Assessment of Hydrogen Adoption Readiness in Energy Sector using Indicator-Based Analysis

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พัชรี เพ็ญจันทร์ : การประเมินความพร้อมของการใช้เทคโนโลยีไฮโดรเจนในภาคพลังงานโดยการวิเคราะห์ตามตัวบ่งชี้. (Assessment of Hydrogen Adoption Readiness in Energy Sector using Indicator-Based Analysis) อ.ที่ปรึกษาหลัก : ดรวีรินทร์ หวังจิรนิรันดร์

ความกังวลทางด้านสิ่งแวดล้อมทั่วโลกทำให้ประเทศต่างๆ เช่น ญี่ปุ่นและไทยแสวงหาแหล่งพลังงานทางเลือกเพื่อให้บรรลุเป้าหมายด้านสิ่งแวดล้อมและแผนดำเนินงานแห่งชาติที่ได้วางไว้ ไฮโดรเจนได้รับการบรรจุเข้าเป็นวาระด้านพลังงานเพื่อเป็นแนวทางในการจัดการกับความท้าทายด้านพลังงานและกำหนดอนาคตของประเทศ การศึกษานี้วิเคราะห์ความพร้อมของญี่ปุ่นและไทยในการนำเทคโนโลยีพลังงานไฮโดรเจนมาใช้โดยการเปรียบเทียบตัวชี้วัด โดยญี่ปุ่นมีประสบการณ์ในการพัฒนาโครงการพลังงานไฮโดรเจน ในขณะที่ไทยกำลังสำรวจศักยภาพของเทคโนโลยี งานวิจัยนี้ได้นำเสนอกรอบดัชนีและตัวบ่งชี้ที่เกี่ยวข้องกับไฮโดรเจนในการประเมินระบบพลังงานของประเทศ กรณีศึกษาประเทศญี่ปุ่นและประเทศไทย การศึกษานี้มีวัตถุประสงค์เพื่อระบุตัวบ่งชี้เพื่อประเมินความพร้อมของเศรษฐกิจไฮโดรเจนเพื่อวัตถุประสงค์ในเชิงพาณิชย์และการกำหนดนโยบาย โดยศึกษาความพร้อมของเทคโนโลยีไฮโดรเจน อุตสาหกรรม และสังคมในการนำไฮโดรเจนไปใช้อย่างเต็มรูปแบบ ผลการศึกษาพบว่าญี่ปุ่นมีความโดดเด่นเหนือกว่าไทยในทั้งในด้านนโยบายและการออกกฎหมาย เทคโนโลยีและนวัตกรรม โครงสร้างพื้นฐาน และศักยภาพทางการตลาด ในขณะที่ไทยจำเป็นต้องปรับปรุงกรอบนโยบายและกฎหมายและการออกกฎหมาย

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Global environmental concerns have led countries like Japan and Thailand to seek alternative energy sources to meet environmental goals and country agenda. Hydrogen has been added to the energy agenda as a way to address the energy challenges and shape the country's future profile. This study analyzes the readiness of Japan and Thailand to adopt hydrogen energy technology by comparing indicators. Japan experienced in developing hydrogen energy projects, while Thailand is exploring the technology's potential. The research proposes a hydrogen-related indicator framework to evaluate a country's energy system in Japan and Thailand case. The study aims to identify indicators to assess the readiness of the hydrogen economy for commercial and policy-making purposes, focusing on the hydrogen technology, industry, and society readiness towards full-fledged hydrogen adoption. Japan outperformed Thailand in policy and legislation, technology and innovation, infrastructure, and market potential, while Thailand needs to enhance its policy and legislative framework.

Field of Study:	Energy Technology and Management (Interdisciplinary Program)	Student's Signature ....
Academic Year:	2022	Advisor's Signature ....

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Chapter 1 Introduction & Background

Hydrogen has drawn the new wave of focus on low-carbon solutions and additional benefits whereby it can assist the countries to the success in the Nationally Determined Contribution and Net-Zero Emission targeted to achieve in 2050 [1, 2]. Governments of many countries have initiated to promote the transformation and innovation of renewable energy [3]. Over 70 million tonnes production of global hydrogen market was worth $135 billion in 2019 while 10 million tonnes of the demand coming from China. Global electrolyzer production potential capacity is currently above 2 GW per annum, and it is forecast to exceed 4.5 GW on the basis of current expansion commitment [4].Developed countries already have experience with large-scale hydrogen projects [5]. Due to its intermittent property, power companies still require natural gas power plants for connection and backup [6, 7].

Typically, large-scale power plants are part of a centralized traditional power grid system that delivers electricity in one direction to each end user. In contrast, the emerging grid is based on a decentralized and independent microgrid infrastructure created by renewable energy sources like solar, wind, and hydrogen fuel cell generators [8, 9]. By integrating a smart grid, users can prioritize the use of renewable energy and meet peak power demands, while also being able to share any excess electricity with neighboring users through a peer-to-peer electricity trading system. rading system operates through an energy certificate scheme known as cap and trade. As countries anticipate increased demand for hydrogen production in order to achieve net-zero emissions targets, the modernized electricity framework allows them to harness local renewable resources at decreasing costs for both renewables and hydrogen. However, expanding this infrastructure requires significant investments and scaling up [7, 10].

European countries, the United States, Japan, and other nations worldwide have implemented strategic plans to transition to a hydrogen-based society. The adoption of green hydrogen is driven by several factors, including the reduced cost of electrolysis facilitated by solar and wind energy, the availability of scalable technologies, the potential benefits for the energy system as a whole, the versatility of hydrogen for various applications, the growing future demand for hydrogen, and the potential synergies that can lower the overall cost of hydrogen across the entire value chain [10]. However, there are several obstacles to widespread adoption, including: 1) the high production costs, which are typically 2-3 times higher compared to grey hydrogen, 2) the absence of dedicated infrastructure for hydrogen transportation, 3) energy losses during the production and distribution process, 4) uncertainty regarding the value and recognition of green hydrogen, and 5) the need to guarantee that the hydrogen produced is sourced from environmentally friendly means. Additional challenges include meeting the fluctuating renewable energy demands for long-duration storage. Despite these challenges, the use of green hydrogen presents opportunities for local industry growth development [10].

This addresses an increasing demand for clearer policy direction for transitioning as there are the unknown challenges faced by private sector [11-14]. On the other side, the policy makers are unable to formulate the policy as the problem identification process does not have information from private sector side. The paper aims to study dimension of hydrogen adoption in energy sector amidst of transition by using indicator-based analysis for at least two selected economies in response to the potential demand from interest seekers to eliminate asymmetric information problem [11, 12, 15]. The index helps the interest seekers to identify the opportunities according to the dimension in each indicators of driven factors so that the key policy makers draw mechanisms in fostering the transition initiation. Hence, the index would be tools for the interest seekers either by public or private side enjoy the advantage being as the first mover in hydrogen economy [16-18].

1.1 Goal

To gain the tools to assess the hydrogen economy status on for commercial and policy making purpose

1.2 Objectives

- To identify the indicators to be considered for the development of index to assess the readiness of hydrogen adoption in energy sector
- To propose policy implications from gap analysis – urgency plan, short term and long term

1.3 Scope of Work

This study assesses hydrogen adoption in energy sector in 2 countries, cases of Japan and Thailand in the aspects of Policy and Legislation, Technology and innovation, Infrastructure, and Market. The assessment period was taken during May 2021 – February 2023.

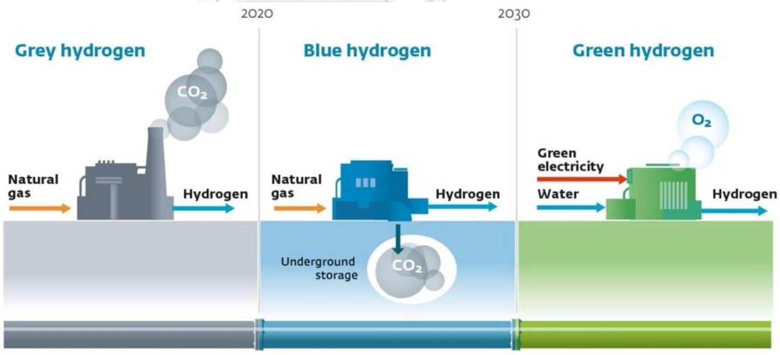
To address the research questions, goals, and objectives outlined earlier, this study is divided into five chapters, including the current chapter. Chapter 2 provides an extensive background and literature review of previous research, which aids in establishing the originality of this study. Chapter 3 outlines the research methodology, including the selection of information sources, dimensions, and indicators. Chapter 4 presents the calculation results and discusses the findings of the study. Finally, Chapter 5 serves as the conclusion of the thesis, summarizing the key findings and implications.

Chapter 2 Theory and Previous Research

2.1 Hydrogen Economy

The concept of the hydrogen economy involves generating molecular hydrogen through various methods such as converting coal, natural gas, nuclear energy, or renewable sources like bioenergy, wind, and solar power. This hydrogen is then transported, stored, and utilized as a fuel in fuel cells where it combines with oxygen to generate electricity (and some heat). Different colors are assigned to different types of hydrogen based on their generation methods [19]. Green hydrogen is produced from water through electrolysis, utilizing renewable electricity like solar and wind power. Nuclear electricity can also be used to generate hydrogen, known as 'yellow hydrogen' Blue hydrogen is produced through steam methane reforming with carbon capture, utilization, and storage (CCUS), using natural gas or biomass, resulting in very low or no CO_2 emissions [10, 20-22] see Figure 1. On the other hand, gray hydrogen is produced through steam methane reforming without CCUS, using natural gas, and it generates a significant amount of CO_2 Furthermore, the incorporation of fuel cells in the propulsion of vehicles or the generation of electricity and heat for residential, commercial, and industrial structures facilitates a more rapid acceptance and implementation of this technology [10, 20-22], see Figure 2-4.

Figure 1 Indication of Hydrogen by shades



Source: [23]

Acknowledging the widespread utilization of hydrogen in the economy encounters notable obstacles in terms of advancing its development and achieving successful commercialization. These challenges encompass a broad spectrum, ranging from the essential requirements of research and development (R&D) to surmounting infrastructure limitations and attaining social acceptance [24]. A rising number of governments have enacted tangible policies aimed at fostering the adoption of hydrogen usage. Currently, 18 governments have formulated comprehensive plans for the implementation of hydrogen energy solutions [25]. Notably, a coalition of governments within the Energy Ministerial has recently announced their objective to achieve a worldwide deployment of 10 million fuel cell electric vehicles (FCEVs) by 2030 [25, 26].

Additionally, countries such as China, Japan, the US, and South Korea have initiated projects with the goal of constructing 10,000 hydrogen refueling stations by 2030 [25].

2.1.1 Transport

The transportation industry stands out as the most promising field for utilizing hydrogen, attracting significant research and investment. In 2018, the government allocated a substantial $700 million towards this cause [25]. Hydrogen has great potential for powering fuel-cell electric vehicles (FCEVs) [20, 27]. Although there were around 11,200 passenger FCEVs available worldwide in 2018, the greatest opportunity for hydrogen lies in the transportation of goods and long-distance trucking [20, 27]. This is mainly because alternative options like battery electric vehicles (BEVs) and hybrid technologies, which offer lower carbon emissions, are still in early stages of development and come with high costs [28]. The increased adoption and success of these vehicles in the market can be attributed to the growing integration of building energy systems with more practical mobility, driven by economic incentives promoting renewable energy consumption in buildings. The greatest potential for hydrogen lies in commodity transport and long-haul trucking, as alternatives such as battery electric vehicles and hybrid technologies are still relatively underdeveloped and expensive. FCEVs operate by generating electricity through a fuel cell stack fueled by hydrogen, which then powers an electric motor. The vehicle's driving capability is determined by the size of the electric motor(s) rather than the capacity of the battery. FCEVs typically have a driving range of 300-500 km, surpassing that of battery electric vehicles, and their range depends on hydrogen storage. Some examples of FCEVs include the Toyota Mirai, Hyundai Tucson, Honda Clarity, Mercedes-Benz GLC F-CELL, and Hyundai Nexon [28].

2.1.2 Energy

Hydrogen has the capacity to serve as both a fuel and an energy storage medium when integrated with renewable power systems. This is due to its ability to utilize surplus energy generated by renewable sources to produce hydrogen fuel. The worldwide shift towards renewable energy sources positions "Green hydrogen" as a key player in the energy landscape [1, 25].

2.1.3 Heat

Hydrogen has the potential to be mixed into current natural gas distribution systems, allowing buildings to utilize it for heating purposes. Around 10-20% of the capacity of existing gas infrastructure can be modified to accommodate hydrogen, often at minimal or no additional cost. This presents a significant opportunity in the near future, with an estimated total of 4 million tonnes of hydrogen being available for heating applications by 2030 [25].

2.1.4 Feedstocks

Currently, the primary utilization of hydrogen is in industrial sectors, particularly in oil refining and ammonia production, which account for about two-thirds of hydrogen feedstocks. However, there is considerable potential for low-carbon hydrogen applications in the future, particularly in steel manufacturing and high-temperature heat production. Realizing this potential would necessitate substantial quantities of low-carbon power generation [25].

