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The Role of Clean Hydrogen Value Chain in a Successful Energy Transition of Japan

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Abstract: The clean hydrogen in the prioritized value chain platform could provide energy incentives and reduce environmental impacts. In the current study, strengths, weaknesses, opportunities, and threats (SWOT) analysis has been successfully applied to the clean hydrogen value chain in different sectors to determine Japan's clean hydrogen value chain's strengths, weaknesses, opportunities, and threats as a case study. Japan was chosen as a case study since we believe that it is the only pioneer country in that chain with a national strategy, investments, and current projects, which make it unique in this way. The analyses include evaluations of clean energy development, power supply chains, regional energy planning, and renewable energy development, including the internal and external elements that may influence the growth of the hydrogen economy in Japan. The ability of Japan to produce and use large quantities of clean hydrogen at a price that is competitive with fossil fuels is critical to the country's future success. The implementation of an efficient carbon tax and carbon pricing is also necessary for cost parity. There will be an increasing demand for global policy coordination and inter-industry cooperation. The results obtained from this research will be a suitable model for other countries to be aware of the strengths, weaknesses, opportunities, and threats in this field in order to make proper decisions according to their infrastructures, potentials, economies, and socio-political states in that field.

Keywords: energy transition; hydrogen economy; SWOT analysis; value chain; strategies; Japan

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1. Introduction

Since the Paris Agreement's ratification in 2015, 195 signatory nations have committed to addressing climate change and establishing a global temperature limit through INDCs with medium- and long-term (2030) objectives [1]. To reach 1.5 °C by 2050, IRENA has allocated contribution to emissions 8.4 $GtCO_2$ to transport, 2.3 $GtCO_2$ to buildings, 13 $GtCO_2$ to power and heat plants, 11 $GtCO_2$ to industry, and 2.2 $GtCO_2$ mitigation to other sectors of the global economy [2].

The energy transition is a trend that will see the world's energy infrastructure transform from fossil fuel-based to zero-carbon between 2050 and 2100. The necessity to control climate change by reducing energy-related CO_2 emissions is its primary goal. The energy sector's decarbonization demands an immediate global effort. While the world's energy transition is beginning, further action is required to cut carbon emissions and mitigate the consequences of climate change [3]. The transition is a long-term opportunity to invest that will fundamentally reshape the energy sector within the next 30 years and well beyond [4]. The critical issue is that, to reach climate ambitions, investment throughout the whole value chain will be required, including all the sectors of the global economy [5]. For this purpose, speeding the adoption of climate change mitigation policies, particularly renewable energy carriers such as hydrogen, may provide a solution owing to hydrogen's applicability as an energy storage source. In general, there are three types of hydrogen: gray hydrogen, which is obtained from fossil fuels and the produced CO_2 is not captured during the process; blue hydrogen, which is obtained from fossil fuels and the produced CO_2 is captured during the process; and green hydrogen, which is obtain from renewable energies [6]. Hence, the importance of green hydrogen becomes clear when there is no superior alternative for decarbonization, particularly for energy-intensive industries.

Hydrogen and hydrogen carriers have specific characteristics; for instance, they are adaptable, sustainable, and safe energy carriers that can be employed as fuel for electricity generation or as feedstock in the industry [7]. Hydrogen can be generated using renewable energy without emissions or carbon-abated fossil energy. It may be stored and delivered in liquid or gaseous form with a high energy density [8]. It may be burned or utilized to create heat and power using fuel cells [9]. While hydrogen is now extensively employed in several industries, its potential has not been fully realized to aid in the transition to sustainable energy [10]. To further eliminate hurdles and cut expenses, ambitious, targeted, and near-term action is required [11]. Green hydrogen is an environmentally friendly alternative that may be utilized for a range of reasons (energy storage, industrial processes, and vehicle propulsion, for example) without emitting pollutants [12].

However, infrastructure and network upgrades are needed to make hydrogen as common and widely available as natural gas is today [13]. Additionally, hydrogen's ability to flow through pipelines roughly three times quicker than methane would make it a cost-effective alternative for large-scale transportation of hydrogen [14]. To make hydrogen available when and where needed, it must first be produced and then stored and distributed along the value chain. Hydrogen's low density necessitates enormous storage quantities at high pressures and temperatures [8]. For both transportation and storage infrastructures, high-capacity solutions are typically required, which can be considered a hurdle [12].

Today, almost all hydrogen production in the world is gray hydrogen, including 48% from natural gas refining, 30% from oil refining by-products, 18% from coal gasification, and the remaining 4% from water electrolysis [15]. Depending on the feedstock in the fossil fuel-based process, 9–12 tons of CO_2 are emitted per ton of produced hydrogen [13]. By substituting hydrogen derived from zero-carbon energy sources instead of hydrogen derived from fossil fuels, the carbon footprint of the energy-intensive industries' sector may be drastically reduced [16]. Carbon-free hydrogen applications in energy systems, whether in the transportation, industry, construction, or power sectors, are diverse [17]. Hydrogen as a fuel may be utilized to power automobiles and electrical appliances via fuel cells and ICEs. The high density of hydrogen in a liquid state allows it to provide the driving force for spacecraft. It can generate combined heat and power (CHP) on a small scale in residential fuel cells as a prime mover [18,19].

As with natural gas, hydrogen can be compressed or liquefied to be transported. For some countries, such as Japan as an island country, this is the only option to purchase significant quantities of this emission-free energy carrier. Furthermore, excess renewable power may be utilised to produce hydrogen for energy storage [20]. This hydrogen can be mixed in a limited content with natural gas in a grid or converted to hydrogen carriers such as methane, methanol, or ammonia for storage [21]. Hydrogen produced via water electrolysis with renewable energy sources or from fossil fuels with a carbon capture unit becomes a fuel that stimulates economic growth and helps decarbonize energy systems [22]. The hydrogen value chain (see Figure 1) can serve as the foundation for a clean energy system and is promising as a safe and sustainable energy carrier.

