Development of a National Hydrogen Strategy and Action Plan for Accelerating Thailand's Net-zero Target

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Contents

Chapter 1. Introduction

As the global energy landscape evolves, understanding the intricacies of green hydrogen production becomes essential. This report aims to provide an overview of the current status and future prospects of green hydrogen production in Thailand. However, it is important to note some limitations that we encountered during our research.

In Chapter 2, we will provide a technical review of the major hydrogen production methods, highlighting their advantages and challenges, especially in the context of Thailand.

Chapter 3 will focus on the current technological landscape in Thailand. While we attempted to be comprehensive in our analysis, there were limitations in the data available to fully capture Thailand's conditions. Nevertheless, we assessed the country's readiness and available resources by relying primarily on the most relevant data sources available.

Chapter 4 focuses on the practical aspects. Our recommendations for areas suitable for demonstration sites are based primarily on interviews, providing a qualitative perspective that may not capture the full range of possibilities. In addition, while we emphasize the importance of economic feasibility for such ventures, we've only been able to provide a list of items needed for a detailed economic analysis (CAPEX, OPEX) at this stage, rather than a complete analysis itself.

Despite these challenges, our primary goal remains to provide stakeholders with the knowledge and insights, albeit with recognized limitations, to navigate the evolving landscape of green hydrogen production in Thailand.

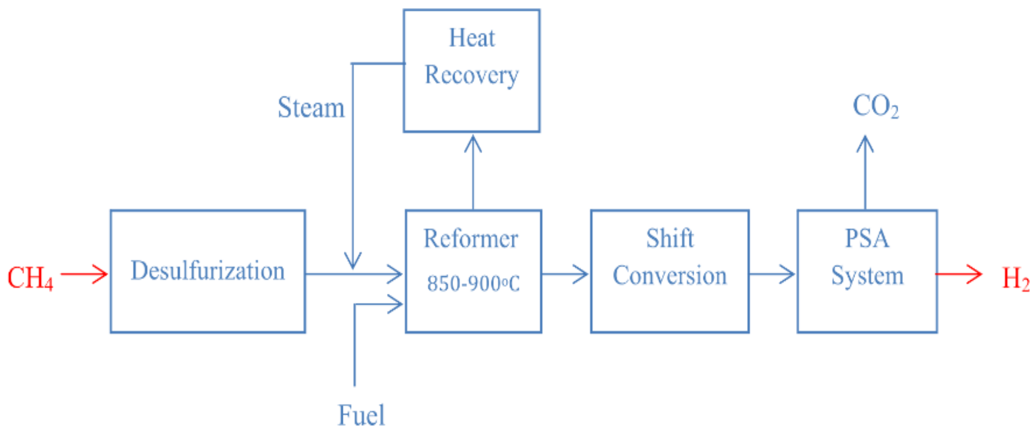
Chapter 2. Major Hydrogen Production Methods

Section 1. Thermochemical Hydrogen Production

1. Steam reforming (SR) technology

Steam reforming (SR) or reforming process in which hydrocarbons (mainly CH_4) is reacted with steam ($H_2O(g)$) and is converted to hydrogen and carbon oxides. The main steps consist of reforming or syngas generation, water-gas shift (WGS), and gas refining. Feedstocks include methane, natural gas and various other gases including methane, ethene, propane, butane, pentane, and light and heavy naphtha. If the feedstocks contain sulfur compounds, a de-sulphurization step is performed before reforming process to prevent catalyst poisoning ([Figure 2-1]).

[Figure 1] Flow diagram of the steam methane reforming (SMR) process



Source: Nikolaidis & Poullikkas (2017)[1]

To produce pure hydrogen and prevent the formation of coking on the catalyst surface, the reforming reaction operating conditions are high temperature, high pressure up to 3.5 MPa,

[1] Nikolaidis, P. & Poullikkas. A., 2017, A comparative overview of hydrogen production processes, Renewable and sustainable energy reviews, 67, 597-611.

and a steam to carbon ratio of 3.5. After the reformer reaction, the gas mixture is fed to the WGS reactor through a heat recovery step, where the CO reacts with the steam to produce additional hydrogen. The gas mixture is then separated into 99.999% pure hydrogen via pressure swing adsorption (PSA) for CO2 separation. CO2 emissions can be reduced through CO2 capture and storage, which involves storing CO2 in reservoirs located in marine and crustal reservoirs.

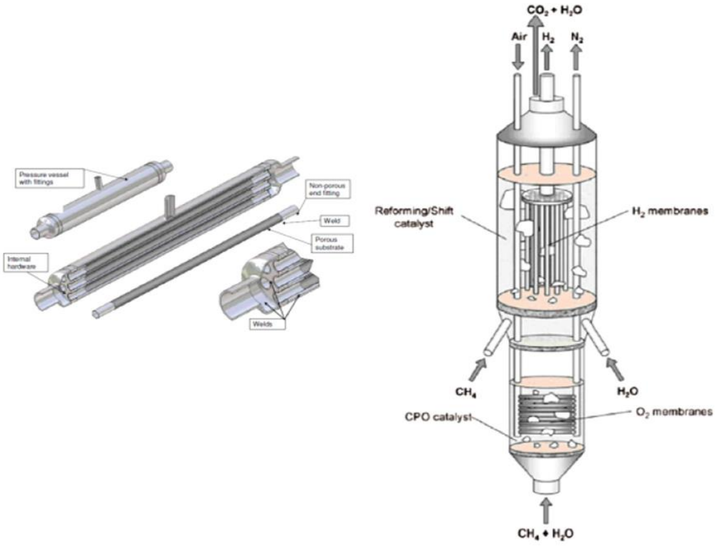
$$\text{Reformer : } C\,H_{nm} + nH_2\,O \rightarrow nCO + (n + 1/2m)H_2$$

$$\text{WGS reactor : } CO + nH_2\,O \rightarrow nCO_2 + H_2$$

[Equation 2-1] Key chemical reactions in the SMR process

In steam reforming, if the carbon feedstock is methane, then n=1 and m=4 according to [Equation 2-1]. Steam methane reforming (SMR) is one of the most common and advanced methods of hydrogen mass production, with conversion efficiencies between 74-85%. In the SMR process, steam and natural gas are reacted over a nickel-based catalyst to produce syngas at a temperature of around 850-900°C. Pressure swing adsorption (PSA) is then used to separate from other elements and obtain 99.999% pure hydrogen. These processes use a portion of natural gas as process fuel for energy production, leading to overall emissions including CO_2 emissions of 0.3-0.4 m^3 per unit of hydrogen produced. Regarding the cost breakdown for SMR, raw materials account for 60.7%, capital investment for 29.1%, and operation and maintenance costs for 10.2%.

[Figure 2] Schematic illustration of a multi-membrane reactor for the SMR process



Source: Nikolaidis & Poullikkas (2017)

Instead of PSA, membranes can be used to separate hydrogen and carbon dioxide, and a typical reactor is membrane reactors (MR). Membranes were tested by applying them directly within the catalytic reaction environment of the SMR or as a downstream layer in the reactor. In the case of palladium catalyst-based MRs, chemical reactions and gas separation are combined in a single unit, as shown in [Figure 2-2], which allows hydrogen and CO_2 to be produced simultaneously and separately. The hydrogen produced in the reformer is adsorbed and separated into atoms on one side of the membrane, dissolved in the membrane, diffused, and separated on the other side. MR enables the same feedstock conversion (methane conversion rate up to 90-95%) at a lower temperature (450-550°C) than conventional PSA-based SMR (850-900°C).

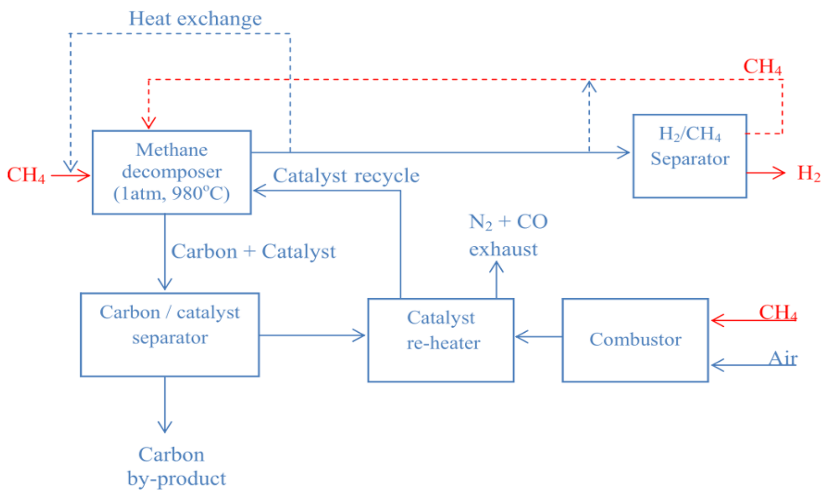
2. Catalytic Decomposition of Methane Technology methane direct pyrolysis hydrogen production technology

Catalytic decomposition of methane (CDM) process thermally decomposes methane through the following reaction [Equation 2-2], and the detailed process is shown in [Figure 2-3].

$$C\ H_{nm} \rightarrow nC_{(s)} + 1/2\ mH_{2(g)}$$

[Equation 2-2] Pyrolysis reaction equation for the CDM method

[Figure 3] Flow diagram of the pyrolysis process



Source: Nikolaidis & Poullikkas (2017)

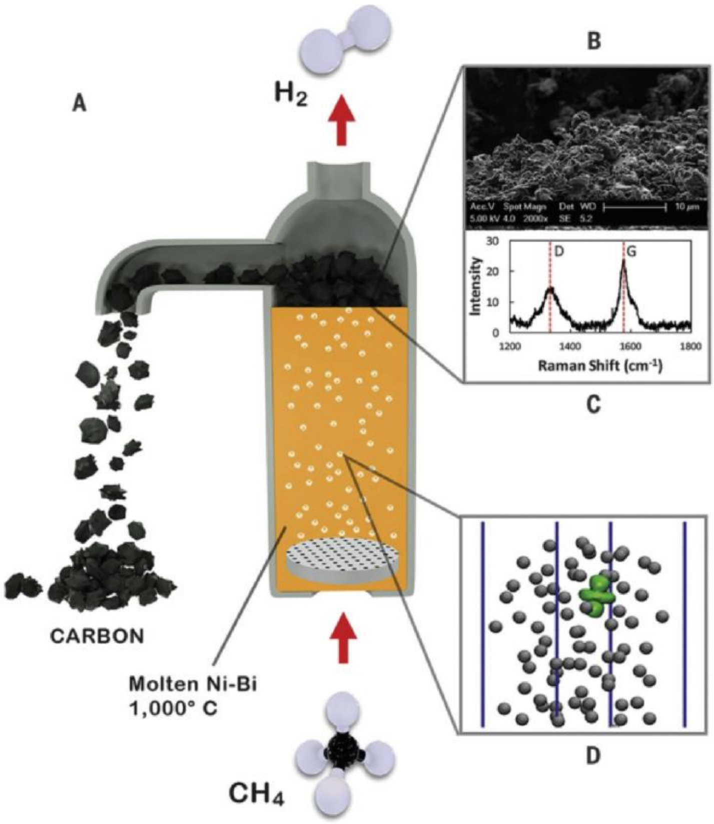
Direct carbon removal from natural gas is achieved in an environment devoid of air and water, under atmospheric pressure, at a temperature of 980°C. The energy requirement for hydrogen production per unit mole (37.6 kJ/mol) is lower than that of the SMR method (63.3 kJ/mol), and combustion can cover about 15-20% of the hydrogen produced in the process. In addition, the pyrolysis process does not include a WGS and CO_2 separation step. Therefore, in terms of capital investment, hydrogen production costs are 25-30% lower than steam conversion or partial oxidation processes. Furthermore, if there is a large market for solid carbon materials produced from the decomposition of natural gas, the price of hydrogen will be lower.

The application of a membrane separation process in the pyrolysis process to selectively recover hydrogen is expected to increase the carbon removal conversion rate. Pd-Ag alloys are used for H2 separation, which can operate at lower temperatures and reduce coke formation. However, the driving force required for hydrogen separation is low due to the low partial pressure of hydrogen in the reaction mixture, and membrane durability is affected by the high temperatures required for carbon removal equilibrium.

The CDM process is a single-step process for producing COx-free hydrogen and carbon nanomaterials such as carbon nanotubes, carbon nanofibers, and carbon nano onions. Compared to the conventional hydrogen production process, the technological competitiveness of the CDM process can be secured if carbon nanomaterials are widely applied. Currently, Fe-, Ni-, noble metal-based and carbon catalysts are being studied, and from a cost perspective, Fe-based catalysts, especially bulk or waste Fe catalysts, are recommended as very promising materials for CDM.

However, the most significant challenge of the CDM process is a separation of deactivated catalyst. The characteristics of the CDM process have been studied in many types of reactors, including fluidized bed, plasma reactor (PLR), and molten-melt reactor. The molten-melt reactor is excellent for commercial applications because it can continuously separate carbon byproducts from solid catalysts, avoiding catalyst deactivation and reactor clogging. Recently, many efforts have been made to commercialize the process, but challenges need to be overcome, such as (a) the environmental and economic issue on the recycling of Fe-based catalysts discarded in the CDM process, and (b) the improvement of the molten-metal reactor, which removes byproduct continuously to avoid catalyst deactivation, as shown in [Figure 2-4].

[Figure 4] Hydrogen production method using Ni-Bi melt catalyst



Source: Qian et al.[2]

Note: (A) Reactor, (B) SEM of carbon, (C) Raman spectroscopy of surface carbon, and (D) molecular dynamics simulation.

3. Hydrogen production technology through biomass gasification

Biomass gasification is a thermochemical process that converts solid-phase biomass, such as wood, agricultural residues, and organic waste into a gaseous mixture of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). This gas mixture is called syngas because it is a synthetically produced gas. Syngas can be burned in gas engines or turbines to generate

[2] Qian, J.X., et al., 2020, Methane decomposition to pure hydrogen and carbon nano materials: State-of-the-art a nd future perspectives, International Journal of Hydrogen Energy, 45(32), 15721-15743.

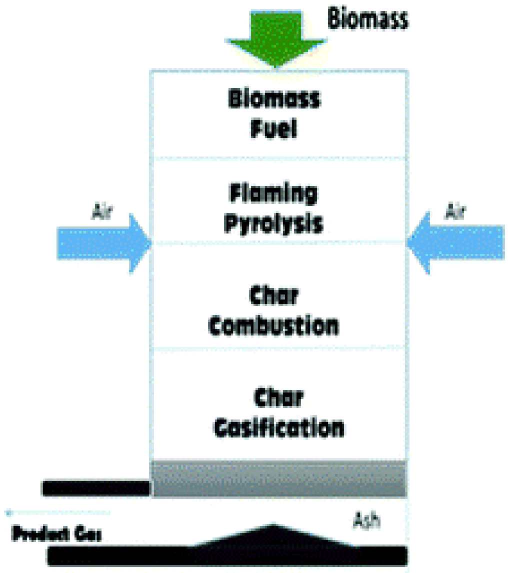
electricity, used as a heat source for heating or combined heat and power (CHP) systems, and as a feedstock for chemical processes to produce various chemicals and fuels. For example, it can be utilized as a feedstock for methanol, dimethyl ether, and other chemicals through the Fischer-Tropsch process. An overview of the biomass gasification process is shown in [Figure 2-5].