2.1.5 Exports

Currently, the majority of hydrogen is produced and used within the same site, known as captive usage. This is common in applications such as ammonia production or petroleum refining. Consequently, there is limited demand for hydrogen transport and storage. However, in the future, as hydrogen finds wider application across various industries, there will be a significant increase in demand, necessitating the development of extensive transport and storage systems. In some cases, hydrogen may need to be converted into suitable forms for transportation, which could incur additional costs. However, this also presents opportunities to produce hydrogen in cost-effective locations and transport it to other areas for use [29, 30].

The export sector provides new avenues for countries engaged in developing the hydrogen economy, enabling partnerships for the import and export of hydrogen. This global trade in hydrogen transforms it into a commodity and supports the establishment of a hydrogen-based economy [31, 32].

Energy is considered a network good that exhibits a club effect. This means that the utility individuals derive from energy increases as the number of consumers within the network grows (club goods are characterized by both excludability and non-rivalry). Investments in infrastructure, such as transportation, water networks, and energy networks, are justified due to the positive externalities they bring to the economy. Therefore, the construction of new infrastructure not only generates direct effects but also indirect effects that enhance factors of productivity within the economy. Although public expenditure on such infrastructure may lead to a crowding out effect by reducing the demand for private factors, it also contributes to increasing their productivity within the public sector. As a result, the theory of economics in network industries suggests that a reduction in costs and an overall increase in production can be expected.

Economic theory provides an explanation for the transition to a hydrogen-based economy. This transition necessitates the establishment of a transmission infrastructure, including an adequate number of hydrogen stations that are well-distributed. A "chicken-or-egg" dilemma arises when there is a lack of demand due to the unavailability of a network, and no agent (such as energy companies or equipment manufacturers) is willing to provide the necessary infrastructure and technology until there is sufficient demand. As a result, both the supply and demand sides need to evolve concurrently. To mitigate risks and costs, a well-organized transition is required to ensure the simultaneous development of both supply and demand.

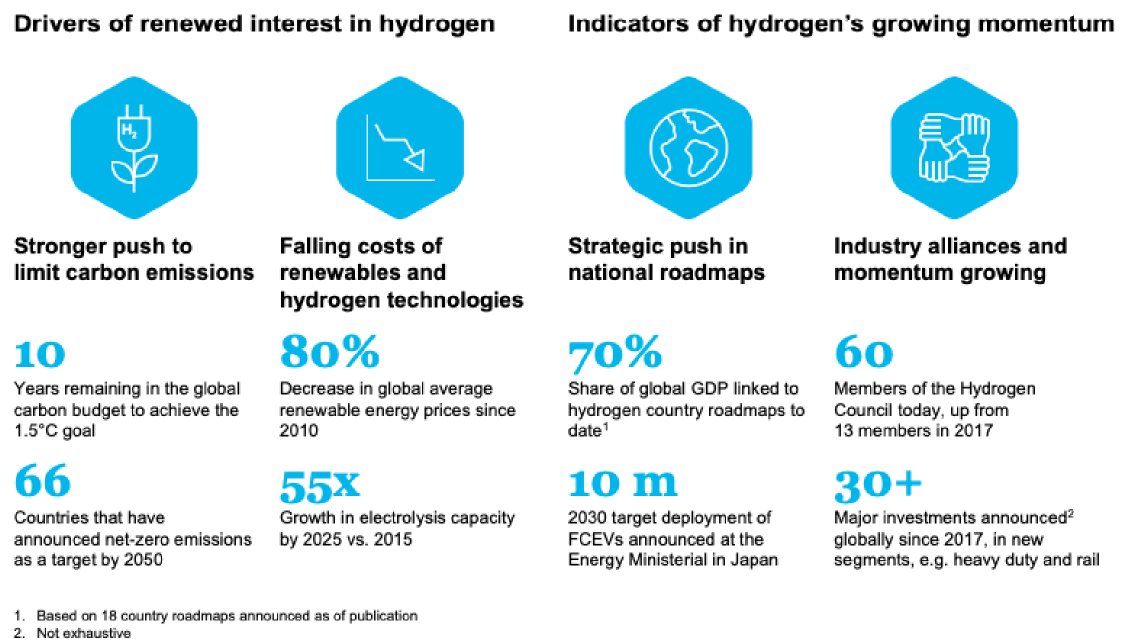


Figure 2 Drivers and indicators of hydrogen's momentum

Source: [25]

2.2 Hydrogen Economy Transition

The timeline of the hydrogen cost competitive transition according to Bloomberg Energy Finance [21], the energy research institute is forecasted as followed:

From 2020 to 2025, hydrogen has the potential to become a viable option in the transportation sector, particularly for large vehicles that require long ranges like trains, trucks, coaches, taxi fleets, and forklifts. Additionally, hydrogen proves to be a competitive alternative for heating and industrial processes due to its demand as a feedstock. However, in the short term, all applications face challenges in terms of cost competitiveness compared to conventional alternatives. This is mainly due to the higher cost of hydrogen technology, limited infrastructure, and lack of scale.

By 2030, as the costs of hydrogen production and distribution decline, many more applications are expected to become competitive against low-carbon alternatives. This includes most road transport applications except for short-range use cases such as compact cars and short-distance buses. Other examples include the use of simple cycle hydrogen turbines for peak power generation, hydrogen boilers, and industrial heating.

Looking further ahead to 2050, most of the evaluated hydrogen applications have the potential to compete favorably against low-carbon alternatives. In a scenario aiming to limit global temperature rise to 2 degrees Celsius, total worldwide CO2 emissions need to be reduced by over 90% compared to current levels. Achieving such a significant reduction requires the widespread adoption of low-carbon hydrogen solutions alongside other measures like electrification and carbon sequestration.

Envisioning the future is crucial for the widespread adoption of hydrogen, but it requires substantial financial support. Cumulative subsidies of USD 150 billion by 2030 are necessary to drive down the cost of clean hydrogen, both from renewable sources and low-carbon hydrogen derived from fossil fuels with carbon capture and storage. The aim is to achieve a delivered cost of USD 15/MMBtu in many regions worldwide by 2030. Furthermore, the delivered costs could potentially decrease even further to USD 7.4/MMBtu by 2050 [21, 22]. This scenario would position clean hydrogen as a competitive option compared to current natural gas prices in countries such as China, India, Brazil, and Germany. Implementing clean hydrogen at these cost levels could lead to the reduction of up to one-third of global emissions from fossil fuels and industry, with a potential reduction of 20% in global emissions achievable for under USD 100/tCO2 by utilizing hydrogen priced at USD 7.4/MMBtu [21, 22].

However, despite the immense potential, the signs of scaling up hydrogen production and utilization are not yet apparent, primarily due to insufficient policy support [22]. Bloomberg New Energy Finance has identified seven key indicators for investors to monitor, as they can provide insights into the emergence of a hydrogen economy [21].

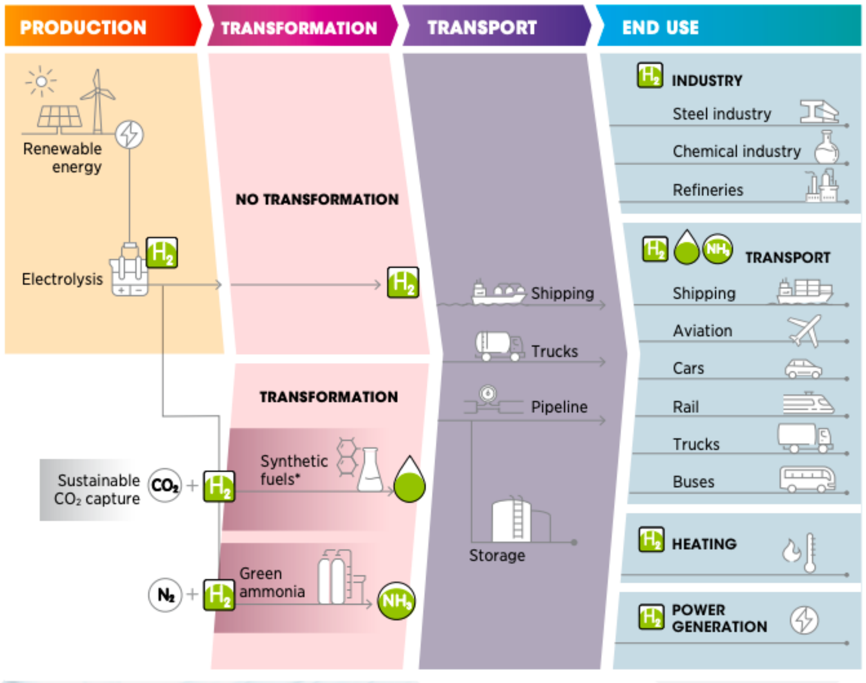


Figure 3 Green hydrogen production, conversion and end uses across the energy system

Source [10]

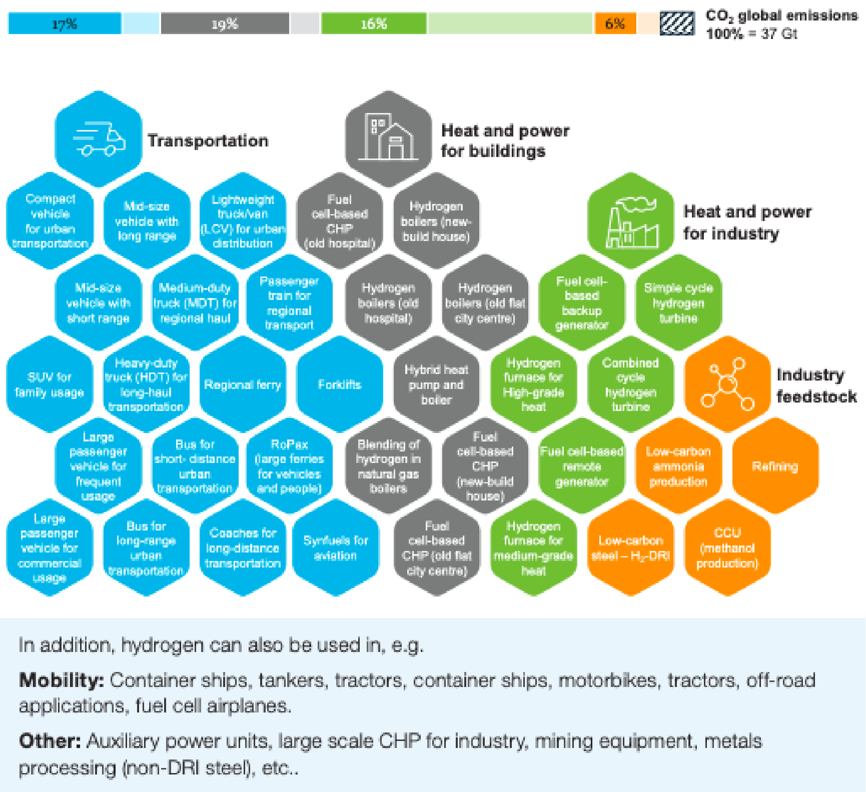


Figure 4 Overview of Hydrogen Applications

Source: [25]

2.3 Current Situation in Japan

In Japan, the government has established an ambitious objective of achieving a net-zero emission society by 2050. To accomplish this goal, the government has outlined a plan that involves revising policies regarding coal-fired power plants, fostering research and development in solar photovoltaic technology and carbon recycling technologies such as bioenergy with carbon capture and storage (BECCS). Furthermore, a communication platform was established in October 2020 to facilitate collaboration among government agencies in their efforts towards decarbonization. These initiatives have been prompted by the growing significance of environmental, social, and governance (ESG) investment, as well as an increasing recognition of the urgent climate risks faced by the business sector [33-35].

In order for Japan to successfully transition towards achieving net-zero emissions by 2050, it is imperative that appropriate measures are implemented [36]. This would involve a significant revision of the current 2030 target (the Nationally Determined Contribution, NDC), which is deemed insufficient. The revision would need to be carried out through Japan's Basic Energy Plan [37], accompanied by concerted efforts from all sectors. For instance, there must be a decisive phase-out of coal power, as the current trajectory falls far short of the target. The aim is to reduce plant emissions from 26% to 4% by 2030. As part of the overall plan, Japan has made the commitment to no longer provide financial support to overseas coal-fired power plants lacking decarbonization strategies. Local governments play a crucial role, as their commitment to achieving net-zero emissions encompasses 58% of Japan's total population and contributes USD 3.3 trillion to the GDP. This commitment serves to encourage and drive actions by cities, regions, and businesses[33, 36].

Furthermore, it is essential to eliminate the use of gas and other fossil fuels in existing residential and commercial buildings, despite the existing lag in progress. This action is necessary to achieve net-zero emissions by 2050 and align with the goal of having Zero Energy Buildings (ZEB) and Zero Energy Houses (ZEH) by 2030 [33, 36].