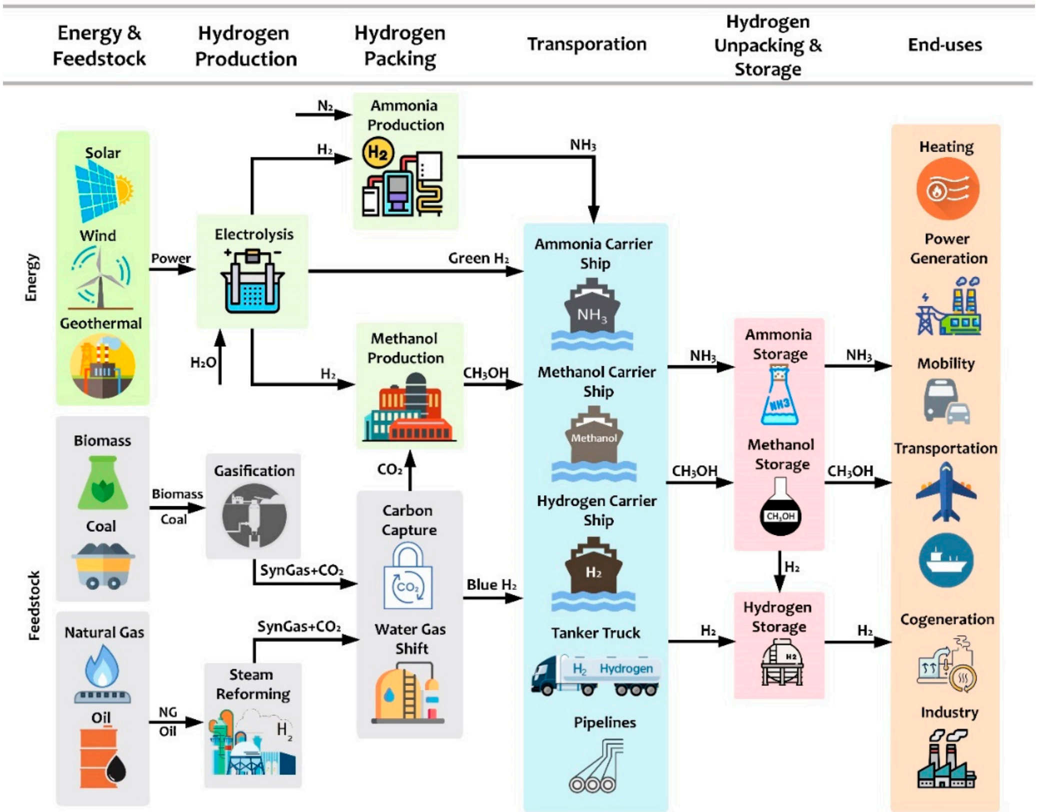

Figure 1. Value chain of clean hydrogen for the successful energy transition.

To better understand the hydrogen economy, we need a complete understanding of the clean hydrogen production value chain. Hydrogen can be based on fossil fuel or completely renewable. Each country makes a decision about it according to its assets and experiences. As far as the authors' knowledge, this kind of analysis has not been studied in the hydrogen value chain. In the present study, a SWOT analysis was designed to analyse the strategies for a successful energy transition to clean hydrogen. A SWOT analysis is extensively used in strategic planning [23,24] because it provides an essential foundation for understanding the state of the item being investigated and developing plans to address the present challenges. Following that, measures for encouraging its growth were offered by using strengths, reducing weaknesses, making use of opportunities, and circumventing threats [25,26]. The SWOT analysis approach may be used to determine the examined item's strengths (aspects to leverage and expand upon), weaknesses (areas to receive aid and assistance), opportunities (areas that can be used for benefits), and threats (elements that could impede the object's development). Internal variables dictate strengths and weaknesses, but external forces describe opportunities and dangers [27].

2. Hydrogen Value Chain

The hydrogen value chain can be considered as a combination of production, transportation and storage, and end user sectors. In the case of a hydrogen value chain, Japan is a pioneer country in a hydrogen national strategy and R&D funding, with successful hydrogen projects on the ground [11]. The data of analysis were gathered and summarized from Japan's hydrogen policy and national strategy based on the guidelines, reports, papers, documents, and statistics. Japan has expressed interest in developing a hydrogen economy in its broader climate and energy policy [28]. Long-term Japanese policy plans aim to commercialize clean hydrogen production using a mix of fossil fuel from overseas, CCS (blue hydrogen), and affordable renewable sources (green hydrogen). Japan also is the undisputed leader in fuel cell research, accounting for over 40% of all patents; it aspires to be the world's first "hydrogen society" by utilizing hydrogen throughout the economy's sectors [29]. Only one country (Japan) had a national hydrogen policy as of 2017.

2.1. Hydrogen Production

As was mentioned before, hydrogen can be generated from fossil fuels (gray and blue hydrogen) and renewable energy (green hydrogen), which are reviewed in this section.

2.1.1. Hydrogen from Fossil Fuels (Gray and Blue Hydrogen)

Nature does not produce vast amounts of hydrogen gas; therefore, it must be synthesized, mainly through the reforming and steam reforming of natural gas, oil, and coal. In the short term, hydrogen is supplied as a by-product for purification and fossil fuel steam reforming [30]. Although usually natural gas is used for steam reforming and production of hydrogen, steam reforming is also applicable to liquid fuels such as oil. In this process, a hydrocarbon feedstock reacts with high-temperature steam at a pressure of 3–35 bar while being accompanied by a catalyst to create hydrogen, carbon monoxide, and a small quantity of carbon dioxide. Afterwards, hydrogen and carbon dioxide are produced by reacting carbon monoxide and steam with a catalyst [31]. Finally, carbon dioxide and other impurities must be captured to keep the hydrogen pure.

Hydrogen may be produced by coal gasification at high temperatures and pressures, resulting in a mixture of hydrogen and carbon monoxide [32]. As a result of adding the excess steam, the synthetic gas generates extra hydrogen and CO_2. While CO_2 needs to be sequestrated, hydrogen is captured through the separation system. Energy AGL and Kawasaki Heavy Industries announced plans to build a coal-fired power station in Latrobe Valley, Victoria, Australia, in April of 2018. The pilot tested the feasibility of converting brown coal to hydrogen and then liquefying it for transport to Japan. If successful, the two companies will target commercialization on a large scale by 2030. The first shipment of liquefied hydrogen from Victoria's port was sent to Kobe in Japan in 2022 [33].

2.1.2. Hydrogen from Renewable Power (Green Hydrogen)

Renewable power to hydrogen (PtH) is the process of generating hydrogen and derivatives from electricity [8]. The first step is electrolysis, splitting water into hydrogen and oxygen by electricity [4]. Hydrogen may then be converted to ammonia, methanol, or diesel [7]. In the case of Japan's strategy, PtH has been explored as a solution for renewable electricity transportation and storage in the long term from a source (e.g., Australia) to Japan. Another advantage of PtH is the prospect of decarbonizing the whole energy system through sector coupling [34]. Additionally, hydrogen may be introduced into natural gas pipes at particular levels. Methane may be created using a methanation process that incorporates hydrogen and CO. As with natural gas, synthetic methane has the same chemical structure and is compatible with the current infrastructure to be utilized in the same manner. Since synthetic methane requires carbon dioxide as an input ($CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$), the life cycle of syngas is essentially zero carbon (although the combustion of synthetic methane eventually releases CO_2). Moreover, hydrogen can be converted into methanol ($CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$) or ammonia ($N_2 + 3H_2 \leftrightarrow 2NH_3$). Both synthetic methanol and ammonia have a large storage capacity and can widely be used in other chemical fields. PtH provides opportunities for the coupling sectors, where renewables may supply heavy industry and transportation, which are challenging to be electrified.

There is a promising chance for Japan to import electricity produced from renewable energy sources, which are converted to hydrogen. While the government's strategy does not address renewable international supply chains, a pilot project by Kawasaki Heavy Industries Ltd. was initiated in 2017. With the support of companies such as Mitsubishi and Statoil, Kawasaki partnered with Hydrogen Nel, a Norwegian manufacturer of hydrogen plants. The companies are undertaking a feasibility study for another demonstration project in Norway that would produce hydrogen from electricity and be transported to Japan via liquid hydrogen tankers. Along with renewable PtH, Norway is investigating the prospect of hydrogen production using natural gas reforming [35].

2.2. Transportation and Storage

Given Japan's limited capability for producing carbon-free hydrogen, improved transportation and long-term storage are essential research goals. Thus, the cost of hydrogen supply chains (overseas transportation and internal distribution) is a critical driver of a hydrogen supply's economic feasibility. Compression, liquefaction, hydrogenation, or conversion to other gases such as ammonia and synthetic methane are all methods for increasing the density of hydrogen for transportation and most end-use applications, as presented in Figure 2 [34]. Conversion of hydrogen to other gases is significant as it can increase the efficiency in long-distance transportation and increase the storage time for the otherwise readily dispersed gas. It must be mentioned that the properties of an energy carrier should be taken into consideration while making a choice. In some instances, pilots for long-distance transportation have used substances such as liquid hydrogen and organic hydrides such as methylcyclohexane. Although liquid hydrogen is ideally suited for cases where high purity hydrogen is required, such as fuel cell vehicle fuel, the necessary refrigeration temperature to store hydrogen in a liquid form poses numerous engineering problems. For hydride carriers, specific hydrogenation and dehydrogenation facilities are required, lowering the purity of the end-use hydrogen but making the hydride mixture easier to carry and store [36]. Hydrogen may also be transformed into ammonia and synthetic methane, which have established markets and infrastructure. However, further study is necessary to mitigate the harmful gases produced by ammonia combustion.