[Figure 5] Biomass Gasification Process Overview

Feedstock	Biomass feedstocks such as woodchips, crop residues, or waste are used. To improve reaction, feedstocks are dried or ground into small particles.
↓	
Gasification reactor	The prepared biomass is fed into a gasification reactor or gasifier. A gasifier is a high-temperature vessel in which the biomass reacts with oxygen (or air) and/or steam, where the oxygen supply creates an oxygen-deficient environment to prevent complete combustion.
↓	
Thermochemical reactions inside the gasifier	Pyrolysis Biomass is decomposed into solid char, liquid volatile organic compounds, and gases through pyrolysis reactions at high temperatures.
	Gasification In the absence of sufficient oxygen, volatile organic compounds undergo gasification and are converted to syngas. The gasification step is typically an endothermic reaction and requires an external energy supply. The syngas produced by the gasifier is a mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), water vapor (H_2O), and trace amounts of other gases. The composition of the syngas depends on factors such as the biomass feedstock and operating conditions.
↓	
Gas Cleaning	Because syngas can contain impurities such as tar, particulates, and sulfur compounds, impurities must be removed to prevent equipment contamination and ensure downstream processing or combustion efficiency. Gas cleaning steps include filtration, cooling, and chemical scrubbing.

Gasifier types include fixed bed gasifiers, fluidized bed gasifiers, and entrained flow gasifiers. A fixed bed gasifier, shown in Figure 1-6, is a stationary reactor in which gasification occurs as biomass or solid fuel is fed into a fixed bed and air or oxygen is supplied from the bottom to the top. As the biomass or fuel at the bottom of the bed is heated, it undergoes pyrolysis (decomposition by heat in the absence of oxygen), releasing volatile gases and leaving behind char (carbonaceous residue). As the gasoline rises through the bed, it reacts with oxygen to form syngas. Fixed-bed gasifiers are relatively simple, robust, and low-maintenance. However, they have lower gasification efficiency compared to fluidized bed and entrained flow gasifiers.

[Figure 6] Schematic of a fixed bed gasifier



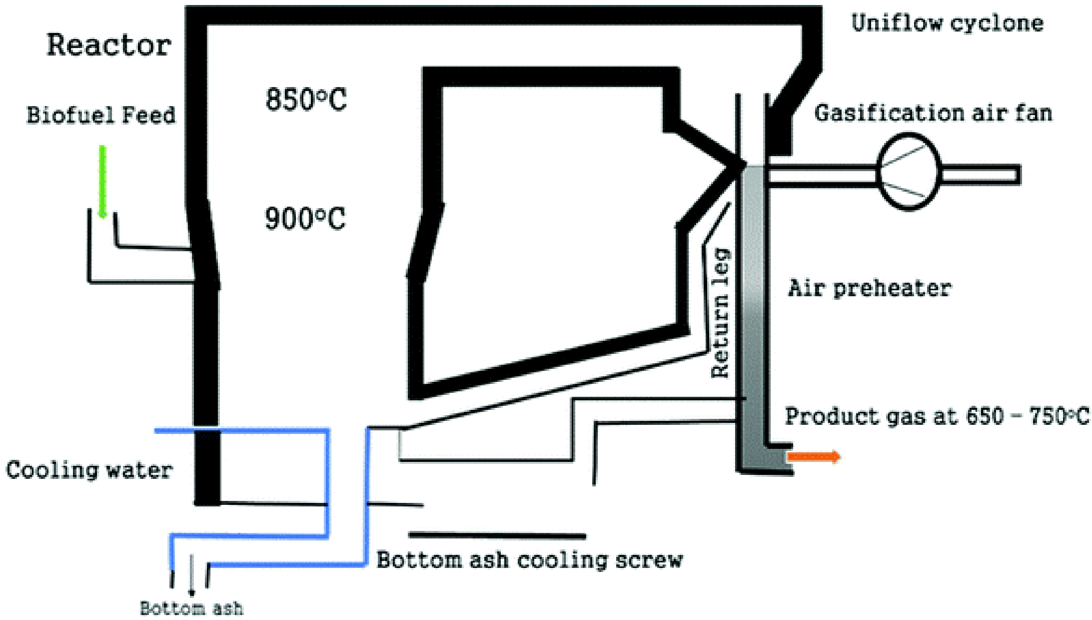
Source: Basu (2010)[3]

Fluidized bed gasifier shown in [Figure 2-7] operates by supplying air or oxygen from the bottom to the top at the layer of inert materials (usually sand or small particles). The fuel particles mix with each other and are suspended in a fluid-like state, allowing uniform heating

[3] Basu, P. 2010, Biomass Gasification and Pyrolysis, Oxford: Elsevier.

and promoting gasification. Fluidized bed gasifiers have higher gasification efficiency and multi-fuel flexibility due to their excellent heat transfer and mixability. However, they are more complex to design and operate than fixed-bed gasifiers.

[Figure 7] Fluidized Bed Gasifier Schematic

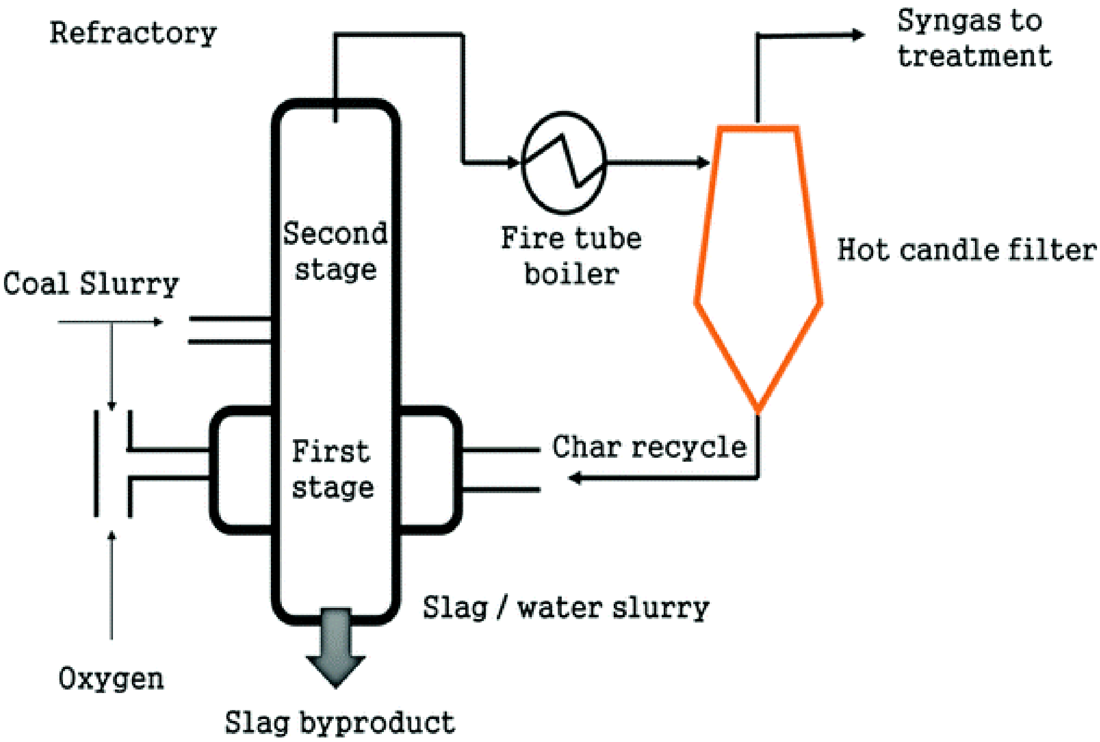


Source: Basu (2010)

Finally, the entrained flow gasifier, as shown in Figure 2-8, is where the solid feedstock is pulverized into fine particles and fed accompanied by a high-speed stream of oxygen or air, resulting in rapid mixing and gasification in the reactor. The gasification process occurs rapidly as the finely ground feedstock enters the gasifier and is quickly converted to syngas, moving through the reaction zone.

Hence, the entrained flow gasifier exhibits high gasification efficiency, making it suitable for a diverse array of feedstocks, including applications in both coal gasification and advanced gasification processes. However, it needs regular and attentive maintenance and can be more complex and costlier to build and maintain than the other type of gasifiers.

[Figure 8] Fixed Flow Gasifier Schematic



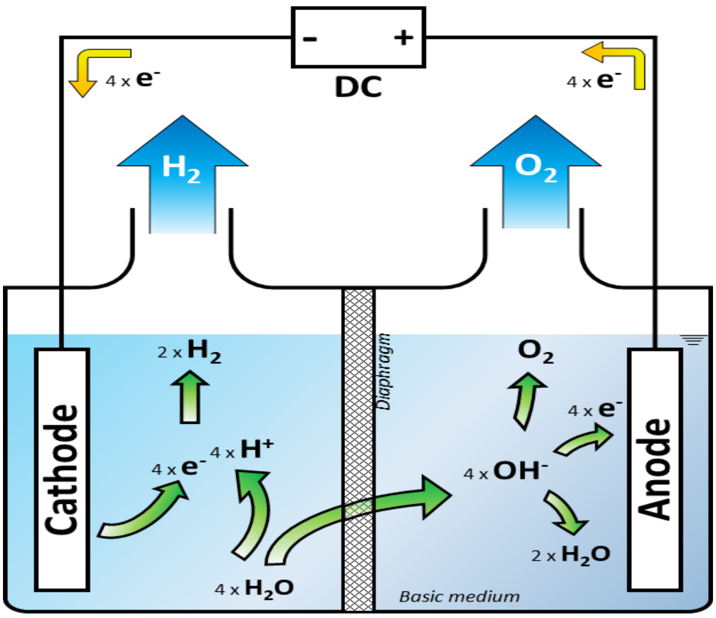
Source: Basu (2010)

Meanwhile, tar formation in the process of biomass gasification poses a significant concern since it can clog equipment, increase maintenance, and make operations difficult. Tar is mainly composed of benzene benzene (38%), toluene (14.5%), single ring aromatic HC (14%), naphthalene (9.5%), double ring aromatic HC (8%), heterocyclic compounds (6.5%), phenolic compounds (4.5%), triple ring aromatic HC (3.5%), quadruple ring aromatic HC (1%), and other compounds in trace amounts. Addressing tar-related issues is essential to maximize the efficiency and performance of the gasification process.

Section 2. Electrochemical Hydrogen Production - Water Electrolysis Hydrogen Production Technology

Water electrolysis is a technology that uses water as a raw material to produce hydrogen and oxygen through an electrochemical decomposition reaction. Experimentally, the water decomposition reaction occurs when a direct current is applied to two electrodes in an electrolyzer. [Figure 2-9] shows a schematic diagram of the basic working principle of a water electrolysis cell.

[Figure 9] Basic operation of a water electrolysis cell



Source: Holst et al. (2021)[4], p.15

When a cell voltage sufficiently higher than the equilibrium voltage is applied

[4] Holst, M., et al., 2021, Cost Forecast for Low-Temperature Electrolysis-Technology Driven Bottom-Up Prognosis for PEM and Alkaline Water Electrolysis Systems, Fraunhofer-Institut für Solare Energiesysteme ISE.

(overpotential), hydrogen is produced through a reduction reaction at the cathode, and oxygen is released through an oxidation reaction at the anode. At the same time, cations (+) or anions (-) move from the cathode to the anode through the separator, and the gases generated at both ends are prevented from mixing by the separator. The equation of the water electrolysis reaction is as follows.

$$H_2O_{(l/g)} \rightarrow H_{2(g)} + 1/2O_{2(g)}$$

[Equation 2-3] Water electrolysis reaction

All types of electrolysis cells work on the same principle can be categorized according to the electrolyte used. Types of electrolysis include Alkaline electrolysis (AEC), which uses saline liquid electrolyte, Polymer electrolyte membrane electrolysis (PEMEC), which uses an acidic ionomer , Anion exchange membrane electrolysis (AEMEC), which uses anionic ionomers, and Solid oxide electrolysis (SOEC), which uses solid oxides as electrolytes. Alkaline water electrolysis is a technique for producing hydrogen based on an alkaline electrolyte such as potassium hydroxide (KOH) solution and the charge-carrying ion is the OH^- (Hydroxide anion).

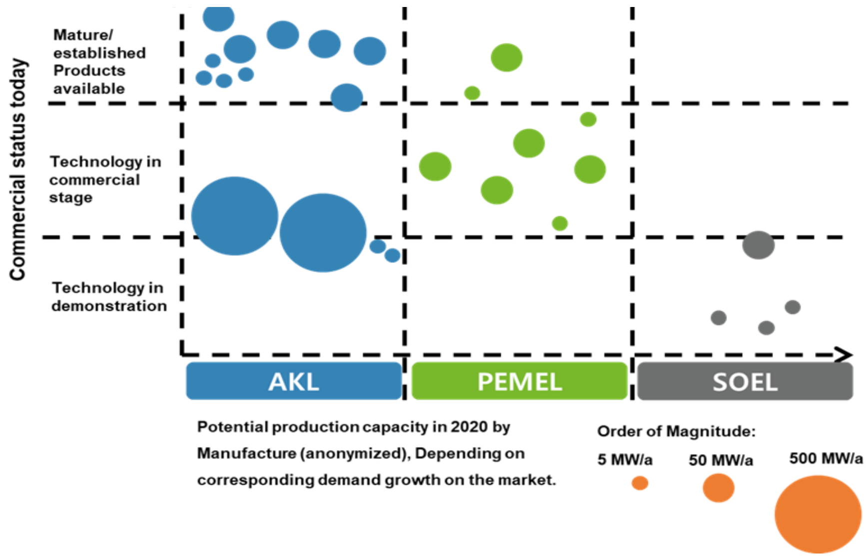
When an electrochemical reactionn occurs in a single cell consisting of electrodes and a separator, hydrogen is produced at the reducing electrode (cathode) and oxygen is released at the oxidation electrode (anode), and the OH^- ions and the electrolyte, KOH, pass through the porous separator. PEM water electrolysis, as opposed to alkaline water electrolysis, use protons (H^+) as a medium and has a cationic conductive polymer membrane as a separator. Oxygen and hydrogen are produced at the anode and the cathode respectively, which is the same as alkaline water electrolysis, but the reaction takes place in an acidic environment. Anion exchange membrane electrolysis (AEMEC) represents a cutting-edge electrolysis technology that combines the advantages of proton exchange membrane (PEM) water electrolysis and alkaline water electrolysis.

The anion exchange membrane electrolysis (AEMEC) is structurally similar with the proton exchange membrane water electrolysis and alkaline water electrolysis. In a manner akin to alkaline water electrolysis, OH^-ions serve as the carriers of electric charge, while resembling PEM electrolysis, AEMEC employs an anion exchange membrane constructed from ionomer materials. In solid oxide electrolysis (SOEC), the reaction occurs at a high temperature of 600~800°C unlike three electrolysis technologies above. When steam is supplied to the cathode, it is converted into hydrogen and oxygen ions (O_2^-) and becomes oxygen molecules after moving toward the anode and meeting electrons through solid oxides.

Alkaline water electrolysis technology is already commercialized and commonly used for large-scale commercialization. While polymer electrolyte membrane (PEM) has been widely demonstrated and commercialized, solid oxide electrolysis (SOEC) and anion exchange membrane electrolysis (AEMEC) technologies stand at the low Technology Readiness Level (TRL) due to few companies and original equipment manufacturer (OEM) involved in the manufacturing and commercialization. [Figure 2-10] shows the technology readiness level of AKL, PEMEL, and SOEL for the major electrolysis manufacturers surveyed by the German National Organization Hydrogen and Fuel Cell Technology (NOW). Basically, a water electrolysis unit cell consists of a pair of electrodes and a separator between the electrodes. The separator transfers anion (-) or cation (+) generated by the electrodes from one electrode to the other, and prevents the mixing of the hydrogen and oxygen. In general, the electrolyte and separator vary depending on types of electrolysis. The electrolyte of the alkaline water electrolysis is generally a highly concentrated potassium hydroxide solution. Gases produced from each electrode are physically separated by a ceramic-polymer composite membrane (separator) that is permeable to KOH solution. To date, this is the most mature technology for producing green hydrogen and the most commercialized for large-scale production.