2.4 Current Situation in Thailand

Thailand is implementing its inaugural legislation specifically aimed at addressing climate change and fulfilling its obligations under the Paris Agreement [38]. Thailand has submitted its Nationally Determined Contribution (NDC), which outlines its plan to reduce greenhouse gas (GHG) emissions. The country intends to achieve an unconditional reduction of 20% from the projected emissions level by 2030, compared to the typical scenario [39]. Additionally, Thailand has expressed its conditional commitment to reduce emissions by 25%, contingent upon receiving increased support in terms of green technology advancements, financial resources, and capacity building. These intentions have been communicated to the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC). Thai authorities, in collaboration with the Energy Minister, the Natural Resources and Environment Minister, and the private conglomerate Siam Cement Group, have commenced the initial stages of developing a preliminary blueprint. This master plan aims to guide Thailand towards achieving a state of zero net carbon emissions. The primary objective of the plan is to establish long-term strategies for climate change mitigation and the reduction of CO2 emissions within the country. The anticipated unveiling of this plan was scheduled to take place during the 26th session of the UN climate change conference (COP26) in Glasgow, Scotland on November 12, 2021, which was hosted by the UK.

The plan encompasses several initiatives designed to transform Thailand's energy landscape and reduce CO2 emissions. These initiatives include diversifying the fuel mix in the power generation sector to decrease carbon intensity, expanding the electric vehicle (EV) industry, and implementing waste management strategies based on the principles of a bio-, circular, and green economy. Furthermore, the plan incorporates measures to promote the production of low-carbon goods, implement smart projects in agricultural and urban areas, and establish a carbon capture and storage system. These efforts aim to set specific targets for emissions reduction and ultimately achieve a state of net zero emissions on an annual basis[40, 41]. However, later in 2022, during COP27 on November 7, 2022, Thailand presented an updated LT-LEDS, which included ambitious objectives aiming for carbon neutrality by 2050 and achieving net zero greenhouse gas emissions by 2065 (ONEP, 2022). These revised targets demonstrate a notable acceleration from Thailand's initial LT-LEDS proposal submitted prior to COP26. In the earlier submission, Thailand had committed to achieving carbon neutrality by 2065 (Thailand Government, 2021) [38].

Regards to energy sector, Thailand's energy authorities and the Federation of Thai Industries are currently in the process of drafting the Thailand Integrated Energy Blueprint (TIEB) [40, 41]. This blueprint aims to establish a goal of zero carbon emissions and develop plans in response to the growing trends in renewable energy and electric vehicles (EVs). It also takes into account the impact of these trends on the supply chain of internal combustion engines (ICE), as well as plans for oil, gas, alternative energy development, and energy efficiency [42].

In addition to renewable energy and EVs, the TIEB considers various other factors, such as the surplus generation capacity, the development of electric and high-speed train systems, the depletion of domestic natural gas reserves, and the advancement of 5G telecommunications. The Secretary General of the National Economic and Social Development Board has emphasized the need for the energy authorities to prepare for the integration of energy storage systems for renewable resources [43]. The cost of these facilities, which is crucial for power trading among businesses and households, is becoming increasingly competitive compared to the traditional fossil fuel-based grid. The future energy business model is expected to shift towards independent power production by businesses and households, with the private sector playing a significant role. Peer-to-peer power trading is also anticipated to become more prevalent.

According to the TIEB, the main sources of energy will be renewable fuels and liquefied natural gas, while reliance on coal and oil will continue to decrease. The plan includes an electricity policy that prohibits the construction of new coal-fired power plants. The Mae Moh plant, with an installed capacity of approximately 650 megawatts, will be the last coal-fired power plant supplying electricity to the state grid. New tenders for power plants will only consider clean fuel options or, at the very least, clean fossil fuels such as natural gas, in accordance with the Power Development Plan 2018-2037 [40, 41, 43]. The plan also aims for a high share of natural gas (55%) and a reduced reliance on coal (18%). Conventional power plants with low efficiency will be phased out more quickly [43].

In terms of oil, Thailand is exploring the potential of hydrogen as an alternative. Efforts are being made to develop Bio-Hydrogenated Diesel (BHD) technology to replace diesel and other jet fuels [41, 43]. Discussions are also underway regarding the improvement of refinery quality to meet Euro 5 standards. Thailand currently utilizes hydrogen mainly for industrial purposes, and there is a limited number of suppliers and demand in the hydrogen sector.

Thailand is also focusing on upgrading its renewable energy sector to boost the bio-economy. Three privatized electricity authorities have invested in the development of a national renewable energy database platform. The Federation of Thai Industries' Institute of Industrial Energy has provided information on EVs, estimating that if all 20 million ICE vehicles in Thailand were replaced with EVs, the country could save up to 100 billion Baht annually in crude and refined oil imports. These savings could be utilized to establish a fund worth up to 2 trillion Baht over the next 30 years. Approximately 200 billion Baht could be allocated to the development of EV charging infrastructure and mitigating the negative impact on the oil-powered vehicle supply chain, with the remainder being allocated to other development projects [40, 41, 43].

The Energy Minister expects that the deadline to achieve the goals outlined in the TIEB will be determined later but should not significantly differ from similar goals set by the US and EU, which aim for zero emissions by 2050. The minister envisions a clear long-term plan and a comprehensive list of actions to be implemented [40, 41, 43].

The production cost of hydrogen, as studied by the guideline for the development and utilization of renewable energy promotion in Thailand in 2021, is made up of several components.

Firstly, it is important to recognize that hydrogen is necessary to accomplish the objective of achieving carbon neutrality by 2050 and attaining net zero greenhouse gas emissions by 2065. This highlights the crucial role of hydrogen in the long-term sustainability goals.

In the short term, international regulations such as the Carbon Border Adjustment Mechanism (CBAM) will have a notable impact. These regulations are likely to influence the production cost of hydrogen and shape its market dynamics.

According to the document by the Energy Research Institute, Chulalongkorn University [44], it presents the opportunities in the market of power plant and factories connected to gas pipeline through the mixture of fuel in the natural gas pipeline network and heating for industry to the factories in other area to the residual oil and the LPG users. They are mostly located the central part of Thailand [44]. The fuel could take the impact on the electricity tariff and thus the impact on GHG mitigation in power system. The forecast of the installed capacity share is expected to be about 35% of the approximate 120,000 MW (120 GW) in 2040. Light duty vehicle (LDV) FCEV in transport sector is possible to reach 610.23 THB per 100 Kilometer. In the short to medium-term (2031-2040), the objective is to achieve a fleet of 10,000 heavy-duty Fuel Cell Electric Vehicles (FCEVs) by the year 2040 [44]. Additionally, plans involve establishing a supply hub for blue and green hydrogen specifically located on the eastern seaboard. It is also crucial for the FCEVs to possess a range of 400 kilometers, ensuring efficient and reliable transportation. To support these vehicles, approximately 70 check points and resting areas will be set up along the designated routes [44].

Looking towards the long-term goals (2041-2050), the target is to increase the number of heavy-duty FCEVs and Light Duty Vehicles (LDVs) to 27,000 by 2050. This estimation takes into account the existing 351 Natural Gas Vehicle (NGV) stations for heavy-duty trucks and their usage patterns. As a result, the requirement for heavy-duty FCEV stations can be determined [44]. Furthermore, the plan includes the establishment of approximately 180 hydrogen refueling stations to cater to the growing demand for FCEVs and ensure widespread accessibility. The estimate figures for the preliminary research, to the case of maximum 25%, 50%, and 75% maximum share in the energy sector (power generation, industrial use, and transportation in 2040), are 2.5, 7, and 18 Mtoe per year respectively [44].

The potential of blue and green hydrogen in Thailand in the maximum case of 25% is possible to reach 0.03-11.94 Mtoe per year and 100.98 Mtoe per year respectively according to the forecast by Chulalongkorn Energy Research Institute based on Gas plan 2018 of the Alternative Energy Development Plan (AEDP) [44].

The blue hydrogen through the steamed Methane Reforming Process with carbon capture storage and green hydrogen in the transition could meet the potential demand without excess supply by 2033. The transition is expected 100% supply of green hydrogen of 1 Mtoe in 2034 [44].

Key driving forces for Thailand's would be the international regulation e.g. CBAM. In the short run, the hydrogen planning in 2022–2030 will be about the preparation of pilot program, technology, infrastructure and regulation to the safety for usage and production [44]. The commercialization phase in the medium-term plan is expected in 2032-2040 in the market of power and heat used in the blending 10-20% in gas pipeline and 10,000 heavy-duty FCEVs. Market incentives would be driven by the impact to the end users and tax incentives [44].

Infrastructure is expected to established in the medium term for the import and export such as the terminal that including the carbon capture storage and carbon capture, utilization, and storage infrastructure. Hydrogen refueling station will be in hub-spoke layout with more than 70 stations to connect within 400 km [44]. Under the regulatory of the standard for controlling the quality and property of the mixed fuel altogether with the storage and transportation [44].

Thereby, according to the potential draft plan, it is inclined that study of the readiness assessment to the hydrogen in Thailand is tentatively beneficial to further development of energy strategy from the visions of the Thai authorities which shape in line with the international theme of development to the net zero emission. Figure 5 present the resource potential to develop the hydrogen economy by Chiyoda Corporation that explored about Thailand hydrogen possibilities. Thailand's hydrogen supply potential could make up to 21,077,000 Normal Cubic Metres Per Hour (Nm3/h) obtained by gasified method, flaring gas, by-product, mid small gas, solar & wind, and biomass. Solar & wind derived hydrogen in central and western region and hydrogen from biomass in undesignated area are accounted for 57.77% and 34.30% of the total supply potential respectively. These two resources are summed up for over than 90% of the potential. The third potential lied in gasified hydrogen with 5.24% in northern and central and eastern region of Thailand. This implies the potential to utilize the current resource for the hydrogen technology and adoption development in the areas [45].

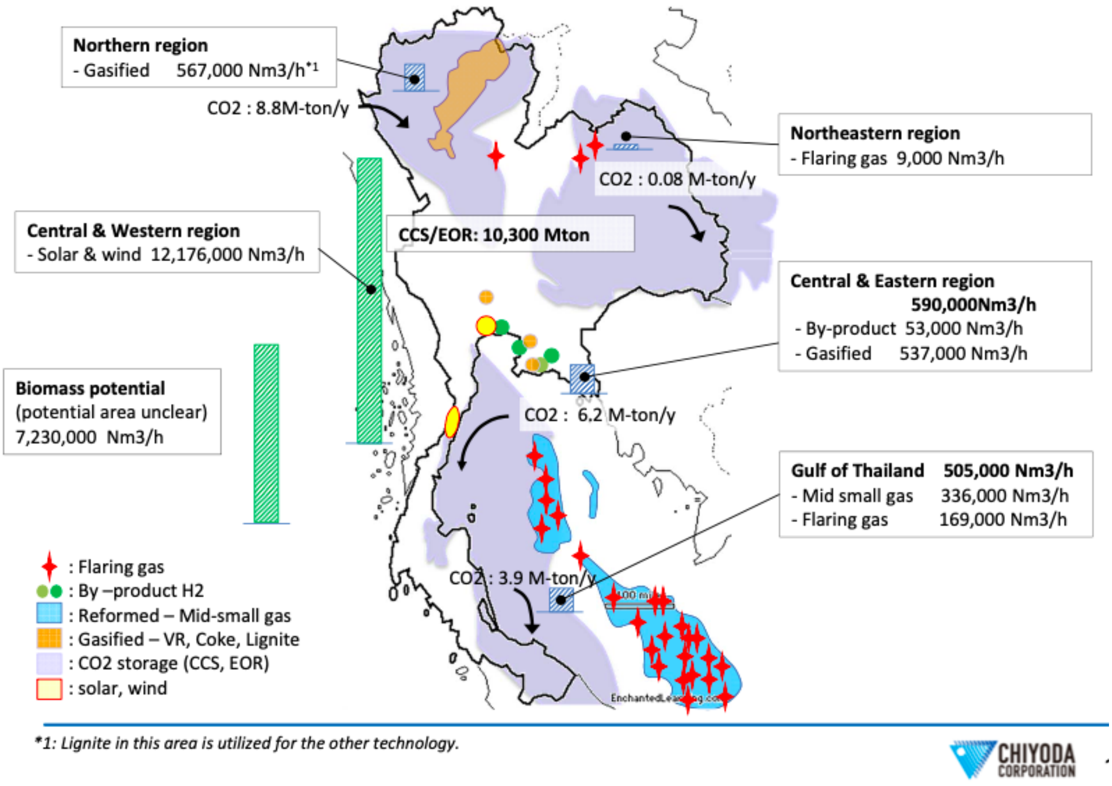


Figure 5 Hydrogen Supply Potentials In Thailand : Resource Map [45]

2.6 Previous Studies on Indicator Selection

The development of indicators has evolved over time. Currently, a group of experts is making efforts to establish guidelines for indicator development[42, 46-53], aiming to facilitate the evaluation of social issues aligned with public policy. They have proposed a checklist to aid in the process [48]. The checklist suggests answering the following questions:

- What is the aspect being measured, such as input, output, or outcome?
- Does it fulfill the SMART criteria, which stands for Specific, Measurable, Attainable, Relevant, and Time-bound?
- Based on the responses to the aforementioned questions, what is the revised indicator being proposed?

However, there is a potential challenge in completing the checklist for indicator development due to the complexity of choices involved. To address this, many research programs and organizations utilize a Multi-Criteria Analysis (MCA) as a tool to determine a set of assessments for decision-making in public policy or organizational contexts [54, 55]. The advantages of using MCA include its ability to identify the most feasible choices, rank them, and constrain options based on value scores. MCA involves identifying different dimensions, such as rating the importance level of each criterion and calculating the combined weight score for each criterion. The options provided by MCA can be combined with expert opinions for further validation [56, 57].