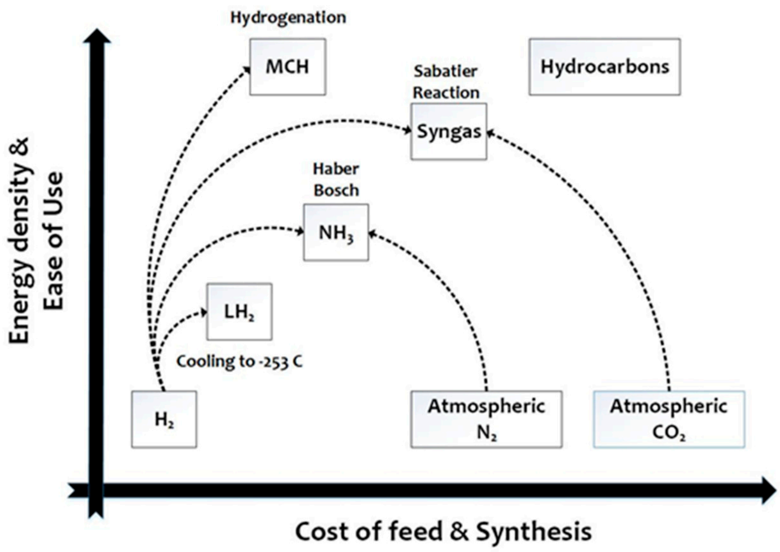

Figure 2. Hydrogen carriers based on energy density and synthesis cost (adapted from [35]).

In terms of internal distribution, there are compact and liquid hydrogen supply networks for specific industrial uses. For hydrogen to play a role in energy transport across Japan, there is a need for scale and innovation in methanation technology and an increase in domestic pipeline networks. The research community now assumes that each energy carrier technology has its competencies and that further R&D is required for a better comparison. Thus, the Japanese government's strategy intends to express the technical advantages and disadvantages of different energy carrier technologies and introduce pilot projects carried out at home and abroad, such as liquefied hydrogen (LH_2), liquid organic hydrides (particularly methylcyclohexane (MCH), SPERA hydrogen with Brunei [37], Chiyoda MCH refuelling stations), ammonia (production of carbon-free ammonia, supply chain with Saudi Arabia, early success in reducing NO_x emissions), compressed hydrogen, and pipelines and transportation [38].

December 2019 marked the world's first transoceanic methylcyclohexane transportation, form Brunei to Japan [39]. Kawasaki Industries introduced the world's first customized hydrogen tanker for liquid hydrogen shipments from Australia to Japan (see Figure 3) [33]. In the summer of 2020, the first shipment of "blue ammonia" arrived in Japan from Saudi Arabia. This blue ammonia was utilized to generate electricity [40]. Japan has bought crude oil from Saudi Arabia for a long period of time, and the two sides are discussing expanding their trade connection to include blue ammonia as well.

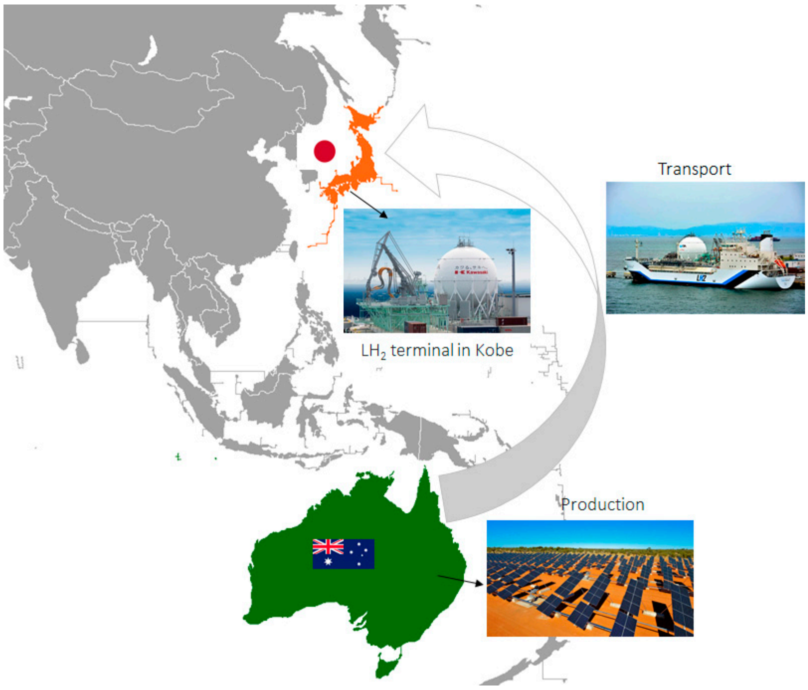

Figure 3. Liquefied green hydrogen shipping by Suiso Frontier from a port in Victoria, Australia, to Kobe, Japan.

2.3. End-Use Sectors

The residential combined heat and power (CHP) and the transport sector currently demonstrate the highest market maturity among end-use sectors of hydrogen [6]. Residential CHPs were introduced into the Japanese market in 2009, and their consumption subsidies were phased out [41]. Although subsidies also lad to fuel cell vehicles' (FCVs) and fuel cell buses' development, a low number of hydrogen fuel stations, backed by stringent regulations and high manufacturing costs, restricts the spread of fuel cell vehicles [42]. These are the areas where Japan is now showing technological supremacy and are prominent parts of the hydrogen economy that can gain public acceptance in the short term; however, they are insufficient to fully achieve Japan's hydrogen economy's potential. In the future decades, power generation may be the primary driver of additional hydrogen capacity, consuming up to 64% of yearly hydrogen use [43]. Large-scale hydrogen generation technology is currently under investigation and the government of Japan has set targets for reducing hydrogen fuel prices to USD 0.17/kWh by 2030 and USD 0.12/kWh by 2050, making it cost competitive with natural gas. Until 2050, hydrogen may provide up to 28% of primary energy. It should be emphasized that these numbers were calculated without consideration for economic or political aspects that may influence the market direction and that the technological prediction for 2010 was extended from the primary base. Diverse end-use plans must be backed up by a robust policy substructure and financial assistance, while technological success is defined by achieving the mentioned degree of market penetration [35]. It is predicted that hydrogen demand share in the residential, commercial, transportation, industry, and power generation sectors of Japan will be 8%, 10%, 4%, 15%, and 64%, respectively, by 2050 [35].

2.3.1. Transport: Fuel Cell Vehicles (FCV)

Toyota and Honda manufactured the most commercial passenger vehicles in the Japanese transportation sector, with Toyota accounting for the largest share [42]. FCVs are similar to gasoline–electric hybrid vehicles in that they use gasoline engines to power electric motors. The distinction is that a fuel cell stack replaces the internal combustion engine. The FCV operates on hydrogen fuel, which can be purchased at hydrogen fuel stations in the same way gasoline fuel is purchased. Despite the significant differences that make them a cleaner alternative to gasoline cars in the transport fleet, FCVs have no emission from exhaust pipes. They are, however, comparable in this respect to battery-powered electric vehicles (BEVs), but still do not have problems related to battery recovery and its environmental issues.