In PEM water electrolysis, the supplied water is decomposed into oxygen and hydrogen ions (H+) at the anode, and hydrogen is produced at the cathode by moving the H+ ions through a cationic conductive membrane. It operates in a corrosive low pH condition and is expensive due to the need to use costly metal catalysts. However, the advantages of PEM are its effective operation at high current densities, compact design, and fast on-off response. AEM water electrolysis, like PEM water electrolysis, uses an ionically conductive polymer electrolyte membrane and is operated in an alkaline environment where OH-ion exchange occurs. It is less dependent on costly metal catalysts than PEM, more compact than alkaline water electrolysis, and can be operated at differential pressures. Nonetheless, it is worth noting that AEMEC technology is in a relatively early stage of development compared to other electrolysis technologies. In the case of solid oxide electrolysis relies on an insulating solid electrolyte capable of conducting oxygen ions (O_2^-) and is distinguished by its operation at elevated temperatures ranging from 600°C to 800°C.

[Figure 10] Hydroelectricity scale and technical maturity



Source: Lauf (2020)[5], p.7

Operating conditions at the high temperature enables a relatively low electricity consumption, thereby enhancing the efficiency of hydrogen production. However, as it is exposed to a high temperature environment, the operating efficiency decreases faster than the beginning of life (BOL) due to agglomeration of electrode particles, interfacial diffusion, and elemental volatilization. Therefore, it is necessary to secure durability. The current technology indicators of the four technologies reviewed above are summarized in <Table 2-1> below.

[5] Lauf, J., 2020, Hydrogen as Fuel: Production and Costs, 14, Energy Security: Operational Highlights.

<Table 2-1> Characteristics of major water electrolysis technologies

Performance metrics	Alkaline Water Electrolysis	Polymer Electrolyte Membrane Water Electrolysis	Anion Exchange Membrane Water Electrolysis	Solid Oxide Water Electrolysis
Cathode (HER)	Ni, Ni-Mo	Pt/C, Pt-Pd	Pt, NiFeCo	Ni/YSZ
Anode (OER)	Ni, Ni-Co	IrO_2, RuO_2	IrO_2, Ni	LSM/YSZ
Charge Transfer	OH^-	H^+	OH^-	O_2^-
Electrolytes	KOH aqueous solution (20-40wt.% KOH)	Proton conductive membrane (PSFA membrane)	Anionic conductive membrane	Oxygen Conductive Membrane
Temperature Range (℃)	60 to 90	RT to 90	50 to 70	700-850
Current Density (A/cm)^2	0.2 to 0.6	1.0 to 2.5	0.5 to 1.5 (lab scale)	0.3-2.0
Technology Readiness Level (TRL)	8-9	7-8	6-7	6-7
Operating Pressure (bar)	0 to 30	0 to 70	0 to 35	1
Stack/Module Size (Nm^3/h, MW_{el})	<1000 Nm^3/h 0.5 to 2.5 MW_{el}	100 Nm^3/h 0.1 - 1.5 MW_{el}	0.5 Nm^3/h < 2.5 MW_{el}	none
Energy Consumption (KWh/Nm^3 H_2)	4.2 to 5.8	4.5 to 6.8	4.8 to 6.9	>3.7
Advantages	◆High TRL ◆Building large systems at MW scale ◆Relatively inexpensive	◆Commercially available latest technologies ◆Minimal downtime (on-off) ◆Suitable for high pressure operation	◆Low-cost materials available ◆Suitable for high pressure operation ◆Compact design	◆Highly efficient
Disadvantages	◆Low operating current density ◆Large footprint ◆Long system uptime	◆High manufacturing cost due to expensive materials and components ◆Short Lifetime	◆Low TRL ◆Low stability ◆Development Stage	◆Low TRL ◆Low stability ◆Development Stage

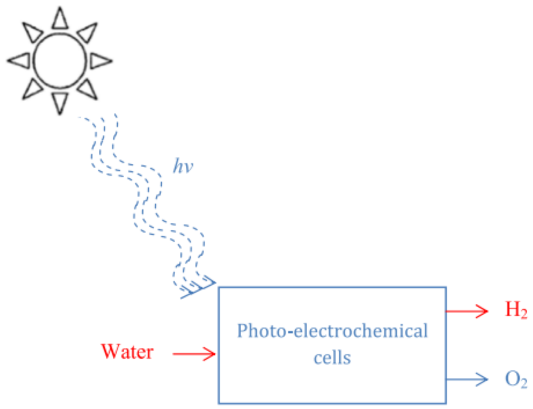
Source: Reconstructed by the Author based on Holst et al. (2021) and Schmidt et al. (2017)[6]

[6] Schmidt, O., et al., 2017, Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy, 42(52), (p. 3)

Section 3. Photoelectrochemical Hydrogen Production - Photoelectrolysis Hydrogen Production Technology

Photoelectrolysis is similar to electrolysis in a way that sunlight is absorbed by semiconductor materials to break down water. In particular, when a photon greater than or equal to a bandgap energy of semiconductor strikes the semiconductor surface of the anode, an electron-hole pair is generated and separated by the electric field between the semiconductor and the electrolyte. The schematic diagram of the photoelectrolysis process is shown in the following [Figure 2-11].

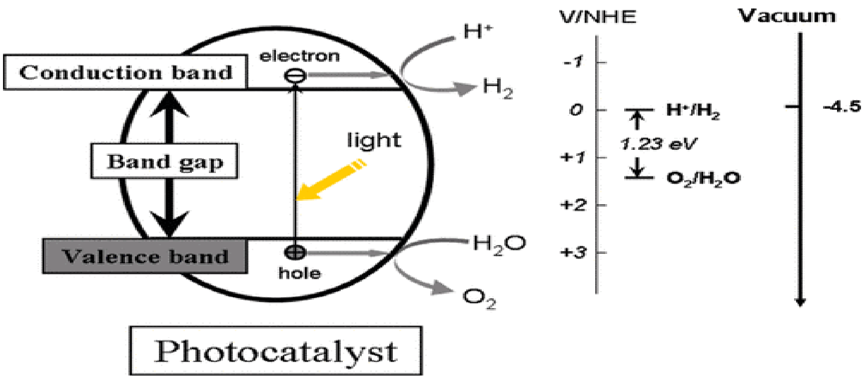
[Figure 11] Flowchart of the photoelectrolysis process



Source: Nikolaidis & Poullikkas (2017)

The photocatalyst absorbs UV and/or visible light from sunlight or illuminated light, causing the electrons in the atoms of the photocatalyst to move from the valence energy level to a higher energy state and leaving the holes in the valence energy level. This creates a negative electron (e-) and positive hole (h+) pair. This step is called the photo-excited state of the semiconductor, and the energy difference between the valence band and the conduction band is called the "band gap". This must match the wavelength of light to be effectively absorbed by the photocatalyst. In the photo-excited state, the excited electrons and holes separate and migrate to the surface of the photocatalyst, where they act as reductants and oxidants, respectively, to produce hydrogen and oxygen in the photocatalytic water splitting reaction. A schematic illustration of the principle of the water photocatalytic system is shown in [Figure 2-12].

[Figure 12] Photocatalytic water separation principle



Source : Chen et al. (2010)[7]

To improve the photocatalysis efficiency, the efficient utilization of visible light and reduction of band gap to improve charge separation during photocatalysis are essential. In addition, material properties such as electronic properties, chemical composition, structure, crystallinity, surface state, and morphology of photocatalysts need to be meticulously studied and optimized. This can be achieved by enhancing the activity of the photocatalyst in the visible light region through a conductive catalyst of the material and band gap engineering, or improving the crystallinity, structure, surface structure of the photocatalyst and inhibiting charge recombination. New catalysts that can replace a widely used platinum should also be developed. Currently, low photocatalysis efficiency and scale-up technology are required for industrial applications of photocatalytic hydrogen technology.

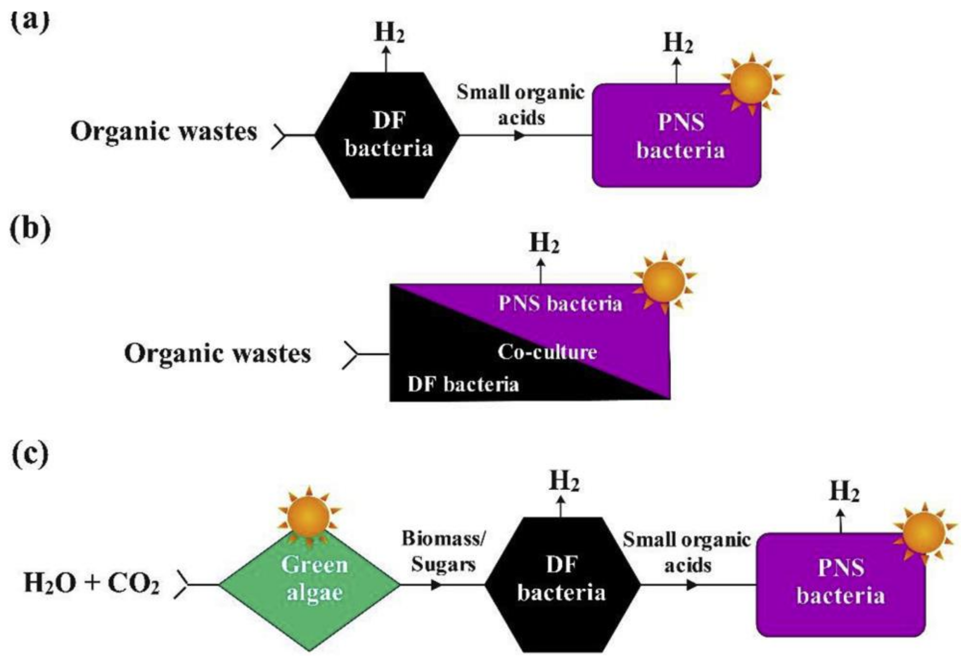
[7] Chen, X., Shen, S., Guo, L., & Mao, S.S., 2010, Semiconductor-based photocatalytic hydrogen generation, Chemical Reviews, 110(11), 6503-6570.

Section 4. Biological Hydrogen Production

Biological hydrogen production can be achieved through a variety of processes, including photobiological, photofermentation, and dark fermentation. In photobiological degradation, microalgae and cyanobacteria absorb solar energy to convert water and carbon dioxide (CO2) into hydrogen. Photofermentative hydrogen production involves bacteria utilizing different carbon sources while leveraging light energy. Dark fermentation, on the other hand, entails eukaryotic bacteria producing hydrogen from organic compounds found in food, agricultural waste, or wastewater.

[Figure 13] Schematic illustration of integrated systems

(a) sequential system, (b) two-component system of dark and photo-fermentation, (c) t hree-component system of bio-photolysis, dark and photo-fermentation



Source: Akhlaghi & Najafpour-Darzi (2020)[8]

[8] Akhlaghi, N., & Najafpour-Darzi, G., 2020, A comprehensive review on biological hydrogen production, Internatio nal Journal of Hydrogen Energy, 45(43), 22492-22512.

[Figure 2-13] shows three integrated systems that have recently been developed to improve the efficiency of biological hydrogen production. In a sequential system, green microalgae or blue-green algae is used to accumulate biomass through the absorption of photosynthetic carbon dioxide (CO2). The integrated process of the dark and photo fermentation utilizes dark fermenting bacteria in light-protected fermenters to accumulate biomass. The biomass is subsequently transformed into hydrogen and organic acids. A three-component system of bio-photolysis, photo and dark fermentation uses organic acids as a substrate for photo-fermentation hydrogen production. When comparing these integrated systems, the three-component system is theoretically more efficient than the two-component one. However, the three-component system requires a higher capital investment for sequential fermenters. In general, organic acid recycling from dark fermentation improves hydrogen production in the three-component system.

Photosynthesis in green and blue-green algae is a simple process that uses only water and light, but new strains with high oxygen tolerance and genetically modified strain should be screened in the process. In addition, waste resources such as wastewater can be utilized as a suitable carbon source, enabling sustainable hydrogen production with low-cost substrates and abundant solar energy.

The improvement of the existing photo-fermentation process requires pretreatment of the wastewater. The dark fermentation process has its own limitations in terms of hydrogen production yields, but controlling operating conditions while applying microbial immobilization technology and generating bio granules can improve hydrogen production through a light-independent process.

Both integrated systems (sequential and two-component systems) face a number of limitations, with sequential systems using mixed cultures of PNS bacteria being preferred. The three-component system offers an alternative approach for generating biomass from green algae when organic substrates or waste are not readily accessible for PNS bacterial hydrogen production. The recycling of wastewater from dark fermentation process can enhance hydrogen production through the three-component system.

Chapter 3. Selection of a Hydrogen Production Method for Thailand

To identify the most appropriate hydrogen production method for Thailand from among the methods reviewed in Chapter 2, it is necessary to review the pertinent factors influencing hydrogen production in Thailand and make a comprehensive evaluation. The hydrogen production technologies can be characterized as internationally accepted or standardized scientific and technological process, as outlined in Chapter 2. Their technical advantages can be determined based on the advantages and disadvantages of each technology or the level of technical efficiency. However, the purpose of selecting hydrogen production technologies in this study is to identify technologies suitable for promoting technology development internally in Thailand or facilitating technology transfer from outside, and ultimately producing hydrogen in Thailand. Therefore, it is necessary to select a hydrogen production method by comprehensively reviewing the current technology development conditions in Thailand and the resources[9] to be invested in hydrogen production[10]. This study reviews the technology development conditions (△ technology level, △ R&D activity and performance, and △ R&D capacity) and available resources (△ resources potential and △ resources development status and plan) of hydrogen production in Thailand. Ultimately, this study conducts a comprehensive analysis by comparing the technology development conditions and available resources for hydrogen production in Thailand, culminating in the selection of the most suitable method for Thailand.

Hydrogen production methods to be selected are limited to Steam Methane Reforming (SMR) technology and water electrolysis technology, which are two of the thermochemical processes in Chapter 2. Steam methane reforming technology and electrolysis technology are

[9] In a broad sense, resources include human skills, labor, etc., but in this study, resources are limited to the feedstock and fuel resources for hydrogen production.

[10] When selecting a hydrogen production method, it is necessary to consider not only the technical and resource conditions, but also the alignment with higher-level policies and the economic importance of a particular production method. However, as it is difficult to find an official cross-ministry policy related to hydrogen production in Thailand and the global hydrogen market is in its infancy, this study focuses on the technical and resource conditions.

considered internationally as blue hydrogen and green hydrogen production technologies, respectively. According to local experts in Thailand, SMR and electrolysis technology are currently being researched in Thailand. Biological hydrogen production or photoelectrochemical hydrogen production are also next-generation technologies that require continuous R&D investment, but they are still in their infancy compared to other hydrogen production technologies internationally, and are not included in the scope of this chapter because of the pressing need for hydrogen production in Thailand and the possibility of technology transfer or technical cooperation from abroad, which may be limited compared to other technologies. Therefore, in Chapter 3, the technology development status of SMR technology and water electrolysis technology, and the resource requirements for both technologies are reviewed in the context of Thailand, and finally, the chapter concludes by identifying the most suitable hydrogen production method for Thailand.

Section 1. Review of Technology Development Conditions for Hydrogen Production in Thailand

The section aims to assess Thailand's technology level by examining and comparing the number of thesis paper and patent applications related to hydrogen technology by country. Technology level is an abstract concept encompassing technical capabilities, technology development skills, and other related aspects, typically quantified and compared against other technologies.

The term 'technology level' is widely applied at home and abroad and serves a basis for identifying strategic industries and allocating R&D budgets. However, there is no standardized methodology for researching technology level, it is tailored and applied according to specific objectives. Among different approaches, using academic papers and patent information is a means of analyzing research outcomes and comparing technology levels, focusing on specific technologies. It is necessary to utilize DB for the thesis papers and patent, employing keywords and queries to extract relevant research papers and patents linked to key technologies. Quantitative analysis can be conducted through the number of papers and journals, while qualitative analysis can be achieved through citations, technology correlation analysis, and network analysis of research subjects. Similarly, concerning patent information, it is possible to analyze the quantity of patents, market share, growth rate, as well as assess citations and impact factors. The DB utilized for extracting papers is Web of science, and the DB utilized for extracting patents is Wintelips. Web of science can compare the status of SCI and SSCI classification, and Wintelips is a DB that can examine the application and registration status of global patents provided by the Korean Intellectual Property Office. To identify papers and patents published within the past decade (from 2013 to 2022), the following criteria was used.