-Identify assessment criteria: The MCA allows for the measurement of key outcomes related to relevant objectives or potential impacts, which may not be adequately covered by traditional checklists. Precautions when setting the criteria include ensuring completeness, avoiding the use of the same words in different criteria, and ensuring independence between each criterion.

-Analyze relative importance of criteria (weighting): This step involves determining the relative importance or weight assigned to each criterion in the decision-making process. The weighting process typically starts with simpler criteria and progresses to more complex ones.

-Perform analysis or assign ratings: Prior to scoring, it is important to explain the significance of the rating scale. The scoring can be done through three basic methods:

- Direct assessment: Experts assess and assign scores (e.g., 0-100, 1-5, 0-10) to each criterion;
- Comparison of criteria: Criteria are compared to make decisions by establishing a hierarchical development from lowest to highest;
- Alternatives comparison: Alternatives are compared to each other using a method that transitions from a simple descriptive hierarchy to a more complex calculation.

-Calculate weighted scores: Once multiple weights and scores are assigned for each choice, the scores are divided by the total score of each option. The criteria associated with the scores for each choice are summarized, resulting in an overall assessment of each choice.

This study adapts the indexing method in the previous research in relevant to the introduction of Autonomous Vehicle Readiness Index 2020 developed by KMPG [13], Energy Transition Index 2020 [58], Bloomberg H2 Economic Ranking [59] and Indicators Related To Power Generation Investment for Each Aspect [60] because there are some mutual characteristics either to the new technology or the sector that it involves with. The shared characteristics help to shape dimension aspect and possible list of proposed indicators to better meet H2 side needs before going to the expert scoring.

Chapter 3 Methodology

3.1 Overall Research Process

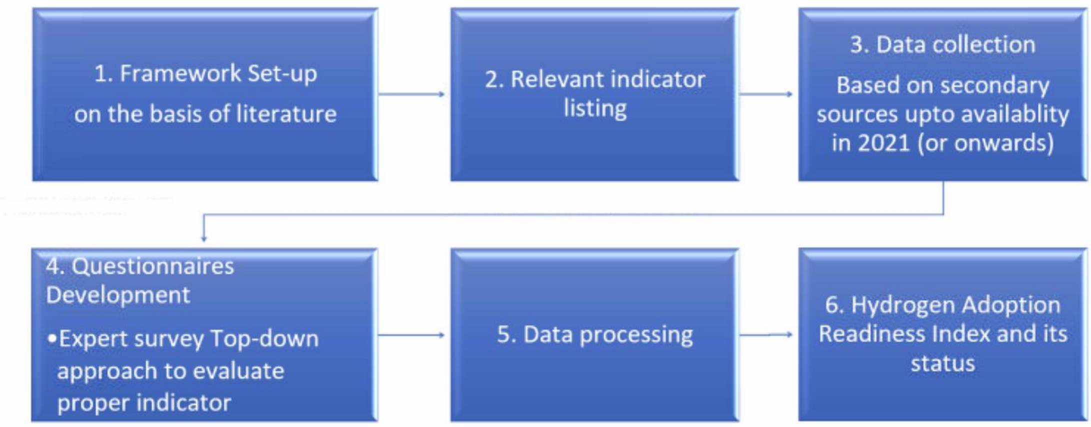


Figure 6 Research Process

Figure 2 illustrates the research steps undertaken in this study. Each stage is described in detail within the corresponding section of this chapter.

Step 1-2 involved establishing the framework and compiling a comprehensive list of relevant indicators. The framework was constructed based on a thorough analysis of collected data and information from various sources, including academic research, energy-related literature, reports generated by the government, research institutes, and business-related publications, which were extensively discussed in Chapter 2. These secondary sources provided valuable insights into the dimensions of the framework and served as the basis for formulating the proposed indicators.

Step 3, data corresponding to each indicator were obtained. This involved collecting data from secondary sources, as well as utilizing expert survey data for dimensions where relevant information was not readily available. By gathering data from various sources, a comprehensive dataset was compiled, ensuring a robust analysis. To validate the relevance of indicators to dimensions of the research, it is proposed to the expert in Step 4.

Step 4, the questionnaire were developed and distributed by the online platform. The questionnaire collected the relevance score of each indicators and input to some indicators.

Step 5-6, the questionnaire were developed and distributed by the online platform. The questionnaire collected the relevance score of each indicators and input to some indicators and proceeded to the data analysis.

3.2 Synthesis of framework

The framework for this study, focused on the hydrogen economy, was adapted from previous research on index development to align with the specific needs of assessing H2 adoption readiness. The framework was used previously in the Case of Japan in my previous analysis. It consists of four main dimensions: Policy and Legislation, Technology and Innovation, Infrastructure, and Market. These dimensions were chosen to evaluate the current stage of hydrogen adoption in Japan. The study identified relevant indicators for hydrogen adoption in the energy sector.

The Japanese Government's "Hydrogen Basic Strategy," formulated in 2017 and outlining the vision for 2050, serves as a key data source and provides the structure for the assessment framework. The strategy includes ten action items: 1. Realization of low-cost hydrogen utilization, 2. Development of international hydrogen refueling stations, 3. Expansion of domestic renewable energy introduction and regional revitalization, 4. Use in the electric power field, 5. Use in mobility, 6. Possibility of hydrogen utilization in industrial process/heat utilization, 7. Fuel cell technology utilization, 8. Innovative technology utilization, 9. International expansion (standardization, etc.), and 10. Public acceptance promotion and regional cooperation. The data set will be normalized on a linear scale of 1-5. The readiness level for hydrogen adoption is assessed based on the strategy outlined in the Japan case study, as shown in Table 1. The process of adoption readiness begins with identifying the need, progresses through the early phase, conducts trials with previous technologies in the primary industry, establishes a presence in the market, and eventually transitions to broader adoption in the market.

The some data input were collected in rubric scoring system by using the criteria on Table 6 and Table 7. The comparative assessment is presented with radar chart and analysis of descriptive statistics. Analysis of the hydrogen readiness expects to propose the policy implication.

Table 1 Hydrogen Adoption Readiness Level

Readiness Level	Readiness Level Description
1 Need identification	The country identifies its need. The production and end use of hydrogen remain in the existing technology and sectors.
2 Early adoption	Normal existing use of hydrogen in the establish sector. Initial market starts to trade in wider sectors with the early stage of regulatory regime, limited support from government investment. R&D is hugely needed the fund by government led policy. The adoption to the end in limited scale.
3 Trial utilisation of the	The government invests in the support to key targeted sectors

introduced hydrogen technology in main industry	where hydrogen energy and transportation systems are commercially accessible but still expensive with subsidies from government. The supply sector tests the water as well as the user. Policy and legislation are laying down to the public hearing.
4 Adoption to market settlement	Market utilisation is still in limited use in few sectors, R&D in some former key areas relies on the private sector pocket and the grant to support start to stop. The production and end use starts to the international trade by the government assistance for the international standard management to drive down the cost. The infrastructure received the subsidies from government fund and operated under special fast-track law.
5 Adoption to the market expansion	End use of the hydrogen is diversified in many sectors with establishment market and infrastructure; The policy is established and environmentally. sustainable hydrogen energy system without carbon emissions in the international scale. Some hydrogen energy technology is adopted and proven to be economically viable.

3.3 Proposed Indicators

Dimension 1 Policy and Legislation was represented by the 8 proposed indicators in Table 2 drawn from previous studies, and includes the represented indicators in the commitment in climate agenda that drive the country to focus on hydrogen as an alternative solution, the government financial instruments that lead to pilot development programs, the establishment of designated responsible entities, the regulatory support for hydrogen production and utilisation, and the government's responsiveness to change. The proposed indicators are described as follows:

P1 - Commitment on GHG mitigation:

The commitment of governments to reduce greenhouse gas (GHG) emissions is critical to the development of policies and legislation related to hydrogen. The percentage of GHG mitigation commitment, provides a framework for countries to develop policies and legislation that promote the deployment of low-carbon technologies, including hydrogen.

P2 - Target year to achieve net zero emission:

Setting a target year to achieve net-zero emissions is important in providing a clear direction for the development of policies and legislation related to hydrogen. This can help to drive investment and effort in low-carbon technologies, including hydrogen, and ensure that policy and regulatory frameworks are aligned with the goal of achieving net-zero emissions.

P3 - Government funding H_2 pilot projects:

Government funding for hydrogen pilot projects is important in supporting the development and demonstration of hydrogen technologies. This can help to de-risk investment in hydrogen and build confidence in the technology, leading to potential increased private sector investment and deployment of hydrogen technologies at scale.

P4 - Establishment of H_2 focus agency:

The establishment of a dedicated hydrogen focus agency can help to coordinate policy and regulatory frameworks related to hydrogen and provide a central point of contact for stakeholders. This can help to streamline the development of policies and legislation related to hydrogen and ensure that the needs of stakeholders are adequately addressed.

P5 - Availability and coverage of technical standards for H_2:

The availability and coverage of technical standards for hydrogen are important in ensuring the safe and efficient deployment of hydrogen technologies. The development of technical standards can also assist in lowering barriers to entry for new market players and facilitate the interoperability of hydrogen technologies. It is regarded one of regulatory support indicators.

P6 - Regulatory support for fuel cell-based power generation (including combined heat and power (CHP) systems):

Regulatory support for fuel cell-based power generation, including combined heat and power (CHP) systems, can help to promote the deployment of hydrogen technologies in the power generation sector in supporting the decarbonization of the electricity sector and raising demand for hydrogen use.

P7 - Regulatory support for hydrogen fuel cell vehicles (FCVs):

Regulatory support for hydrogen fuel cell vehicles (FCVs) can help to promote the deployment of hydrogen technologies in the transportation sector. This can help to support the decarbonization of the transportation sector and increase the demand for hydrogen.

P8 - Government's responsiveness to change:

The responsiveness of governments to changes is important in ensuring that policies and legislation that may relate to hydrogen remain relevant and effective. Government’s adaptability of their policies and regulatory frameworks to changing circumstances and technological developments in order to promote the deployment of hydrogen technologies is considered relevant in this study. The data of government's responsiveness provided by Klaus Schwab World Economic on The Global Competitiveness Report in 2019 [61].

Table 2 Proposed Indicators for Policy & Legislation

Code	Indicator	Information Source	Literature Reference
P1	Commitment on GHG mitigation	[33, 38]	[53, 62]
P2	Target year to achieve net zero emission	[22, 63]	[31, 53, 62]
P3	Government funding H_2 pilot project	[22, 64]	[5, 65]
P4	Establishment of H_2 focus agency	[5, 66]	[31, 67]
P5	Availability and coverage of technical standard for H_2	[68] Survey	[22]
P6	Regulatory support for fuel cell-based power generation (including combined heat and power (CHP) systems)	[68] Survey	[22]
P7	Regulatory support for hydrogen fuel cell vehicles (FCVs)	[68] Survey	[22]
P8	Government’s responsiveness to change	[61]	[22, 61]

Dimension 2 Technology and Innovation Policy was represented by 4 proposed indicators (Table 3) including the representative indicators of the advancement in technologies, efforts from the private sector that make investment in hydrogen solution, the government instruments that lead to pilot development programs, and status of hydrogen technology readiness. The proposed indicators are detailed following:

T1 - H_2 related patent:

The number and quality of hydrogen-related patents is a key indicator of innovation in the hydrogen sector. Patents provide an indication of the level of research and development activity in the hydrogen sector and the potential for future innovation. The patent landscape also provides insights into the areas of technology development that are of most interest to industry players. This study employed the available data in the patents in fuel cell vehicle.

T2 - Industry investment on H_2:

Industry investment in hydrogen technologies relates in driving innovation and commercialization in the sector. Investment in research and development, as well as deployment of hydrogen technologies, can help to advance the technology readiness level and increase the competitiveness of hydrogen technologies in the market.

T3 - Value of H_2 pilot project:

The value of pilot projects related to hydrogen provides an indicator of the investment and innovation levels in the development and implementation of hydrogen technologies. Pilot projects not only reduce investment risks in hydrogen technologies but also contribute to valuable data and insights into the performance of these technologies in real-world applications.

T4 - Technology Readiness:

Technology readiness is a measure of the maturity of a technology and its readiness for commercial deployment. The assessment of technology readiness referred to the expert intuition viewed in the real-world situation according the rubric criteria.

Table 3 Proposed Indicators for Technology & Innovation

Code	Indicator	Information Source	Literature Reference
T1	H2 related patent	[69-71]	[53, 69, 72]
T2	Industry investment on H2	[22, 73]	[30]
T3	Value of H2 pilot project	[22]	[6, 72, 74-77]
T4	Technology Readiness	Survey	[11, 13, 78-84]

Dimension 3 Infrastructure (Table 4) is focused on the development, implementation and connection among stakeholders engaged in a hydrogen economy proposed on . Three proposed indicators that are relevant to this theme are:

I1- Readiness of hydrogen refueling stations (HRS): which refers to the availability and accessibility of hydrogen refueling stations for vehicles. The readiness of HRS relates to the widespread adoption of hydrogen fuel cell vehicles, as it enables long-distance travel and promotes confidence among users that they will be able to refuel their vehicles. A higher number of HRS indicates a more mature hydrogen economy and a greater potential for the adoption of hydrogen as a fuel.

