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Beyond the Hype: The Rainbow of Hydrogen Technologies and Policies

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Beyond the Hype:
The Rainbow of Hydrogen Technologies and Policies

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Abstract

The transition towards a sustainable energy system requires alternative energy carriers that reduce carbon emissions while meeting global demands. Hydrogen is a possible option for industrial heat, transportation fuels, and electricity production. This paper provides an overview of hydrogen production pathways, including gray, blue, turquoise, green, pink, and gold/white hydrogen, evaluating their economic and environmental impacts. It also discusses current and potential US policies promoting hydrogen, such as the IRA 45V Hydrogen Tax Credit and the Department of Energy's Hydrogen Hubs initiative. Based on several interviews with experts in the field, the paper discusses several policy issues that need to be addressed and require additional research.

Keywords: Hydrogen Economy, Alternative Energy Carriers, Industrial Heat, Hydrogen Production Pathways.

JEL Codes: Q45; Q55; L52

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1 Introduction

The transition towards a sustainable energy system requires the exploration and adoption of alternative energy carriers that can meet global demands while reducing carbon emissions. Among the alternatives, hydrogen is often considered a viable product to replace industrial heat, heavy-duty transportation fuels, and electricity production. Hydrogen can be produced from diverse feedstocks using a variety of processes, and its environmental impact largely depends on the production method. In this paper, we provide an overview of the different pathways for hydrogen production and evaluate their economic and environmental implications. We also review the current policy landscape both within and outside of the US. Finally, we summarize the lessons from four structured interviews of experts who have been involved in hydrogen policy formation and academic research and have directly worked with the hydrogen industry.

Hydrogen production can be classified into several categories based on the feedstock and the production process. The most common classifications include gray, blue, turquoise, green, pink, and gold/white hydrogen, each representing different production methods and associated environmental impacts. Gray hydrogen is produced from natural gas through steam methane reforming (SMR) and is the most established and widely used method. However, it is carbon-intensive, releasing significant amounts of CO_2 into the atmosphere. Blue hydrogen is similar to gray hydrogen but incorporates carbon capture, utilization, and storage (CCUS) technology to mitigate CO_2 emissions, offering a transitional solution by reducing emissions associated with hydrogen production from fossil fuels.

Turquoise hydrogen is produced via methane pyrolysis, which generates solid carbon instead of CO_2. While promising, this method requires further technological advancements and scalability. Green hydrogen, generated through water electrolysis powered by renewable energy sources such as wind, solar, and hydropower, is considered the most sustainable option, as it produces no direct CO_2 emissions. Pink hydrogen is produced through electrolysis using nuclear energy, sharing the environmental benefits of green hydrogen but depending on the availability and public acceptance of nuclear power. Gold/white hydrogen, which is natural hydrogen geologically sourced, is still under exploration and not yet commercially viable on a large scale.

The economic viability and environmental impact of hydrogen production methods vary significantly. Gray hydrogen remains the cheapest due to established infrastructure and technology. However, its high carbon footprint necessitates alternatives like blue hydrogen, which, although more expensive, reduces emissions through CCUS. Green hydrogen, while environmentally superior, currently faces high production costs due to the price of renewable energy and electrolyzer technology. Pink hydrogen offers a lower-carbon alternative if nuclear energy is readily available, but its adoption is limited by nuclear energy's societal and regulatory challenges.

A comprehensive comparison of production costs and emissions for each pathway is critical for policy-making and investment decisions. According to the International Energy Agency (IEA), the levelized cost of hydrogen (LCOH) varies widely across different production methods, with green hydrogen expected to become more competitive as renewable energy costs decline and electrolyzer efficiencies improve. Emissions intensity also varies, with green and pink hydrogen offering the lowest emissions profiles, followed by blue and turquoise hydrogen.

In recent years, the United States has implemented several policies to support the development of a hydrogen economy. Key initiatives include the IRA 45V Hydrogen Tax Credit, part of the Inflation Reduction Act, which aims to incentivize clean hydrogen production by providing financial benefits to producers who achieve specified emissions reductions. The Department of Energy's Hydrogen Hubs under the Bipartisan Infrastructure Law focuses on establishing regional hydrogen production hubs to create a robust hydrogen infrastructure and supply chain across the country. The Hydrogen Demand Initiative (H2DI) seeks to stimulate demand for clean hydrogen through various applications, including transportation, industrial processes, and power generation.

The development of a hydrogen economy presents a significant opportunity for decarbonizing various sectors and achieving climate goals. However, careful consideration of production methods, economic viability, and environmental impacts is required. Our structured interviews highlight that while significant federal proposals aim to support the industry's growth, especially in decarbonizing hard-to-abate sectors, there are ongoing challenges that require technological innovation and more refined policy support. Experts interviewed emphasized the need for amending policies to ensure realism and comprehensive support, with particular concerns over the practicality of current tax credits and the stringent requirements for clean hydrogen production standards. Several additional measures were suggested to foster market adoption and stimulate investment in hydrogen technology, addressing both supply-side and demand-side challenges. We discuss these in depth below, but many of them focus on policies that consider the entire hydrogen value chain and, in particular, growing the demand side of the market, as well as establishing a regulatory framework that establishes robust safety guidelines and an oversight body to ensure hydrogen is handled safely across the value chain.

The paper is organized as follows. Section 1 introduces the role of hydrogen in the transition to a sustainable energy system, outlining the potential for various hydrogen production pathways. Section 2 provides an in-depth overview of these production methods, including gray, blue, turquoise, green, pink, and gold/white hydrogen, along with their economic and environmental impacts. Section 3 focuses on U.S. hydrogen policies, particularly those that aim to support hydrogen development, such as the IRA 45V Hydrogen Tax Credit and the Hydrogen Hubs initiative. Section 4 examines the challenges and opportunities associated with hydrogen adoption, while Section 5 discusses policy issues that require further refinement and suggests additional measures to promote widespread hydrogen use. Finally, Section 6 concludes the paper by summarizing the key findings and outlining areas for future research.

2 Hydrogen Pathway Overview

The methods of hydrogen production can be categorized in various ways, including the feedstock from which hydrogen is separated, the types of chemical reactions involved, and the additional technologies required. The U.S. Department of Energy classifies methods of hydrogen production based on the processes by which hydrogen is generated. [1] The type of feedstock used also influences the categorization of hydrogen production methods. [2, 3] To visually represent the various methods of hydrogen production, hydrogen color codes, or hydrogen rainbow, are employed, assigning names to different hydrogen production methods. [3] This paper discusses various methods of hydrogen production, including thermochemical and electrochemical processes, as well as the emerging focus on natural hydrogen. It also compares the production costs and carbon emission levels associated with each method. The thermochemical hydrogen production methods discussed include steam reforming, steam reforming with carbon capture and sequestration, and pyrolysis. The electrochemical methods include water electrolysis using renewable energy or nuclear energy as the primary energy sources. Each hydrogen production method involves distinct reactions and processes, each with its own advantages and disadvantages.

2.1 Steam Reforming (Gray hydrogen)

Fossil fuels represent one of the most readily separable feedstock chemicals for hydrogen production. The methods for hydrogen production utilizing fossil fuels include hydrocarbon reforming and hydrocarbon pyrolysis. At present, the predominant method for hydrogen production involves the chemical separation of hydrogen from methane-rich natural gas, known as steam methane reforming (also referred to as the 'Gray' hydrogen). [3] The process of steam methane reforming mainly consists of three stages: the reformer, Water Gas Shift (WGS) reactor, and purifier.

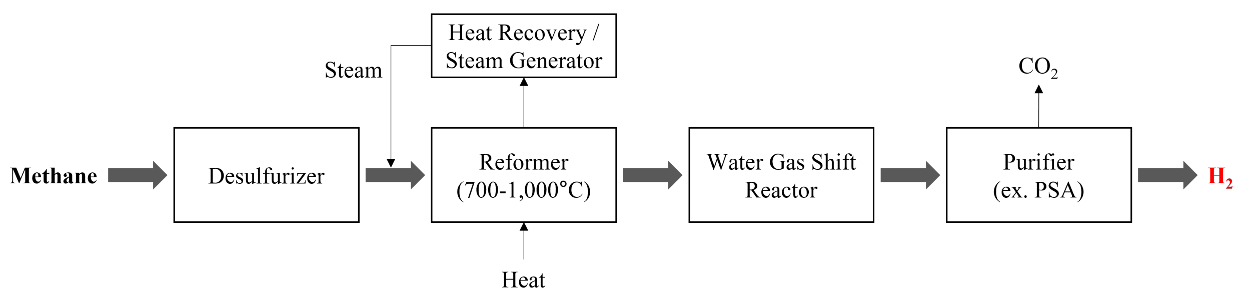


Figure 1: Flow diagram of the steam methane reforming process [4]

In the primary reactor of the hydrogen production process, known as the reformer, steam and natural gas, mainly methane, undergo reactions at high temperatures ranging from approximately 700°C to 1,000°C and high pressures ranging from 3 to 25 bar. For the steam reforming reaction, nickel-based catalysts are predominantly employed. [5] The products from the reformer, mainly comprising hydrogen, carbon monoxide, and carbon dioxide, are then introduced into the Water Gas Shift (WGS) reactor, a reactor designed to further enhance the hydrogen and to decrease carbon monoxide content. Through WGS equilibrium reactions, these products undergo a reaction aimed at substituting carbon monoxide with hydrogen. Subsequently, to elevate the hydrogen concentration within the syngas, a purifier, where pressure swing adsorption (PSA) is commonly adopted, is employed to remove carbon dioxide, resulting in the production of H_2 gas with near 100% purity. [6] The key chemical reactions that constitute steam methane reforming process are as follows: [7]

Steam methane reforming:

$$CH_4 + H_2O + (Heat) \rightarrow CO + 3H_2 \tag{1}$$

Water Gas Shift reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{2}$$

Steam methane reforming is already a mature technology and accounts for a significant portion of hydrogen production in the United States. On a global scale, it constitutes approximately 62% of the total hydrogen production. [8] This is attributed to the cost-effectiveness and efficiency of hydrogen production using steam methane reforming, making it the most economical method for obtaining hydrogen.

In the United States, industrial gas companies, oil and gas companies, and chemical companies utilize steam methane reforming to produce hydrogen. For instance, Air Liquide constructed a steam-reforming methane facility in La Porte, TX, in 2012, capable of producing 120 million standard cubic feet per day (mmscfd) of hydrogen. [9] Another industrial gas manufacturer, Air Products, also built a steam methane reforming facility in Baytown, TX in 2015, capable of producing 125 mmscfd of hydrogen. [10] At the time, it was one of the largest-scale hydrogen production plants using steam reforming. Major oil and gas companies such as Chevron and ExxonMobil also own numerous hydrogen production plants near their refinery facilities. This is crucial for supplying pure hydrogen, which is necessary for the production of advanced hydrocarbon compounds like ethylene in refineries to make plastics and advanced chemicals. Consequently, in the United States, there is a significant distribution of hydrogen production facilities utilizing steam reforming, particularly in regions like the Gulf Coast and Louisiana, where refineries are concentrated.

However, the steam reforming method utilizing natural gas is a process that emits a considerable amount of carbon dioxide. According to a recent analysis by the International Energy Agency (IEA), the direct emissions of CO_2 through the natural gas steam reforming process are approximately 9 kg CO_2 equivalent per kg of hydrogen (CO_2-eq/kg H_2). Taking into account additional factors such as greenhouse gas leakage from upstream and midstream natural gas production, the overall carbon dioxide equivalent emissions reach a level of approximately 10-13 kg CO_2-eq/kg H_2. [8] This indicates a significant amount of carbon dioxide emissions resulting from hydrogen production for industrial purposes, especially given that the annual hydrogen production in the United States is approximately 10 million metric tons.

2.2 Steam Reforming with CCUS technology (Blue hydrogen)

Various methods are being considered to reduce CO_2 emissions in hydrogen production using steam reforming. Among these methods, the integration of Carbon Capture, Utilization, and Storage (CCUS) technology directly into steam reforming plants is gaining attention for its technical maturity and efficiency in CO_2 reduction. The International Energy Agency (IEA) projects that approximately 40% of hydrogen production by 2070 will involve fossil fuel reforming methods incorporating CCUS technology. [11]

Various carbon capture technologies are directly integrated into the steam methane reforming process to mitigate CO_2 emissions during steam methane reforming. In the steam methane reforming process depicted in Figure 2, there are three key points where CO_2 capture can occur: the syngas stream after passing through the CO shift reactor, the tail gas stream after passing through the H_2 purification reactor, and the final flue gas stream after multiple rounds of reforming. [12] These points are crucial for CO_2 capture. Given that these gas streams have different CO_2 concentrations, temperatures, and pressure conditions, different CO_2 capture technologies are required for each point.

