demand-side interventions, Germany proposed grants for hydrogen fueled vehicles and switchover incentives for green hydrogen adoption in heavy industries. As part of the demand-side initiative, France plans to develop green hydrogen hubs to bring together local authorities and technology providers and create a hydrogen ecosystem to increase hydrogen adoption in transport and heavy industries. France plans policy instruments like taxes, GOs, and compensation mechanisms to reward green hydrogen adoption in heavy industries. Alike France, the UK also plans to develop industrial clusters to foster low carbon hydrogen market demand in heavy industries and the transport sector. The UK plans to extend the RTFO scheme to promote the use of low carbon hydrogen in the transport sector, and also plans to bring a certification scheme to track the guarantee of origin new policy through consultation that will permit low carbon hydrogen injection into the national gas grid

To make the green hydrogen business profitable and remove price uncertainty, Germany and the UK plan to implement market driven CfD schemes. Germany implements the CCfD scheme to internalize carbon emission costs and make green hydrogen use more competitive against high carbon energy sources in heavy industries. The UK proposed a hydrogen business model based on the CfD scheme to attract private investors and create long-term business opportunities; under this scheme, the UK plans to pay the differential amount from levy funds without replying to government subsidies. In contrast, France provides tax rebates on green hydrogen producers.

To support demands in industries and the transport sector, the UK and Germany plan to upgrade the existing gas network and develop a dedicated hydrogen distribution network and refueling stations in the next few years.

Being part of the European clean hydrogen alliance, France and Germany aim to play a lead role in green hydrogen development within Europe and support large scale deployment by 2030. The alliance aims to strengthen the hydrogen value chain to create an integrated hydrogen market and overcome structural barriers to cross-country trade. The UK aims to capitalize on the mixed pathway (green and blue) using the LCHS and certification scheme to explore international trade opportunities.

Building on the above policy analysis, a technology push and market pull model (Figure-1) is proposed for green hydrogen development that can be followed by countries aspiring to upscale green hydrogen development.

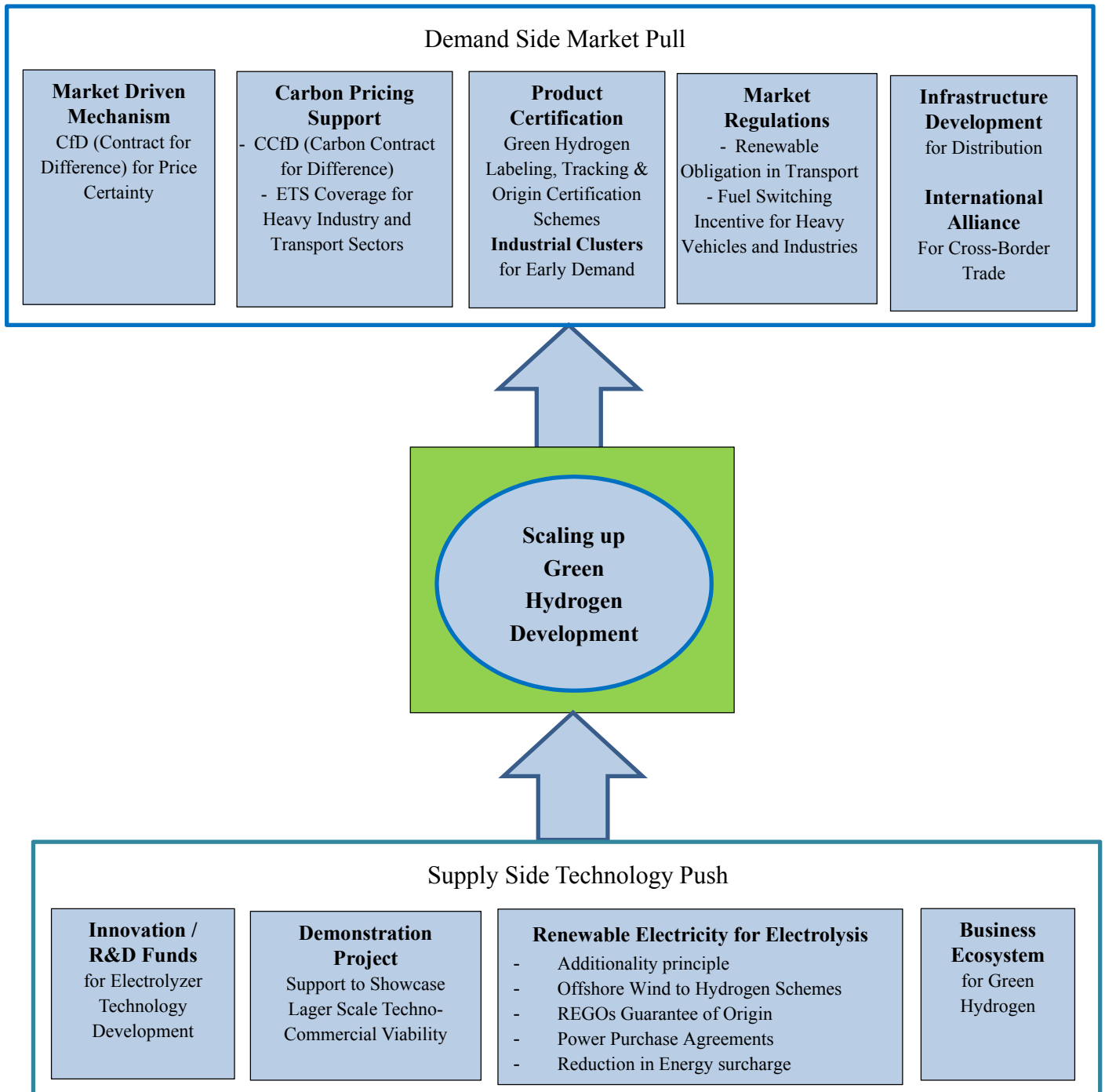


Figure 1. Policy push-pull model for scaling up green hydrogen development

6. Conclusions

We conducted policy analysis of lead countries involved in green hydrogen development and discerned their policy interventions. We observed that all leading countries have policies focused on supply-side technology push. However, only three countries, France, Germany, and the UK, have policy actions focused across the entire value chain and aim to create green hydrogen demand using a policy mix strategy. We also observed that policy interventions in France, Germany, and the UK are diverse and have a great variety. Such diversity in policy interventions is understandable as policy actions in respective countries are influenced by local political and geographical factors. Germany and France selected green hydrogen pathways; in contrast, the UK plans mixed pathways relying on green and blue hydrogen development.

The paper highlighted technical and commercial barriers to scaling green hydrogen development and discussed how demand-side policy interventions could be more effective when complemented with supply-side policy actions. Based on policy analysis, a policy model based on technology push and market pull is proposed, which can help policymakers create a conducive environment to scale-up green hydrogen development.

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