I2 aimed to evaluate the investment in the development and construction of pipelines for the transportation of hydrogen from production sites to the end-users. The availability of a robust hydrogen pipeline infrastructure is relevant for the development of a hydrogen economy, as it enables the transportation of hydrogen in distances. A higher level of investment in pipeline infrastructure indicates a greater commitment to the development of a hydrogen economy.

I3 - Investment in hydrogen production with carbon capture and utilization or storage (CCUS): This indicator refers to the investment in the development and implementation of technologies that enable the production of hydrogen with reduced carbon emissions. Carbon capture, utilization, and storage (CCUS) technologies can reduce the carbon footprint of hydrogen production and enable the production of low-carbon hydrogen. A higher level of investment in CCUS technologies indicates a greater commitment to the development of a low-carbon hydrogen economy.

Table 4 Proposed Indicators for Infrastructure Dimension

Code	Indicator	Information Source	Literature Reference
I1	Readiness of hydrogen refueling stations (HRS)	[85, 86]	[78, 87-93]
I2	Investment in H2 transportation infrastructure (pipeline)	[34]	[67, 94, 95]
I3	Investment in hydrogen production with carbon capture and utilization or storage (CCUS)	[94]	[67, 94, 95]

Dimension 4 Market (Table 5) is focused on elements of market supply and deployment of hydrogen technologies in various sectors. The proposed seven indicators that are relevant to this dimension are:

Proposed indicator M1 - Market potential for hydrogen production supplies: This indicator seeks to evaluate the potential market for hydrogen generation. It considers the availability of hydrogen and the demand from various sectors.

Proposed indicator M2 - Renewable energy market potential for green hydrogen production: This indicator aims to assess the potential for producing green hydrogen using renewable energy sources. It takes into account the availability of renewable energy sources, such as solar and wind power, and the demand for low-carbon hydrogen.

Proposed indicator M3 - Cost competitiveness of hydrogen: This indicator aims to evaluate the cost competitiveness of hydrogen compared to other fuels.

Proposed indicator M4 - Potential market share of hydrogen in power generation: This indicator aims to assess the potential market share of hydrogen in the power generation sector. It determines the percentage of power generation derived from hydrogen.

Proposed indicator M5 - Potential market share of hydrogen in transportation: This indicator refers to the potential market share of hydrogen in the transportation sector. It considers the cost competitiveness of hydrogen compared to other fuels and the availability of hydrogen refueling infrastructure.

Proposed indicator M6 - Potential market share of hydrogen in other uses: This indicator refers to the potential market share of hydrogen in sectors such as agriculture, building, and industrial usage. It considers the cost competitiveness of hydrogen compared to other fuels and the availability of hydrogen infrastructure.

Proposed indicator M7 - Social acceptance of hydrogen-related technology use and production: This indicator assesses the social acceptance of hydrogen technologies, including hydrogen production, storage, and transportation. It takes into account public perceptions regarding the safety and reliability of hydrogen technologies. Expert evaluation considers societal readiness levels (SRL) to assess social perceptions towards infrastructure development. Higher levels of social acceptance indicate greater potential for hydrogen market adoption.

Table 5 Proposed Indicators for Market Readiness

Code	Indicator	Information Source	Literature Reference
M1	Market potential for supplies of H2 production	[96, 97]	[37, 42, 98-100]

M2	Renewable energy market potential for green H2 production	Survey	[42, 88, 101, 102]
M3	Cost competitiveness of H2	[34, 103]	[22]
M4	Potential market share of H2 in power generation	Survey	[104, 105]
M5	Potential market share of H2 in transportation	Survey	[89, 106]
M6	Potential market share of H2 in other use	Survey	[22]
M7	Social acceptance to the use and production of the H2 related technology	Survey	[22]

Table 6 Rubric Scoring Criteria

Code	Proposed Indicators	Scoring criteria				
		1	2	3	4	5
P1	GHG mitigation target	No commitment on GHG reduction	<30% within 2050	30-50% within 2050	50-80% within 2050	80-100% within 2050
P2	Target year to achieve net zero emission	No commitment on GHG reduction	achieve in 2060	achieve in 2050	achievement in 2040	achievement in 2030
P4	Establishment of H_2 Focus Agency	No				Yes
P5	Availability and coverage of technical standard for H_2	refer to Table 7 (below)				
P6	Regulatory support for fuel cell-based combined heat and power (CHP) systems	refer to Table 7 (below)				

P7	Regulatory support for hydrogen fuel cell electric vehicles (FCEVs)	refer to Table 7 (below)				
T4	Technology Readiness	Basic Research (TRL 1-2)	Proof of Concept and Lab Scale (TRL 3-4)	System Validation in the Relevant Environment (TRL 5-6)	Prototype and Full Scale Demonstration (TRL 7-8)	Commercialisation (TRL 9)
M2	Renewable energy market potential for green H_2 production	Not likely that hydrogen is produced by renewable source more than 1% in 2030	likely that hydrogen is produced by renewable source more than 1% in 2030	likely that hydrogen is produced by renewable source between 1%-2%in 2030	likely that hydrogen is produced by renewable source between 3%-5%in 2030	likely that hydrogen is produced by renewable source more than 5%
M4	Potential market share of H_2 in power generation	no potential use in power generation	<1% of power generation comes from hydrogen source within 2030	>1-3% of power generation comes from hydrogen source in 2030	>3-5% of power generation comes from hydrogen source in 2030	>5% of power generation comes from hydrogen source in 2030

M5	Potential market share of H_2 in transportation	no potential share target of Fuel Cell Vehicle	<1% of total cars on road within 2030	>1-3% of total cars on road within 2030	>3-5% of total cars on road within 2030	>5% of total cars on road within 2030
M6	Potential market share of H_2 in other use (Buildings, agriculture, or in industry)	<10% increases in consumption	<20% increases in consumption	<20% increases in consumption	>25%-30% of increases in consumption in 2030	>30% increases in consumption in 2030
M7	Social Technology to the use and production of the H_2 related technology	isolated idea, concept, Technology with potential for (sub-) systemic change, Low awareness and salience of hydrogen needs	Proof of concept with potential for systemic change	Socio-technical (sub-) system prototype NIMBYs accept	successful demonstration of positive systemic change and functional in good society sub system	integrated into normal practice within good life and society system

	Situation	Low awareness and salience of hydrogen needs	Perceived risks and benefits of hydrogen energy Opponents have negative attitude towards the hydrogen technology and related infrastructure	The NIMBYs[1] are neutral to hydrogen technology and do not accept its infrastructure The indifferent/ambivalent groups neither do not accept nor remain neutral the hydrogen & remain neutral to its infrastructure	The NIMBYs are positive to hydrogen technology but do not accept its infrastructure The indifferent/ambivalent groups are positive to the hydrogen technology and remain neutral to its infrastructure	People are able to support the hydrogen energy usage and its related infrastructure

NIMBY abbreviation for not in my back yard: a person who does not want something unpleasant to be built or done near where they live

Cambridge Dictionary. (n.d.). NIMBY | English meaning-- Cambridge Dictionary. Retrieved November 4, 2022, from https://dictionary.cambridge.org/dictionary/english/nimby

Table 7 The regulatory support criterion when the projects in energy and industrial sector around the world confronts the legal, political, and public domains according to Rubric Criteria for Indicators P5- P7 [68]

Criterion	5 – Good Practice	3	1 – Poor Practice
1. Representative	● Open access to process ● Participant funding available ● Other jurisdictions may participate	● Public participation present, but access and funding restricted	● No public participation
2. Transparent, Accountable, Impartial	● Timely publication and notice ● Registry easy to navigate ● Panel members, Commissioners free of conflict of interest ● Regulator independent	● Short notice, lack of communication ● Registry difficult to navigate ● Regulator has ties with industry but is not captured ● Some accountability mechanisms	● No public information ● Regulator captured ● No accountability mechanisms ● No or only unjustified decision statement ● High level of discretion

Criterion	5 – Good Practice	3	1 – Poor Practice
3. Deliberative	• Stakeholder, public participation in process design • Process facilitates deliberation • Creates shared body of knowledge/public forum	• Some stakeholder input into process • Some multi-way dialogue, efforts to mutually inform	• Government/regulator sole process designer • Process favours one-way communication, polarization, litigation • Closed forum
4. Well-informed	• Decision-makers obligated to consider all relevant information • Diverse knowledge sources • Mechanisms to address uncertainty (follow up, adaptive management) • Alternatives considered	• Discretionary factors to consider	• No direction to consider any factors • Legislation does not address sources of knowledge • No follow up, adaptive management
5. Integrated	• Requires cumulative impact assessment as	• cumulative impact assessment provided	• cumulative impact assessment not mentioned

Criterion	5 – Good Practice	3	1 – Poor Practice
	necessary ● Cohesive with other legislation, policy	for but not required or resourced ● Some effort at cohesion	● Not aligned with broader policies, strategies
6. Efficient	● Assessment proportionate to potential impact ● Not overly onerous or costly ● Coordination reduces duplication, boosts collaboration	● Multiple assessment levels, may not be proportionate ● Some timelines; may be discretionary, subject to variation, overly long ● Some coordination	● “One size fits all” approach ● No time limits ● Overly resource intensive, time consuming ● Substantial duplication, no coordination
7. Legitimate	● Process has public support ● Process carried out correctly ● Outcome socially and politically acceptable	● Process has some support ● Process carried out with few issues ● Outcome contested; narrowly acceptable	● Process lacks public support ● Process correctness in question or before courts ● Outcome rejected on multiple dimensions across many groups

Criterion	5 – Good Practice	3	1 – Poor Practice
8. Equitable	● Risks, benefits equitably distributed ● Future generations protected ● Other jurisdictions protected ● Local communities protected	● Some consideration of risks, benefits ● Some representation of local communities	● No consideration of risk, benefits; risks disproportionately borne without compensation ● No consideration of future generations and outside jurisdictions
9. Sustainable	● Social, economic, environmental interests balanced ● Durable and Adaptable	● Some effort to balance interests ● Somewhat durable	● Some interests sacrificed for others

3.3.1 Normalisation

Normalisation is a process that convert the original units of measurement to common units of measurement. Min-Max normalisation transformed the indicators so as to obtain the same range of the indicators by the subtraction of the minimum value and division of the range of index values. Normalisation is performed for a scale adjustment and transform skewed indicator. The data set will be normalized on a linear scale of 1-5 shown in (1).

$$x_i' = 1 + (n-1)(\frac{x_i - Min_x}{Max_x - Min_x}) \quad (1)$$

Where, x_i' is normalized value based on 1-5 scale, x_i is value of the original data set $X = [x_1 \dots x_i]$, and n is equal to 5 (n=5).

$\mathrm{Min_x}$ and $\mathrm{Max_x}$ are referred lowest an highest value/scale in the original data set X, respectively.

If the indicators have an inverse relationship with the scale, the normalization will be calculated using to the reverse formula shown in (2)

$$x_i' = 1 + (n-1)(\frac{x_i - Max_x}{Min_x - Max_x}) \quad (2)$$

Any secondary data availability is explored and later check whether it can be proceeded with reference to the distance to target or making to rubric score. Such indicator is dropped off in case that the data do not exist or unavailable.

3.3.2 Data Calculation Processing

Code	Description	Data Processing
P1	Percent of target	Rubric Scoring
P2	Target Year	Rubric Scoring
P3	Government funding H_2 pilot project value	Min-Max method with data from other 5 countries
P4	Establishment of H_2 Focus Agency	Rubric Scoring
P5	Availability and coverage of technical standard for H_2	Rubric Scoring (Survey)
P6	Regulatory support for fuel cell-based combined heat and power (CHP) systems	Rubric Scoring (Survey)
P7	Regulatory support for hydrogen fuel	Rubric Scoring (Survey)

	cell electric vehicles (FCEVs)	
P8	how the government is capable of respond to the change in new policy and draw the supporting measure	Rescaled from its original data of 7 point
T1	No. of patent (fuel cell)	Min-Max method with data among 8 countries
T2	R&D budget for hydrogen & fuel cell (Public) / Public RD&D Energy spending to reflect the industry investment	Min-Max method with data among 8 countries
T3	Value of H_2 Pilot Project	Min-Max method with among 8 countries
T4	Technology Readiness	Rescale TRL for rubric scoring (Survey)
I1	No. of FC vehicle / Fueling station	Min-Max method with data among 9 countries
I2	H_2 transportation infrastructure (pipeline) in kilometer	Min-Max method with data among 8 countries
I3	Investment value in hydrogen production with carbon capture and utilization or storage (CCUS)	Min-Max method with data from other 6 countries
M1	Market potential for supplies of H_2 production	Direct calculation to the forecasted figure of hydrogen generation to the total forecasted 219.2 Billion by 2030 and rescale 5 point
M2	Renewable energy market potential for green H_2 production	Rubric Scoring (Survey)
M3	competitive price against green alternative in any sector $/kg (of around $2)	Min-Max method with data from other 6 countries to create rubric scoring
M4	Potential market share of H_2 in power generation	Rubric Scoring (Survey)
M5	Potential market share of H_2 in transportation	Rubric Scoring (Survey)

M6	Potential market share of H_2 in other use	Rubric Scoring (Survey)
M7	Social acceptance to the use and production of the H_2 related technology	Rubric Scoring (Survey)

Chapter 4 Result and Discussion

4.1 Survey outcomes

There are 6 responses received online targeting the experts in the energy sector. 3 of them work in private sector. Their responsibilities are the area of coordination, management and engineering. While 3 of them are in the academia. 3 experts who performed the survey are from Japan. 2 of them have taken charge in hydrogen economy study more than 5 years of experience. The professional experience in hydrogen ranged from 1 year to more than 10 years, the survey responses provide with decision include all the proposed indicator list to four dimensions where the score of indicator relevancy shown on the data from the expert survey contained no lower outliers and fell into the 2SD range in each proposed indicator.