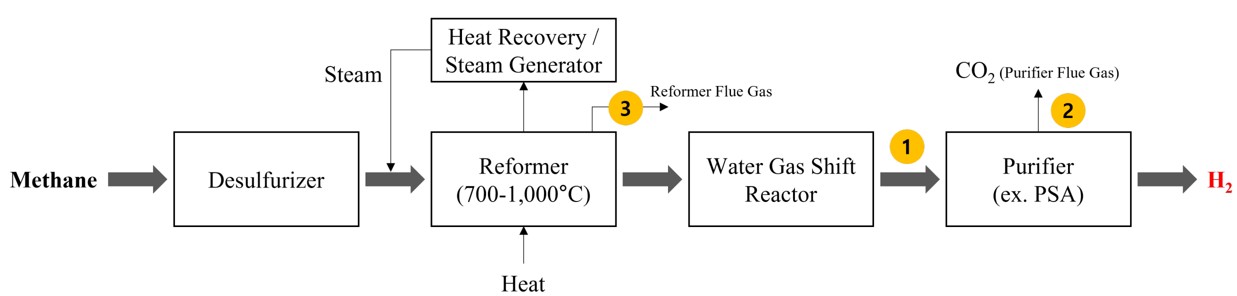


Figure 2: CO_2 capture points within the steam methane reforming process [4, 12]

Prominent CO_2 capture technologies include amine adsorption, Pressure Swing Adsorption (PSA), CO_2 separation membranes, and cryogenic technology. [13] Among these, the technologies that are technically mature and economically viable and widely employed in operational steam reformers with CCUS are amine adsorption and PSA. [12] Amine adsorption involves reacting the acidic gas CO_2 with the basic liquid alkylamine to wash out CO_2 from the gas stream. This process utilizes a column in the amine wash reactor where the CO_2-containing gas stream passes through and directly reacts with liquid amine. Amine adsorption exhibits the highest CO_2 capture performance among various CO_2 capture technologies and is economically advantageous due to its relatively low energy consumption. The type of liquid amine used varies depending on the pressure, temperature, and target CO_2 removal quantity of the gas stream. Several industrial processes commonly use aqueous methyldiethanolamine (MDEA). [13] Amine adsorption is typically applied to the syngas stream before H_2 PSA or to the final flue gas stream. [12]

PSA is a process that utilizes physical attractive forces between gas molecules and adsorbent materials to physically adsorb CO_2. Compared to amine adsorption, PSA does not require heat exchangers or chemical reaction processes, allowing for relatively rapid CO_2 capture. Unlike the H_2 PSA process commonly included in steam methane reforming, which utilizes different adsorbents, CO_2 PSA captures only CO_2. CO_2 PSA equipment is added separately and is typically applied to the tail gas stream after passing through H2 PSA to adsorb CO_2. [12]

The advantages of reducing CO_2 emissions in hydrogen production by modifying existing steam methane reforming processes have led to the construction and planned development of steam-reforming plants incorporating CCUS technology worldwide. According to the latest report from the IEA, as of 2023, 16 H_2 production facilities with CCUS are operational globally, producing 0.6 million metric tons of hydrogen annually while capturing 11 million metric tons of CO_2. [8] Currently, most of these facilities involve retrofitting chemical plants in the North American region with CCUS technology. Assuming all planned construction projects, including those in the planning stage, are realized, the amount of hydrogen produced from CCUS-integrated hydrogen production facilities is expected to increase approximately 15-fold to 9 million metric tons per year by around 2030, as per the IEA report. [8] In the United States, industrial gas companies and major oil and gas companies operating steam methane reformers are actively planning to adopt steam-reforming facilities with CCUS technology. ExxonMobil, for instance, recently announced plans to construct the world's largest methane reforming reactor in Baytown, TX, with a target operational start in 2027. [14] This reactor, capable of producing 1 billion square cubic feet of hydrogen, integrates

CO_2 capture technology from Honeywell, aiming for a high 98% CO_2 capture rate.

However, hydrogen production using CCUS-integrated reformer processes currently faces several limitations. First, existing operational reformers with CCUS exhibit low CO_2 capture rates. Despite having CCUS facilities, all 16 operational reformer facilities partially capture CO_2 generated during the reforming process. According to the IEA, even among reformers equipped with similar CCUS facilities, those with a capture rate as low as 60% emit over twice as much CO_2 compared to plants achieving a 99% capture rate. [8] To significantly reduce the amount of CO_2 generated during hydrogen production, a minimum capture rate of 90-95% is required, but facilities achieving this level of capture rate are currently nonexistent. Two plants under construction in North America aim to achieve a 90-95% CO_2 capture rate in the near future. [8] Secondly, a practical challenge lies in the inadequate infrastructure and supply chain for CCUS. Even with high levels of CO_2 capture in the hydrogen production process, additional devices such as heat exchangers, compressors, and pipelines are required during the compression, transport, and storage of the captured CO_2. Notably, large-scale storage space and compressors are essential for CO_2 storage, and the current infrastructure is vastly insufficient. In the United States, where CO_2 storage reservoirs and hydrogen production with CCUS sites are often located far apart, the need for large-scale CO_2 transport pipelines becomes crucial.

2.3 Methane Pyrolysis (Turquoise hydrogen)

Although the CCUS technologies have been improved and efforts have been made to reduce carbon emissions during the reforming process, achieving a complete reduction of carbon emissions to 'zero' during the hydrogen production process is realistically challenging. Methane pyrolysis is a method gaining significant attention in recent research for minimizing carbon emissions while extracting hydrogen from hydrocarbons. Methane pyrolysis involves utilizing substantial heat to 'decompose' methane into hydrogen and carbon molecules. This process allows for the separation of carbon in the form of solid carbon rather than gaseous carbon dioxide during pyrolysis, enabling the nearly 'zero' emission of carbon dioxide in the hydrogen production process. While the hydrogen yield per unit of injected hydrocarbon fuel is lower than steam reforming, the method is gaining prominence due to its environmentally friendly approach, given the almost negligible emission of gaseous carbon dioxide. The fundamental chemical reaction for methane pyrolysis is expressed as follows: [13]

Methane Pyrolysis:

$$CH_4 + (Heat) \rightarrow 2H_2 + C \tag{3}$$

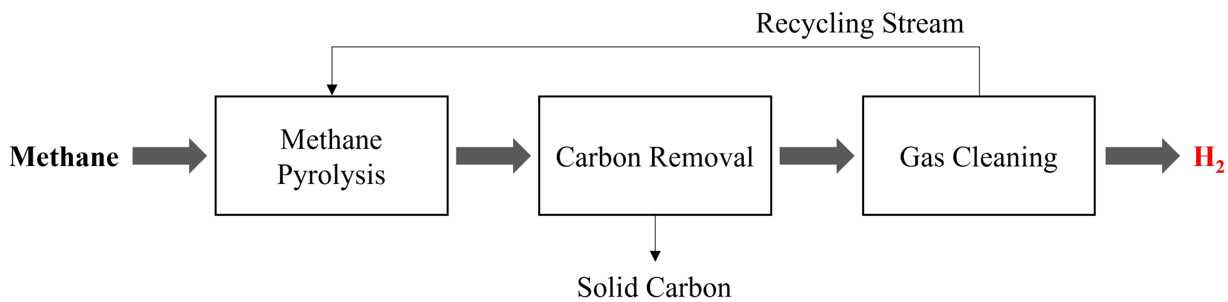


Figure 3: Flow diagram of methane pyrolysis [13]

Figure 3 provides a concise schematic representation of the typical process of methane pyrolysis. [13] Methane pyrolysis can be divided into three stages: the methane pyrolysis stage, the carbon removal stage, and finally, the gas cleaning stage. The main reactor where the methane pyrolysis reaction occurs is explored through three methods: catalytic pyrolysis utilizing catalyst chemical reactions, plasma pyrolysis employing high-temperature plasma, and thermal pyrolysis utilizing thermochemical reactions. In particular, much research focuses on the development of catalytic materials, such as nickel, iron, and cobalt, among others, to conduct efficient pyrolysis at relatively low temperatures (around 800°C) while ensuring high hydrogen yield from chemically stable methane. [13] Carbon generated through the pyrolysis reaction primarily possesses a small particle size and forms highly dispersed solid carbon. It resembles the commercial carbon black used in producing high-performance tires, rubber, or black ink. In the carbon removal stage, solid carbon is separated from the gas stream using filter systems or cyclone systems. [13] In the gas cleaning stage, any remaining unreacted methane or undetached carbon particles are separated using PSA (Pressure Swing Adsorption) or membrane devices to produce a pure hydrogen product. Any remaining methane is recycled through a recycle stream back to the methane pyrolysis stage. [13]

Methane pyrolysis offers the advantage of not emitting gaseous carbon dioxide in the hydrogen production process, but it is also burdened with several current technological limitations. The primary controversial aspect of hydrogen production through methane pyrolysis revolves around the issue of where to source the heat required for pyrolysis. A substantial amount of heat, approximately 74.9 kJ/mol, must be supplied to break down chemically stable methane molecules into hydrogen and carbon molecules. The injected heat is primarily utilized to elevate the temperature of the reactor. High-temperature reaction conditions are essential for industrial-scale methane pyrolysis processes, requiring temperatures above 800°C with appropriate catalysts and over 1,000°C in non-catalytic approaches. [13] While the ideal approach involves obtaining heat through emission-free energy sources such as solar or wind power, the current capacity of emission-free grid electricity falls significantly short of meeting the demand. Consequently, considerable time would be required before utilizing such energy for hydrogen production. Currently, methane pyrolysis remains at Technology Readiness Levels (TRL) 3-4 for most related technologies, indicating that substantial effort and time will be necessary before reaching commercialization. [15]

2.4 Water electrolysis using renewable energy (Green Hydrogen)

When extracting hydrogen from hydrocarbon fossil fuels, a certain amount of carbon will inevitably be generated. To completely eliminate carbon emissions in the hydrogen production process, water electrolysis has gained attention. Water molecules, the most abundant molecule on Earth, consist of one oxygen atom and two hydrogen atoms. Water electrolysis involves utilizing electrical energy to separate oxygen and hydrogen atoms, strongly bonded through covalent bonds, into hydrogen and oxygen molecules. The generated hydrogen is then used in the form of hydrogen gas. Below is the simplified chemical reaction for water electrolysis: [16]

Water Electrolysis:

$$2H_2O + (Energy) \rightarrow 2H_2 + O_2 \tag{4}$$

A substantial amount of energy is required to break the strong molecular covalent bonds between hydrogen and oxygen in water molecules, inducing an endothermic and non-spontaneous water dissociation reaction. Applying a high direct current voltage to the electrolysis cell generates a significant electrical potential difference between the electrodes of the electrolysis cell, allowing water molecules to undergo decomposition. Depending on the type of electrolyzer, water is electrochemically decomposed to either O_2 and positively charged ions (cations) through oxidation or H_2 and negatively charged ions (anions) through reduction at one of the electrodes. [16]

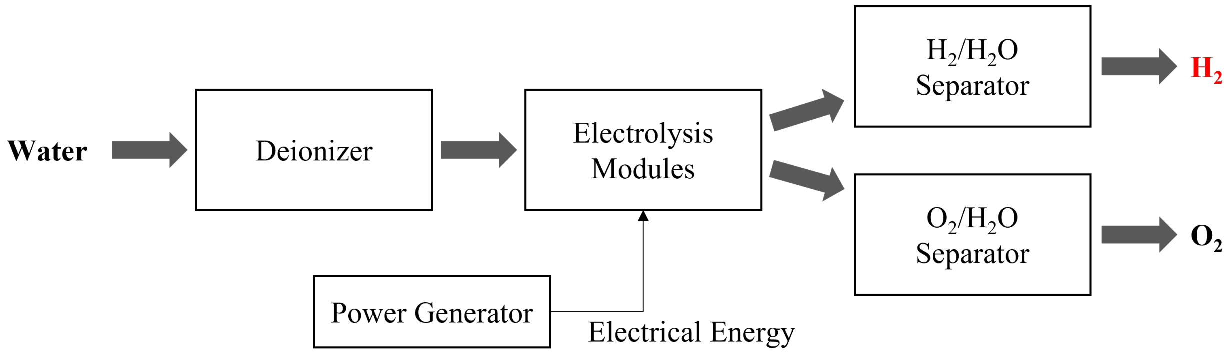


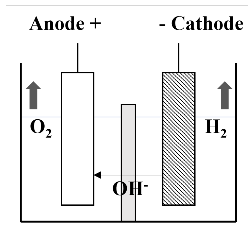
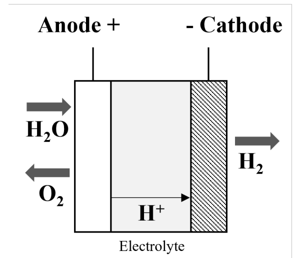
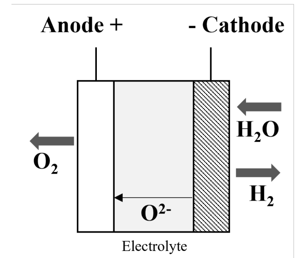
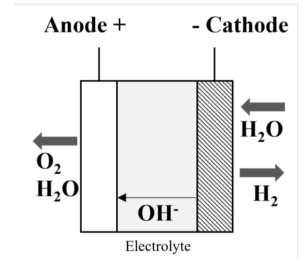
Figure 4: Flow diagram of the water electrolysis process [4]