FCVs have twice the driving range of BEVs and much faster tank filling times. Hydrogen has an energy density approximately three times that of Toyota batteries when stored at the high pressure employed in Toyota Mirai tanks [42]. While the technological complexity of FCVs increases their cost, manufacturers can still enhance their future performance. The FCV cruising range is likely to increase with an increasing hydrogen pressure stored in the tank [36]. Therefore, their cruising range can be close to gasoline vehicles without hurting usability with adequate research and development. Toyota introduced the Mirai model at the end of 2014. According to the brochure, the car has a cruising range of 650 km, which dropped to 500 km under actual testing by the US EPA. In March 2016, Honda introduced the Clarity, with a nominal cruise range of 750 km, which reached 590 km under EPA testing [18]. Compared to a BEV, Japan's popular 2018 Nissan Leaf takes up to 1 h to charge 80% of its battery at fast-charging stations. It takes 7.5 h at home to reach the full range of the 270 km claimed in the brochure. With approximately 3 min of immediate refuelling time and a longer range, FCVs offer a closer driving experience to conventional vehicles than BEVs offer. On the plus side, their fuel cells can operate as off-grid generators in the event of a blackout. Figure 4 shows the trend of FCVs' cumulative sales in different countries.

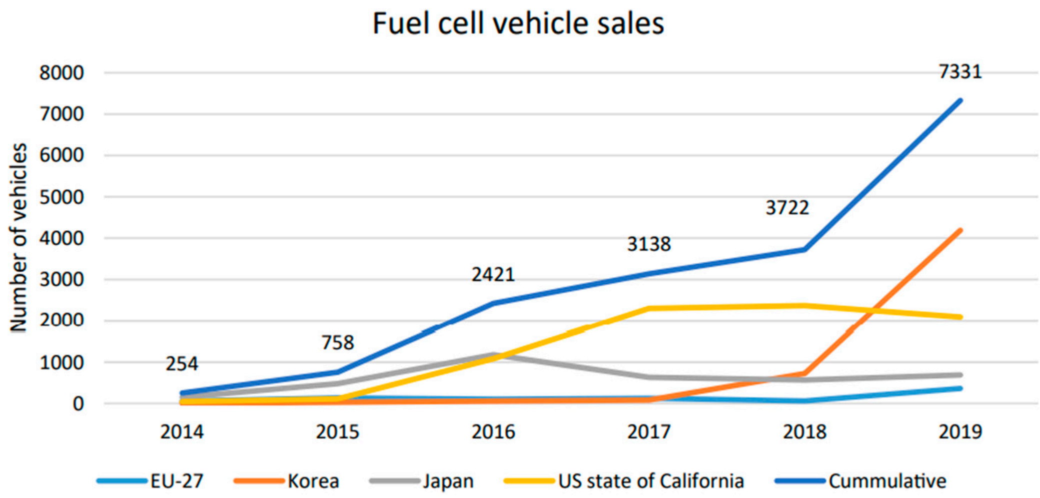

Figure 4. Global and cumulative annual sales of FCVs from 2014 to 2019 [18].

By 2030, the international council on clean transportation (ICCT) estimates that heavy electric vehicles' and hydrogen fuel cell vehicles' overhead costs (ownership, operation, and fuel) can be 25–30% and at least 5–10% lower than diesel vehicles [44]. Heavy-duty transportation is essential for decarbonization, and automakers who offer various low-carbon solutions are endorsed. Although heavy vehicles include only one-tenth of all vehicles, they account for 40% of carbon emissions, which is still growing. As we look at the list of emerging technologies—natural gas, electric batteries, and fuel cells—many issues need to be considered from a long-term business planning perspective [45]. Electric battery trucks are low-carbon solutions in which renewable energy or core energy is a major contributor. Fuel cell vehicles can operate as portable power generators for emergency shutdowns. The power supply capacity of fuel cell buses and vehicles for disaster relief facilities in Japan for a hospital are two buses (455 kWh/unit) and eight FCVs (120 kWh/unit), respectively [35].

2.3.2. Cogeneration Systems

The use of fuel cells as the main drivers for generating electricity and heat is called cogeneration, where electricity is used to meet electrical needs and heat is used for heating applications so that total cogeneration efficiency can be up to 90%. Today, many commercially launched projects are developing fuel cell cogeneration programs. Japan is a major leader in small-scale cogeneration facilities [16]. Figure 5 shows the schematic diagram of CCHP systems based on the polymer electrolyte membrane fuel cells (PEMFC).

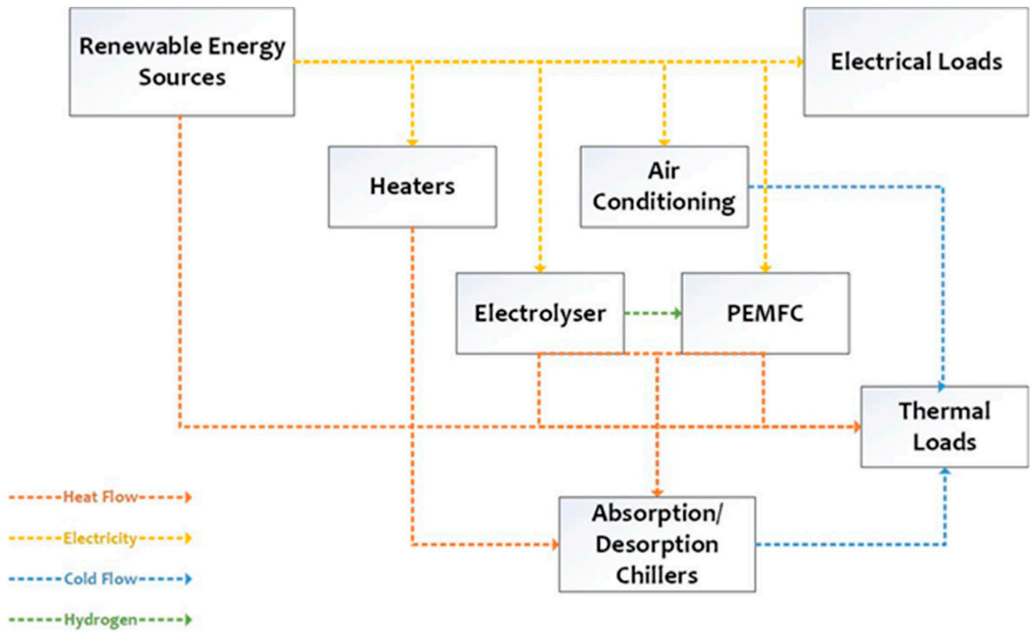

Figure 5. A flowchart of a tri-generation system based on a fuel cell (adapted from [16]).

The polymer electrolyte membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC) are two commercially advanced options, which usually work with natural gas with a primary application in cogeneration systems. Fuel cell units for the home were introduced under the Enefarm trademark by several prominent Japanese energy providers and manufacturers in 2009 [46]. It is a cogeneration system offered in PEMFC and SOFC types. The PEMFC model covers 90% of the sales. It is not intended to supply a home's full electrical needs, but rather a portion of it and its complete hot water needs, with its 700 W and 1000 W power-generating capacity. The government currently provides sliding-scale subsidies based on the type of fuel cell, price, and variables such as the fuel type or building retrofit. With more subsidies, cost competition increases, performance improves among equipment manufacturers, and customers are encouraged to buy and install cheaper systems [16]. Higher subsidies are given to SOFCs that perform better technically but have a smaller share of sales due to higher costs. The initial investment in a single PEMFC or SOFC system is 2.5–3.5 times greater than typical electric and heating systems [16]. Still, consumers without subsidies can return their investment in 12 to 13 years with possible yearly savings of around JPY 50,000 in energy costs [35].