<Table 3-1> Keywords used for searching papers and patents

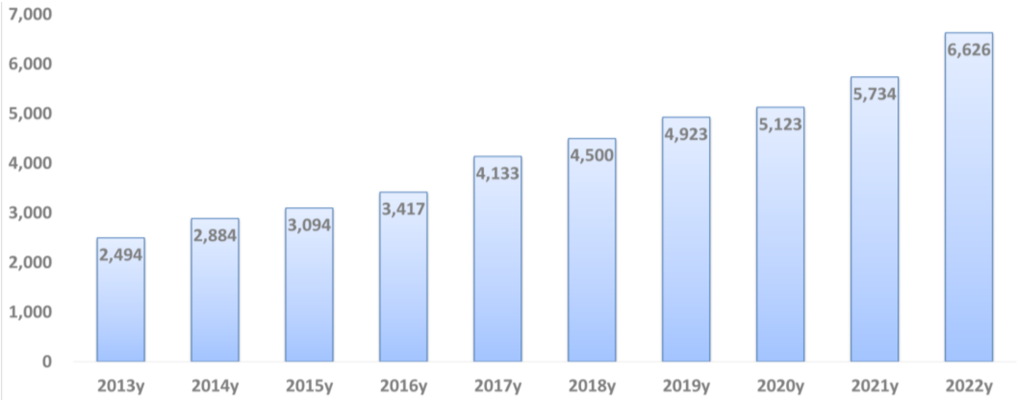
Category	Technology	Keywords
Hydrogen Production	01. Alkaline water electrolysis	((((alkalin* and electrolys*) OR AEL) AND (hydrog* OR electrod* OR (water and decompos*) OR (hydrogen and product*))))
	02. Polymer electrolyte water electrolysis	(((polymer* and electroly*) OR PEME) AND (hydrog* and product*))
	03. High temperature water electrolysis	(((high* AND temperat* AND electrolys*) OR HTEL) AND (hydrog* OR electrod* OR (water AND decompos*) OR (hydrog* AND product*)))
	04. Anion exchange membrane water electrolysis	(((solid* AND oxid* AND electrolys*) OR SOEL) AND (hydrog* OR electrod* OR (water AND decompos*) OR (hydrog* AND product*)))
	05. Material parts	((((hydrog* AND (storage* OR store*)) AND (high* AND press*))) AND ((cylinder* OR liner* OR vessel*) OR (HDPE OR polyethylene) OR (metal* OR alumin*) OR fiberglass OR (carbon* AND fiber*) OR (nonmetal* OR plastic*))))
	06. Next-generation production technology	(((hydrog* AND product*) AND ((photobio* OR photoelectrochemical OR photocatalyst) OR (decompos* AND methane))))
Hydrogen Storage & Transportation	07. Liquid hydrogen charging station	((liquid* AND hydrog*) AND ((supply* OR charg* OR refuel*) AND ("high pressu*" OR "low pressu*"))))
	08. Liquid hydrogen tank trailer	((((hydrog* AND liqui*) AND (storage* OR store* OR transp*)) AND (trailer* OR BOG OR lorry OR truck OR vehicle))))
	09. Liquid hydrogen storage tank	((((hydrog* AND liqui*) AND (storage* OR store*)) AND tank))
	10. Hydrogen liquefaction	(((hydrog* AND liqu*) AND ((low* AND temper*) OR cryogenic OR LOHC OR cold-box OR ortho-para OR LH2))))
	11. Hydrogen pipe network	(((hydrog* AND liqu*) AND (distribut* OR transport OR convey*) AND ("network*" OR "pipeline*"))))
	12. Next-generation hydrogen storage technology	(((("hydrogen storage*" AND (underground* OR reservoir OR aquifer OR fault)))))
Overseas hydrogen storage and transportation	13. Ammonia-Hydrogen	(("hydrogen storage*" AND (absorb* OR ((boron* OR borane*) OR nitr* OR (ammon* AND Bor*)))))
	14. Liquid hydrogen transport ship	((((hydrog* AND liqui*) AND (storage* OR carrier*)) AND (ship* OR cargo))))
	15. Liquid hydrogen reception base	((((hydrog* AND liqui*) AND (distribut* OR convey*))) AND (hub OR site))))
	16. Next-generation technology	((((hydrog* AND liqui*) AND (distribut* OR convey*)) AND (LOHC)))

1. Technology Level

A. The number of research papers

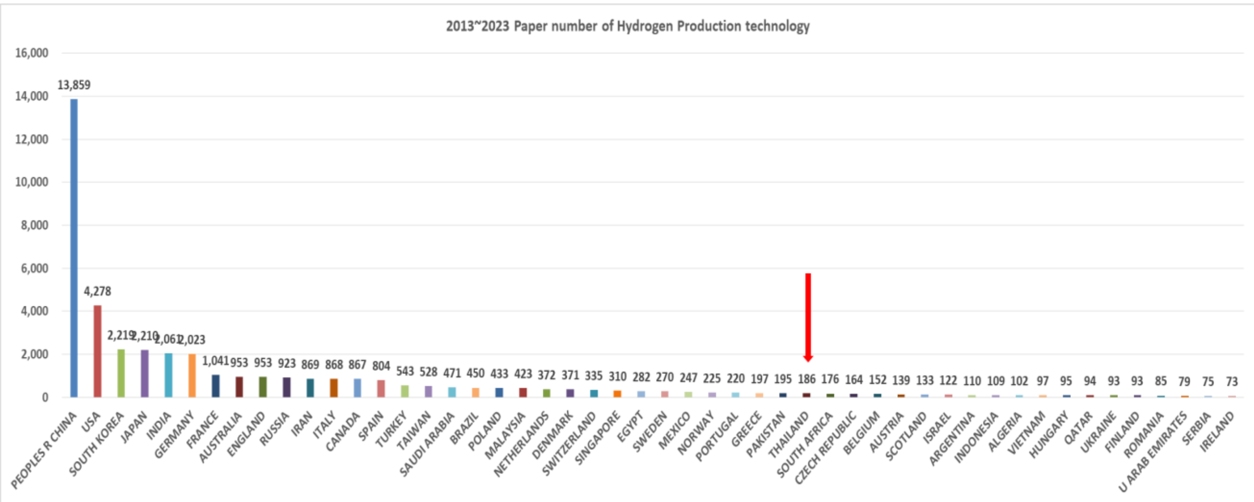
From 2013 to 2022, 42,928, papers covering hydrogen production, storage, and transportation technologies worldwide were published in 118 countries. The number of papers had increased from 2,494 in 2013 to 6,626 in 2022, representing an average annual growth rate of 11.5%. China published the most papers with 13,859, followed by the United States (4,278), Korea (2,219), Japan, India, Germany, France, and Australia.

[Figure 14] Number of research papers on hydrogen production technology (by year)



Source: Author

[Figure 15] Number of research papers on hydrogen production technology (by country)

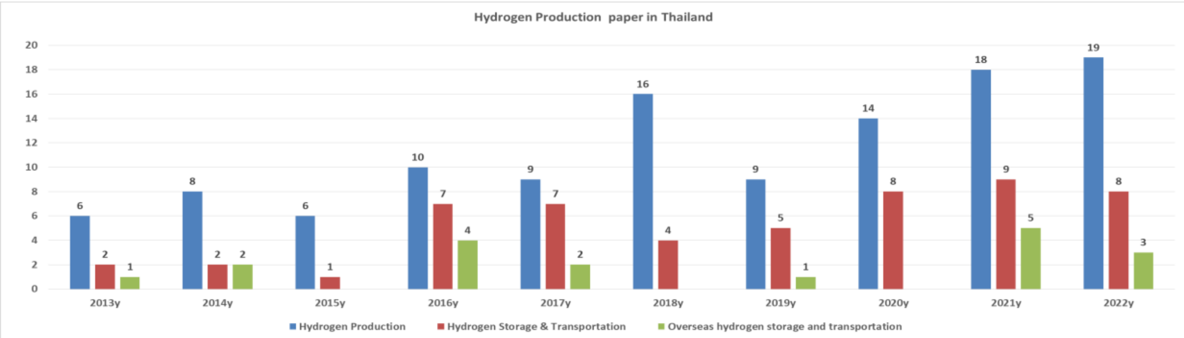


Source: Author

Thailand published 186 papers, ranking 32nd out of 118 countries. Among Southeast Asian countries, Malaysia (423) and Singapore (310) are the next highest, followed by Indonesia (109) and Vietnam (95).

Of the 186 papers in Thailand, 115 are related to hydrogen production technology, 53 papers to storage and transportation, and 18 papers to overseas storage and transportation. These numbers have shown a consistent growth trend, starting from 9 papers in 2013 and reaching 30 papers in 2022.

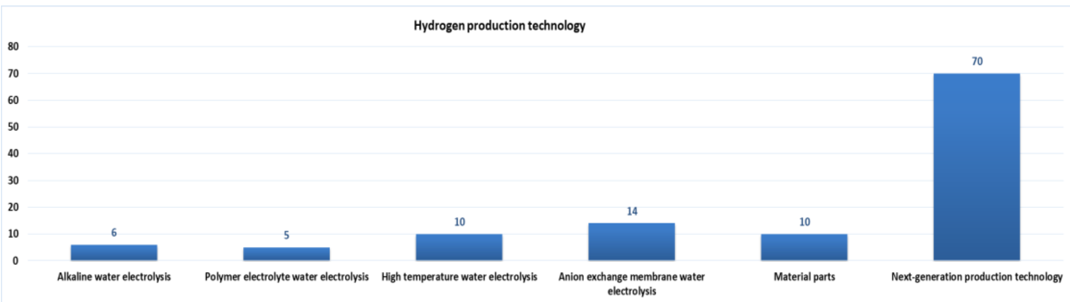
[Figure 16] Number of research papers on hydrogen production in Thailand (by year)



Source: Author

By technology, papers related to SMR technology are the most prevalent, with a total of 70 papers. Following this, there are 10 papers on high-temperature electrolysis, 14 on anion exchange membrane technology, 6 on alkaline electrolysis, and 5 on polymer electrolyte. Additionally, 10 papers are related to material development.

[Figure 17] Number of research papers on hydrogen production in Thailand (by technology)

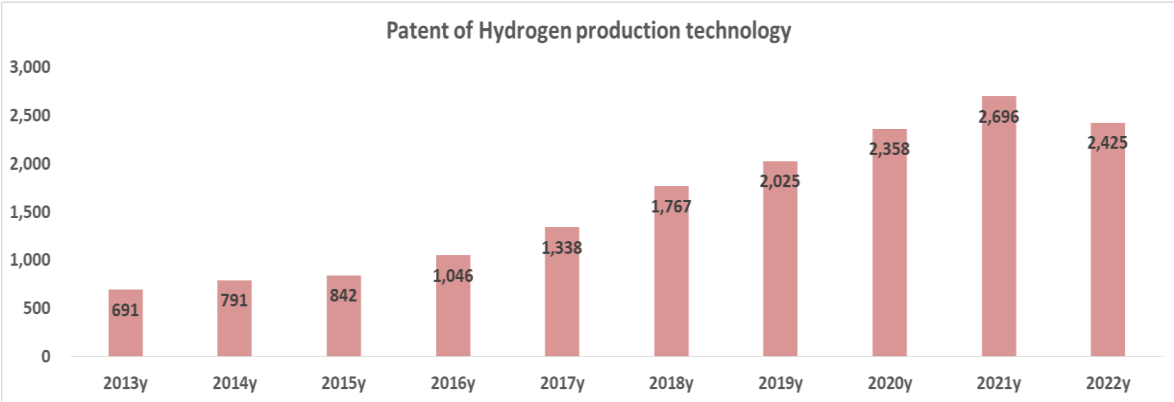


Source: Author

B. The number of patents

From 2013 to 2022, there were 15,979 patents related to hydrogen technology worldwide, representing a compound annual growth rate of 15%. In 2022, 2,425 patents were issued, more than tripling the 691 patents issued in 2013.

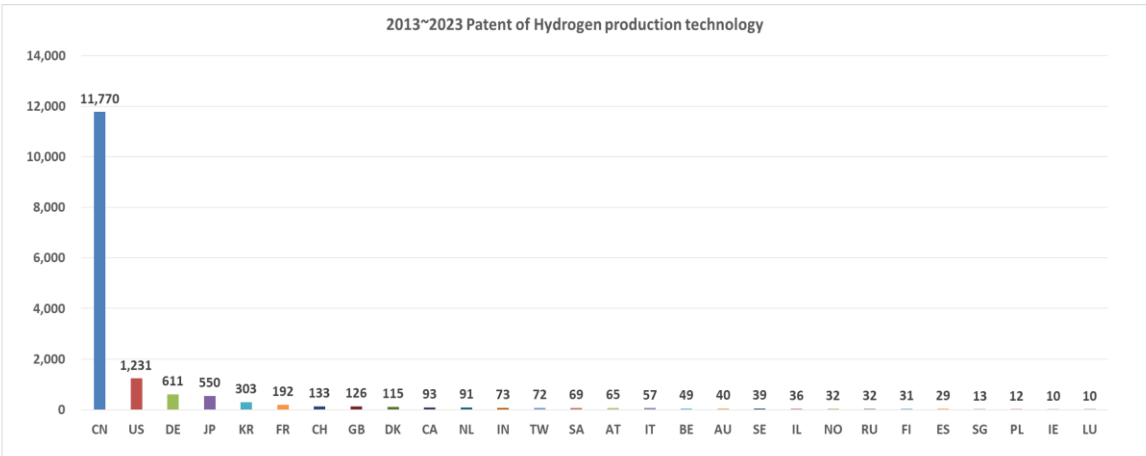
[Figure 18] Number of patents on hydrogen production worldwide (by year)



Source: Author

A total of 15,979 patents related to hydrogen technology are issued across 61 different countries. China possesses the majority of these patents, with a significant share of 11,770. The United States comes next with 1,231 patents, followed by Germany with 611, Japan with 550, South Korea with 303, and France with 192.

[Figure 19] Number of patents on hydrogen production (by country)



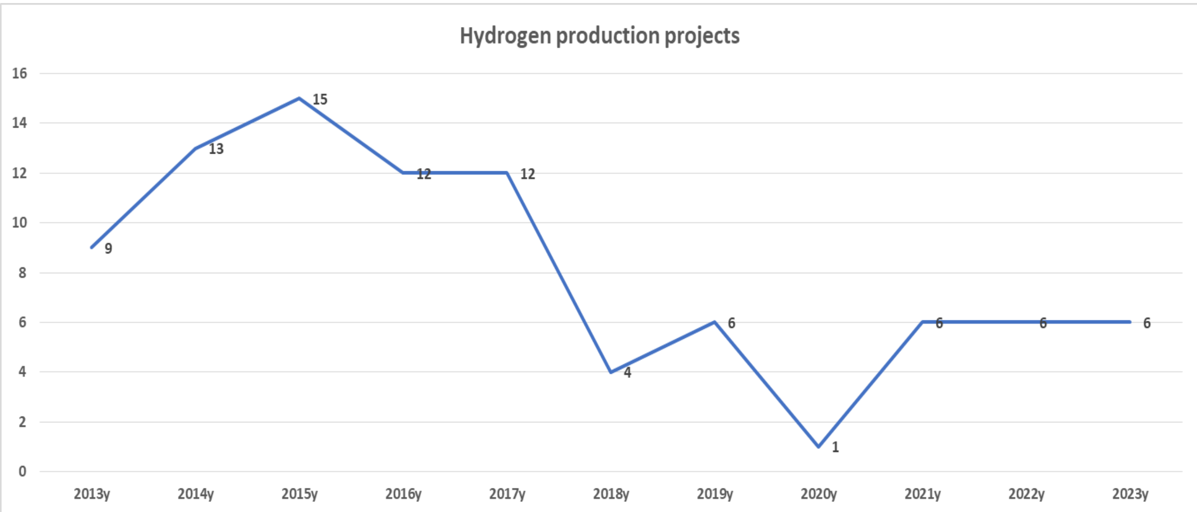
Source: Author

There are 28 countries with more than 10 patents while the remaining countries, including Thailand, have not yet made advancements in patent development. Consequently, looking ahead to future R&D, there is a need to generate outcomes that can establish intellectual property rights.