Figure 4 illustrates a simplified water electrolysis process flow diagram. [4] Water used in electrolysis typically passes through a deionizer to ensure only pure water is utilized. The generated hydrogen and oxygen gases, after the electrolysis reaction, pass through a separator to filter out any remaining unreacted water molecules. The produced hydrogen is usually in the form of gaseous hydrogen, compressed at high pressure, stored in hydrogen tanks, and transported to the point of use. If renewable energy sources such as solar or wind power are used to produce hydrogen through electrolysis, the entire process minimizes carbon involvement and becomes the most environmentally friendly method for hydrogen production, simultaneously lowering the overall climate impact. According to the color-coded classification system that simplifies the understanding of hydrogen production methods, hydrogen produced through this approach is referred to as 'Green hydrogen'. [3]

The most crucial aspect of hydrogen production through water electrolysis is the electrolysis module, which separates water into hydrogen and oxygen. Various electrolysis technologies are currently being studied, and the water electrolysis method is categorized based on the type of technology. Four prominent electrolysis technologies that have either entered the commercialization phase or are close to commercialization are Alkaline Electrolysis (AE), Proton Exchange Membrane Electrolysis (PEM), Solid Oxide Electrolysis (SOE), and Anion Exchange Membrane Electrolysis (AEM). [17] Each technology exhibits distinct characteristics in terms of the water electrolysis method, operational conditions, electrolyzer composition, and advantages and disadvantages. Table 1 illustrates the characteristics of each technology.

Among the four water electrolysis technologies, Alkaline electrolysis (AE) and Proton Exchange Membrane (PEM) water electrolysis are closest to commercialization. As both

Table 1: Technical comparison of each electrolysis technologies

	Alkaline Electrolysis	PEM Electrolysis	Solid Oxide Electrolysis	AEM Electrolysis
TRL status [17]	9-10 (Market Uptake)	9-10 (Market Uptake)	7-8 (Demonstration)	6 (Large Prototype)
Operating diagram [19]				
Operating temperature [20]	65-100°C	20-200°C	500-1,000°C	20-200°C
Electrolyte [19]	Liquid KOH	Solid polymeric materials	Solid ceramic materials	Solid polymeric materials
Anodes [19, 20]	Ni-coated stainless steel	Ir/Ru oxides	$LaSrMnO_3$+Y-Stabilized ZrO_2 (LSM-YSZ)	Ni-based materials
Cathodes [19, 20]	Ni alloys	Pt	Ni/YSZ	Ni, Ni-Fe
Efficiency [20]	50-70%	50-70%	Above 80%	40%
Capital cost [20]	1,100-1,300 USD/kWe	2,000-2,500 USD/kWe	2,000+ USD/kWe	N/A
Advantages [19, 20, 21]	• Non-noble electrode • Large-scale applicable	• Fast start-up • Compact size • High purity H_2	• High efficiency • Non-noble electrode	• Compact size • Non-noble electrode • Stable structure
Disadvantages [19, 20, 21]	• Slow start-up • Toxic electrolyte • Unstable structure	• High capital cost due to noble metals	• Fragile due to ceramic materials • High temperature operation needed	• Technical readiness (electrodes activity and electrolyte conductivity)

technologies have distinct advantages and disadvantages, the choice of technology depends on the nature of the hydrogen production project. Alkaline electrolysis is a mature technology that has been demonstrated through various projects. It offers the advantage of producing hydrogen at a relatively lower cost and does not require the use of noble metal catalysts. These benefits make it suitable for large-scale hydrogen production or projects emphasizing efficiency relative to cost. On the other hand, PEM electrolysis is often preferred for projects that require a relatively compact system size. Its excellent response performance and fast startup characteristics make it particularly well-suited for projects involving renewable energy sources with intermittent characteristics, such as solar or wind power, where a continuous and stable electrical supply is challenging. Nel Hydrogen, one of the world's largest hydrogen companies, has adopted both technologies based on the nature of the projects they undertake. [18]

While not yet commercialized, there is a growing number of technology development and demonstration projects for Solid Oxide Electrolysis (SOE) and Anion Exchange Membrane (AEM) electrolysis, both of which offer distinct advantages. In the case of SOE, several large-scale demonstration projects are underway, leveraging its high efficiency. For instance, in May 2023, Bloomenergy, a hydrogen company in the United States, installed a 4MW SOE system at the California NASA research center. [22] The global chemical company Topsoe is constructing a factory aimed at commencing operations in 2025, with the goal of producing a 500MW/yr capacity SOE electrolyzer. [23] AEM is a technology that combines the advantages of both Alkaline electrolysis and PEM electrolysis. It is the focus of active technological development by major universities, research institutes, and startups. While efforts are currently concentrated on maturing the technology without large-scale demonstration projects yet, the expectation is that with sufficient technological development, AEM could lead to the creation of the most stable and cost-effective electrolysis systems. [17]

As the adoption of water electrolysis increases, it holds the potential to supply a greater amount of hydrogen as a carbon-free production. However, beyond the drawbacks inherent in each type of electrolysis technology, the expansion of the industry is being delayed due to several challenges. First, there is an issue with the supply chain for electrolyzers and related components. Many experts are particularly concerned that the production of electrolyzer cells and stacks may fall short of the required quantity in the future. According to the International Energy Agency (IEA), by 2030, the cumulative production of electrolyzers is estimated to be around 67% of the cumulative 600GW required (following IEA's Net Zero Emissions by 2050 Scenario), reaching only approximately 400GW. [8] This shortfall raises concerns about the feasibility of hydrogen production projects utilizing water electrolysis as previously announced, potentially jeopardizing the progress of these projects. Consequently, issues related to the production and supply chain of electrolyzers could impede the development of the carbon-free hydrogen production industry through water electrolysis. Especially in the case of the United States, the supply for electrolyzers may become more challenging in the future. According to the International Energy Agency (IEA), China currently accounts for approximately half of the global electrolyzer production, followed by the European Union with around 20%. [8] For the United States, which aims to expand its green hydrogen production market based on various support policies, it is crucial to find ways to significantly increase domestic electrolyzer manufacturing capacity. To increase domestic green hydrogen production without being affected by political conflicts with China, securing a stable electrolyzer supply chain is essential. A recent report published by the Department of Energy also emphasizes that in order to increase green hydrogen production in the United States, there must be a dramatic increase in domestic electrolyzer manufacturing capacity. [24]

The production of hydrogen through water electrolysis faces another critical supply chain issue. Specifically, the supply chain for the critical minerals required for electrolyzer production may become vulnerable in the future. According to a recent analysis, the projected global production of critical minerals used in almost all types of electrolyzers will be insufficient to meet the global demand if hydrogen production via water electrolysis becomes widespread. [25] Particularly, the supply shortage of critical materials used in PEM electrolyzers is expected to be severe. The analysis indicates that assuming the global production capacity of platinum, palladium, and iridiumâkey materials for PEM electrolyzer electrodesâremains at 2022 levels, there will be a shortage of approximately 20% compared to the global PEM demand by 2050. [25] Moreover, these platinum group metals (PGMs) are predominantly mined in specific countries, with South Africa alone accounting for about 70% of global platinum production and 80% of iridium production, highlighting their monopolistic position. [25] As hydrogen production via water electrolysis gains momentum, the increasing demand for PGMs and other critical materials could lead to unprecedented supply shortages. Many materials essential for electrolyzer production are also crucial for lithium-ion battery manufacturing, potentially creating competition between these two green technologies for limited critical materials. Additionally, the monopolistic production structure of these critical materials in certain countries could exacerbate global supply chain constraints. The United States anticipates that this critical material supply chain issue will pose significant challenges for future hydrogen production via water electrolysis. A recent Department of Energy report analyzing the supply chain for water electrolyzers identifies the overreliance on imported critical materials as one of the highest-risk supply chain challenges. [24] The report highlights several critical materials to illustrate the severity of this issue. Graphite and activated carbon, essential materials for various electrolyzers including PEM electrolyzers, were entirely dependent on imports for domestic use in the United States as of 2020. China, producing 62% of the world's graphite, holds a dominant market position. The situation is similar for platinum, with the United States relying on imports for about 79% of its domestic platinum consumption in 2020, particularly from South Africa. [24]

Thirdly, there is an issue with a shortage of solar and wind resources and their high cost. According to the International Energy Agency (IEA), hydrogen produced through water electrolysis utilizing electricity generated from current wind and solar power has the highest production cost when compared to hydrogen produced through other methods. [8] While the costs of wind and solar power generation are steadily decreasing due to technological advancements, they still remain relatively high compared to other hydrogen production methods once one considers the intermittency and non-dispatchability of the resources. According to BloombergNEF's analysis, to produce the hydrogen required to limit global temperature rise to 1.5°C, approximately 31,320 TWh of electricity would be needed, considering all of the hydrogen is produced by water electrolysis. This exceeds the *total global* electricity generation currently produced. [26] Therefore, to make water electrolysis using renewable electricity widely adoptable, wind and solar power generation facilities must be constructed to provide low-cost and sufficient renewable electricity. The situation concerning the grid power in the United States is similarly challenging. According to a recent report, to adequately support the increasing demand for electrolytic hydrogen production in the United States, an additional 1.8 TW of solar and wind power generation capacity will be required by 2050. For reference, the total installed generation capacity in the United States was 1.12 TW in 2020. [24]

Lastly, water electrolysis faces an issue related to significant water consumption. According to research, utilizing water electrolysis requires approximately 10-15 liters of deionized pure water to produce 1 kg of hydrogen. [27] This substantial water requirement has led to the design of most currently constructed water electrolysis facilities to ensure an adequate water supply. In regions adjacent to the sea, seawater desalination technology can be employed to obtain a sufficient amount of water from the ocean. However, in areas like deserts with abundant solar energy but scarce water resources, in areas like inland regions, or in areas not adjacent to the sea, finding a water source can be challenging. [28] Moreover, water scarcity is a critical issue that poses a threat to human survival, alongside climate change. The significant water consumption challenge associated with water electrolysis could serve as a major obstacle to the widespread adoption of hydrogen production through water electrolysis in the future.