If the costs continue to decline by 12% annually, reaching the target price by the end of this decade seems plausible. It also demands a growth rate higher than the past 9 years, which is quite a challenge for an objective such as this. A total of 53 million units are expected to be in use in Japan by 2050, representing nearly 10% of the country's homes [35]. Already, prices have dropped by more than 40% for SOFCs and almost 70% for PEMFCs since their launch. MEYI hopes to achieve the millions of fuel cell installations, however it will be required further cost reductions. The size and cost of domestic CHP systems have been reduced, making them more practical.

The recent advancements include reducing the amount of platinum used by the PEMFC by 10–30%, equipment size by 40–60%, and the repair and maintenance frequency from once every 5 years to more than 10 years. By replacing 10% of Japan's heating systems with fuel cells, the International Energy Agency forecasts that Japan's total residential energy consumption would be reduced by 3% and carbon emissions would decrease by 4%. The Enefarm brand on the market has more than 50% power generation efficiency and 87% cogeneration efficiency [35].

2.3.3. Power Generation

As part of efforts to achieve the 2050 carbon target, Japan aims to increase the use of ammonia as fuel. Ammonia is expected to be used primarily as a fuel in coal-fired power plants. To successfully meet the demand for ammonia and develop a supply chain, the advancement of power generation technologies based on the direct combustion of ammonia remains crucial as Japan plans to eliminate half of its coal-based power generation capacity by 2030 [47]. Both pure hydrogen and a combination of natural gas or coal can be used to produce electricity through burning. Natural gas-fired power plants are generally compatible with hydrogen; therefore, these opportunities are being examined in Japan and elsewhere. Turbines that mix up to 50% of hydrogen have already been commercialized in the integrated gasification combined cycle (IGCC). Mitsubishi Hitachi Power Systems (MHPS) and Kawasaki Heavy Industries investigated direct and co-combustion technologies [48].

Although it is free of CO_2 emission, hydrogen combustion emits nitrogen oxide (NO_x). The combustion of natural gas can be twice as polluting when the reaction is too fast, leading to unstable combustion and high flame temperatures. Techniques such as injecting water to temper the flame and diluting the fuel with inert gases are being examined to tackle the problem [35]. As water injection conserves fuel, Kawasaki created an alternative technique dubbed "micromix" that delivers hydrogen in small quantities and burns in micro-flames. Micromix may be utilized to burn pure hydrogen while reducing NO_x emissions. Electricity generation from hydrogen combustion, due to its scalability, is expected to be more cost effective than fixed fuel cells. Hydrogen power plants can be developed more quickly than fixed fuel cells. Conversely, generating electricity in a small-scale distributed power generator has less of an advantage. To operate as a large-scale power plant, a sufficient volume of hydrogen fuel is also required to be supplied [35].

Mitsubishi Japan is developing a gas turbine with ammonia fuel. Mitsubishi Power, a wholly owned subsidiary of Japan's Mitsubishi Heavy Industries, plans to commercialize a gas turbine system [49]. The turbine combines selective catalytic reduction with a newly developed combustion technology to prevent nitrogen oxides' pollution from direct ammonia combustion. The company is working to divert demand for electricity generation at industrial plants and small power plants on remote islands to clean energy forms.

Mitsubishi Power is expected to establish larger units to produce ammonia-burning gas turbines. The company is also developing technology to convert fuels from natural gas to hydrogen in combined cycle gas turbine (CCGT) systems while investigating the feasibility of using ammonia as a fuel. It is also developing a system for splitting ammonia into hydrogen and nitrogen using waste heat in which hydrogen will be used to perform CCGT. The project, once commercialized, will be the world's first gas turbine on this scale, powered entirely by ammonia to generate electricity. Japanese laboratories and engineering companies (such as IHI and Toyota Energy Solutions) have tested and developed small gas turbines with an ammonia fuel capacity of 50–2000 kW [48] (see Figure 6).

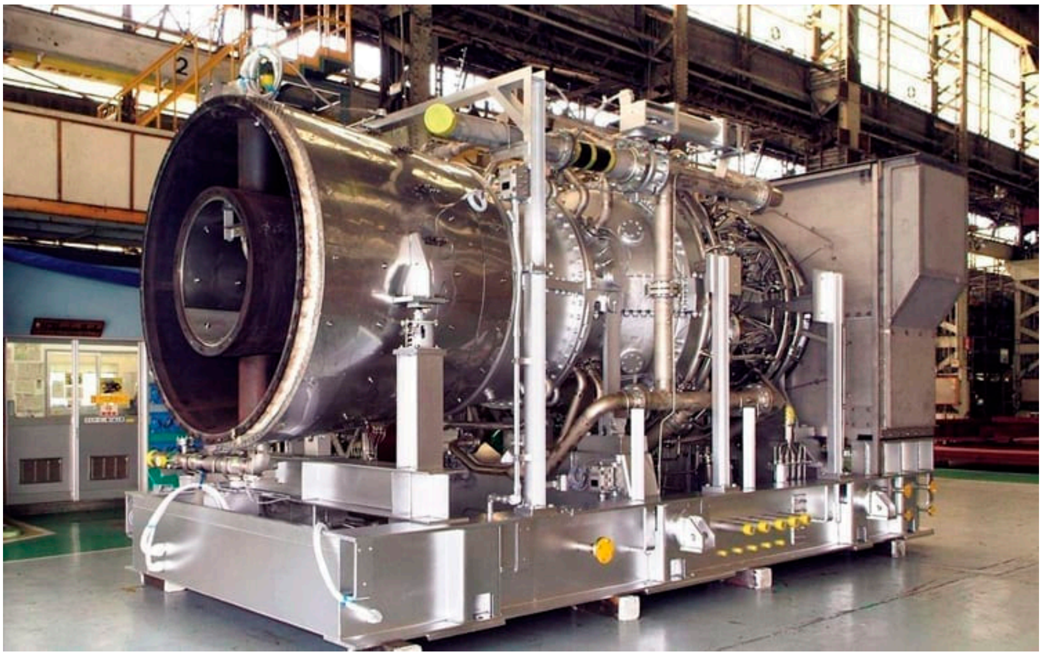

Figure 6. Fully ammonia, 40 MW (H-25 series) gas turbine developed by Mitsubishi [49].

2.3.4. Industry

Almost all of the hydrogen consumed by Japanese industry is now produced as a by-product of an industrial process. Hydrogen produced as a by-product of oil refining is recycled in the same feed plant to desulfurize the oil. Recently, as demand for better grades of petrochemicals increased, refineries in Japan and other areas of the world began purchasing hydrogen from other facilities to satisfy demand. At the moment, Japan's primary hydrogen provider is the caustic soda sector, which supplies high-purity hydrogen to gasoline stations and other facilities. It would not be a sustainable source of hydrogen in the future. Additionally, steel making generates hydrogen by-products, some of which are sold (e.g., the Kitakyushu Hydrogen Demonstration Project [50]).

The quantity and quality of hydrogen produced as a by-product may vary depending on the feed type and production process. If low-quality hydrogen requires additional refining, this can increase costs, while supply inconsistencies complicate purchases. In contrast to France, which picked industrial hydrogen as the initial step toward establishing a green hydrogen market, Japan has no decarbonization target for industrial hydrogen. According to the French strategy, 10% of industrial hydrogen will be achieved by electrolysis with zero emissions by 2023 and 20–40% by 2028 [35]. Japan, as with France, is expanding electrolysis-based hydrogen generation; the primary distinction is the high cost of renewable energy. While bidding-based pricing is becoming more prevalent, many projects are still priced using the FiT system. In addition to the high cost of electricity, the intermittency of renewable energy lowers the electrolysis capacity and, thus, increases the marginal costs of hydrogen production.