2. R&D Activity

The current status of R&D projects and technological achievements in Thailand were identified through the data from the National Research Council of Thailand (NRCT) and the Ministry of Higher Education, Science, Research and Innovation and experts' interviews. In Thailand, a total of 90 R&D projects pertaining to hydrogen production were implemented between 2013 and 2023, with a notable concentration of projects occurring around the year 2015.

[Figure 20] Number of R&D project on hydrogen production in Thailand



Source: Author

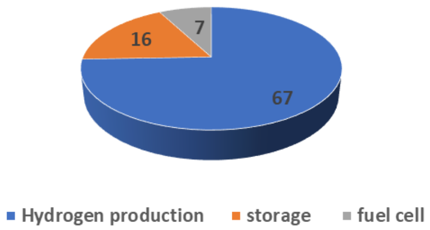
3. R&D Capacity

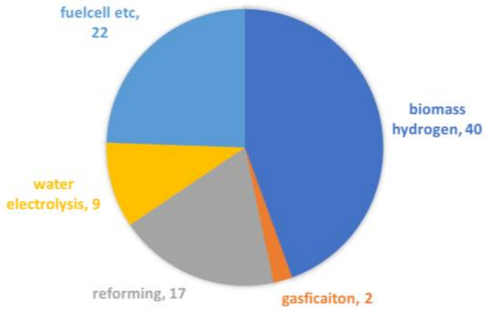
In order to analyze Thailand's capabilities in hydrogen production technology, this study conducted a survey and analysis of the R&D status, as well as interviews with local experts. With the support of NXPO, we conducted interviews with professors and managers from King Mongkut's University of Technology Thonburi (KMUTT), Chulalongkorn University (CU), ENTEC, PTT, and Toyota Motor Thailand Co.

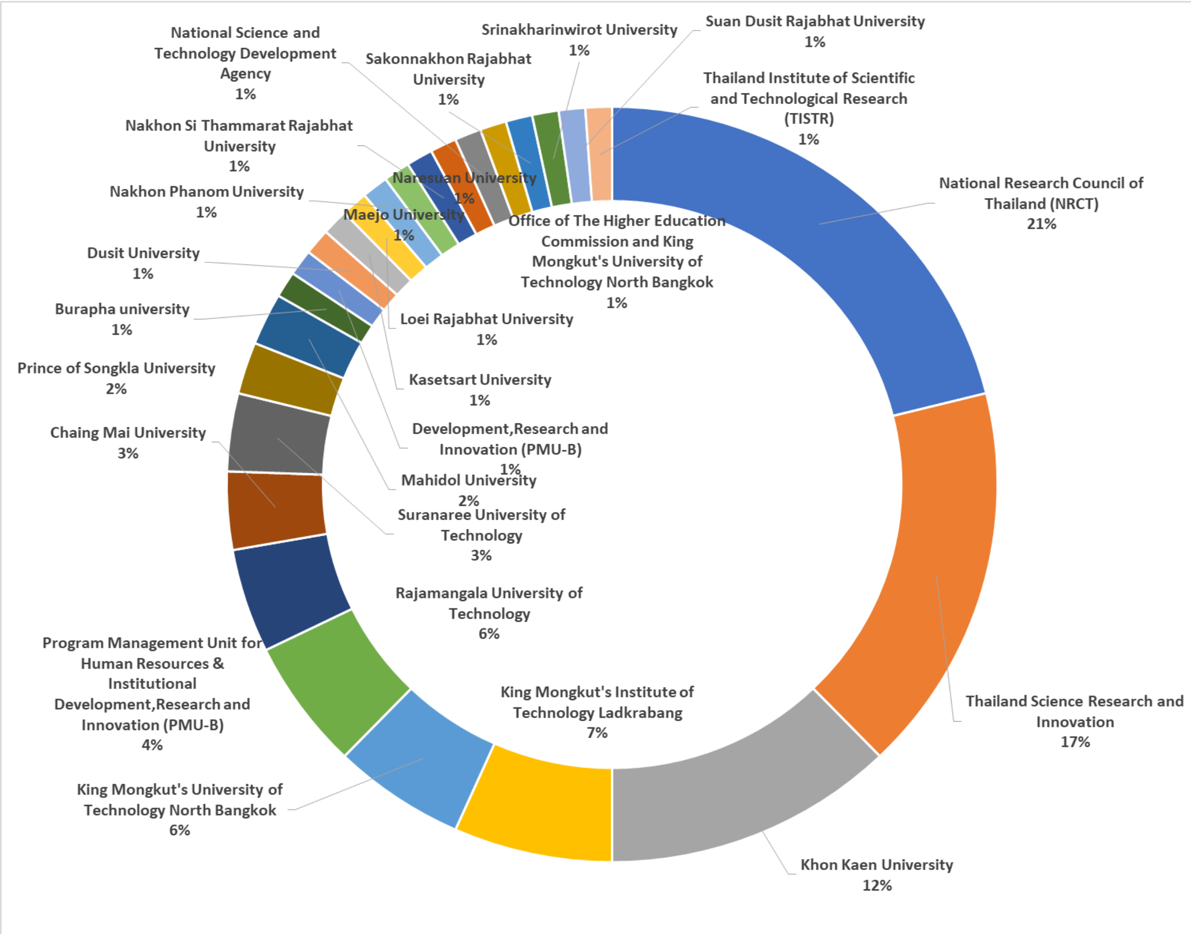
The findings revealed that Thailand currently relies on by-product hydrogen from the petrochemical and refining sectors, and there are plans to transition from gray hydrogen to blue hydrogen using CCUS technology. Although there is a lack of research on water electrolysis technology to produce green hydrogen, four to five universities and companies (PTT).

The company is currently conducting research on water electrolysis technology. Most of the research is on alkaline water electrolysis technology, and some research on PEM water electrolysis technology and SOFC water electrolysis technology is being conducted at Chulalongkorn University and Chiang Mai University. However,

the level of technology development capacity stands at below TRL3. In contrast, hydrogen production through biomass gasification has been more actively studied and, while not yet commercialized, is assessed at a TRL7 or higher, indicating its readiness for practical application. Although various studies are underway, the Thai government needs to support the technology in the long term, including financial and related policies. Among these technologies, experts suggest that hydrogen production from biomass is uniquely applicable to Thailand. Additionally, AEM electrolysis technology, classified as a next-generation electrolysis method alongside alkaline and PEM electrolysis, carries cost-related challenges but has garnered significant interest from local companies for demonstration projects.


16
7
67
Hydrogen production
storage
fuel cell


fuelcell etc, 22
biomass hydrogen, 40
water electrolysis, 9
reforming, 17
gasficaiton, 2


National Science and Technology Development Agency 1%
Srinakharinwirot University 1%
Suan Dusit Rajabhat University 1%
Sakonnakhon Rajabhat University 1%
Thailand Institute of Scientific and Technological Research (TISTR) 1%
Nakhon Si Thammarat Rajabhat University 1%
Narasuan University 1%
National Research Council of Thailand (NRCT) 21%
Nakhon Phanom University 1%
Maejo University 1%
Office of The Higher Education Commission and King Mongkut's University of Technology North Bangkok 1%
Dusit University 1%
Burapha university 1%
Loei Rajabhat University 1%
Prince of Songkla University 2%
Kasetsart University 1%
Development,Research and Innovation (PMU-B) 1%
Chaing Mai University 3%
Mahidol University 2%
Suranaree University of Technology 3%
Rajamangala University of Technology 6%
Program Management Unit for Human Resources & Institutional Development,Research and Innovation (PMU-B) 4%
King Mongkut's Institute of Technology Ladkrabang 7%
Thailand Science Research and Innovation 17%
King Mongkut's University of Technology North Bangkok 6%
Khon Kaen University 12%

Section 2. Review of Available Resources for Hydrogen Production in Thailand

1. Research Scope and Framework

A. Scope

This section reviews the availability of resources for hydrogen production within the geographical scope of Thailand. The resources required to produce hydrogen can be broadly categorized as feedstock, which contains the element hydrogen (H) and is converted into hydrogen through a chemical process, and fuel, which provides the energy required for the conversion process. In addition to feedstock and fuel, hydrogen production requires various inputs such as hydrogen production technology, labor, and capital. However, this study assumes that inputs other than feedstock and fuel are sufficiently available, as they do not depend on Thailand's resource endowment and can be developed and utilized through policy measures.

The feedstocks and fuels for hydrogen production are dependent on the hydrogen production technology. Therefore, in order to review the available resources for hydrogen production in Thailand, it is necessary to first review the resources as feedstocks and fuels for the candidate hydrogen production technologies. In the case of steam methane reforming (SMR), as discussed in Chapter 2, natural gas, ethane, propane, etc. can be considered as feedstocks, while resources as fuels serve as fossil fuels to provide heat. This study focuses on natural gas, a representative feedstock for the SMR process, and biogas[11], a renewable energy source composed mainly of methane, as the key feedstocks for SMR. In addition, natural gas, which can provide high heat to produce steam, is considered as a fuel (see <Table 3-2>).

On the other hand, water electrolysis technology, as indicated by its name, utilizes water and electricity for hydrogen production. In this case, the required feedstock resource is water, and the fuel resources are renewable energy and fossil fuel to generate electricity. In this study, water as a feedstock was determined to be sufficient within the geographical scope of

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[11] Feedstocks for biogas production include waste such as animal waste and industrial wastewater that contain or ganic materials.

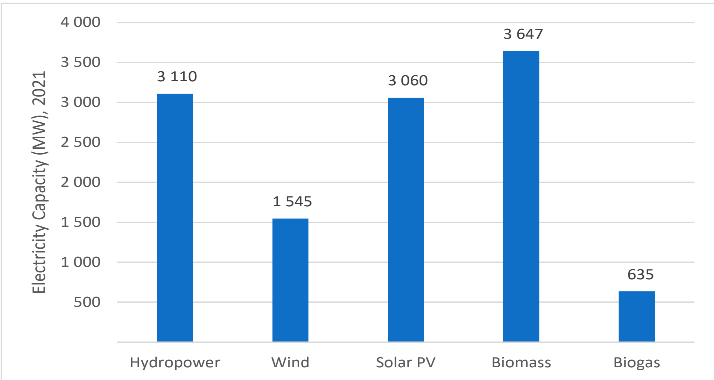
Thailand based on the results of Molden (2007)[12] and was not included in the analysis scope of the available resource review[13]. In addition, this study only considered electricity generated from renewable energy as a fuel input to the water electrolysis technology, and therefore only considered renewable energy as a fuel. This is to limit the analysis of electrolysis technology to the so-called "green hydrogen" production technology and to focus on the availability of resources for green hydrogen production. The renewable energy sources for electricity generation are solar, wind, biomass, biogas, and hydropower, which are currently operational in Thailand, as shown in [Figure 3-8] (see <Table 3-2>).

<Table 3-2> Resources as a Fuel and a Feedstock for Review

Technology	Resource as a Fuel	Resource as a Feedstock
Steam Methane Reforming	Natural Gas (for Heat)	Natural Gas, Biogas
Water Electrolysis	Solar, Wind, Biomass, Biogas, Hydropower (for Electricity)	*(Water)*

Note: Water for the electrolysis has not been reviewed in this study.
Source: Authors

[Figure 21] Renewable Electricity Capacity in Thailand, 2021



Note: Hydropower denotes renewable hydropower in IRENA (2022; 2023), Biomass denotes bagasse and other so lid biofuels in IRENA (2022; 2023).
Source: IRENA (2022; 2023)[14] [15]

[12] Molden, D. (Ed.), 2007, Water for food water for life: A comprehensive assessment of water management in agriculture, London: Earthscan, and Colombo: International Water Management Institute.

[13] According to Molden (2007), Thailand falls into the 'Little or no water scarcity' group, meaning that the country is assessed to have a sufficient amount of water resources.

[14] IRENA, 2022, Renewable Capacity Statistics 2022, Abu Dhabi: The International Energy Agency.

[15] IRENA, 2023, Renewable Capacity Statistics 2023, Abu Dhabi: The International Energy Agency.

B. Framework

This study examines Thailand's resource potential and resource development status and plan for hydrogen production resources summarized in Table 3-x1. The resource potential is an indicator for reviewing the endowment of resources in Thailand to understand how abundant the hydrogen production resources are in Thailand. A high resource potential for a specific hydrogen production technology in Thailand signifies that the inputs can be readily obtained in the country. Therefore, all factors held constant, it is logical to prioritize the utilization of Thailand's high-potential resources for hydrogen production in the aspects of a resource security and industrial supply chain management.

On the other hand, to accurately assess the available supply of a resource suitable for hydrogen production, it is necessary to calculate the resource's potential quantity while subtracting the planned consumption for future utilization. For example, natural gas can be used as a fuel for power generation and as a raw material for petrochemicals. Against this backdrop, the maximum quantity of natural gas available for hydrogen production is determined by subtracting the planned consumption of natural gas from its potential amount. However, this study only analyzes the potential amount in order to examine the total endowment of resources in Thailand, not dependent on other resource utilization plans16.

In terms of resource development status and plans, we reviewed the current status of resource development (or production) in Thailand, and whether there are any plans to continue or further develop the resources in the future, such as in national plans. This was done to examine the government's commitment to the utilization of each resource and the ease of input into the hydrogen production process. Resources currently being actively developed or being planned for large-scale development in the future are more likely to be utilized than those that do not exist. Nevertheless, given the absence of a comprehensive national hydrogen strategy or plan in Thailand at present, it is challenging to assume that all resources outlined in the national plan will be used for hydrogen production. However, due

[16] In addition, this study does not consider the issue of efficient resource allocation considering the input of resource potential to other industrial processes in addition to hydrogen production, as it is beyond the scope of this study.

to the nature of resource and energy infrastructure development, which requires large-scale capital investment, it is expected that the resources reflected in the national policy will be able to utilize some of the existing facilities and infrastructure, thus simplifying the procurement of hydrogen production resources.

2. Resource Potentials

A. Steam Methane Reforming

This study considered natural gas as a fuel and natural gas and biogas as feedstock to produce hydrogen through the water vapor methane reforming process, as summarized in <Table 3-2>, and reviewed the potential of these resources.

(1) Natural Gas as a Fuel

Thailand possesses natural gas resources with estimated reserves totaling 4,658.87 billion cubic feet (bcf) as of 2022 according to the Department of Mineral Fuels (DMF)[17] [18]. Furthermore, in 2022, Thailand's natural gas production reached 2,648 million standard cubic feet per day (mmscfd) in 2022 as reported by the Energy Policy and Planning Office (EPPO)[19] [20] (Figure 3-x2-(a)). When expressed in terms of the Reserve to Production ratio (R/P ratio), a widely employed method for indicating the availability of an exhaustible resource such as natural gas or oil, the R/P ratio is 4.8 years, which means that natural gas can be produced for about 4.8 years under current reserves and production rates[21] ([Figure 3-9]).