2.5 Water electrolysis using nuclear energy (Pink hydrogen)

The hydrogen production method through water electrolysis, as discussed earlier, inherently comes with limitations due to its reliance on renewable energy sources such as solar and wind power. As an alternative to address these challenges, there is an ongoing discussion about utilizing the heat and energy generated from nuclear power plants to perform water electrolysis and produce hydrogen. This approach fundamentally follows the water electrolysis system depicted in Figure 4 but substitutes the supplied electrical energy with that generated by a nuclear power plant. When considering the nuclear power plant, this alternative method offers several advantages over utilizing renewable energy sources. Firstly, the cost of hydrogen production is estimated to be lower than when using electricity produced by onshore/offshore wind turbines or solar panels. According to the International Energy Agency (IEA) analysis, the unit cost of hydrogen production is less than half when using electricity produced by a nuclear power plant compared to electricity generated through typical renewable energy sources. [8] Additionally, when designing nuclear power plants and water electrolysis technology concurrently, some technical advantages can be considered. Nuclear power plants inevitably generate a significant amount of waste heat in addition to the electricity produced. In the water electrolysis system, this waste heat can be utilized to heat the electrolyzer stack or increase the temperature of the inlet gas stream, thereby improving the overall mechanical efficiency of the system. Particularly, if high-temperature water electrolysis systems like Solid Oxide Electrolysis (SOE) are considered and recycle the substantial waste heat generated by nuclear power plants, efficient and cost-effective hydrogen production becomes achievable. [29] Finally, a water electrolysis system utilizing nuclear power plants can serve as an alternative for countries where renewable energy sources are not abundant. According to BloombergNEF, many countries such as China, Korea, Japan, some countries in Europe, and Southeast Asia lack a sufficient amount of solar and wind energy to produce hydrogen through water electrolysis. In these nations, nuclear energy could be utilized as an alternative to renewable energy. [26]

However, hydrogen production using nuclear power plants comes with several significant limitations. Above all, it is not widely accepted as an innovative hydrogen production method due to the inherent risks and waste disposal issues associated with nuclear power plants. Despite being a carbon-free hydrogen production method, there are widespread concerns about the safety of nuclear power plants themselves and the fear that nuclear waste could further contaminate the environment. Even a country like Germany, which is known for opposing nuclear energy, does not mention hydrogen production using nuclear power plants in its recently announced 2030 National Hydrogen Strategy due to the risks of nuclear power plants. [30] Another drawback of hydrogen production using nuclear power plants is that the location of the hydrogen production facility highly depends on the location of the nuclear power plant. Many nuclear power plants operating worldwide are often situated far from urban centers due to the risks of accidents and waste disposal issues. If a hydrogen production facility using water electrolysis is constructed near a nuclear power plant, hydrogen production will also inevitably occur at a considerable distance from urban areas. In such cases, additional infrastructure for transporting, conveying, and storing hydrogen to the regions where it will be utilized for power generation or as an energy source for transportation would be required. To address these issues, there are numerous research and demonstration projects integrating Small Modular Reactor technology, creating small-scale nuclear power plants, with water electrolysis systems. [31]

2.6 Natural hydrogen (Gold/White hydrogen)

Recent interest in naturally producing hydrogen has been on the rise. Classified as ‘natural hydrogenâ or ‘geologic hydrogenâ, this new pathway is garnering increased attention from both academia and industry due to its vast potential. Commonly referred to as ‘gold hydrogenâ or ‘white hydrogenâ within the hydrogen color code [3, 32], natural hydrogen was first documented in academia in 1888, when Dmitri Mendeleev reported hydrogen emissions from a coal mine in Ukraine. [33] However, significant attention to the commercial potential of natural hydrogen began in 2012 following a project in Bourakebougou, a village in Mali, Africa. Aliou Diallo, a Malian businessman and former presidential candidate, became aware of a burning borehole in a small Malian village and invested in its exploration. Analysis revealed that the gas emitted from the borehole consisted of approximately 98% hydrogen, with a consistent output over time. [34] This discovery spurred numerous subsequent studies and motivated researchers worldwide to search for natural hydrogen-emitting sites. Natural hydrogen's primary advantage lies in its straightforward extraction from geological formations, making it a simpler and potentially more cost-effective method of obtaining hydrogen compared to various production pathways. Experts estimate that with adequate exploration and appropriate extraction techniques, hydrogen can be produced at a cost of approximately 50 to 70 cents per kilogram hydrogen, which is significantly cheaper than the production cost of gray hydrogen. [32] Furthermore, natural hydrogen does not generate carbon-intensive byproducts, positioning it as a potential clean fuel. Recent modeling by the U.S. Geological Survey (USGS) estimates that the global reserves of natural hydrogen could amount to approximately 5 trillion tons, sufficient to meet humanity's needs for over a millennium. [35] Additionally, the continuous generation of hydrogen through ongoing subterranean reactions suggests that it may be a renewable energy source with minimal depletion concerns.

Natural hydrogen, with its immense potential, has remained largely undiscovered by numerous oil and gas companies despite their extensive drilling activities for oil and gas. This is primarily because the search for hydrogen was not a priority in oil drilling, and the mechanisms through which natural hydrogen is generated and stored differ fundamentally from those of oil. [32] Research indicates that over 80% of natural hydrogen is produced through water-rock reactions, including serpentinization. Minerals such as olivine, which is rich in iron and abundant in the Earth's mantle, are considered critical for natural hydrogen production. [32, 36] The process involves the oxidation of the iron in olivine when it comes into contact with water, resulting in the release of oxygen from the water and the subsequent production of hydrogen under high-temperature and high-pressure conditions beneath the Earth's surface. [36, 37] The hydrogen thus generated is believed to accumulate beneath impermeable layers such as salt strata, forming hydrogen-rich layers. Additionally, a portion of natural hydrogen is produced through radiolysis, a reaction where radioactive materials decompose water molecules beneath the Earth's surface. [32, 36]

The environmental benefits, potential economic advantages, and the nearly limitless production possibilities of natural hydrogen have made it a focal point of significant interest across both academic and industrial sectors. This interest mirrors the historical oil exploration era, with governments and various companies around the world actively pursuing the exploration of natural hydrogen resources and securing drilling rights for these opportunities.

In the United States, the US Geological Survey (USGS) is leading efforts to investigate the distribution and extent of natural hydrogen deposits within the country. Recently, the Department of Energyâs Advanced Research Projects Agency-Energy (ARPA-E) program has announced funding of approximately $20 million to support teams developing technologies for the exploration and development of natural hydrogen. [32, 38] Similarly, the government of South Australia, after completing research indicating significant potential for natural hydrogen production in the region, has commenced substantial support for related projects and exploration initiatives. [39]

Additionally, recent reports have highlighted substantial natural hydrogen deposits in the abandoned mines of Lorraine in northeastern France [40], and Albania has also been noted for discovering the worldâs largest hydrogen reserves. [41] Furthermore, countries such as Canada, South Korea, and Spain are making diverse efforts to seize early opportunities in the global natural hydrogen market. [40]

Nevertheless, significant technical, scientific, and economic challenges remain, including the development of effective exploration technologies, the efficient drilling of discovered hydrogen, and the estimation of the quantities of economically viable hydrogen reserves. Despite these uncertainties, if effectively developed, natural hydrogen represents a resource with immense potential and could serve as a crucial element in the decarbonization of industry and the achievement of a net-zero society.

2.7 Comparison of production costs and emissions for each hydrogen production pathway

To conduct a more refined comparison of the various hydrogen production pathways examined in the preceding sub-sections, it is meaningful to analyze and compare the production costs and greenhouse gas emissions of each method. This focuses on evaluating the economic feasibility and environmental sustainability of conventional hydrogen production methods, excluding the relatively recent and emerging pathways of natural hydrogen production (gold/white hydrogen).

Figure 5 presents the production costs (left axis) and emission intensity (right axis) for each hydrogen production pathway, as reported by the IEA in its 2023 report. [8] While the IEA report categorizes hydrogen production technologies with precise terminology to avoid confusion, this paper adopts the hydrogen rainbow classification for ease of understanding. [3] As discussed in the previous section, hydrogen produced through natural gas steam reforming without CCUS is referred to as gray hydrogen, while production using the same method but with CCUS is labeled blue hydrogen. Hydrogen generated via electrolysis powered by wind (onshore and offshore) or solar panel is classified as green hydrogen, and hydrogen produced using nuclear energy is mapped as pink hydrogen.

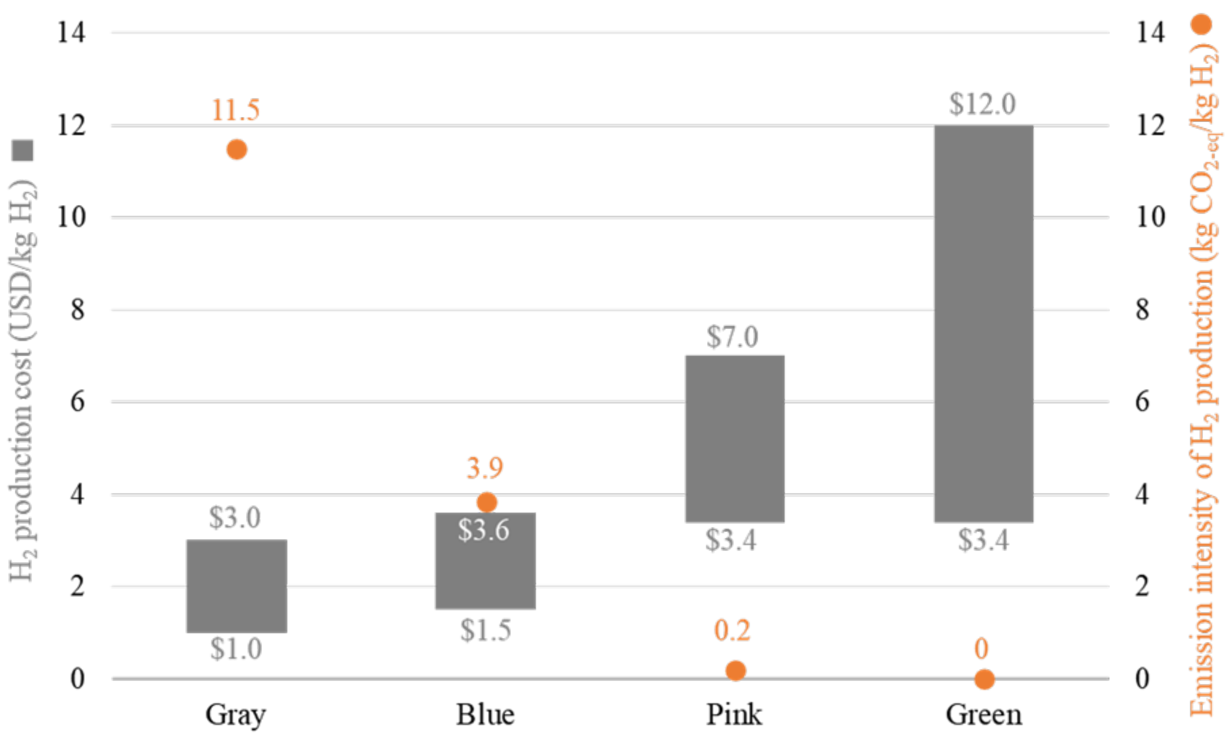


Figure 5: Production cost and emissions comparison of each hydrogen production pathways [8]

The IEA's analysis of the Levelized Cost of Hydrogen (LCOH) reflects the production cost per kilogram of hydrogen, encompassing both investment and operating costs across each technology. Rather than presenting LCOH as a single-point estimate, the IEA provides a range to account for variations in investment costs, energy source prices, and operational expenses, which may differ depending on the production location and timing. [8] The production costs of gray hydrogen and blue hydrogen shown in Figure 5 are based on 2021 data from the IEA report. This choice was made because natural gas prices surged abnormally in 2022 due to the Ukraine-Russia war, and the use of 2021 figures ensures a more accurate comparison with other production methods.

When comparing the minimum observed LCOH for each hydrogen production technology presented in Figure 5, gray hydrogen demonstrates the lowest production cost at approximately $\$1.0/kgH_2$, followed by blue hydrogen at around $\$1.5/kgH_2$, indicating relatively low production costs. These figures are substantially lower than the production cost of green hydrogen - minimum around $\$3.4/kgH_2$ - produced using renewable energy sources such as wind or solar power. According to the IEA report, the most cost-effective option for hydrogen production at present remains gray hydrogen through methane steam reforming. However, green hydrogen is projected to experience a significant reduction in LCOH over time. For example, the price of solar panel modules has already fallen by approximately 80% between 2010 and 2020, and while the pace of price reductions may moderate, further meaningful declines are anticipated. [42] Should technological advancements continue at the current pace, and with the deployment of more low-carbon power plants alongside falling electricity prices for electrolysis, optimistic projections suggest that hydrogen production costs could reach approximately $\$1/kgH_2$ by 2030 in regions with abundant solar resources, such as Australia, Chile, the Middle East, and the southwestern United States. [8, 43] Similarly, the production cost of hydrogen using wind power could decrease to about $\$2/kgH_2$ in areas with sufficient wind resources, such as the northeastern U.S. (offshore wind) and the Midwest (onshore wind). [8, 44] Notably, green hydrogen produced within the U.S. stands to benefit from various financial incentives under recent hydrogen production policies introduced by the Biden Administration. With these subsidies in place, the production cost of green hydrogen could approach levels comparable to those of gray hydrogen, which has traditionally been the dominant production method.