While industrial demand is unlikely to help Japan's hydrogen economy, the country will profit from decreasing green hydrogen costs. Due to distribution and storage infrastructure availability, industrial parks are excellent laboratories for hydrogen pilot projects. Industrial applications for hydrogen may eventually extend beyond raw materials since hydrogen can replace hydrocarbons in boilers, direct heating, and cogeneration. Similarly, as green hydrogen becomes cheaper, industries will be able to reduce their emissions [35]. Hydrogen usage's potential shares for paper and pulp, chemical fiber, glass, ceramics, non-ferrous metals, manufacturing, chemicals, and steel industries of Japan are predicted to be 25%, 8%, 1%, 9%, 2%, 5%, 37%, and 13%, respectively, by 2050 [35].

2.3.5. Aerospace Industry

The air travel industry is anticipated to be one of the fastest expanding modes of transportation, rising at 5% per year by 2030. Kerosene is by far the most frequently utilized aviation fuel in commercial aircraft. Kerosene and other airplane fuels are often produced to a strict specification, including resistance to large temperature fluctuations. It should be emphasized that the aviation sector obtains the majority of its fuel from oil sources. Global interest in deploying alternative fuels for aviation is developing to ensure energy security and to mitigate the environmental effect of fossil fuels. Methane, methanol, and liquid hydrogen are considered environmentally friendly alternatives to kerosene [51].

Liquid hydrogen can replace kerosene as airplane fuel. Since liquid hydrogen can be generated from renewable primary energy sources, it is more environmentally friendly than kerosene. In addition to high energy density and improved combustion kinetics, aircrafts powered by liquid hydrogen have lower maintenance costs and longer engine life. On the other hand, liquid hydrogen shows some issues when used as aircraft fuel. Low ignition energy is a barrier when burning in large engines. In addition, there is the potential for traces of unburned hydrogen during combustion, which can cause the metal to be brittle [52]. Liquid hydrogen emits fewer greenhouse gases at each distance travelled. Reports suggest that hydrogen and liquefied natural gas are more environmentally friendly than other alternative fuels. However, the cost of hydrogen is higher than conventional kerosene, ammonia, and methanol. More R&D is required to lower hydrogen production costs by improving production and storage technologies for practical applications such as commercial-scale airplane fuels [17].

Green Hydrogen International (GHI) has ambitions to build over 50 hydrogen storage caverns, storing up to 6 terawatt-hours of energy and transforming the dome into a significant green hydrogen storage hub, comparable to the importance of the Henry Hub in the natural gas market [53]. Several potential applications for its hydrogen have been discussed, including clean rocket fuel, clean aviation fuel, green ammonia for fertilizer synthesis or sale to Asia, especially Japan, and as a natural gas alternative in power plants. Hydrogen City is ideal because of its access to low-cost renewable energy sources, ample unused land, salt domes, and proximity to Corpus Christi's energy port.

3. SWOT Analysis

SWOT analysis is a strategic planning and strategic management technique that is used to assist a person or organization in identifying the strengths, weaknesses, opportunities, and threats associated with business competition or project planning [54]. In the SWOT analysis of the hydrogen economy, the strengths, the weaknesses, the opportunities, and the threats were as follows.

3.1. Strengths

Hydrogen, the missing component in the clean energy mix, is expected to significantly alter the value chains of energy systems in the years ahead. The primary driver of the rising policy emphasis on hydrogen has been the climate change urgency. Hydrogen enables economies to diversify away from fossil fuels.

While international hydrogen trade may expand dramatically, analysts doubt that hydrogen will yield the same level of money that oil and natural gas yield now (Figure 7). Thus, hydrogen cannot be a modern, clean alternative to oil. In contrast to oil and natural gas, hydrogen is a conversion industry rather than an extraction one; hence, its economic impact will likely be limited. Hydrogen will be more competitive and include a broader range of businesses than oil and natural gas. As the cost of green hydrogen continues to decline, more and diversified players will enter the hydrogen industry [13]. By 2050, the profit from oil and natural gas exports for fossil fuel exporter countries will decline. The market for hydrogen exports will be fiercer and will attract a broader range of participants than the oil and natural gas sector. Hydrogen exports have the potential to someday provide the same level of money that oil and natural gas exports already provide.

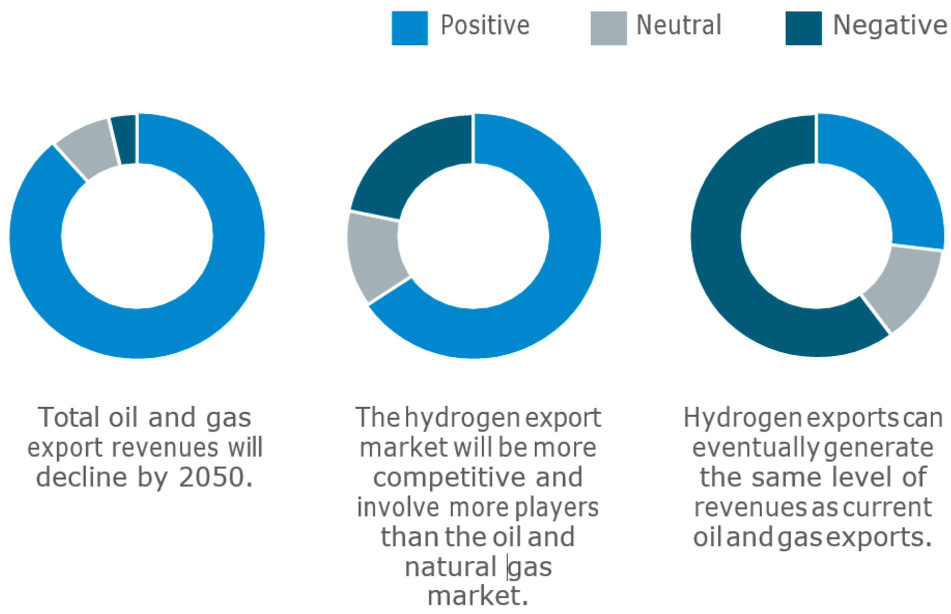

Figure 7. Expert opinions on the future profitability and market structure of hydrogen [13].

Natural gas costs climbed in 2021 and 2022; therefore, green hydrogen was already competitive with gray hydrogen across Europe.

3.2. *Weaknesses*

3.2.1. Obstacles of FCV

The biggest obstacle to developing a hydrogen vehicle is the lack of a fuelling infrastructure. BEV chargers are faster to deploy and easily accessible as they can be installed wherever there is access to the power grid, e.g., homes and parking structures. Due to the high expenses imposed by administrative and technological limits, the infrastructure of hydrogen recharging stations cannot be built as fast [17]. The availability of FCVs is highly dependent on the expansion of refuelling stations, which have expanded to 100 stations in Japan since 2018 (see Figure 8).