Table 8 Relevance Score - Dimension 1 Policy & Legislation

Code	Indicator	Relevance Score from expert survey
Dimension 1 Policy & Legislation		
P1	Commitment on GHG mitigation	9.00
P2	Target year to achieve net zero emission	8.33
P3	Government funding H_2 pilot project	9.33
P4	Establishment of H_2 focus agency	9.00
P5	Availability and coverage of technical standard for H_2	9.00
P6	Regulatory support for fuel cell-based power generation (including combined heat and power (CHP) systems)	9.67
P7	Regulatory support for hydrogen fuel cell vehicles (FCVs)	9.50
P8	Government's responsiveness to change	7.67

Table 9 Relevance Score - Dimension 2 Technology & Innovation

Dimension 2 Technology & Innovation		
Code	Indicator	Relevance Score from expert survey
T1	H_2 related patent	8.00
T2	Industry investment on H_2	9.00
T3	Value of H_2 pilot project	8.00
T4	Technology Readiness	8.50

Table 10 Relevance Score - Dimension 3 Infrastructure

Dimension 3 Infrastructure		
Code	Indicator	Relevance Score from expert survey
I1	Readiness of hydrogen refueling stations (HRS)	9.50
I2	Investment in H_2 transportation infrastructure (pipeline)	9.83
I3	Investment in hydrogen production with carbon capture and utilization or storage (CCUS)	8.00

Table 11 Relevance Score – Dimension 4 Market

Dimension 4 Market		
Code	Indicator	Relevance Score from expert survey
M1	Market potential for supplies of H_2 production	7.67
M2	Renewable energy market potential for green H_2 production	9.00
M3	Cost competitiveness of H_2	9.33
M4	Potential market share of H_2 in power generation	7.00
M5	Potential market share of H_2 in transportation	7.50
M6	Potential market share of H_2 in other use	8.50
M7	Social acceptance to the use and production of the H_2 related technology	9.00

Interesting information from the survey on the policy and legislation which is presented **Table 12** is that the representation indicators in the energy system for building the infrastructure and the potential technological development (P5) identified to be representative, deliverable, well-informed, integrated, efficient, legitimate, equitable, as reflect from third degree of the supportive process in regulatory development both to Japan and Thailand while the transparency and sustainability are given the fourth degree of the process to Japan. For the support to the development to the adoption for the utilisation of fuel-cell based power sector (P6), the experts reflect all nine criteria to the third degree to Japan, however, the regulatory support to the fuel-cell vehicles presented the better fostering environment than that of hydrogen fuel cell usage in the power sector. Overall, Thailand received the score from expert to the third degrees readiness in most subcategories to the representative Policy & Legislation indicators. Only the category of sustainability to availability and coverage to the technical standard was given to the fourth degree.

Table 12 Breakdown Readiness Results of Represented Regulatory Support Indicators

Criterion	Represented Regulatory Support Indicators					
	P5		P6		P7	
	Japan	Thailand	Japan	Thailand	Japan	Thailand
1. Representative	3.83	3.8	3.67	3.8	4.33	3.8
2.Transparent, Accountable, Impartial	4.00	3.6	3.83	3.6	4.00	3.8
3. Deliberative	3.33	3.6	3.83	3.4	3.50	3.6
4. Well-informed	3.67	3.4	3.83	3.6	4.17	3.8
5. Integrated	3.17	3.2	3.50	3.4	3.83	3.2
6. Efficient	3.20	3.8	3.17	3.6	3.50	3.8
7. Legitimate	3.83	3.6	3.67	3.6	4.17	3.6
8. Equitable	3.50	3.4	3.67	3.8	3.67	3.4
9. Sustainable	4.17	4.2	3.83	3.8	4.17	3.5
Score	3.66	3.622	3.67	3.622	3.93	3.61

Note: P5 - Availability and coverage of technical standards for H_2

P6 - Regulatory support for fuel cell-based power generation (including combined heat and power (CHP) systems)

P7 - Regulatory support for hydrogen fuel cell vehicles (FCVs)

4.2 Policy and Legislation Readiness Score:

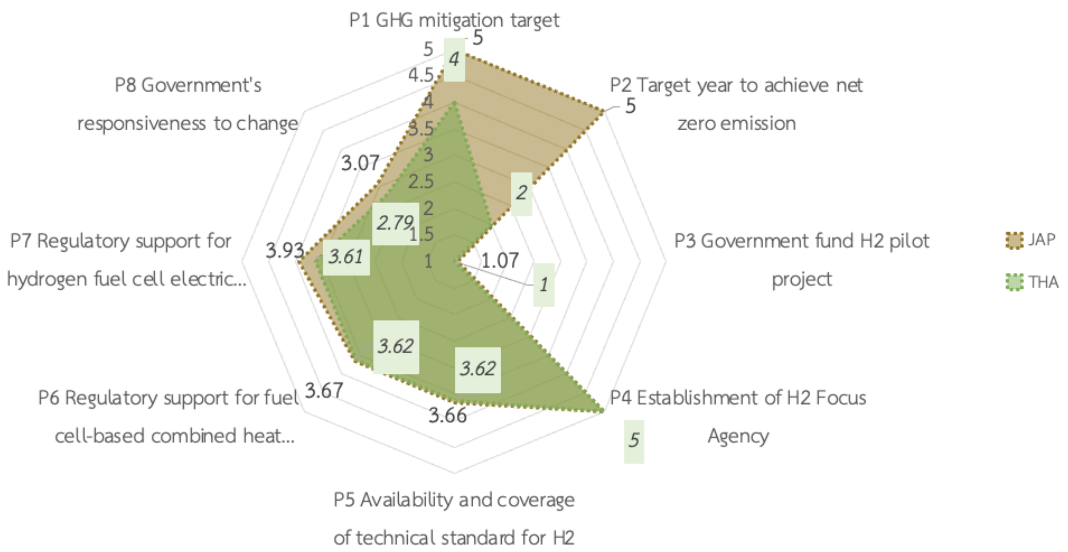


Figure 7 Policy & Legislation Readiness Score

Table 13 Policy & Legislation Readiness Score

Code	Indicators	Japan Score	Thailand Score
P1	GHG mitigation target	5.00	4.00
P2	Target year to achieve net zero emission	5.00	2.00
P3	Government fund H2 pilot project	1.00	1.00
P4	Establishment of H2 Focus Agency	5.00	5.00
P5	Availability and coverage of technical standard for H2	3.66	3.62
P6	Regulatory support for fuel cell-based combined heat and power (CHP) systems	3.67	3.62
P7	Regulatory support for hydrogen fuel cell electric vehicles (FCEVs)	3.93	3.61
P8	Government's responsiveness to change	3.07	2.79
	Score	3.80	3.21

Japan scores higher in policy and legislation compared to Thailand, with a score of 3.80 compared to 3.21 according to Figure 7 and Table 13. This suggests that Japan has a more comprehensive set of policies and regulations in place to support the adoption of hydrogen technology. Thailand set the target to the achievement in climate target to reach carbon neutrality by 2050 and net zero GHG emissions by 2065. Thailand pledged for 30-40% reduction within 2030 reduction [38, 107, 108]. This implies 74.2% reduction commitment within 2050. The research set the criteria for 50-80% within 2050 to fall in 4 score (P1), however, Thailand still set commitment year of achievement in the net zero emission by 2065 (P2) while the research set the criteria for having no commitment to get the lowest score of 1 and having the criteria to get the score of 2 in this for the achievement in 2060. The author scored the case of Thailand for 2 based on the reference to the achievement in net-zero commitment by Thailand within year 2065. Thailand needs to work on developing a more robust framework to support the adoption of hydrogen technology. A gap analysis compares the current state of a project or initiative against a desired or benchmarked state, identifying areas that need improvement. Based on the provided table, a gap analysis for the Hydrogen Adoption Readiness Index between Japan and Thailand was analysed as follows:

It has been observed that the Japanese government has made significant efforts to achieve the goals of climate agenda. However, when compared to other developing countries focusing on hydrogen, the government funding for hydrogen pilot projects appears to be lower based on the data provided in secondary sources. While the government's support for related laws and legislation processes is above average, its responsiveness to change is at a moderate level of 3.07.

To enhance the policy and legislation dimension, improvements can be made in supporting funding for pilot programs and engaging in regulatory processes that involve stakeholders and public participation. There is also a need for better dissemination of diversified knowledge to share information such as risks and benefits with local communities. It is possible to establish an integrated regulatory development program for the hydrogen economy sector by implementing a dialogue program for impact assessment and aligning it with other legislations and policies.

It has been observed that the Thailand government has made some efforts to achieve the goals of climate agenda. The government funding for hydrogen pilot project was placed. While the government's support for related laws and legislation processes is above average, its responsiveness to change is at lower than moderate level of 2.79. The session sharing among the stakeholder and research institutions is feasible to create a comprehensive regulatory development program for the hydrogen economy sector by introducing a dialogue program to evaluate its impact and ensuring alignment with existing legislations and policies to other renewables alternatives and risk on investment and security. Japan's score GHGs target 5.00, while Thailand's score is 3.00, indicating that Japan is better prepared to achieve net-zero emissions. There is a gap between the two countries in this area, suggesting that Thailand needs to set more ambitious efforts to target to achieve net-zero emissions. Both Japan and Thailand have similar scores of 1.00 Government fund H2 pilot projects (P3), indicating that both countries have the same level of government funding for H2 pilot projects. While, establishment of H2 Focus Agency (P4): Both Japan and Thailand have high scores of 5.00, indicating that both countries have established H2 focus agencies. Availability and coverage of technical standard for H2 (P5): Japan has a slightly higher score than Thailand in this area (3.66 vs. 3.62), suggesting that Japan has a more developed technical standard for H2. For regulatory support for fuel cell-based combined heat and power (CHP) systems (P6), Japan has a slightly higher score than Thailand in this area (3.67 vs. 3.62), suggesting that Japan has better regulatory support for fuel cell-based CHP systems. On regulatory support for hydrogen fuel cell electric vehicles (FCEVs) (P7), Japan has a significantly higher score than Thailand in this area (3.93 vs. 3.61), indicating that Japan has better regulatory support for FCEVs. Japan has a higher score in Government's responsiveness to change (P8) than Thailand in this area (3.07 vs. 2.79), suggesting that Japan is more responsive to changes in the H2 industry.

4.3 Technology & Innovation Readiness Score

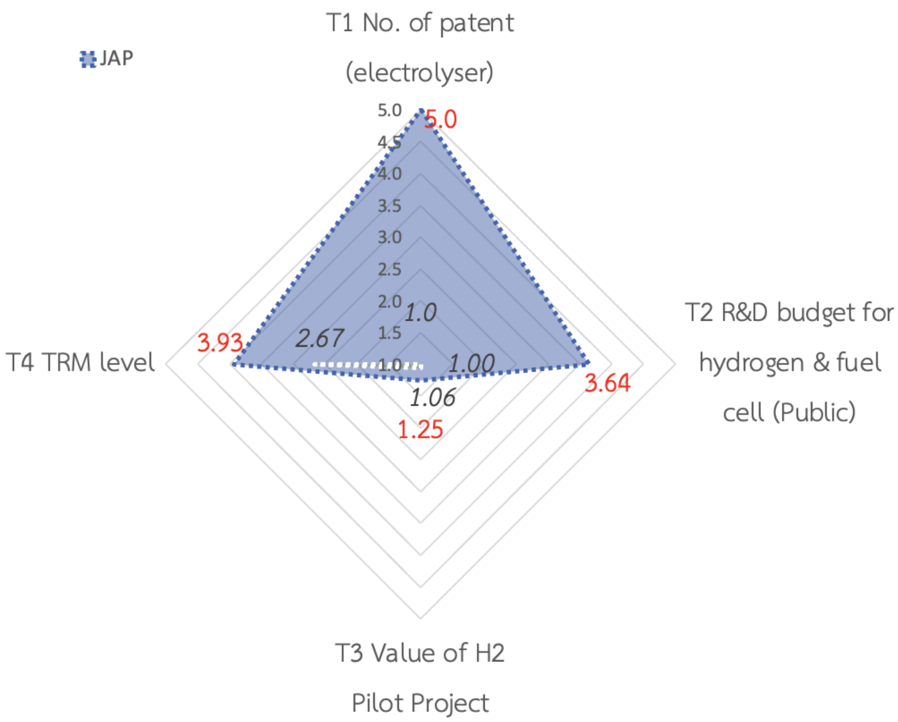


Figure 8 Technology & Innovation Readiness Score

Table 14 Technology & Innovation Readiness Score

Code	Indicators	Japan Score	Thailand Score
T1	H2 related patent	5.00	1.00
T2	Industry investment on H2	3.64	1.00
T3	Value of H2 pilot project	1.25	1.06
T4	Technology Readiness Level	3.93	2.67
	Score	3.46	1.43

Japan scores significantly higher in technology and innovation compared to Thailand, refer to Figure 8 and Table 14, with a score of 3.46 compared to 1.43. This suggests that Japan is more advanced in developing and implementing technology related to hydrogen. Thailand needs to invest more in technology and innovation to catch up with Japan.