Blue hydrogen (natural gas steam reforming with CCUS) is expected to become the most cost-effective method for producing clean hydrogen over the coming decades in regions with abundant natural gas resources, such as the Middle East, North Africa, Russia, and the United States. While the technology is already attractive, with production costs in the mid-$1 range per kilogram of hydrogen, further advancements in CCUS technology and improvements along the learning curve for the installation and operation of CCUS facilities are expected to reduce CAPEX by an additional 20%. Some optimistic forecasts suggest that by 2050, production costs could approach \$1/kgH_2. [11]

In addition to production costs, a thorough understanding of the emission intensity associated with each hydrogen production technology is essential for accurately comparing their benefits. The IEA, in its 2023 report, [8] provides a comprehensive analysis of the emission intensity for various hydrogen production methods. This analysis takes into account not only the direct emissions generated during hydrogen production but also the emissions associated with the energy required for production and the extraction, processing, and supply of raw materials like methane. The emissions are evaluated across upstream and midstream processes, with the analysis benchmarked to 2021 data. For clarity, Figure 5 presents the median values from the IEA's analysis in a scatter plot format.

Gray hydrogen, which currently accounts for the majority of global hydrogen production, emits between 10 and 13 kgCO_2-eq per kg of hydrogen. This figure includes approximately 9 kgCO_2-eq/kgH_2 of direct emissions from the steam methane reforming process and 2.4 kgCO_2-eq/kgH_2 of indirect emissions from the extraction, processing, and delivery of methane. However, if the same production pathway incorporates CCUS technology with a capture rate of approximately 93%, the resulting blue hydrogen reduces total emissions to between 1.5 and 6.2 kgCO_2-eq per kg of hydrogen. Thus, even transitioning the existing global hydrogen production to blue hydrogen would yield significant decarbonization benefits.

The decarbonization potential would be even greater with a shift to pink or green hydrogen. According to the IEA, pink hydrogen - produced using nuclear energy - has an extremely low emission intensity of approximately 0.1 to 0.3 kgCO_2-eq per kg of hydrogen, even when accounting for indirect emissions from the nuclear fuel cycle, including uranium mining, conversion, enrichment, and fuel fabrication. As for green hydrogen, if emissions from the manufacturing of solar panels and wind turbines are excluded, the direct and indirect emissions are effectively zero. However, this outcome assumes the use of dedicated renewable electricity for electrolysis. If electricity from the current grid system is instead used for electrolysis, the emission intensity could reach as high as 24 kgCO_2-eq per kg of hydrogen. This underscores that achieving decarbonization through green hydrogen requires the decarbonization of local electricity grid systems as a prerequisite. [8]

The Energy Futures Initiative Foundation (EFIF), a leading U.S. energy research institution, published a report in February 2023 that provides a comparative apple-to-apple analysis of hydrogen production costs and emission levels across various hydrogen production pathways in the U.S. [45] Figure 6 presents selected data from the report. The EFIF report evaluates different hydrogen production methods that are currently under research or in commercial production within the U.S., comparing both the production costs and life cycle emissions of each pathway. In particular, the report offers examples of various blue and green hydrogen production methods, providing detailed analyses of their performance. The values presented in Figure 6 are derived from a subset of data processed from the EFIF report. The blue hydrogen in Figure 6 represents a production facility with a 96.2% CO_2 capture rate and advanced upstream control technologies, illustrating an optimized case for blue hydrogen production. For green hydrogen, the values shown in Figure 6 are based on the average of two scenarios defined in the report: the optimistic scenario assumes a production facility in Texas with electricity priced at \$26/MWh and a 40% capacity factor, while the pessimistic scenario assumes a facility in Washington state with electricity priced at \$67/MWh and a 19% capacity factor. [45]

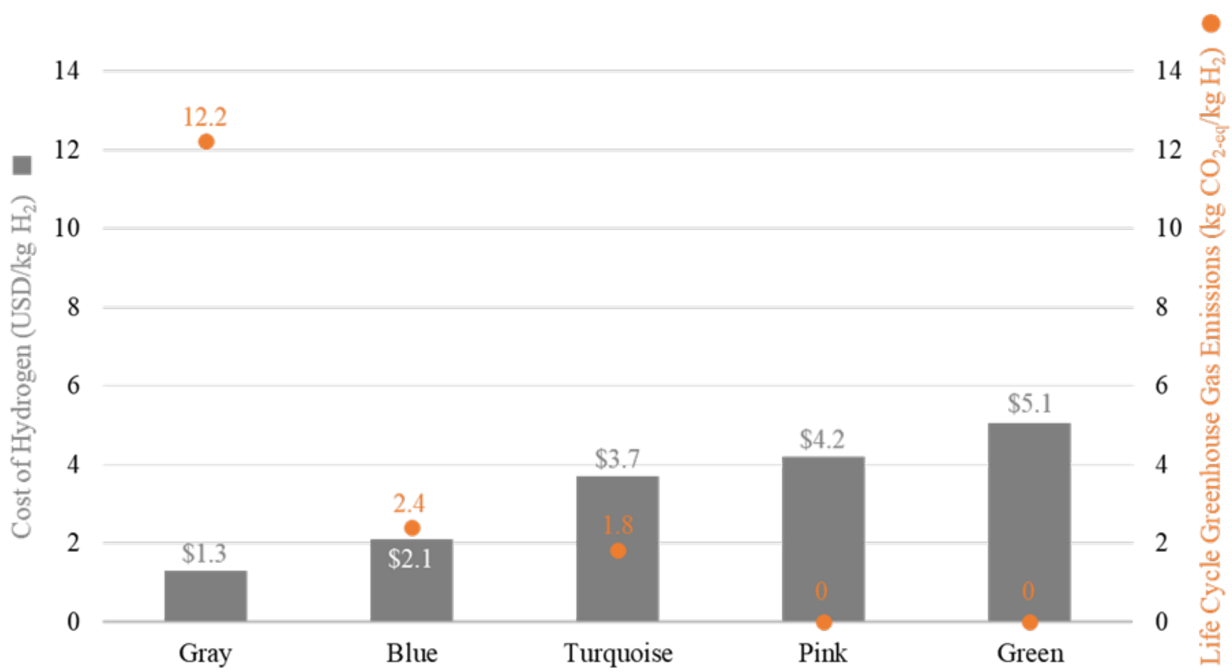


Figure 6: Production cost and life cycle greenhouse gas emissions of each hydrogen production pathways in the U.S. [45]

While Figure 5 presents the production costs of various hydrogen production pathways as ranges between minimum and maximum values, Figure 6 displays the average production costs based on actual hydrogen production facilities in the U.S. or corresponding data points. Similar to the global data shown in Figure 5, the trend indicates that production costs increase for green hydrogen, while life cycle greenhouse gas emissions decrease. Although environmentally friendly hydrogen production methods may currently be less economically viable compared to gray hydrogen, significant efforts are underway at both the government and private-sector levels in the U.S. to enhance the economic feasibility of blue, pink, and green hydrogen. Academic institutions are actively researching the technologies required for blue and green hydrogen production, while private companies are installing test beds to demonstrate these technologies and building large-scale blue and green hydrogen production facilities for commercial scaling. Most notably, the U.S. government has pledged overwhelming support for environmentally friendly hydrogen production technologies, exemplified by the Biden administration's Inflation Reduction Act (IRA). The extent to which the IRA influences the economic viability of environmentally friendly hydrogen productions will be discussed in detail in the following section.

3 US Hydrogen Policies

As discussed above, while various hydrogen production technologies exist, none are yet fully mature in terms of technological readiness, cost competitiveness, and emission levels. For hydrogen to play a pivotal role in decarbonizing hard-to-abate sectors and achieving an ultimate net-zero society, proactive policy support to make technological innovation and to foster market adoption of new technologies is essential. The U.S. government has recognized the potential of hydrogen energy and related technologies since the 1990s and 2000s, providing comprehensive federal support through legislation such as the Hydrogen Future Act of 1996 and the Energy Policy Act of 2005. Over successive administrations, various hydrogen-related policies have been introduced and implemented, solidifying hydrogen energy as a key component of the U.S. energy strategy, including under the Trump Administration. In particular, the Department of Energy (DOE), the lead agency for hydrogen initiatives, launched the 'H2@Scale' initiative in 2017. This initiative aimed not only to support hydrogen research and development but also to promote public-private partnerships, leading to the execution of over 30 collaborative projects through the 'H2@Scale CRADA' (Cooperative Research and Development Agreement) by the end of 2020. [46] In November 2020, during the final year of the Trump Administration, the government unveiled the Hydrogen Program Plan, outlining a long-term framework for hydrogen technology development. This plan delineates the hydrogen value chain into distinct segmentsâproduction, transportation, storage, conversion, and utilization - while specifying key technological areas and R&D support strategies for each segment. [47]

Since recognizing hydrogen energy as a core element of its national energy strategy, the U.S. government has provided bipartisan support for the development of hydrogen energy and related technologies. Under the Biden Administration, this support has significantly expanded in both scale and specificity. The Biden Administration's hydrogen policies differ from those of previous administrations in three key ways. First, the scale of support has increased substantially. Although the previous administrations also prioritized hydrogen technology, the Biden Administration's Infrastructure Investment and Jobs Act (IIJA) allocated nearly $10 billion to hydrogen programs alone, reflecting a dramatic shift in scale. Second, the Biden Administration has established clear long-term goals and roadmaps. Previous administrations often implemented hydrogen strategies as ad hoc initiatives without systematic design under a comprehensive long-term framework. In contrast, the Department of Energy (DOE) introduced the U.S. National Clean Hydrogen Strategy and Roadmap in June 2023, providing a well-defined strategic direction and roadmap for U.S. hydrogen policy over the coming decades. This roadmap builds upon the Hydrogen Program Plan (2020) introduced under the Trump Administration, offering a more comprehensive and long-term framework. While maintaining critical policy continuity in energy support strategies, it incorporates broader and more expansive concepts. The third key difference lies in the focus of government support. Rather than concentrating solely on hydrogen R&D, the Biden Administration emphasizes community engagement and policies aimed at commercializing hydrogen technologies. A notable example is the tax credit incentives for hydrogen production included in the Inflation Reduction Act (IRA) of 2022. Under the IRA, tax benefits are not granted indiscriminately to hydrogen production facilities but are instead tied to criteria such as community involvement and job creation. Furthermore, the policy includes mechanisms to rigorously evaluate commercial projects to ensure that tax credits are effectively allocated. These initiatives are designed to ensure that hydrogen does not remain merely a future technology with potential but instead plays a critical role in industrial decarbonization within the U.S. and becomes a key component of the nation's energy mix. Even with a potential change in administration in 2025, bipartisan efforts to support hydrogen energy across successive U.S. governments suggest that interest in hydrogen will not wane. The long-term roadmaps and support policies established under the Trump and Biden Administrations will likely foster further growth of the U.S. hydrogen industry.

In this section, the paper will explore two key pillars of the Biden Administration's hydrogen policy: the hydrogen-related provisions under the IIJA (2021) and the IRA (2022). Understanding these policies will offer valuable insights into the U.S. governmentâs strategic direction for hydrogen and serve as an important milestone for stakeholders seeking to enter the hydrogen industry.