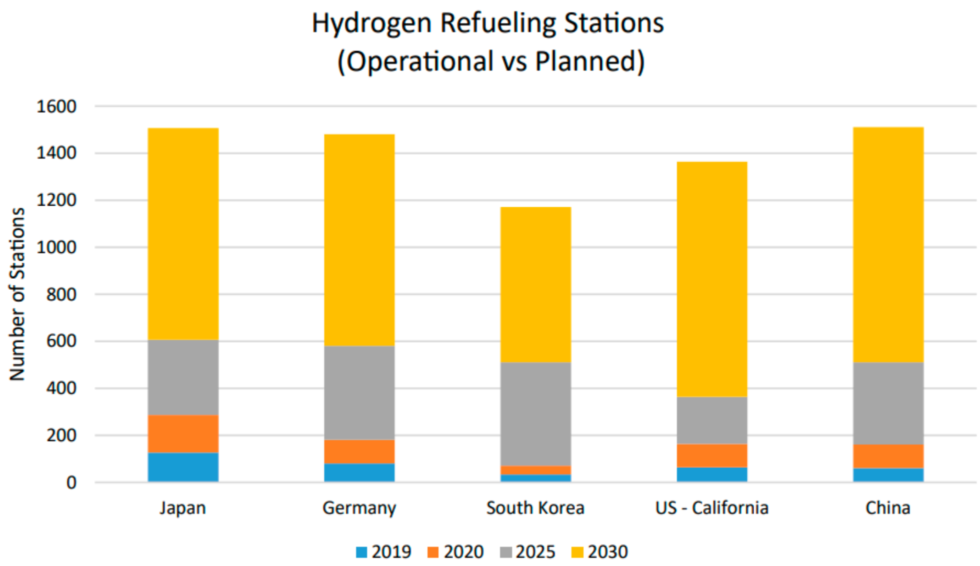

Figure 8. Current and planned number of hydrogen stations worldwide [18].

3.2.2. High Prices and the Small Number of Customers

The expense of building and operation is what separates Japan from other countries. According to reports, a hydrogen station costs twice or three times in Japan as it costs in Europe due to significantly more demanding requirements. Capital and operating subsidies are calculated based on 2.3 and 1.2 times the total cost, depending on the station's characteristics. Even with subsidies, given the small number of FCVs on the road, companies are trying to justify investing in hydrogen infrastructure. According to the hydrogen strategy of Japan, each gasoline station should service around 900 automobiles each year to remain profitable, a goal that is hoped to be achieved by 2030 [35]. While the number of FCVs depends on the quantity of fuel stations, they are seldom created due to high costs and consumer uncertainty.

3.2.3. Regulatory Barriers

Hydrogen is difficult to regulate as an industrial gas, and standards are set for sizeable chemical plants with a high explosion risk. The same rules now apply to fuel stations. For example, hydrogen gas stations should be surrounded by more space than conventional gas stations. This is a high cost for cities with high real estate costs, such as Tokyo [55]. Additionally, these stations are fitted with sensors that promptly shut off the pump whenever a leak is detected. The government is now reviewing safety measures as part of its ongoing reform of fuel stations, which began in June 2016. Vehicles must be fuelled by professionals who are licensed to utilize high-pressure gases. As the car-filling process is automatic, Japan can follow the US path and legalize self-service pumps.

3.2.4. PtH Challenges for Japan

German PtH technology is ahead of Japan, and there are numerous factors why Japan has yet to catch up. Japan's natural gas pipeline network is only half the length of Germany's and is less integrated than Germany's. In other words, even if enough hydrogen is generated, it will be challenging to distribute. Another constraint on hydrogen transportation using natural gas pipelines is the lower mixing concentrations permitted by Japanese pipe requirements, which are lower than those permitted for European pipes [56]. Hydrogen may also be combined with natural gas. Other issues include using excess renewable energy to make hydrogen. Even if electricity is available for free, hydrogen generation is economically impractical when relying on restricted power for electrolysis, as Shibata has demonstrated. The rebate must be large enough to cover production costs. Investing in renewable electricity that lacks attractiveness looks highly impossible.

3.3. Opportunities

Hydrogen is anticipated to impact the energy trade geography, substantially regionalizing energy interactions. With the cost of renewable energy decreasing and the cost of hydrogen transportation increasing, the coming geopolitical map is anticipated to show an increase in the regionalization of energy interactions. Renewables may be installed in any country, and renewable power can be exported via transmission lines to bordering countries. Additionally, hydrogen enables the conveyance of the energy generated by renewables across larger distances via pipelines and ships, enabling the utilization of previously untouched renewable resources in remote regions. Existing natural gas pipelines might be reused to carry hydrogen with minor technological modifications [13].

Renewable energy-rich countries may become providers of green hydrogen, with geoeconomic and geopolitical consequences. For the most cost-effective use of green hydrogen, places with an ample supply of renewable energy sources, land for solar or wind fields, and water availability are ideal. Existing power plants might be transformed into hydrogen production and consumption hubs if they use these environmental factors.

Hydrogen trading and capital movements will result in new types of dependency and a reorientation of bilateral ties. International bilateral agreements are fast developing, shifting from traditional hydrocarbon-based energy arrangements. Over 30 nations have hydrogen policies in place, including plans for hydrogen import and export, showing that international hydrogen commerce is poised to expand significantly [57]. Countries that have not previously exchanged energy are forging bilateral ties around technologies and materials related to hydrogen. As economic relations between countries shift, their political relationships may also shift.

Hydrogen is a conversion process, not an extraction process, and can be generated economically in various locations. This will make it more challenging to extract profits similar to those created by crude oil, which currently represents around 2% of the world's GDP. Additionally, when the green hydrogen cost declines, additional and varied competitors will make market entry, further increasing hydrogen's competitiveness. The technological potential for green power will produce enormous volumes of green hydrogen, far outstripping world demand estimates by many orders of magnitude. Numerous nations have shown an interest in becoming hydrogen exporters, reducing the risk of export concentration. Even net energy importers are set to become green hydrogen exporters based on their plans and developing bilateral agreements.

Hydrogen cross-border trade will expand in the 2030s, in lockstep with green hydrogen's cost competitiveness. Demand will begin to accelerate beyond 2035 based on several decarbonization forecasts. According to IRENA, two-thirds of green hydrogen production in 2050 will be utilized locally, with the remaining one-third traded internationally [13]. Pipelines, particularly modified natural gas pipelines, are expected to support around half of this commerce. The remainder would be loaded aboard ships as hydrogen derivatives, notably, ammonia.

Countries and regions may establish technical leadership and determine the norms of a rising market in the short to medium term. A foothold in the hydrogen value chain may help businesses compete more effectively. The immediate economic stakes are substantial, as is the market potential. In the long run, nations with abundant renewable energy resources might become hubs of green industries, attracting energy-intensive companies.

In the future years and decades, equipment manufacturing presents a chance to create profit. The hydrogen value chain is complex, and most investments could go towards renewable energy. By the middle of the century, estimations indicate more than a USD 50 billion market for electrolysers, and nearly a USD 21 billion market for fuel cells will be created along this value chain [13]. While China, Europe, and Japan have established a firm foothold in producing and selling electrolysers, the business is still in its infancy. Innovation and new technologies have the potential to alter the manufacturing world as we know it.

While any kind of hydrogen has the potential to increase energy independence and resilience, the majority of the advantages are likely to accrue from green hydrogen. Today, there are three primary ways that hydrogen might help energy security: firstly, by lowering import dependency; secondly, by reducing price fluctuations; and, thirdly, by increasing the energy system's flexibility and resilience via diversifying primary energy resources. The majority of these advantages are related to green hydrogen.

It is improbable that hydrogen trade flows will become politicized or cartelized. This is because hydrogen may be created using a wide number of primary energy sources and in many locations across the planet. Indeed, hydrogen is a product, not a raw resource or energy source. As a result, green energy economic relations are improbable to be as susceptible to geopolitical impact as crude oil and natural gas trade flows.