During the study period, Japan demonstrated notable innovation in the field of hydrogen, as evidenced by a significant number of published patents related to hydrogen. Furthermore, the country has made considerable investments in the industry, although there is still room for improvement in this regard. In comparison to the other seven countries analyzed in the study, Japan's pilot projects investigating hydrogen are relatively extensive. However, when evaluating the local estimated readiness index dimension, which assesses the practical demonstration and real-world testing of the technology, Japan's score stands at 1.25, indicating the requirement for further progress.

On the other hand, Japan's technological readiness scores high at 3.93 due to the ongoing commercialization of hydrogen technology within its society. This has led to the cumulative development of local skills and expertise surrounding hydrogen technology. Consequently, the overall score for technology and innovation stands at 3.46. The lower average score is primarily influenced by the lack of emphasis on piloting efforts. This may be attributed to higher investment and dedication from the private and public sectors in research, experimentation, policy formulation, and theoretical studies, rather than in actual pilot projects. Piloting endeavors are generally expensive with limited immediate returns and higher risks involved.

Thailand has recorded a relatively low number of hydrogen-related patents published during the study period, indicating lower preparedness in innovation in the field align with other indicator scores indicating the need for further advancements. The data parallel to the rest indicators that Thailand needs the improvement of industry investment (1.00), the pilot program investment (1.06), overall technology readiness (2.67).

4.4 Infrastructure Readiness Score

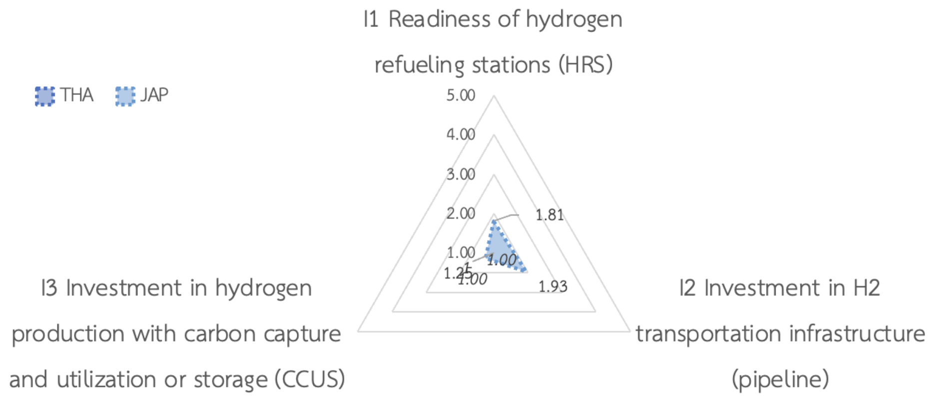


Figure 9 Infrastructure Readiness

Table 15 Infrastructure Readiness Score

Code	Indicators	Japan Score	Thailand Score
I1	Readiness of hydrogen refueling stations (HRS)	1.81	1.00
I2	Investment in H2 transportation infrastructure (pipeline)	1.93	1.00
I3	Investment in hydrogen production with carbon capture and utilization or storage (CCUS)	1.25	1.00
	Score	1.67	1.00

The infrastructure aspect consisted of three indicators that gauged the physical connectivity needed to meet the local market demand for hydrogen, encompassing factors like the extent of supply lines, refueling stations, and supporting systems like carbon capture. In general, all aspects of the infrastructure dimension received low readiness scores, as depicted in Figure 9 and Table 15. This can be attributed to the strict regulations in Japan and Thailand. Challenges related to the construction and expansion of current infrastructure that could be repurposed to facilitate hydrogen-related operations, such as existing natural gas supply lines, pose a significant issue to both countries. Japan scores higher in infrastructure compared to Thailand, with a score of 1.67 compared to 1.00. Japan has made more progress in developing infrastructure to support the adoption of hydrogen technology, including HRS and transportation infrastructure, compared to Thailand. Thailand needs to invest more in infrastructure to catch up with Japan. However, both countries need to invest more in infrastructure to support the adoption of hydrogen technology. Additionally, both countries should focus on investing in hydrogen production with carbon capture and utilization or storage (CCUS) to reduce the carbon footprint.

Readiness of Hydrogen refueling stations (HRS) (I1):

Japan has a higher score than Thailand in this area (1.81 compared to 1.00). This suggests that Japan has made more progress in developing the necessary infrastructure for refueling stations to support the adoption of hydrogen technology. Thailand needs to invest more in developing and implementing refueling stations to catch up with Japan.

Investment in H2 transportation infrastructure (pipeline) (I2):

Japan also scores higher than Thailand in investment in H2 transportation infrastructure (pipeline) (1.93 compared to 1.00). This indicates that Japan has made more progress in developing the necessary infrastructure to transport hydrogen, while Thailand needs to invest more in this area to support the adoption of hydrogen technology.

Investment in hydrogen production with carbon capture and utilization or storage (CCUS) (I3):

Both Japan and Thailand have a low score in investment in hydrogen production with carbon capture and utilization or storage (CCUS) (1.25 for Japan and 1.00 for Thailand). This indicates that both countries need to invest more in this area to promote the development of hydrogen technology while reducing the carbon footprint.

4.5 Market Readiness Score

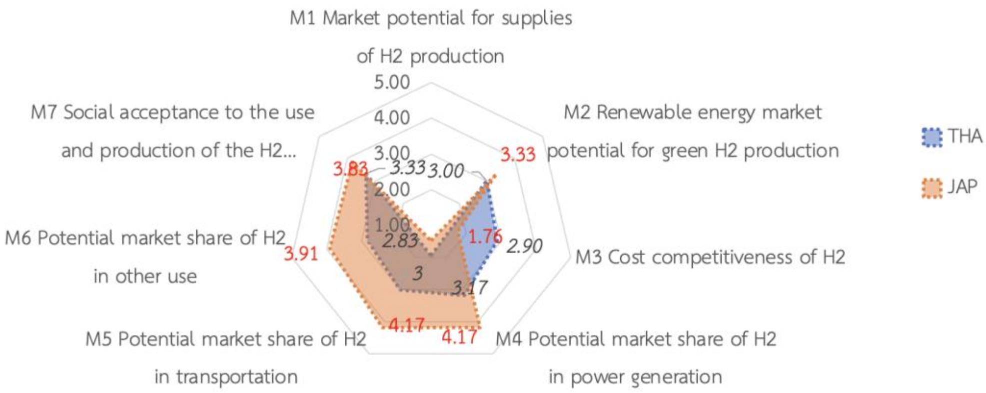


Figure 10 Market Readiness

Code	Indicators	Japan Score	Thailand Score
M1	Market potential for supplies of H2 production	0.57	0.16
M2	Renewable energy market potential for green H2 production	3.33	3.00
M3	Cost competitiveness of H2	1.76	2.90
M4	Potential market share of H2 in power generation	4.17	3.17
M5	Potential market share of H2 in transportation	4.17	3.00

M6	Potential market share of H2 in other use	**3.91**	**2.83**
M7	Social acceptance to the use and production of the H2 related technology	**3.83**	**3.33**
	Score	3.11	2.63

Table 16 Market Readiness Score

Japan scores higher in the market compared to Thailand, with a score of 3.11 compared to 2.63, refer to Figure 10 and Table 16. This suggests that Japan has a more favorable market environment for the adoption of hydrogen technology. Thailand needs to work on developing a more conducive market environment to support the adoption of hydrogen technology.

Market potential is a critical factor that affects the adoption of hydrogen technology. In this regard, Japan has a higher score than Thailand in all sub-indicators, except for the cost competitiveness of H2 (M3) sub-indicator. Japan's scores for potential market share of H2 in power generation (M4), potential market share of H2 in transportation (M5), and potential market share of H2 in other use (M6) are all higher than Thailand's scores in these areas. Looking at the result shown in the research, it can be analyzed according to Thailand's roadmap towards 2030 when is the period for the preparedness for readiness before commercialization on the scale 1-5. Thailand is fallen with the result of between 1% to 3% of power generation comes from hydrogen source in 2030 and between 1 to 3% of total cars on road within 2030, given the possible bias by the respondent intuition. Achieving a specific target like producing 1%-2% of hydrogen from renewable sources in 2030 depends on various factors such as government policies, technological advancements, investment in infrastructure, and the availability of renewable resources in Thailand. The result presented with the optimistic side of the survey respondents. This suggests that Japan has a greater potential to adopt hydrogen technology in various sectors.

However, both Japan has higher score in the social acceptance to the use and production of the H2 related technology sub-indicator (M7). Both countries still need to work on educating and raising awareness among the public to promote the adoption of hydrogen technology.

In terms of cost competitiveness of H2 (M3), Thailand has a higher score than Japan. This indicates that the cost of producing and using hydrogen in Thailand may be lower than in Japan, which could be an advantage for Thailand to attract investment in hydrogen-related projects and may have caused by inaccurate input.

Overall, Japan has a higher score in the market sub-indicator, indicating that Japan has a more favorable market for the adoption of hydrogen technology. However, Thailand's higher score in the cost competitiveness of H2 sub-indicator could be an advantage for attracting investment in hydrogen-related project. Towards 2030, without the driving force, which would possible to be driven the proper key targeted energy sector such as transportation such as the heavy-duty vehicles like ship, aircraft, big, the adoption of the hydrogen technology in market that would not be that promising. This would require further evaluation towards the market needs or possible business engagement by the private sector.

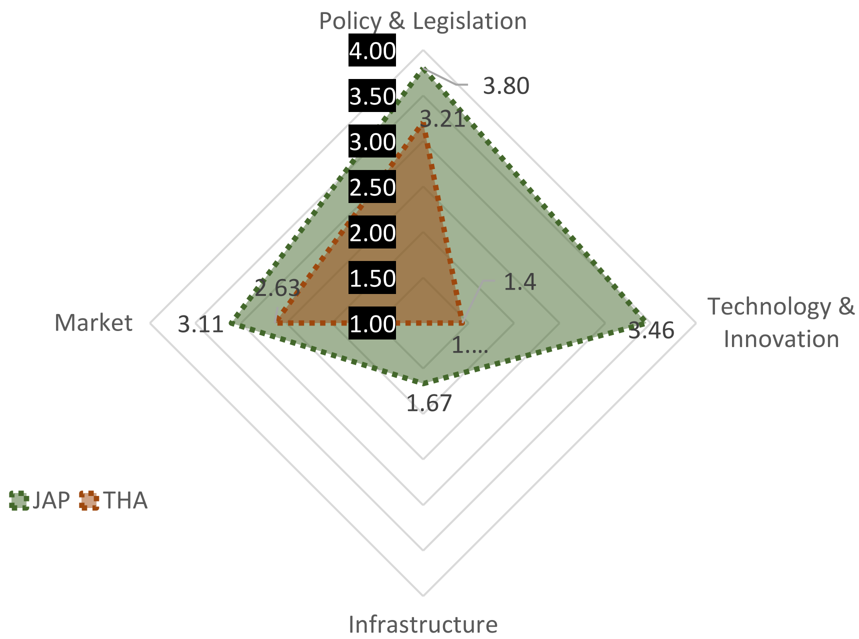


Figure 11 Hydrogen Adoption Readiness Score

Table 17 Hydrogen Adoption Readiness Overall Score

Indicators	Japan Score	Thailand Score
Policy & Legislation Score	3.80	3.21
Technology & Innovation	3.46	1.43
Infrastructure	1.67	1.00
Market	3.11	2.63

Hydrogen Adoption Readiness Index	3.01	2.07

4.6 Hydrogen Adoption Readiness Score

The overall score for hydrogen adoption readiness for Japan was calculated to be 3.01. Based on the findings presented in Figure 11 and Table 17 . This places Japan at readiness level 3, which indicates the country is at the stage of trial utilization of hydrogen technology in major industries. This suggests that the government is actively investing in this potential pathway to support key sectors. The policy and legislation framework is also adequately developed. However, it indicates that widespread adoption of hydrogen is still limited. Additionally, it highlights a lack of international management in the supply lines, which is crucial for reducing local costs of commercialization. Japan demonstrates strong readiness in terms of policy, legislation, technology, and the market.