3.1 Regional Clean Hydrogen Hubs

In November 2021, the Biden Administration signed the Infrastructure Investment and Jobs Act (IIJA), also known as the Bipartisan Infrastructure Law (BIL). This legislation aims to rebuild America's roads, bridges, and railways, expand access to clean drinking water, ensure high-speed internet for all Americans, address the climate crisis, and promote environmental justice for underserved communities. [48]

Specifically related to hydrogen support, the IIJA allocates approximately $75 billion under the Clean Energy and Power section. This includes $8 billion for the 'Regional Clean Hydrogen Hubs' initiative, $1 billion for the 'Clean Hydrogen Electrolysis Program,' and $500 million for the 'Clean Hydrogen Manufacturing Recycling Research, Development, and Demonstration Program'. [48] Among those hydrogen programs, the 'Regional Clean Hydrogen Hubs' initiative is particularly noteworthy, receiving the largest budget allocation among new projects under the Clean Energy and Power section of the IIJA. As part of this, on October 13, 2023, DOE, through the Office of Clean Energy Demonstrations (OCED), selected seven regional clean hydrogen hubs, allocating $7 billion to the total budget of the 'Regional Clean Hydrogen Hubs' initiative. The OCED was established to manage and oversee clean energy projects derived from the IIJA and the Inflation Reduction Act (IRA), with a combined budget of approximately $25 billion for clean energy initiatives, including the regional hydrogen hub projects. [49] The details of the seven selected regional clean hydrogen hubs are provided in the Table 2. [50]

OCED aims to produce over 3 million tons of clean hydrogen annually through the

Table 2: Details of selected regional clean hydrogen hubs

Project Name	States	Federal cost share ($M)	Feedstocks (H2 Color)	End uses
Appalachian Hydrogen Hub	West Virginia, Ohio, and Pennsylvania	925	Natural Gas (Blue)	Hydrogen fueling station, pipelines
California Hydrogen Hub	California	1,200	Renewables (Green) and Biomass (Blue)	Decarbonizing public transportation, heavy duty trucking, and port operations
Gulf Coast Hydrogen Hub	Texas	1,200	Renewables (Green) and Natural gas (Blue)	Fuel cell electric trucks, industrial processes, ammonia, refineries and petrochemicals, and marine fuel (e-Methanol)
Heartland Hydrogen Hub	Minnesota, North Dakota, and South Dakota	925	Renewables (Green) and Nuclear (Pink)	Agriculture (Fertilizer production), ammonia, and power generation
Mid-Atlantic Hydrogen Hub	Pennsylvania, Delaware, and New Jersey	750	Renewables (Green) and Nuclear (Pink)	Heavy transportation (e.g., trucks, buses, refuse trucks, street sweepers), manufacturing and industrial process improvements, and combined heat and power
Midwest Hydrogen Hub	Illinois, Indiana, and Michigan	1,000	Renewables (Green), Nuclear (Pink), and Natural gas (Blue)	Steel and glass production, power generation, refining, heavy-duty transportation, and sustainable aviation fuel
Pacific Northwest Hydrogen Hub	Washington, Oregon, and Montana	1,000	Renewables (Green)	Heavy duty transportation, agriculture (fertilizer production), industry (generators, peak power, data centers, refineries), and seaports (drayage, cargo handling)

hydrogen hub projects, representing nearly 30 percent of the U.S. National Clean Hydrogen Strategy and Roadmap's goal of producing 10 million metric tons of clean hydrogen per year by 2030. [51] Additionally, the project seeks to supply clean hydrogen to sectors that are traditionally difficult to decarbonize and where hydrogen can replace carbon, including fuel cell vehicles, maritime and heavy-duty transportation, residential and commercial heating, and electric power generation, including energy storage and backup power. The projected total carbon dioxide emission reduction from these seven hydrogen hubs is approximately 25 million metric tons of carbon dioxide emissions annually from end users, roughly equivalent to the combined annual emissions of 5.5 million gasoline-powered cars. One of the reasons the hydrogen hub concept is well-regarded is its efficiency in establishing the necessary connecting infrastructure—such as pipelines, hydrogen stations, and hydrogen storageâby producing and using hydrogen in adjacent areas. The seven selected clean hydrogen hub consortia will negotiate and coordinate with the DOE regarding the specifics of their projects before commencing their proposed initiatives.

The DOE has allocated the remaining funds from the $8 billion budget set by the Bipartisan Infrastructure Law, aside from the $7 billion designated for the seven hydrogen hubs, to the 'Clean Hydrogen Hubs Demand-side Support' project. [52] The White House and DOE emphasize the importance of policy-driven demand-side support as a critical condition for the success of the clean hydrogen hub projects. [53]

The Biden Administration has made it clear that for the clean hydrogen hub projects to succeed, both 'supply-push' and 'demand-pull' policies must be implemented in tandem. There are concerns that many hydrogen projects are experiencing delays due to inadequate financing from the private sector, driven by worries over perverse economic incentives and potential hydrogen market failures. [54] In markets based on innovative technologies, the private sector alone finds it challenging to undertake investments in large-scale infrastructure or secure debt financing without appropriate policy intervention due to the risks associated with market uncertainties. Furthermore, there is hesitation in entering long-term sales contracts for potential hydrogen off-takers because of the current uncertainty in future demand and the anticipated sharp decline in supply prices driven by innovative technology development, which could disadvantage early market entrants. [53]

To address uncertainties and issues on the demand side and to further invigorate the clean hydrogen market, the federal government has decided to allocate $1 billion for demand-side support. In January, the DOE commissioned a consortium to analyze demand-side issues and formulate related policies. This consortium is led by the Energy Futures Initiative Foundation (EFI) and includes commodity market information experts S&P Global, financial exchange operator Intercontinental Exchange (ICE), law firm Dentons, specializing in energy regulatory issues, and the MIT Energy Initiative. [55, 56]

This project, named the Hydrogen Demand Initiative (H2DI), is tasked with analyzing the issues on the hydrogen demand side and designing foundational policies to ensure the success of clean hydrogen hub projects. Moving forward, this consortium will leverage their expertise to closely collaborate with the DOE and the seven preliminary hydrogen hubs to establish the initial market structure for clean hydrogen. They will design the necessary demand-side support, federal government support, and regulations, and develop mechanisms for various types of purchase contracts to stimulate the early hydrogen market. Additionally, to accommodate the anticipated growth of the hydrogen market, they will establish appropriate trading systems and floors and amend related laws and regulations.

The government expects visible results from the consortium within this year. These demand-side policies and studies are anticipated to stimulate the early hydrogen market, create jobs, and significantly contribute to the overall decarbonization of the United States, particularly in hard-to-decarbonize sectors such as industrial, long-haul transportation, chemical, and manufacturing. [55]

3.2 Clean Hydrogen Production Tax Credit

On August 16, 2022, the Biden Administration enacted the Inflation Reduction Act (IRA). This legislation addresses a wide range of issues, including the expansion of health insurance subsidies, prescription drug reform, and corporate tax modifications. Notably, it allocates substantial funding for energy security and climate change mitigation, providing Investment Tax Credits (ITC) and Production Tax Credits (PTC) to support related projects. [57]

The IRA specifies various policy supports to promote the development of clean hydrogen and fuel cell technologies, as well as to stimulate related industries and markets. These policies include the expansion of existing federal tax credits, the introduction of new federal tax credits, and direct investment support measures.

According to the DOE, the IRA encompasses nine programs that financially support hydrogen-related projects, either directly or indirectly. These programs include the Advanced Energy Project Credit (section 48C), Alternative Fuel Refueling Property Credit (section 30C), Carbon Capture and Sequestration Tax Credit (section 45Q), Clean Hydrogen Production Tax Credit (section 45V), Clean Vehicle Credit (section 30D), Elective Payment for Energy Property, Energy Credit (section 48), Energy Storage Credit (section 48), and Qualified Commercial Clean Vehicles Credit (section 45W). [58]

The hydrogen-related tax credit programs include provisions such as a tax credit of up to 30% of the installation costs for setting up and operating clean fuel refueling facilities, including hydrogen, in specific areas (Section 30C). Additionally, for the purchase of hydrogen electric vehicles for commercial use, tax credits are provided up to $7,500 for class 1-3 vehicles (under 14,000 lb) and up to $40,000 for class 4 and above vehicles (over 14,000 lb) (Section 45W). [58]

Among these, the Clean Hydrogen Production Tax Credit (section 45V) program has particularly drawn the attention of stakeholders in the hydrogen industry. This program, which is the most substantial in terms of budget and potential impact among hydrogen-related programs within the IRA, creates a new 10-year incentive for clean hydrogen production with a tax credit of up to $3.00 per kilogram. It specifies that hydrogen production facilities that commence construction by 2033 are eligible for the tax credit.

The DOE has defined the criteria for qualified clean hydrogen to be eligible for the IRA's 45V production tax credit. According to the Clean Hydrogen Production Standard (CHPS) Guidance, the tax credit applies only to processes and production facilities that emit no more than 4 kilograms of CO_2 per kilogram of hydrogen produced (4kg CO_2eq/kgH_2). [59]

However, when section 45V of the IRA was initially announced, there was concern among media and research institutions about the ambiguous definition of clean hydrogen. This ambiguity raised fears that the primary goal of decarbonization might be compromised, potentially allowing carbon-intensive industries and related facilities to benefit more significantly from the tax credits. [60, 61]

To address these concerns and to establish more precise tax credit guidelines, on December 22, 2023, the U.S. Department of the Treasury and the Internal Revenue Service

(IRS) issued detailed guidance for the clean hydrogen production credit under the IRA (Notice of Public Rulemaking; NPRM). The key aspects of the IRS's detailed guidance include finalizing the amount of the clean hydrogen production tax credit based on carbon emissions levels, introducing the GREET-45VH2 simulation model for analyzing and determining carbon emissions, and implementing the Energy Attribute Certificate (EAC) to assess clean hydrogen eligibility. [62] The specifics of the guidance are as follows: firstly, the IRS has set out the criteria for tax benefits based on the amount of carbon dioxide emitted during hydrogen production, as shown in the Table 3. [63]

Table 3: Tiered Clean Hydrogen Production Tax Credit

Lifecycle GHG emissions rate (kgs of CO_2e per kg of clean H_2)	Applicable percentage	Credit amount / if PWA* met (per kg of clean H_2 produced)
< 0.45	100%	\$0.60 / \$3.00
0.45 to < 1.5	33.4%	\$0.20 / \$1.00
1.5 to < 2.5	25%	\$0.15 / \$0.75
2.5 to ≤ 4	20%	\$0.12 / \$0.60

* PWA (Prevailing Wage and Apprenticeship requirements) [64]

The tiered credit rates, as outlined above, vary according to the lifecycle greenhouse gas (GHG) emissions level of hydrogen production. The IRS has adopted the definition of lifecycle GHG emissions from 'Clean Air Act section 211(o)(1)(H)'. According to this definition, lifecycle greenhouse gas emissions refer to the aggregate quantity of greenhouse gas emissions, including direct and significant indirect emissions, as determined by the Administrator, related to the full fuel lifecycle, encompassing all stages of fuel and feedstock production and distribution. Based on this definition, the IRA 45V only includes emissions up to the point of production ("well to gate") and specifies the GREET-45VH2 model developed by Argonne National Lab as the standard simulation model for measuring these emissions. [63]

Furthermore, when producing hydrogen via electrolysis using electricity, a facility must meet the IRS's Energy Attribute Certificates (EAC) criteria to be recognized as a clean hydrogen production facility. The EAC criteria consist of several main requirements: the electricity must be time-matched to the period during which the electrolyzer is operating, initially on an annual basis and later transitioning to an hourly basis by 2028 as tracking systems improve; the electricity must be deliverable to the electrolyzer by being located in the same grid region as described in the NPRM and GREET documentation, based on the DOE's 2023 National Transmission Needs Study; and the electricity must be incremental to existing generation, sourced from new clean power plants built within three years before the hydrogen production. [63]

Without these EAC criteria, the production of hydrogen could inadvertently increase grid electricity emissions or result in hydrogen produced from unknown electricity sources receiving the clean hydrogen production tax credit, thereby deviating from its original purpose. To prevent this, the EAC standards are established based on these three pillars.

It is therefore meaningful to examine the extent of tax credit benefits each hydrogen production pathway can receive when applying the tiered credit rates specified by the IRA, based on its life cycle greenhouse gas emissions rate outlined in Table 3. Figure 7 provides an intuitive illustration of how the production costs of various hydrogen production pathways in the U.S., as analyzed in Figure 6, could decrease with the application of tax credits under the IRA. The data presented in Figure 7 is sourced from the analysis conducted by EFIF. [45]

Examining Figure 7, it becomes evident that the production cost of gray hydrogen, which does not qualify for tax credits under the IRA, remains unchanged at $1.3/kgH_2$. The primary purpose of the IRAtax credits for environmentally friendly hydrogen production methods (blue, turquoise, pink, and green hydrogen) is to enhance their economic viability to levels comparable to that of gray hydrogen. Thus, the key focus is on determining how much the production costs of these clean hydrogen methods will be reduced relative to gray hydrogen through the IRA's support.

For blue hydrogen, considering its life cycle greenhouse gas emissions, it qualifies for a tax benefit of up to $0.75/kgH_2$. With this benefit, the production cost is reduced to $1.3/kgH_2$, bringing it on par with the production cost of gray hydrogen. This is a primary reason why many blue hydrogen projects are actively seeking to qualify for IRA tax credits. If these benefits are granted, blue hydrogen could quickly replace gray hydrogen, leveraging the proximity and similarity of infrastructure between the two production methods.