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[17] DMF, Petroleum Reserves, https://dmf.go.th/public/reserve/data/index/menu/943/year/2022 (accessed on 24 July 2023)

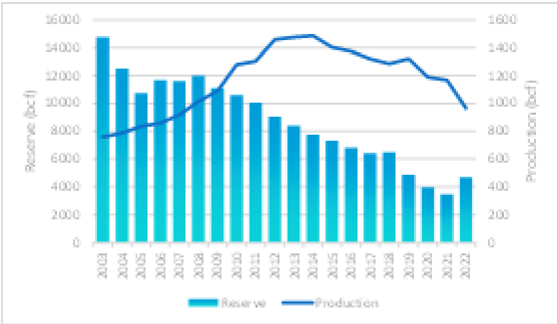
[18] Based on proved reserve (P1), including the Thailand-Malaysia joint development area, probable (P2) and possible (P3) reserves in 2022 are 3,267.84 and 3,127.74 bcf, respectively. Proved reserves are generally expected to be certain of commercial recovery and are the most conservative reserves with a 90% or greater probability of recovery. Probable reserve (P2) and possible reserve (P3) are reserves with a 50% and 10% probability of recovery, respectively. However, reserves are subject to change based on exploration and drilling results, technological advancements, and changes in economic conditions under current technology.

[19] EPPO, Natural gas production and import, natural gas statistics, https://www.eppo.go.th/index.php/th/energy-information/static-energy/static-gas, (accessed on 24 July 2023)

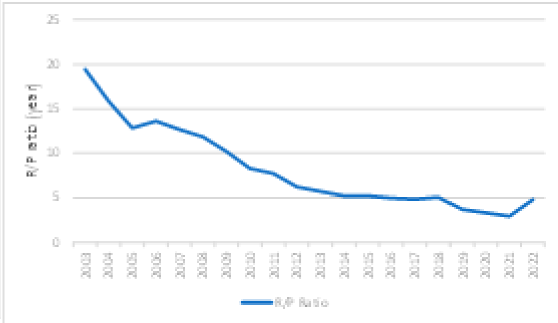
[20] This translates to about 967 billion cubic feet of annual production.

[21] However, the R/P ratio is not a fixed value because it is a variable quantity that changes based on the technology and

[Figure 22] Natural Gas Reserve, Production, and R/P Ratio in Thailand



(a) Reserve and Production



(b) R/P Ratio

Source: DMF, EPPO

Reserves, as mentioned earlier, can be a direct indicator of the amount of natural gas, but reserves are inherently limited in their comparability to renewable energy resources due to their concept of *stock*, not *flow*. Since renewable energy resources are either replenished within a certain period of time or are infinite, they are always considered to have more potential than natural gas because they can have a conceptually infinite value when approached with the same concept of reserves. Therefore, as stated earlier, this study aims to determine the resource potential by the amount that can be utilized annually, and accordingly, the potential of natural gas is evaluated based on its annual production volume.

The annual production of natural gas was calculated using projections from the Natural Gas Management Plan 2018-2037 (Gas Plan 2018)[22] of the Ministry of Energy (MOE) in Thailand. According to MOE (2020a), the demand for natural gas in 2037 is 5,348 mmscfd, with the Gulf of Thailand contributing roughly 28% of the demand, equivalent to 1,497 mmscfd[23]. When production is converted to bcf, it is estimated that about 547 bcf of natural gas can be produced in 2037[24]. Using the actual production in 2022 (967 bcf) and the projected

economics of the reserves.

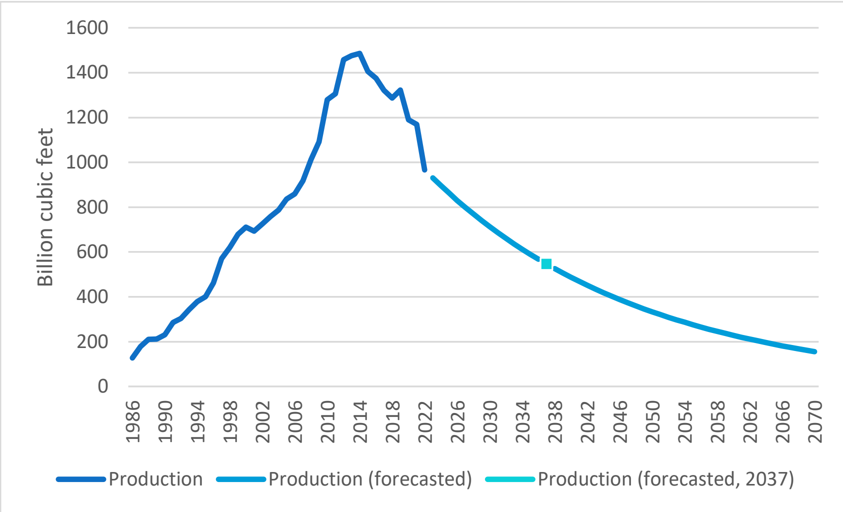
22 MOE, 2020a, Natural Gas Management Plan 2018-2037 (Gas Plan 2018)

23 According to MOE (2020a), onshore gas fields are not expected to produce until around 2032.

24 This figure may differ from the actual forecast because it is a backward calculation using the proportion of the Gulf of Thailand's production to natural gas demand in 2037.

production of 547 bcf in 2037, the average annual decline rate is 3.73%. Assuming the constant annual decline rate, this analysis suggests that the field is expected to produce 713 bcf and 333 bcf of natural gas by 2030 and 2050, respectively, as shown in [Figure 3-10]. The average annual natural gas production from 2023 through 2050 is about 584 bcf.

[Figure 23] Domestic Natural Gas Production Forecast



Note: The decline rate of natural gas production is assumed to be 3.73% (See text).
Source: Authors' calculation based on EPPO and MOE (2020a)

According to the Petroleum Institute of Thailand (2018)[25], natural gas from the Gulf of Thailand is typically 'wet' gas. This means that 1 million standard cubic feet (scf) of natural gas carries a calorific value of approximately 24.57 tonne of oil equivalent (toe)[26][27]. Utilizing this calorific conversion factor, the annual production of natural gas in calories is shown in <Table 3-3>. In 2050, natural gas production amounts to approximately 8,194 ktoe, accounting roughly 24% of Thailand's total primary commercial energy production, which stood at 34,549 ktoe[28] in 2022.

[25] Petroleum Institute of Thailand, 2018, Assessment of Resilience against Liquefied Natural Gas Import Disruption in Thailand. in Nakamura, T., Young, S. J., and Kutani, I. (Eds), Assessment of Readiness for Fossil Fuel Import Disruption, ERIA Research Project Report 2017, No. 6, Economic Research Institute for ASEAN and East Asia

[26] A unit that expresses the amount of energy produced by burning a ton of oil.

[27] MOE, 2023, Energy Statistics of Thailand 2023.

[28] *Ibid.*

<Table 3-3> Natural Gas Potential as a Fuel

Year		2022	2030	2037	2040	2050	2023-2050 average
Natural Gas (only used as a fuel)	bcf	966.52	713.14	546.57	487.67	333.49	583.67
	ktoe	23,747.40	17,521.83	13,429.12	11,982.12	8,193.85	14,340.79
Natural Gas (used as a fuel and feedstock)	bcf	150.79	111.26	85.27	76.08	52.03	61.06
	ktoe	3,704.90	2,733.63	2,095.11	1,869.36	1,278.35	2,237.35

Source: Authors' calculation based on EPPO, MOE (2020a;2023), and Yamada et al., (2019)

On the other hand, natural gas can also be utilized as a feedstock. Hence, to derive a comprehensive assessment of the potential of natural gas as a fuel and a feedstock for SMR, it is necessary to recalculate the potential by considering the ratio of the inputs. In other words, the above is the result of the SMR process using only natural gas as a fuel, i.e., and biogas as a feedstock, and the amount that can be utilized as a fuel will be reduced if natural gas is used as a feedstock as well as a fuel. According to Yamada et al. (2019)[29] , when 250.000 moles of methane is input as feedstock for SMR, the required methane as fuel is 46.213 moles. In this context, approximately 15.6%[30] of methane can be input as fuel when there is a total of 296.213 moles[31] of methane. Therefore, 52.03 bcf of natural gas, which corresponds to about 15.6% of the 333.49 bcf of natural gas produced in Thailand in 2050, can be used as a fuel (<Table 3-3>).

[29] Yamada, M., Fujikawa, K., and Umeda, Y., 2019, Scenario input-output analysis on the diffusion of feul cell vehicles and alternative hydrogen supply systems, Journal of Economic Structures, Vol. 8, No. 1, pp. 1-22.

[30] 46.213 moles / 296.213 moles

[31] 250.000 moles (feedstock) + 46.213 moles (fuel)

(2) Natural gas as a Feedstock

The natural gas potential as a feedstock was also utilized by calculating the annual production through the same process as above. However, natural gas was considered as a fuel for SMR for the both cases shown in <Table 3-2>, so the natural gas potential as a feedstock should be calculated by subtracting the amount that is used in the SMR process as a fuel from the amount of natural gas produced in Thailand. In other words, when natural gas is utilized as both a fuel and a feedstock, the amount of natural gas production, except for the amount that is also used as a fuel, can be utilized as a feedstock.

Unlike the potential of natural gas as a fuel, which was expressed in calories, the potential of natural gas as a feedstock was converted to the amount of methane contained in natural gas to make it comparable to another resource, biogas. The proportion of hydrocarbons in natural gas varies depending on the gas field from which it is produced, but according to PTTNGR[32], it is typically more than 70% methane. According to Tisdale (1996)[33], natural gas produced in Thailand contains about 83.35% methane, while Nikomborirak (2011)[34] explained that natural gas contains about 76% methane based on Thai onshore gas fields. This study conservatively assumed that natural gas produced in Thailand contains about 70% methane, and the methane contained in the annual production of natural gas was calculated in volume units[35] as shown in <Table 3-4>. In 2030 and 2050, Thailand is expected to produce 11.93 billion m^3 and 5.58 billion m^3 of methane, respectively.

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32 PTTNGR, The Basic of Natural Gas, https://pttngr.pttplc.com/Knowledge/Knowledge?ID=BasicNG1 (accessed on 24 July 2023)

33 Tisdale, P., 1996, Natural Resource Accounting: A Case Study of Natural Gas in Thailand, Thailand Development Research Institute.

34 Nikomborirak, D., 2011, Gas in Thailnad. in APEC Policy Support Unit (Eds.), The Impact and Benefits of Structural Reforms in the Transport, Energy and Telecommunications Sectors in APEC Economies, Asia-Pacific Economic Cooperation

35 1 bcf = 28,316,847 m3 to convert to SI units.

<Table 3-4> Natural Gas Potential as a Feedstock

Year		2022	2030	2037	2040	2050	2023-2050 average
Natural Gas (used as a fuel and feedstock)	bcf	815.73	601.88	461.29	411.59	281.46	492.61
Methane (used as a fuel and feedstock)	billion m^3	16.17	11.93	9.14	8.16	5.58	9.76

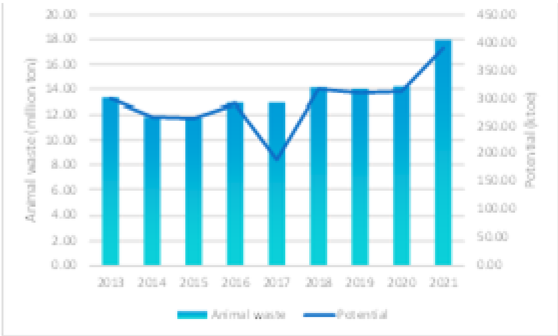
Source: Authors' calculation based on EPPO, MOE (2020a;2023), and Yamada et al., (2019)

(3) Biogas as a Feedstock

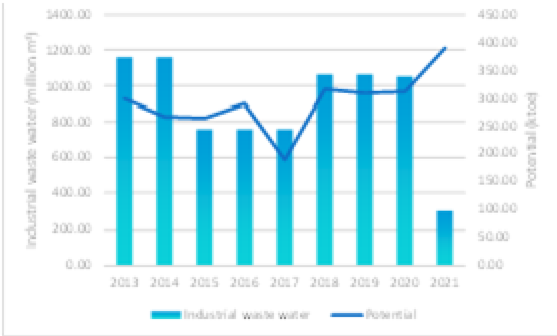
The potential of biogas as a feedstock was calculated by using the potential in the Thailand Alternative Energy Situation report of the Department of Alternative Energy Development and Efficiency (DEDE) of MOE. The Thailand Alternative Energy Situation report records the amount of animal waste, industrial wastewater, and landfill waste that can be used as a feedstock for biogas, and the amount of energy that can be obtained from them is recorded as energy potential (see [Figure 3-11]). Animal waste, industrial wastewater, and landfill waste are commonly used to produce biogas through anaerobic fermentation, and this study assumes that the energy potential recorded in the Thailand Alternative Energy Situation is the biogas potential[36].

[36] In the Thailand Alternative Energy Situation report, animal waste and industrial wastewater are described as biogas energy potential.

[Figure 24] Waste Generation and Energy Potential in Thailand



(a) Animal waste



(b) Industrial waste water

(c) Municipal solid waste

Source: DEDE (2013-2021)[37]

On the other hand, biogas is produced from animal waste, industrial wastewater, and landfill waste generated by human activities, so the biogas potential can change depending on human activities. In general, as the economy and population grow, there is a tendency for the amount of waste generated from human activities to increase. Therefore, it is plausible that the amount of organic waste resources in Thailand will experience long-term growth, leading to a corresponding increase in biogas potential. However, in order to take a conservative approach to the resource potential, this study estimated the biogas potential using the latest waste generation and energy potential (2021) recorded in the Thailand Alternative Energy

37 DEDE, 2013-2021, Thailand Alternative Energy Situation 2013-2021 *(each annual report)*

Situation[38]. According to DEDE (2021), the generation of animal waste was about 18 million tons in 2021, which has a biogas energy potential of 389.16 ktoe. Industrial wastewater generated about 309 million m^3 in 2021, and when converted to biogas energy, this volume equates to 1,487.67 ktoe. Municipal waste generated a total of 16 million tons, of which the biogas energy potential from landfill waste is about 0.69 ktoe (<Table 3-5>).

To compare the biogas potential as a feedstock with the natural gas potential, the biogas potential was also converted to the volume of methane contained in the biogas. First, the biogas conversion factor presented by DEDE (2021) ($10^6 m^3$ = 495.39 toe) was applied to convert the potential expressed in energy units (ktoe) in the Thailand Alternative Energy Situation report to volume units. In addition, to estimate the methane volume in the biogas by volume, we used the methane composition ratio[39] in biogas presented by Huertas et al. (2011)[40] and applied the smallest value of 50% to be conservative. With the above conversion process, the biogas energy potential of 1,874.52 ktoe in 2021 corresponds to a total of 3.78 billion m^3 of biogas, and the methane contained in 3.78 billion m^3 of biogas has a potential of about 1.89 billion m^3.

<Table 3-5> Biogas Potential as a Feedstock

Year			2021
Biogas Energy Potential	Animal waste	ktoe	389.16
	Industrial waste water		1,484.67
	Municipal solid waste (Landfill waste)		0.69

[38] Since natural gas production often follows a bell-shaped curve over time, and Thailand's natural gas production peaked around 2015, as shown in Figure 3-x3, it is not a conservative approach to estimate the current level of production as potential. Therefore, we calculated a forecast for natural gas.

[39] Huertas et al. (2011) suggested methane composition ratios of 50-80, 50-80, and 50-70% for agricultural waste, landfills, and industrial waste, respectively.

[40] Huertas, J. I., Giraldo, N., and Izquierdo, S., 2011, Removal of H_2S and CO_2 from Biogas by Amine Absorption. in Markoš, J. (Eds.), Mass transfer in chemical engineering processes, Intech, pp. 133-135. quoted in Chen, X.Y., Vinh-Thang, H., Ramirez, A.A., Rodrigue, D., and Kaliaguine, S., 2015, Membrane gas separation technologies for biogas upgrading, RSC Advances, 5, 24399.