The overall score for hydrogen adoption readiness for Thailand was calculated to be 2.07. Based on the findings presented in in Figure 11 and Table 17. This places Thailand at readiness level 2, which indicates the country is at the stage of early adoption. This suggests that hydrogen is currently used in established sectors in a typical manner. However, in the early stages of regulatory implementation, the market for hydrogen begins to expand into broader sectors with limited government investment support. There is a significant need for government-led policies to provide funding for research and development (R&D) as reflected by the score of 1.43. The overall adoption of hydrogen remains limited in scale until further advancements are made. While the real situation in Thailand may not seem to be that ready and promising in the market with the current direction for driving the related sector to the commercialization that soon before 2030. Given the current focus in developing other area of focus in transportation sector, battery electricity in now more on the focus for Thailand. Only a limited number of capacity of the big corporates shows the interest for the early investment and research.

However, the infrastructure dimension is the main area that requires significant improvement. This suggests the need for the establishment of an expedited infrastructure law to accelerate overall adoption. Furthermore, there is room for improvement in the type of hydrogen produced. The analysis shows a notable disparity between Japan's preparedness to build its hydrogen economy based on non-renewable or nuclear sources compared to renewable energy in the initial stage.

SWOT Analysis

Strengths:

Both Japan and Thailand have established policies and legislation related to hydrogen adoption, with Japan having a higher score in this area. Japan and Thailand have established H2 pilot projects and H2 focus agencies, indicating a commitment to H2 adoption and innovation. Both countries have made investments in H2 transportation infrastructure and have some level of readiness for hydrogen refueling stations. Japan has a high score in the area of technology and innovation, with a strong patent portfolio, higher technology readiness level, and greater industry investment in H2.

Weaknesses:

Thailand has a lower score in most areas compared to Japan, indicating a lack of/ lesser readiness for hydrogen adoption. Both countries have a low score in investment in hydrogen production with carbon capture and utilization or storage (CCUS), indicating a lack of emphasis on carbon-neutral H2 production. Both countries have a low score in cost competitiveness of H2, indicating that H2 production and use may not be economically feasible without further investment and innovation.

Opportunities:

Japan and Thailand have the potential to collaborate on H2 adoption and innovation, leveraging each other's strengths and resources. Both countries can increase investment in H2 production with CCUS and cost competitiveness of H2, making H2 adoption more feasible and attractive.

Threats:

Other countries may have greater H2 adoption readiness and could lead the way in H2 innovation, potentially making Japan and Thailand less competitive in the global H2 market. Without sufficient investment and innovation, H2 adoption may not be economically feasible and could result in a lack of interest from industry and consumers.

Chapter 5 Conclusions and Policy Implications

The goal of this study was to develop a Hydrogen Adoption Readiness Index as a tool for assessing the readiness of the Japanese and Thailand market for the adoption of hydrogen technology. The study identified four key dimensions: policy & legislation, technology & innovation, infrastructure, and market, based on a thorough review of existing literature. Subsequently, indicators were determined for each dimension and validated for their relevance. The indicators were given equal weight, and a scoring system was established using a combination of secondary data and expert surveys. In cases where necessary, normalization was applied to estimate the readiness score for each indicator. Finally, the overall readiness scores for Japan and Thailand were calculated based on the cumulative scores of the four dimensions.

The results indicated that Japan has strong support for policy and legislation regarding hydrogen. The country's policies and laws are comprehensive, covering various sectors like transportation, power generation, and other applications. However, the infrastructure aspect was found to be the weakest due to regulatory constraints and limitations in construction and physical development. Nonetheless, Japan showed promise in technology and innovation, displaying a high level of competence and local expertise in developing new hydrogen technologies. The market potential for adopting hydrogen in Japan also seemed favorable. The readiness survey identified several areas within the system where the adoption of hydrogen technology was likely to succeed. However, cost competitiveness was a drawback, as the estimated delivery cost in Japan was relatively expensive compared to other studied nations interested in hydrogen development, including Thailand.

Apart from that, it implies to the strengthening targets and policies by continuously reviewing and updating GHG mitigation targets and policies to align with international standards and emerging technologies. Fostering a favorable policy environment could encourage private sector investment in the hydrogen sector. Urgency plan for Japan is on Technology and Innovation Leadership by increasing the investment in research and development to maintain Japan's technological edge in the hydrogen industry. Support collaboration between academia, industry, and research institutions could be the innovation driver and accelerator to the commercialization of hydrogen technologies. For Medium-Term Plan, it could be on 3 issues. Firstly, on the infrastructure expansion by mean of continuation to invest in hydrogen refueling stations, transportation infrastructure, and hydrogen production with CCUS, it would assist the country in the achievement of the climate mitigation target and hydrogen adoption. Secondly, collaboration support with industry stakeholders to ensure the development of a robust and comprehensive hydrogen infrastructure network. Thirdly, cost competitiveness improvement: Implement measures to reduce the cost of hydrogen production, storage, and distribution. Support research and development efforts focused on cost-effective technologies, such as electrolysis and hydrogen storage systems. Long-term plan can be drawn on market development and international cooperation and policy alignment and harmonization. Market Development and International Cooperation would be on strengthening market promotion and awareness campaigns to encourage the adoption of hydrogen technologies in various sectors, including power generation and transportation and collaborating with international partners to establish global standards and facilitate cross-border hydrogen trade. Policy Alignment and Harmonization would work with other countries to align policies, regulations, and standards for hydrogen adoption. Foster international cooperation could help addressing common challenges and creating a conducive global environment for hydrogen development.

To Thailand side, the policy implication can be placed on strengthening policy and legislative framework by enhancing the existing climate change law and developing comprehensive policies and legislation to support hydrogen adoption. This should include incentives, regulations, and standards to promote investment, research, and development in the hydrogen sector, given the view by the survey result to see the small percent to the stage of the market towards 2030. Urgency Plan is to accelerate Technology Readiness by increasing the investment in research and development to improve technology readiness level. Foster collaborations with international partners and institutions to expedite the transfer of knowledge and technology and preparation of development of the local skill. Medium-Term Plan can focus on the infrastructure development and financial and investment facilitation. The consideration to develop infrastructure by the increase investment in hydrogen refueling stations and transportation infrastructure, including pipelines and storage facilities. Encouraging the public-private partnerships helps to expedite the deployment of infrastructure. Financial Support and Investment Facilitation can be proceeded with the establishment of financial mechanisms, such as subsidies, tax incentives, and low-interest loans, to attract industry investment in the hydrogen sector, and to facilitate access to financing and streamline administrative procedures to encourage private sector participation.

Long-Term Plan for Thailand market can be placed in the same way as Japan market which are market development and the international collaboration. Market Development and Promotion Implement strategies can be built upon the creation of a robust market for hydrogen, including promoting public awareness, supporting demonstration projects, and fostering collaborations with industry stakeholders to increase the adoption of hydrogen technologies in power generation, transportation, and other sectors. International Collaboration: Engage in partnerships and knowledge exchange with countries leading in hydrogen adoption, such as Japan, China, the US, and South Korea. These countries may be willing to leverage their expertise and experiences to accelerate Thailand's hydrogen readiness.

These policy implications, urgency plans, medium-term plans, and long-term plans can help both Japan and Thailand to address the identified gaps, leverage their strengths, and overcome weaknesses to accelerate their respective hydrogen adoption readiness and establish themselves as leaders in the hydrogen economy.

The study encountered some limitations. Initially, the researchers aimed to collect more primary data from industry experts but received a low response rate, primarily because of the limited number of accessible experts in the hydrogen field. Additionally, the use of surveys as the selected instrumentation posed limitations. To encourage responses, the survey questions were concise and high-level, resulting in limited detailed information from the experts.

Future work can build upon this study's methodology by refining the selection and scoring of indicators. Structural analysis using multivariate methods or multivariate analysis can better validate the categorization of indicators, provided that corresponding data is collected. Establishing dependent and independent variables and exploring the theory of planned behavior (TPB) can help explain individuals' readiness to adopt new technologies within the framework dimensions. Testing multicollinearity among the sub-variables of the main framework can reduce misleading indicators caused by inter-correlations and yield more accurate results. Scoring methods could be enhanced using evidence-based approaches and considering the potential changes in these values over time. For instance, integrating time-series analysis with the readiness framework could provide valuable insights. Furthermore, future research should focus on conducting comparative assessments with other countries to obtain a more accurate understanding of Japan and Thailand's position in the international market.

Appendix Survey Questions

No.	Questions	Description	Remarks
	Q1P Please score the proposed indicators according to their relevance as drivers of hydrogen adoption readiness.		
1	Q1P1 Commitment on GHG mitigation		P1
2	Q1P2 Target year to achieve net zero emissions	- Having a target year; and the timing of that target year (earlier is better)	P2
3	Q1P3 Government funding for H_2 pilot projects	- Availability of funding; level of support;	P3
4	Q1P4 Establishment of H_2 focus agency		P4
5	Q1P5 Availability and coverage of technical standards for H_2 supply chain technologies		P5
6	Q1P6 Regulatory support for fuel cell-based power generation (including combined heat and power (CHP) systems	- Availability of laws, regulations and standards relevant to hydrogen technologies, or the consideration of developing them;	P6
7	Q1P7 Regulatory support for hydrogen fuel cell electric vehicles (FCEVs)	- Availability of laws, regulations and standards relevant to hydrogen technologies, or the consideration of developing them;	P7

8	Q1P8 Government's responsiveness to change	P8
9	Q1PC1 Please select any of the indicators that you believe should be removed (if any)	
10	Q1PC2 If you believe additional indicators are necessary, please list them below:	
	1.2 Weighting check - Dimension 1 Policy and Legislation	
11	Q1 Weighting Check – No Q1W2 According to Table 2 and/or your proposed set of indicators, if it should not be equally weighted, how would you allocate out of 100%?	Weighting Allocation
12	Q2W2 According to /or your proposed set of indicators, if it should not be equally weighted, how would you allocate out of 100%?	
	Please score the proposed indicators according to their relevance as drivers of hydrogen adoption readiness.	
13	Q2T1 H_2 related patents	T1
14	Q2T2 Industry investment in H_2 and related technology	T2
15	Q2T3 Value of H_2 pilot projects	T3
16	Q2T4 Technology Readiness Level	T4
17	Q2TC1 Please select any of the indicators that you believe should be removed (if any)	
	1.2 Weighting check - Dimension 2 Technology and innovation	
18	Q2W1 According to Table 3and your proposed set of indicators, should the set of proposed indicators be equally weighted?	
	Q2 Weighting Check - No	
19	Q2W2 According to Table 3 and/or your proposed set of indicators, if it should not be equally weighted, how would you allocate out of 100%?	
	Q3I Please select score the proposed indicators on the basis of your opinion of their relevance to Hydrogen Adoption	
20	Q3I1 Readiness of hydrogen refueling stations (HRS)	I1
21	Q3I2 Investment in H_2 transportation infrastructure (pipeline)	I2
22	Q3I3 Investment in hydrogen production with carbon capture and utilization or storage (CCUS)	I3
23	Q3IC2 If you believe additional indicators are necessary, please list them below:	
	1.2 Weighting check - Dimension 3 Infrastructure	
24	Q3W1 According to Table 4 and your proposed	

	set of indicators, should it be equally weighted?		
	Q3W Weighting Check - No		
25	Q3W2 According to Table 4 and your proposed set of indicator, if it should not be equally weighted, how would you allocate out of 100%?		
	1. Indicator Relevancy - Dimension 4 Market		
26	Q4M Please select score the proposed indicators on the basis of your opinion of their relevance to Hydrogen Adoption		
27	Q4M1 Market potential for supplies for H_2 production		M1
28	Q4M2 Renewable energy market potential for green H_2 production		M2
29	Q4M3 Cost competitiveness of H_2		M3
30	Q4M4 Potential market share of H_2in power generation		M4
31	Q4M5 Potential market share of H_2 in other use		M5
32	Q4M7 Social acceptance to the use and production of the H_2 related technology		M7
33	Q4MC1 Please select any of the indicators that you believe should be removed (if any)		
34	Q4MC2 If you believe additional indicators are necessary, please list them below:		
	4.2 Weighting check - Dimension 4 Market		
35	Q4W1 According to Table 5and your proposed indicators, should the set of proposed indicators be equally weighted?		
36	Q4W2 According to Table 5. If it should not be equally weighted, how would you allocate out of 100%?		
37	Q5R1J Please evaluate the process to develop the availability and coverage of technical standards for Hydrogen Economy for Japan		P5
38	Q5R2J P6 Regulatory support for fuel cell-based power generation including combined heat and power (CHP) systems in Japan		P6
39	Q5R3J P7 Regulatory support for hydrogen fuel cell vehicles (FCVs) in Japan		P7
40	Q5R4 M2 Renewable energy market potential for green H_2 production		M2

41	Q5R6 M4 Potential market share of hydrogen fueled cell in power generation including combined heat power system		M4
42	Q5R7 Please score the potential market share of H_2in transportation (M5)		M5
43	Q5R8 Please score the potential market share of H_2 in other use (M6)		M6
44	Q5R9 Please score the social acceptance of the use and production of hydrogen related technology (M7)		M7
45	Q6.1 Which type of organisation do you belong to?		
46	Q6.2 What country are you primarily working in?		
47	Q6.2 What working area is closest to your own responsibility?		
48	Q6.3 How long have you engaged in work related to hydrogen economy development?		

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