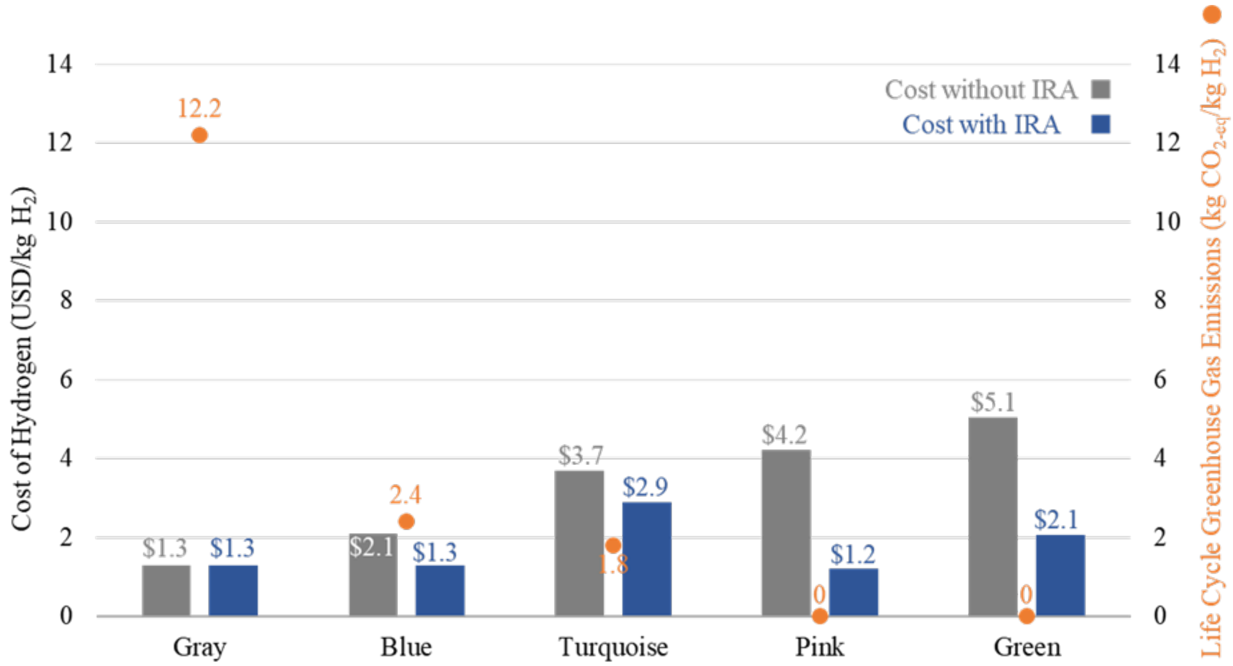


Figure 7: Cost and emissions comparison of each hydrogen production pathways in the U.S. after applying IRA tax credit [45]

Pink hydrogen has the potential to receive the maximum tax credit of $3/kgH$_2$. If this benefit is realized, pink hydrogen could achieve a production cost as low as $1.2/kgH$_2$ - below the cost of gray hydrogen. While social concerns and other issues related to nuclear energy must be addressed, pink hydrogen offers an environmentally friendly and the most cost-effective hydrogen production option. Recognizing this potential, the U.S. government is actively working to incorporate pink hydrogen-related facilities and regions into the hydrogen hub program.

For green hydrogen, which relies on solar and wind energy, achieving the full IRA tax credit would lower the production cost to approximately $2.1/kgH$_2$. Although this remains higher than the cost of other hydrogen production methods, it represents a sufficiently competitive price given current technological advancements. If green hydrogen production costs reach around $2/kgH$_2$, many regions and private companies are expected to increase their investment in green hydrogen projects. Since green hydrogen offers environmental benefits that gray, blue, and pink hydrogen lack, demand for hydrogen produced from solar and wind energy is likely to emerge, even with a slight green premium. The U.S. government is providing substantial funding to support the development of solar- and wind-based hydrogen production through various hydrogen technology development programs and the hydrogen hub initiative. Alongside the tax support provided by the IRA, further reductions in the cost of solar panels, wind turbines, and related technologies are expected to drive down green hydrogen production costs. In the near future, these developments could enable green hydrogen to achieve production costs comparable to those of gray hydrogen.

4 Other Countries' Hydrogen Policies

The United States has recently provided significant policy support for hydrogen under the Biden Administration. However, countries around the world have been interested in hydrogen and have implemented various policy supports, established relevant laws, and continued cooperation at the national level. This study aims to examine the current policies of major countries regarding the hydrogen value chain.

4.1 European Union

The European Union (EU) has long recognized hydrogen as a key component for achieving carbon reduction and a net-zero society. In 2020, the EU launched the "Hydrogen Strategy for a Climate-Neutral Europe" initiating comprehensive policy support and legislative measures to foster the hydrogen industry across the continent. As part of this strategy, the EU officially established the European Clean Hydrogen Alliance to centralize hydrogen-related policy efforts within the EU. This alliance provides an overarching strategic roadmap for the hydrogen sector, manages policy support programs, assembles and administers investment funds, and fosters cooperation among public, industrial, and civil society sectors. [65]

Additionally, the EU introduced "A Roadmap to 2050" to establish a hydrogen ecosystem within Europe. This roadmap outlines a three-phase approach to invigorate the hydrogen industry and secure global leadership in hydrogen by 2050. The first phase, from 2020 to 2024, aims to install at least 6 GW of renewable hydrogen electrolyzers and produce 1 million tonnes of renewable hydrogen. This phase focuses on decarbonizing existing hydrogen value chains and introducing hydrogen to hard-to-decarbonize industries such as industrial plants and heavy-duty transport. The second phase, from 2025 to 2030, targets the installation of at least 40 GW of renewable hydrogen electrolyzers and the production of 10 million tonnes of renewable hydrogen. During this phase, hydrogen will play a crucial role in the integrated energy system and be applied to sectors such as steelmaking. This phase also involves the creation of "Hydrogen Valleys" in select regions to support the establishment of localized hydrogen ecosystems. The third phase, from 2030 to 2050, focuses on the maturation of renewable hydrogen technologies and their application across all hard-to-decarbonize sectors.

To execute phase 2 by 2030, the EU plans to invest up to 42 billion euros (approximately USD 47 billion) in supporting the installation of electrolyzer systems and up to 340 billion euros (approximately USD 380 billion) to establish up to 120 GW of solar and wind energy production facilities for renewable hydrogen production. [65]

Based on this foundational strategy, the EU is steadily designing and implementing hydrogen policies. As of the first quarter of 2022, the EU has added various policy initiatives, including over 750 hydrogen projects and the "Recovery and Resilience Plan," which supports clean hydrogen with a budget of 9.3 billion euros (approximately USD 10.4 billion) involving over 15 countries. [66]

Recently, the European Commission introduced the "RePowerEU Plan" to reduce dependence on gas imports from Russia and enhance Europe's energy independence, with hydrogen being a significant component. Through the "Hydrogen Accelerator" program, the EU aims to install 17.5 GW of electrolyzer systems and produce 10 million tonnes of renewable hydrogen by 2025, with an additional 10 million tonnes of renewable hydrogen to be imported by 2030. This plan involves appropriate policy support and infrastructure investment, including the introduction of carbon contracts for difference to make green hydrogen more affordable for the industry. [67, 68]

4.2 China

China, the world's largest producer of hydrogen (producing approximately 35 million tonnes in 2021) and the leading manufacturer of electrolyzers, has only recently developed a comprehensive policy roadmap for its national hydrogen industry and the entire hydrogen value chain at the central government level. In March 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) unveiled the country's first long-term comprehensive plan for the hydrogen energy sector, the "Hydrogen Industry Development Plan (2021-2035)." [69, 70] This plan classifies hydrogen energy as a major energy source in China's future national energy system and as a key means to achieve the country's carbon neutrality goal by 2060. The plan sets phased objectives in five-year increments through 2035.

In the first phase, by 2025, the government aims to produce 100,000 to 200,000 tonnes of green hydrogen annually, have 50,000 hydrogen fuel cell vehicles on the road, and achieve an annual reduction in CO_2 emissions of 1 to 2 million tonnes. The second phase, up to 2030, focuses on building the hydrogen energy industry value chain and ecosystem. The third phase, extending to 2035, aims to actively utilize hydrogen energy in various fields such as transportation, energy storage, and industry, significantly increasing the share of green hydrogen in final energy consumption. The plan also includes detailed policies on hydrogen transportation and utilization, international cooperation to establish global leadership in the hydrogen industry, and other specific policy measures. [70, 71]

Furthermore, the China Hydrogen Alliance, established under the leadership of NDRC and CHN Energy and currently involving around 100 related Chinese companies and institutions, released a report in 2022 titled "China's Green Hydrogen New Era: A 2030 Renewable Hydrogen 100 GW Roadmap," which further extends the government's hydrogen policy goals. This report projects that the installation of 100 GW of electrolyzers by 2030 will lead to a dramatic reduction in the cost of green hydrogen production. [72] Currently, the cost of green hydrogen production in China is 20-25 RMB per kg (approximately 2.8-3.5 USD per kg). The report anticipates that through aggressive electrolyzer installation and industry expansion, this cost could be reduced to the current cost of hydrogen production from coal and industrial byproducts, which is 10-13 RMB per kg (approximately 1.4-1.8 USD per kg). [72]

Despite the relatively late development of a national hydrogen strategy compared to other countries, China has numerous resources at its disposal. These include abundant and diverse underground critical materials, technological capabilities of Chinese companies distributed across the entire hydrogen industry value chain, and the active participation of state-owned enterprises such as Sinopec and SPIC. With the government's declared focus on fostering the hydrogen energy industry, it is expected that relevant legal frameworks will be rapidly established and specific support policies for the hydrogen industry will be actively implemented.

4.3 Australia

Australia recognized the potential of hydrogen earlier than many other countries and began formulating national support and strategies. In 2018, it established the "National Hydrogen Roadmap," which outlined the development of technology across the entire hydrogen industry value chain, market status and projections, and future investment strategies. [73] In 2019, Australia developed the "Australia's National Hydrogen Strategy," providing more specific support measures for the development of the hydrogen industry. This strategy offered tailored plans and support policies for expanding the hydrogen industry across different states, taking into account their unique circumstances. These policies cover all regions within Australia and the entire hydrogen industry value chain, accompanied by detailed implementation plans. A noteworthy aspect of this strategy is the concept of "Hydrogen Hubs," designed to facilitate the production, transportation, and utilization of hydrogen within neighboring areas. This policy has inspired similar strategies in countries such as the United States, Japan, and Germany. [74] The strategy undergoes biennial reviews, with the latest 2023 review reporting approximately $300 billion in hydrogen investments and successful export collaborations with various countries, indicating successful strategy execution. [75]

The core of Australia's national hydrogen strategy is to leverage its abundant underground resources and renewable energy sources, such as solar power, to produce hydrogen inexpensively and establish itself as a leading global producer and exporter of hydrogen. The 2019 strategy includes various policy support measures to lower the cost of green hydrogen production and support for blue hydrogen production through technologies such as CCUS. [74] Additionally, Australia actively pursues international cooperation with major hydrogen-consuming countries to export the produced hydrogen. It maintains economic cooperation in hydrogen transport and export with key potential hydrogen consumers such as South Korea, Japan, Singapore, and Germany. In 2022, Australia completed a demonstration voyage transporting liquefied hydrogen produced in Australia to Japan using the world's first liquefied hydrogen carrier. [76] Australia and South Korea continue to strengthen economic cooperation in the hydrogen sector. Recently, KEPCO, a South Korean state-owned utility company, and the Western Green Energy Hub, one of Australia's green hydrogen hubs, agreed to enhance cooperation on hydrogen export and large-scale infrastructure project development. [77] Thus, Australia is striving to establish itself as a global leader in the hydrogen production market, leveraging its rich natural resources and expanding its influence in the global market through various international collaborations.

5 Current Policy Issues

As previously discussed, the hydrogen industry in the United States, especially the low-carbon industry, is in its nascent stages, and various policy supports are being designed to foster this innovation-driven sector. Notably, recent federal government proposals for both supply-side and demand-side policies aim to facilitate the growth of the hydrogen industry within the U.S. and lay the groundwork for hydrogen to be actively utilized in decarbonizing hard-to-abate industries. However, there is still a need for technological innovation, and more refined policy support is required to incentivize these advancements to develop.

To gain insights into future hydrogen policy design, we conducted interviews with four experts both at MIT and outside of MIT who have been involved in hydrogen policy formulation, academic research, and direct participation in the hydrogen industry. The aim was to gather current policy issues for U.S. hydrogen policy designers and legislators to consider in their future policy development. The following are the policy issues that the experts identified as being important topics for further discussion and academic research.

1. Amending Hydrogen Policies that Ensuring Realism while Including Comprehensive Support

As discussed in the previous section, the hydrogen-related policies of the Biden Administration are unprecedented in their scale and scope. Many of the experts we talked to agree that the federal government's high level of interest and strong commitment to supporting the hydrogen industry has resulted in well-crafted policies that integrate diverse perspectives. Notably, the federal decision to allocate substantial budgetary support to initiate the development of the nascent U.S. clean hydrogen industry is considered a significant first step. One expert remarked in an interview, "I think there are a lot of good things to be said for the policies. The federal government did a very good job for the United States to make green and blue hydrogen competitive with gray hydrogen." However, there are still opinions that current policies are incomplete and require modifications to be more comprehensive and practical. In particular, criticisms have been raised regarding the recent Notice of Public Rule Making (NPRM) for the 45V tax credit issued by the IRS, arguing that it lacks practicality or is excessively stringent relative to the goal of advancing the clean hydrogen industry.