	Total		1,874.52
Biogas	Total	billion m^3	3.78
Methane	total	billion m^3	1.89

Source: Authors' calculation based on DEDE (2021) and Huertas et al. (2011)

(4) Summary for Steam Methane Reforming

The potential amount of resources required for the hydrogen production method through steam methane reforming is summarized in <Table 3-6>[41]. When natural gas is employed both as a fuel and a feedstock, it is estimated that about 1,278.35 ktoe of natural gas can be utilized as a fuel, along with about 5.58 billion m^3 (methane basis) of natural gas utilized as a feedstock. On the other hand, if natural gas is utilized as a fuel and biogas is utilized as a feedstock, it is estimated that 8,193.85 ktoe and 1.89 billion m^3 (methane basis) of natural gas and biogas can be utilized, respectively[42].

Natural gas has a higher potential than biogas as a feedstock[43] for steam methane reforming. Based on the methane contained in each resource, 1.89 billion m^3 of biogas can be used as a feedstock, while 5.58 billion m^3 of natural gas can be used, which is about three times more. In addition, this study assumed that only domestically produced natural gas can be used to produce hydrogen through the SMR process, but due to the internationally traded nature of natural gas, the potential amount of natural gas that can be used for SMR is likely to be larger if imports are also considered.

[41] For natural gas, we conservatively utilized 2050 production.

[42] Based on the methane input as a raw material, it is judged that only a smaller amount of natural gas is required as a fuel than the former because the input is less than the latter. However, this may vary depending on the actual SMR process utilizing biogas.

[43] Using 5.58 billion m^3 of natural gas containing methane as feedstock, 1,278.35 ktoe of natural gas as fuel is required to operate the SMR process. Therefore, it is estimated that a smaller amount of fuel (natural gas) would be required if 1.89 billion m^3 of biogas containing methane is used as a feedstock. Therefore, assuming that all the natural gas produced in Thailand can be used in the SMR process, the amount of natural gas input as a fuel is not decisive in selecting the SMR production method in terms of input resources.

<Table 3-6> The Summary of Resources Potential for SMR

The way of use	Potential
Natural Gas (Fuel) Natural Gas (Feedstock)	1,278.35 ktoe 5.58 billion m^3 *(of methane)*
Natural Gas (Fuel) Biogas (Feedstock)	8,193.85 ktoe 1.89 billion m^3 *(of methane)*

Note: Natural gas potential in 2050.

Source: Authors' calculation based on EPPO, DEDE (2021), MOE (2020a;2023), Huertas et al. (2011), and Yamada et al., (2019)

B. Water Electrolysis

As shown in <Table 3-2>, this study only considers electricity generated from renewable energy sources as a fuel for the electrolysis process, and examines the generation potential of solar, wind, biomass, biogas, and hydropower as renewable energy sources. In addition, as mentioned above, water, which is the raw material for the electrolysis process, is considered to be abundant in Thailand and was excluded from the scope of the potential review.

On the other hand, renewable energy potential varies across different studies, owing to the technical assumptions used for the potential calculation and the scope of the potential, etc. This study focuses on the renewable energy generation potential described in IRENA and ACE (2022) study[44] due to the consistency of references and results. In addition, for solar and biomass, whose energy potential is presented in the DEDE’s Thailand Alternative Energy Situation report, the power generation potential was also calculated based on DEDE's criteria and compared with the results based on IRENA and ACE (2022). However, in the case of biogas power generation, IRENA and ACE (2022) do not provide the results, so the calculation was based on the previously utilized biogas potential.

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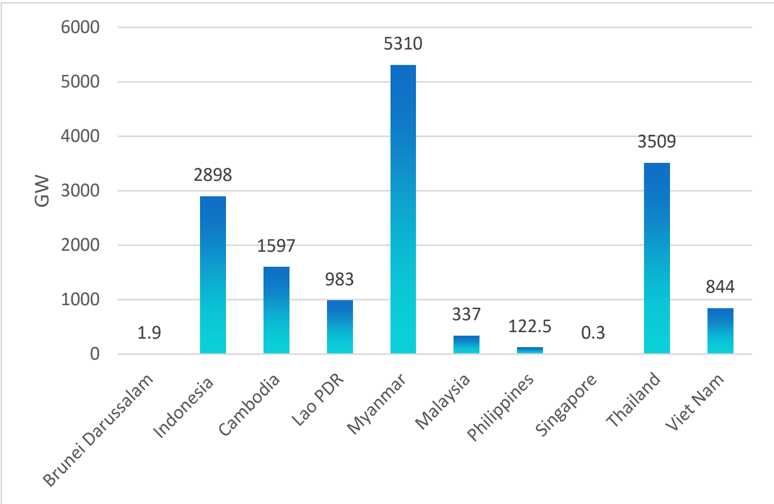
[44] IRENA and ACE, 2022, Renewable energy outlook for ASEAN: Towards a regional energy transition, 2nd ed., Abu Dhabi: International Renewable Energy Agency; and Jakarta: ASEAN Centre for Energy.

(1) Solar Photovoltaic (PV) as a Fuel

Thailand is considered to have one of the highest solar power potentials among the Association of Southeast Asian Nations (ASEAN) member states. According to IRENA and ACE (2022), Thailand has a solar potential of 3,509 GW, the second largest potential after Myanmar (5,310 GW) ([Figure 3-12]). This is approximately 1,100 times the installed solar capacity of 3,060.3 MW in Thailand as of 2021.

[Figure 25] Solar PV Potential in ASEAN Member States



Source: IRENA and ACE (2022)

In this study, the solar potential of Thailand was calculated by converting the potential solar capacity of Thailand, which IRENA and ACE (2022) indicated, into energy units. In order to convert solar power expressed in terms of installed capacity to energy units, the average capacity factor of solar power in Thailand needed to be determined. The capacity factor represents the proportion of the theoretical maximum power generation of a specific power generation facility to the actual power generation. It serves as an indicator of how the power generation facility operates within a specific period. Therefore, if the maximum annual power generation that can be produced from the solar potential capacity of IRENA and ACE (2022) above is multiplied by the empirical annual capacity factor, the amount of electricity expected to be generated can be determined. In this case, the theoretical maximum annual power generation can be calculated by multiplying the capacity of the generating facility by 8,760 hours[45].

The capacity factor of Thailand's Solar PV facilities was calculated based on the installed capacities and the amount of actual power generation in Thailand as presented by DEDE (2019; 2020; 2021) (see <Table 3-7>) and the arithmetic average of the annual capacity factor for each year from 2019 to 2021 was used. The annual capacity factor of Thailand's solar PV installations was calculated to be around 19.2% on average[46]. According to IRENA and ACE (2022), the annual maximum power generation of 3,509 GW of solar PV is about 30,788,840 GWh[47]. By applying the capacity factor of 19.2%, the annual solar power generation potential is calculated at roughly 5,904,823 GWh. Since 1 million kWh (1 GWh) is about 85.21 toe, the solar power potential in toe is about 503,150 toe (<Table 3-8>).

<Table 3-7> Capacity Factors of Solar PV in Thailand

Year		2019	2020	2021	2019-2021 average
Capacity	MW	2982.6	2979.2	3060.3	-.
Output	GWh	5145.9	5031.4	5015.1	-.
Capacity Factor	%	19.70	19.23	18.71	19.21

Note: The year 2020 is a leap year.

Source: Authors' calculation based on DEDE(2019; 2020; 2021)

<Table 3-8> Solar PV Potential as a Fuel

Year		2022
Solar PV	GW	3,509

45 In a normal year, 24 hours/day×365 days=8,760 hours.

46 The actual amount of electricity generation may vary depending on future environmental conditions, facility operation plans, etc.

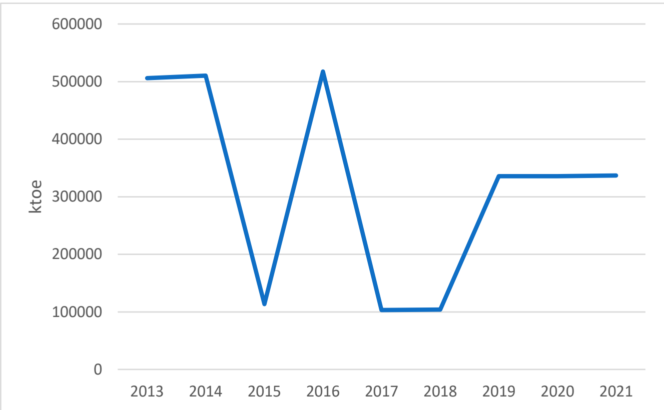
47 3,509 GW × 24 h/day × 365 days = 30,788,840 GWh

	GWh	5,904,823.56
	ktoe	503,150.02

Source: Authors' calculation based on DEDE (2019; 2020; 2021), IRENA and ACE (2022)

The potential of solar energy is also presented in DEDE's Thailand Alternative Energy Situation report. As of 2021, the solar energy potential was about 337,012 ktoe (DEDE, 2021), which is significantly different from the result (503,150 ktoe) calculated based on the potential solar PV capacity of IRENA and ACE (2022) above. However, Thailand's solar energy potential, according to the DEDE report, has shown a large variation by year, and the solar energy potential presented in 2013, 2014, and 2016 was around 500,000 ktoe, which is similar to the potential based on IRENA and ACE (2022) (see [Figure 3-13]).

[Figure 26] Thailand's Solar Energy Potential in DEDE (2013-2021)



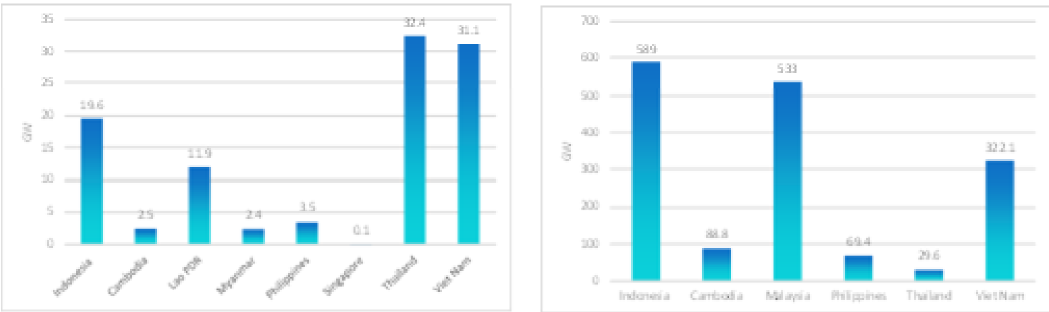
Source: DEDE (2013-2021)

(2) Wind Power as a Fuel

Thailand's onshore wind potential is considered to be high compared to other ASEAN countries, but its offshore wind potential is considered to be relatively low. According to IRENA and ACE (2022), Thailand's onshore wind potential is estimated at 32.4 GW, the highest among ASEAN member states, and 21 times higher than the approximately 1.5 GW installed in

Thailand as of 2021. Meanwhile, the offshore wind potential amounts to 29.6 GW, which is similar to the onshore wind potential, but lower compared to Indonesia (589 GW), Vietnam (322.1 GW), Cambodia (88.8 GW), and others ([Figure 3-14]).

[Figure 27] Wind Potential in ASEAN Member States



(a) Onshore wind (b) Offshore wind

Note: Potential values for onshore wind are not available for Brunei Darussalam and Malaysia; Potential values f or offshore wind are not available for Brunei Darussalam, LAO PDR, Myanmar, and Singapore.
Source: IRENA and ACE (2022)

As with solar PV, this study calculated the potential by converting the amount of potential wind power capacities into energy units. However, since only onshore wind power is currently installed in Thailand, the wind power capacity and generation data from DEDE (2019; 2020; 2021) cannot be considered to reflect the utilization characteristics of offshore wind power. Therefore, only the potential capacity of onshore wind power presented by IRENA and ACE (2022) was converted into energy units based on the capacity factor calculated using the data from DEDE (2019; 2020; 2021). On the other hand, the potential capacity of offshore wind power was converted into energy units using the median capacity factor (40.5%) of offshore wind in 2018 as presented by the IEA (2019) [48] [49]. However, the capacity utilization of offshore wind varies significantly depending on the conditions of the geographical area where the offshore wind is installed, so the actual capacity factor of offshore wind in Thailand may be different.

Based on the above discussion, Thailand's wind power potential in terms of energy units is as

48 IEA, 2019, Offshore Wind Outlook 2019, Revised ver., Paris: International Energy Agency.

49 According to the IEA (2019), as of 2018, the capacity utilization of offshore wind ranged from 29% to 52%.

follows. The annual capacity factor of onshore wind power in Thailand, as calculated via DEDE (2019; 2020; 2021), shows a distribution of 24.3%-27.8%, with an average capacity utilization of 26.1% (see <Table 3-9>). Based on the potential capacity of Thailand's onshore wind power (32.4 GW) provided by IRENA and ACE (2022), the maximum annual power generation is 283,824 GWh[50], so the annual power generation potential is about 74,149 GWh (about 6,318 ktoe) when multiplied by the capacity utilization rate of 26.1%. On the other hand, for offshore wind power, the annual maximum power generation was calculated to be about 259,296 GWh[51], and when multiplied by the annual capacity utilization rate of 40.5%, it was analyzed to have a power generation potential of about 105,015 GWh (about 8,948 ktoe) (see <Table 3-10>).

<Table 3-9> Capacity Factors of Onshore Wind Power in Thailand

Year		2019	2020	2021	2019-2021 average
Capacity	MW	1,506.8	1,506.7	1,545.3	-.
Output	GWh	3,670.3	3,219.5	3,552.4	-.
Capacity Factor	%	27.81	24.33	26.24	26.12

Note: The year 2020 is a leap year.

Source: Authors' calculation based on DEDE(2019; 2020; 2021)

<Table 3-10> Wind Power Potential as a Fuel

Year		2022
Onshore Wind	GW	32.4
	GWh	74,148.66
	ktoe	6,318.21
Offshore Wind	GW	29.6
	GWh	105,014.88
	ktoe	8,948.32

50 32.4GW×24hour/day×365day=283,824GWh

51 29.6W×24hour/day×365day=259,296GWh

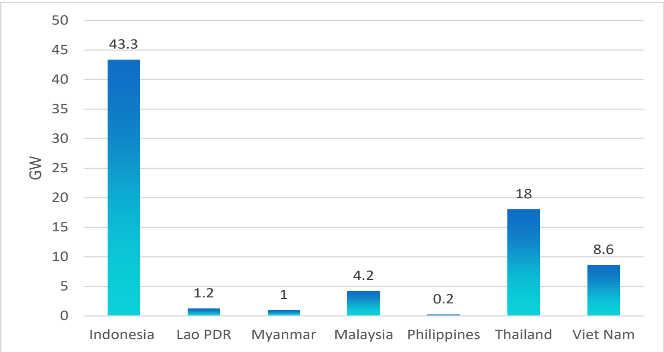
Source: Authors' calculation based on DEDE (2019; 2020; 2021), IRENA and ACE (2022)

(3) Biomass as a Fuel

According to IRENA and ACE (2022), Thailand's potential biomass capacity for electricity generation is estimated to be 18 GW ([Figure 3-15])[52]. This is the second largest potential capacity among ASEAN member states after Indonesia (43.3 GW).

In 2021, Thailand had approximately 3.6 GW of installed biomass power generation capacity, as reported by DEDE53. Furthermore, the potential capacity (18 GW) for biomass power in the country is estimated to be around five times greater than the existing installations.

[Figure 28] Biomass Generation Potential in ASEAN Member States



Note: Potential values for biomass are not available for Brunei Darussalam, Cambodia, and Singapore.

Source: IRENA and ACE (2022)

In order to estimate the power generation potential that can be produced from the above 18 GW of biomass capacity, the capacity factor was calculated based on the biomass power generation capacity and output from DEDE (2019; 2020; 2021). The capacity factor of biomass power generation facilities was around 60%, with an average capacity factor of about 60.7% (<Table 3-11>). Therefore, if the maximum power generation of 18 GW of biomass capacity potential of about 157,680 GWh54 is multiplied by the capacity factor of 60.7%, the annual

[52] Unlike solar and wind, the output of biomass can vary over time, and IRENA and ACE (2022) do not specify when to calculate a specific potential.