A few years back, hydrogen was regarded as a minor energy source in the global energy debate. It is becoming a critical component of decarbonization initiatives for more difficult-to-abate sectors, with an increasing number of nations and businesses banking on its widespread adoption.

3.4. Threats

The hydrogen industry will be fiercer and less profitable than the oil and natural gas industries. Green and blue hydrogen will not produce the same level of returns that oil and natural gas produce now. The hydrogen supply will be controlled by the rate of capital deployment and the production cost, especially in areas where markets, in the long run, are uncertain. Blue hydrogen would adapt to the changes in the gas market, increasing dependency on imports and market instability. Additionally, the predicted cost reductions in green hydrogen mean that investing in fossil fuel-based supply chains may become stalled.

The raw materials required for hydrogen and renewables will increase awareness of material-supplying security concerns. While geological supplies of the majority of minerals and metals are now adequate, markets may become highly constrained due to fast-expanding demand and the long lead times associated with mining and processing projects [58]. A seemingly minor change in demand or supply might result in significant price changes. Such volatility might have repercussions across the hydrogen supply chain, affecting the total cost of equipment and the income of raw material exporters. Supply shortages are possible, especially during hydrogen trade's inception, when the providers' number is low and bilateral agreements control the bulk of the trade.

4. Recommended Strategies

To monitor and control hydrogen's contribution to climate change efforts, certificates of origin based on a transparent and reliable system will be required. Transparency in the manner in which emissions are measured will be critical. Carbon lock-in is a well-known concern if hydrogen plans continue to rely on fossil fuels and impede energy savings and electrification. Robust and well-considered legislative frameworks may assist in ensuring that hydrogen contributes successfully to greenhouse gas emission reductions.

Assisting developing countries in their early adoption of hydrogen technology has the potential to improve everyone's energy security while averting the global decarbonization divide from worsening. A diverse hydrogen market would decrease supply chain-associated risks and improve energy security for everyone. Access to technology, education, capacity building, and inexpensive financing will be vital for hydrogen to fully fulfil its promise of decarbonizing the global energy sector and contributing to international peace and equality. Implementing hydrogen trade links might pave the way for establishing local hydrogen value chains, stimulating green industries, and creating jobs in nations with abundant renewable energy resources.

The market for hydrogen-related equipment is still in its infancy and is very fragmented and complex. Electrolysers and fuel cells are two critical parts of the hydrogen value chain. These two types of equipment provide the best opportunity for governments and businesses to acquire value and position themselves as industry leaders in the future years and decades. These technologies are more developed than those in other value chain segments. Electrolysers were regarded more strategically than any other component of the hydrogen value chain, while fuel cells were considered critical for technical leadership [13]. Developed strategies based on the SWOT analysis are presented in Table 1.

Table 1. SWOT strategies.

	Strengths (S):	**Weaknesses (W):**
	S1: No infrastructure is required for fuel transfer (due to the transportation methods available for compressed gases). S2: Readiness of community for the energy transition. S3: Control of power fluctuations for optimal integration with alternating renewable energy sources is possible. S4: Energy security.	W1: The low availability and high cost of small electrolysis systems are problematic W2: No support for after-sales services. W3: High purchase cost. W4: Conversion to hydrogen is not cheap. W5: Conversion equipment is expensive, and the process consumes a lot of energy. W6: Undeveloped hydrogen infrastructure.
Opportunities (O):	**SO Strategies:**	**WO Strategies:**
O1: Support of Japanese government. O2: New job opportunities. O3: Diversity of companies in the energy sector. O4: Reducing environmental impacts. O5: Carbon dioxide emission-limiting norms may be an incentive to accelerate the development of hydrogen technology. O6: High social acceptability.	• Faster development of renewable energy through financial incentives. • Utilizing LNG terminals for clean hydrogen imports. • Large-scale development of blue hydrogen. • Popularization of FCVs.	• Use budget programs to reduce the cost of purchasing equipment and systems. • Accelerate the development of hydrogen technology to increase efficiency. • Create new business lines for employment and expand the workforce to support services. • Government incentives for the development of infrastructure (government subsidies and tax breaks). • Foreign investments in technology development related to hydrogen industry.
Threats (T):	**ST Strategies:**	**WT Strategies:**
T1: Inexperienced users. T2: Insufficient business plan. T3: Inadequate legal framework. T4: Many barriers, especially low cost and efficiency, prevent large-scale hydrogen technology's introduction. T5: Unconfirmed market potentials	• Develop a suitable platform for business plans. • Propose appropriate laws and policies. • Cooperate in the development of international projects. • Encourage private sector participation.	• Utilization of international experiences in the clean hydrogen industry. • Improving hydrogen infrastructure. • Creating suitable conditions for holding training courses for required technicians. • Establishment of needed hydrogen industry standards.

5. Conclusions and Policy Recommendations

The hydrogen economy promises to improve Japan's energy security and lower greenhouse gas emissions. To assist stake holders/decision makers in comprehending the current state of the hydrogen economy in Japan and afterward developing practical long-term strategies that advance the development of the hydrogen economy in Japan, a SWOT analysis of the current state of the hydrogen economy in Japan was conducted, and practical strategies were recommended.

Several sub-factors were considered in the SWOT analysis, including abundant global resource reserves, high development potential, and environmental benefits (all of which are regarded as strengths); high cost, a lack of critical technologies, and incomplete hydrogen infrastructure (all of which are considered as weaknesses); state funding, high social acceptability, and deepened cooperation (all of which are regarded as opportunities); and a lack of investment channels and competitive pressures from other renewable resources (among the threats). These sub-factors were identified to illustrate the current state of Japan's hydrogen economy. Four distinct types of strategies (SO, WO, ST, and WT strategies) were identified, with SO strategies focusing on the large-scale development of coal–hydrogen technologies with CCS and the popularization of fuel cell vehicles; WO strategies focusing on government subsidies and tax breaks, as well as foreign capital importation; ST strategies focusing on encouraging private sector participation in industrialization; and WT strategies focusing on establishing clean hydrogen industry and market standards, technologies, and infrastructure.

As a resource- and raw material-poor yet economically and sophisticated country, Japan will need to develop hydrogen in its energy infrastructure during the next several decades to address energy and climate issues. The government concentrates its efforts on the full zero-carbon hydrogen supply chain, from manufacturing to transportation and end-use applications. Japan's ambitious approach includes several cross-sectoral experimental initiatives involving local and overseas industry and government players. At the moment, economic and technological hurdles and uncertainties remain. Before considering the integration of hydrogen into large-scale economic and energy programs, the government is awaiting the results of pilot projects. While the public budget is steadily increasing, the government's caution against any long-term commitments remains limited and reflective. The carbon mitigation of Japan's energy infrastructure is still based on nuclear energy, renewable energy sources, energy efficiency measures, and natural gas. Japan's success depends on its capacity to create and use huge quantities of clean hydrogen at a cost comparable with alternative fuels. Cost parity is also dependent on implementing an effective carbon tax and carbon pricing. Hence, global policy coordination and inter-industry cooperation will be increasingly needed.

Investment in hydrogen supply chain is a challenging, high-risk, decision-making activity. Part of the complexity comes from the existence of factors including cost, technical readiness, safety, environmental impacts, and ease of handling. All this means that in order to reduce the risk of investment, we need to use multi-criteria decision-making methods by weighting the importance of factors. A SWOT analysis is a qualitative method. We should move towards qualitative–quantitative methods such as SWOT-AHP. Additionally, introducing qualitative–quantitative decision support tools for helping such decisions is necessary for future research.

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