One of the issues under discussion is the transition of the 'Time-matched' criterion to an 'Hourly-matching' standard for Energy Attribute Certificates (EAC) starting in 2028. As previously noted, the detailed regulations for the 45V tax credit stipulate that hydrogen production facilities must meet EAC standards to be recognized for clean hydrogen production, which involves evaluating the cleanliness of the energy used in electrolysis. Initially, the 'Time-matched' standard measures the matching degree on an annual basis, but from 2028 onward, it will be assessed on an hourly basis.

Experts argue that the hourly matching standard is excessively stringent and should be relaxed to better support the nascent clean hydrogen production industry. One expert stated in an interview, "The question is whether we will require 'annual matching' of green electricity production and high electrolysis, or require much more draconian 'hourly matching.' If it's 'hourly matching,' then we won't get a lot of electrolyzers built." They argue that the hourly matching standard is too demanding given that the U.S. does not yet have sufficient green hydrogen production capacity or a fully decarbonized grid, which could slow the growth of green hydrogen production. The amount of renewable energy needed for green hydrogen production is currently significantly less than what the U.S. grid can supply. Pushing for hourly matching prematurely may force producers to source renewable energy at high costs, reducing the market competitiveness of clean hydrogen against gray hydrogen, even with the 45V tax credit.

Recent research suggests that using hourly matching could hinder near-term clean hydrogen production compared to annual matching. [78] They suggested that a system where clean hydrogen producers are required to buy renewable electricity collectively could eliminate the need for stringent matching requirements. One expert advocating for annual matching in the initial stages of the clean hydrogen market compared it to a buffet where "it's like going to a buffet and bringing your 'own' fork and spoon, rather than expecting the buffet to provide 'its' fork and spoon along with the food."

Conversely, proponents of implementing the hourly matching mechanism from the outset argue that stricter controls are necessary to prevent the misuse of clean hydrogen tax credits by less clean fuels like methane. They claim that tools enabling hourly matching have already proven effective in established markets like the renewable energy credit (REC) market. [79]

The IRS's recent regulations indicate that the hourly matching standard will take effect in 2028. However, given the range of opinions on this matter, it is crucial to design policies that consider diverse perspectives and align with the original goal of supporting the clean hydrogen industry through federal funding.

The Treasury's temporal matching choice reflects a trade-off similar to the way policy measures emissions from electric vehicles (EVs). For both low-carbon hydrogen and EVs, the objective may be to address two distinct market failures. First, without a carbon price, the relative prices of zero- or low-carbon hydrogen and vehicles are incorrect, making high-carbon alternatives too cheap. Subsidies and policies like fuel economy standards aim to correct these relative prices. Second, these policies may seek to address network externalities between hydrogen and hydrogen infrastructure, and EVs and EV charging infrastructure. And, relatedly, they may stimulate demand from industries such as steel manufacturing or from consumers, such as drivers.

However, tension likely exists between these two goals when assigning the temporal matching to green hydrogen and, similarly, carbon intensities to EVs. For EVs, CO_2 emissions from the electricity sector vary significantly across the country. If the primary goal were to correct relative prices for electric and gasoline vehicles, EV subsidies would vary regionally based on grid emission intensities, and CO_2 emissions under fuel economy standards would also vary. Despite this, Congress, the EPA, and NHTSA have chosen to overlook this heterogeneity, presumably to prioritize the second policy objective. Similarly, for green hydrogen, the second policy goal might necessitate a broader temporal matching compared to the first market failure's objectives.

The second concern raised by many experts involves the use of Argonne National Lab's (ANL) GREET-45VH2 tool, proposed by the IRS for measuring lifecycle emission levels. While most experts did not question the effectiveness of the software itself, they expressed concerns about relying on a single model for lifecycle emission measurement and the uncertainties that decision-makers may face when the model is updated in the future. One expert stated in an interview, "One of the problems in the 45V policy is that the emissions accounting has to be done using one particular model coming out of ANL. There's a concern that if that model is updated, if some changes are made to that model, it is going to affect the revenue that individuals and producers are going to make from the subsidy. So, that creates a lot of uncertainty, which is problematic if you're going to make investment decisions."

Several stakeholders have also raised this concern. The American Chemistry Council (ACC) recently issued a brief statement expressing concerns about the IRS's newly announced 45V clean hydrogen tax credit standards. One of the major points of concern is the potential for changes in the GREET-45VH2 model to alter the projected scenarios for future clean hydrogen production projects. [80] Given the substantial federal budget support and the significant initial investments required from the private sector for clean hydrogen production projects, there is a possibility that the profitability of these projects could be significantly adjusted based on the results calculated by the GREET-45VH2 model. This creates uncertainty in investment decisions, which could delay active investment from the private sector. This issue needs to be carefully considered during the additional policy design and adjustment processes.

2. Designing Policies that Consider the Entire Hydrogen Value Chain

Most of the policy support announced to date has focused on directly supporting hydrogen production. However, to revitalize the clean hydrogen industry and move closer to achieving a net-zero society, policy design and support must consider the entire hydrogen value chain. One expert stated, "We need to have an integrated view of hydrogen, not only hydrogen production, but transportation, storage, and use." For clean hydrogen to be used across various industries and to achieve significant decarbonization effects, policies must account for the entire value chain, including hydrogen production, transportation, and storage, as well as its final use.

Another expert expressed concern, stating, "It's complicated by the fact that there's no connective tissue between off-takers and suppliers. For example, there are no hydrogen pipelines in most parts of the country. Someone has to invest in those hydrogen pipelines and make sure they don't leak." Specifically, some industries that are crucial for decarbonization, such as steel manufacturing or the cement industry, are often located far from regions where clean hydrogen is produced. Furthermore, to meet the EAC (Energy Attribute Certificate) conditions included in the detailed guidelines of section 45V, future clean hydrogen production facilities are likely to develop in isolated locations, physically separated from demand centers. In such cases, support for hydrogen transportation and storage technologies and industries will be essential to connect clean hydrogen producers with end users.

Alongside the hydrogen value chain from production to usage, it is now time to address hydrogen safety through policy measures. One expert emphasized, "Also, the safety consideration should be part of the concept of the integrated system. In the DOE, the entity responsible for hydrogen has to have an integrative approach to the problem as well as safety." Hydrogen is inherently flammable and, being the lightest molecule, is physically challenging to handle. Moreover, considering the entire hydrogen value chain significantly broadens the range of stakeholders involved. At this early stage of clean hydrogen industry activation, it is crucial for the federal government to establish safety guidelines and designate a supervisory body responsible for oversight and management.

3. Additional Policy Support and Future-Oriented Planning for the Demand-side

So far, hydrogen-related policies have focused on short-term hydrogen demand. The 45V and hydrogen hub-related policies aim to replace the annual demand for 100 million tons of 'gray' hydrogen with 'blue' and 'green' hydrogen as a short-term goal. The carbon emissions from the production and use of 'gray' hydrogen account for approximately 3% of global carbon emissions, a significant amount. Replacing this with cleaner alternatives would be a notable short-term success. However, there are criticisms that current policies and support are insufficient in driving the demand-side transition from 'gray' to 'blue' and 'green' hydrogen.

One expert pointed out, "There's nobody willing to sign up for new clean hydrogen off-take agreements. Why would an ammonia producer want to convert to blue or green hydrogen when they can just buy gray hydrogen?" This highlights the need for incentives and additional policy support to stimulate demand. While the 45V tax credit can significantly reduce the supply price of clean hydrogen, there are multiple uncertainties, such as the intermittency of renewable energy leading to supply instability, the lack of hydrogen pipelines causing delivery uncertainties, and policy uncertainties due to potential changes in administration. These factors make it difficult to expect large-scale voluntary off-take agreements from the private sector.

The EU addresses unclear demand issues through regulation. In October 2023, the EU announced a new Renewables Energy Directive, mandating that 42% of the current hydrogen usage in the industrial sector must be replaced by renewable fuels of non-biological origin (RFNBOs) by 2030. Furthermore, the EU aims to increase this target to 60% by 2035. [81] Non-compliance with this regulation could result in penalties enforced by the Court of Justice of the European Union (CJEU).

Similarly, Japan has recently introduced demand-side regulations. Under the amended

Energy Conservation Act, eight specific industries within five sectors are required to submit medium- to long-term decarbonization plans to the government, which will oversee their implementation. The targeted sectors include the steel industry, chemical industry, cement manufacturing industry, paper industry, and automobile manufacturing industry—all of which already heavily utilize hydrogen. The Japanese government anticipates that this regulation will lead to an increased demand for clean hydrogen. [82]

While implementing mandatory regulations at the governmental level, as seen in the EU or Japan, might be challenging, it is crucial to discuss additional incentives or policy support to encourage voluntary off-take agreements and construction investments by the private sector.

There was also an opinion that the simple market mechanisms of the current hydrogen market need improvement. One expert emphasized the importance of establishing an appropriate market structure for hydrogen as a key policy consideration. The expert stated, "In the current market, there is no trading and price discovery mechanism. All of the supply has to be contracted through literal contracts with off-takers. Most of those contracts are take-or-pay contracts. We need market mechanisms that enable price discoveries, but also the more efficient use of these very capital-intensive hydrogen production facilities." To activate the hydrogen market, it is necessary to have more producers and consumers participating in the market and to establish a market structure that allows for the flexible and efficient distribution and use of hydrogen. The roles played by various trading platforms and pricing systems like the 'Henry Hub' in the natural gas market should be replicated in the hydrogen market through the design and development of appropriate platforms. The recently launched Hydrogen Demand Initiative (H2DI), led by EFIF, is expected to propose innovative solutions to this issue.

In addition to supporting short-term demand, there is also a perspective that long-term hydrogen demand needs to be explored and supported. One expert noted in an interview, "We are talking about 100M tons of 'gray' hydrogen globally, and that's the market we have to focus on. But that's not going to change the world. If we want to change the world, we have to access new applications like airplanes, shipping, and a much wider range of industrial processes that could adopt hydrogen. The really big question with hydrogen is how much demand there will ultimately be." Currently, the U.S. federal government is investing substantial budgets and resources to revive the clean hydrogen industry. To ensure that these investments do not result in short-term gains only, it is essential to discover new demand and applications for hydrogen that can be used extensively. Such future-oriented efforts will encourage private companies to invest more actively in the hydrogen industry with greater certainty about future demand. It is time to begin meticulous preparation and effort to uncover future hydrogen demand. Another expert added, "We should start detailed analysis on the entire hydrogen demand or application side to understand: what decarbonization options are available, what are the cheapest options, and where does hydrogen fit. Once we have that entire demand map, we should really focus on incentivizing a certain demand sector where hydrogen really fits."

4. Designing Hydrogen Policies with Globalization in Mind

Currently, federal hydrogen policies are primarily focused on revitalizing the domestic hydrogen industry. However, to further develop the hydrogen industry, achieve net zero, and enhance national competitiveness, it is crucial to consider policies with a globalization perspective. Specifically, the U.S. could explore opportunities to export hydrogen to countries such as those in Europe, Japan, and South Korea, which are eager to adopt hydrogen but face challenges in self-production due to technological and geographical constraints.

Recently, the EU and Japan announced their intention to jointly develop policies to create both the supply and demand for clean hydrogen. [83] The EU is also maintaining close governmental cooperation with Australia for the joint development of the clean hydrogen industry. [84] Such initiatives reflect a global trend where countries are engaging in comprehensive collaborations either to supply hydrogen production resources or to meet the clean hydrogen demand of industries requiring decarbonization. Given the substantial investment and budget support required, as well as the need for coordination among various industries and stakeholders, governments are taking a leading role in negotiating and driving these global hydrogen cooperation efforts.

One expert interviewed stated, "I think, from the policy standpoint right now, there's so much attention paid towards making everything in the US. Countries in Europe are looking to purchase hydrogen. They have demand-side policies like regulations on heavy industries to decarbonize. What's very likely going to happen is the US is going to produce hydrogen and export it."

To maintain hegemony in the hydrogen industry from both supply and demand perspectives, and to leverage hydrogen as a national competitive advantage, the US should design policies with a focus on globalization. Given the substantial federal investment to kickstart the hydrogen industry, it is now time to consider additional policies and support measures that will not only help the U.S. achieve net zero but also enhance its competitiveness in the global market.

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