[53] DEDE, 2021, Thailand Alternative Energy Situation 2021

[54] 18 GW × 24 hour/day × 365 day = 157,680 GWh

biomass power generation potential is estimated to be about 95,672 GWh (about 8,152 ktoe) (<Table 3-12>).

<Table 3-11> Capacity Factors and Efficiency of Biomass Generation in Thailand

Year		2019	2020	2021	2019-2021 average
Capacity	MW	3,410.1	3,517.4	3,646.5	-.
Input	ktoe	8,090	7,535	8,135	-.
Output	GWh	19,110.8	17,845.1	19,259.5	-.
Capacity Factor	B	63.97	57.76	60.29	60.67
Efficiency	B	25.14	23.30	23.89	24.11

Note: The year 2020 is a leap year.

Source: Authors' calculation based on DEDE (2019; 2020; 2021)

<Table 3-12> Biomass Generation Potential as a Fuel

Year		2022
Biomass Generation	GW	18
	GWh	95,671.99
	ktoe	8,152.21

Source: Authors' calculation based on DEDE (2019; 2020; 2021), IRENA and ACE (2022)

Meanwhile, DEDE's Thailand Alternative Energy Situation report presents the energy potential of solid biomass. Thailand's solid biomass has an energy potential of approximately 36,459 ktoe as of 2021 (DEDE, 2021). Based on the biomass power generation and biomass input recorded by DEDE (2019; 2020; 2021), the biomass power generation efficiency in 2021 stood at around 23.9% (see <Table 3-11>). Assuming that Thailand's solid biomass potential and biomass power generation efficiency remain at the 2021 level, the country has the potential to generate approximately 8,710 ktoe of electricity. Therefore, when comparing the outcomes based on the DEDE report with the findings from IRENA and ACE (2022), there is no significant disparity in the results, particularly when considering the results related to solar energy.

(4) Biogas as a fuel

IRENA and ACE (2022) do not provide the potential for biogas power generation. Therefore, this study estimates the biogas power generation potential by utilizing the biogas potential used in the resource potential analysis of the SMR process and the efficiency of biogas power generation facilities in Thailand. As previously discussed, the Thailand Alternative Energy Situation report by DEDE provides data on the energy potential of biogas sources, including animal waste, industrial wastewater, and landfill waste (municipal solid waste). According to this report, the combined potential for these sources amounted to approximately 1,875 thousand tons of oil equivalent (ktoe) in 2021.

On the other hand, the results of calculating the power generation efficiency based on the capacity, biogas input, and electricity output of biogas power plants currently operating in Thailand are shown in <Table 3-13>. The capacity factor of biogas power plants varied by more than 10% in 2019, 2020, and 2021, while the power generation efficiency was analyzed to be constant at around 24%. Assuming that the biogas production and biogas power generation efficiency in Thailand remain at the 2021 level, the potential biogas resource of approximately 1,875 ktoe is estimated to have the capacity to generate about 448 ktoe (5,257 GWh) of electricity. If the biogas power generation potential (5,257 GWh) and the capacity factor in 2021 (28.71%) are used to calculate the capacity of biogas power generation facilities, the figure is about 2 GW. Thus, it is expected that the installation of biogas power generation facilities with a maximum capacity of about 2 GW is feasible based on the existing efficiency and utilization rate.

<Table 3-13> Capacity Factors and Efficiency of Biogas Generation in Thailand

Year	2019	2020	2021	2019-2021 average

Capacity	MW	530	557.2	635.4	-.
Input	ktoe	653	522	575	-.
Output	GWh	1,908.6	1,414.7	1,597.9	-.
Capacity Factor	%	41.11	28.90	28.71	32.91
Efficiency	%	25.13	23.30	23.89	24.11

Note: The year 2020 is a leap year.

Source: Authors' calculation based on DEDE(2019; 2020; 2021)

<Table 3-14> Biogas Generation Potential as a Fuel

Year		2022
Biogas Generation	GW	2.06
	GWh	5,256.56
	ktoe	447.91

Source: Authors' calculation based on DEDE (2019; 2020; 2021), IRENA and ACE (2022)

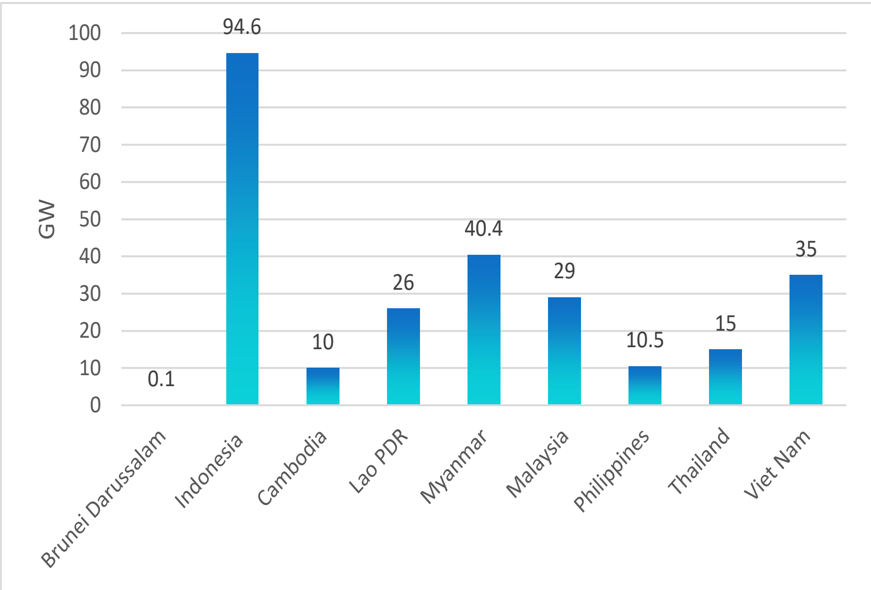
(5) Hydropower as a Fuel

According to IRENA and ACE (2022), Thailand's hydropower potential is assessed to be low compared to other ASEAN member states. The estimated hydropower potential for Thailand is around 15 GW, which is significantly lower when compared to Indonesia (94.6 GW) and Myanmar (40.4 GW), both of which have substantial hydropower potential (IRENA and ACE, 2022) ([Figure 3-16]). However, Thailand's installed hydropower capacity as of 2021 was approximately 3,110 MW[55] (DEDE, 2021), suggesting that the country has the potential to expand its hydropower capacity on a scale about five times larger than its current hydropower

[55] Large hydropower 2918.4GW, small hydropower 191.7GW in 2021 (DEDE, 2021)

capacity.

[Figure 29] Hydropower Potential in ASEAN Member States



Note: Potential values for hydropower are not available for Singapore.

Source: IRENA and ACE (2022)

In order to calculate the generation potential based on the hydropower potential of Thailand as presented by IRENA and ACE (2022), the capacity factor of hydropower facilities in Thailand was calculated as shown in <Table 3-15>. According to DEDE (2021), hydropower facilities are broadly categorized into large hydropower and small hydropower, and small hydropower refers to hydropower with a generating capacity of 12 MW or less, often located downstream. Since IRENA and ACE (2022) do not specify hydropower potential by size, this study opted for a conservative approach by employing the average annual capacity factor for hydropower, which stood at 17.4%. This rate is slightly lower than the average annual capacity factor of small hydropower facilities observed during 2019-2021. Given Thailand's hydropower potential of 15 GW provided by IRENA and ACE, the maximum power generation capability is estimated at 131,400 GWh. When this figure is multiplied by the 17.4% capacity factor of the existing hydropower facilities, the annual power generation potential amounts to 105,014.9 GWh (as presented in <Table 3-16>). This potential equates to approximately 1,950.4 thousand tons of oil equivalent (ktoe).

<Table 3-15> Capacity Factors of Hydropower in Thailand

Year			2019	2020	2021	2019-2021 average
Large Hydropower	Capacity	MW	2,919.7	2,919.7	2,918.4	-.
	Output	GWh	5,689.9	3,869.9	3,812.6	-.
	Capacity Factor	%	22.25	15.09	14.91	17.42
Small Hydropower	Capacity	MW	187.8	190.4	191.7	-.
	Output	GWh	440.5	347.7	473.9	-.
	Capacity Factor	%	26.78	20.79	28.22	25.26

Note: The year 2020 is a leap year.

Source: Authors' calculation based on DEDE (2019; 2020; 2021)

<Table 3-16> Hydropower Potential as a Fuel

Year		2022
Biogas Generation	GW	15 GW
	GWh	22,885.10
	ktoe	1,950.04

Source: Authors' calculation based on DEDE (2019; 2020; 2021), IRENA and ACE (2022)

(6) Summary for Water Electrolysis

<Table 3-17> provides an overview of the resource potential for hydrogen production through the water electrolysis, focusing on renewable energy with significant potential in Thailand. Among these sources, solar, wind, and biomass are identified as the most promising. Solar energy is anticipated to yield 503,150 ktoe of electricity per year, which is about twice the combined total of all other renewables (25,817 ktoe). Following solar, wind is the second largest renewable energy contributor, with a projected electricity generation of 15,267 ktoe from a combination of onshore and offshore wind. Biomass, on the other hand, has a potential

of 8,152 ktoe per year, which is less than wind in total, but more than onshore wind.

<Table 3-17> The Summary of Resources Potential for Electrolysis

The way of use	Potential of fuels (ktoe)
Solar PV (Fue, Electricity) *Water (Feedstock)*	503,150.02
Wind (Fuel, Electricity) *Water (Feedstock)*	6,318.21 (onshore), 8,948.32 (offshore) 15,266.53 (total)
Biomass (Fuel, Electricity) *Water (Feedstock)*	8,152.21
Biogas (Fuel, Electricity) *Water (Feedstock)*	447.91
Hydropower (Fuel, Electricity) *Water (Feedstock)*	1,950.04

Note: Natural gas potential in 2050; Due to its low scarcity, Water as a feedstock is not considered in this study.

Source: Authors' calculation based on DEDE (2019; 2020; 2021), IRENA and ACE (2022)

3. Resource Development Status and Plan

This section reviews the current development status and future development plans of resources that can be utilized for SMR and electrolysis. According to the framework of the study defined in Section 3.1, the current development status and plans of natural gas and biogas were reviewed for SMR, and that of renewable energy sources (solar, wind, biomass, biogas, and hydropower) were reviewed for electrolysis.

A. Steam Methane Reforming

(1) Natural Gas

As described in the review of resource potential, Thailand is one of the natural gas producers, with estimated natural gas reserves of 4,658.87 bcf as of 2022[56]. Thailand's natural gas reserves are concentrated in the Gulf of Thailand. A total of 4,410.48 bcf of natural gas exists in the Gulf of Thailand, compared to 367.08 bcf onshore, making 94.7% of natural gas reserves in the Gulf of Thailand (DMF, 2022)[57].

Thailand's natural gas production peaked at 4,073 mmscfd in 2014 and has been declining since, with production of 2,648 mmscfd in 2022[58]. According to the Natural Gas Management Plan 2018-2037 of the MOE (2020a), natural gas demand in 2037 was expected to reach 5,348 mmscfd, while only 28% of that demand can be met by natural gas produced in the Gulf of Thailand[59]. In other words, in 2037, Thailand's natural gas production is expected to decline to about 1,497 mmscfd, or 37% of its current level[60], and the country will need to secure reliable sources of natural gas demand that cannot be met by domestic production[61].

As the shortage of natural gas production in Thailand has become visible, the Natural Gas Management Plan 2018-2037, as one of its action plans, seeks to accelerate the exploration and production of natural gas in the country. As a specific target within this plan, Thailand aims to sustain a production level of 1,500 mmscfd (MOE, 2020). Given that Thailand's production is already projected to reach 1,500 mmscfd by 2037, it is probable that there will be a determined effort to aggressively pursue natural gas exploration to attain this objective. Additionally, the Natural Gas Management Plan 2018-2037 includes initiatives aimed at promoting the use of natural gas, signifying a strong policy commitment to harnessing natural gas resources within the country.

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56 DMF, Petroleum Reserves, https://dmf.go.th/public/reserve/data/index/menu/943/year/2022 (accessed on 24 July 2023)

57 DMF, 2022, Annual Report 2022

58 EPPO, Natural gas production and import, natural gas statistics, https://www.eppo.go.th/index.php/th/energy-information/static-energy/static-gas, (accessed on 24 July 2023)

59 As noted in the potential review, onshore gas fields are not expected to be produced after 2032.

60 The domestic natural gas production in 2037 is counted backward using the Gulf of Thailand production share and the demand, so it may differ from actual projections in MOE (2020a).

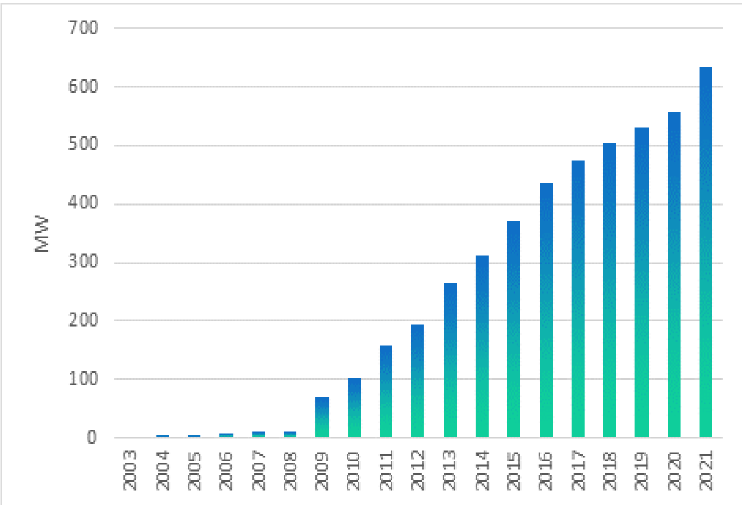
61 The MOE's (2020a) projections indicate that the country will need to secure 4% of its natural gas needs from Myanmar and an additional 68%, excluding Myanmar procurement and domestic production.

(2) Biogas

Biogas power generation in Thailand has been expanding at a rapid pace (see [Figure 3-17). In 2003, there were only 0.3 MW of biogas power plants in Thailand, but by 2021, this had expanded to 635 MW (IRENA, 2022; 2023). The cumulative capacity of biogas power plants has been steadily increasing, with an average annual growth rate of 53% during 2003-2021. The recent expansion of biogas power generation capacity has also been significant, with 78 MW of capacity added in 2021 compared to 2020, representing an increase of about 14%.

According to the MOE's Power Development Plan 2018-2037 (PDP 2018), Thailand aims to install 1,565 MW of cumulative biogas power generation capacity by 2037[62] (MOE, 2020b). This is about 2.5 times the capacity of biogas power plants in 2021, and requires an average annual capacity expansion of 5.8%. Therefore, Thailand demonstrates a strong commitment to advancing the implementation of biogas power generation within the nation.

[Figure 30] Biogas Generation Capacity in Thailand (Cumulative)



Source: IRENA (2022; 2023)

Meanwhile, in Thailand, biogas is utilized not only for power generation but also for heat production, with 688 ktoe of heat produced from biogas as of 2021 (DEDE, 2021). According

[62] MOE, 2020b, Thailand power development plan 2518-2037 (PDP 2018)

to MOE's Alternative Energy Development Plan 2018-2037 (AEDP 2018), the country aims to produce 1,283 ktoe of heat from biogas by 2037 (MOE, 2020c) . This is 1.9 times higher than the heat production in 2021, indicating that there is the government's will to develop biogas resources. On the other hand, the AEDP 2018 targets not only heat production from biogas but also 2,023 ktoe of heat from biomethane by 2037 (MOE, 2020c), and the Gas Plan 2018 plans to promote the utilization of biomethane to replace LNG imports (MOE, 2020a). Given that biogas is a key resource for biomethane production, promoting the utilization of biomethane is likely to boost biogas production.

(3) Summary for Steam Methane Reforming

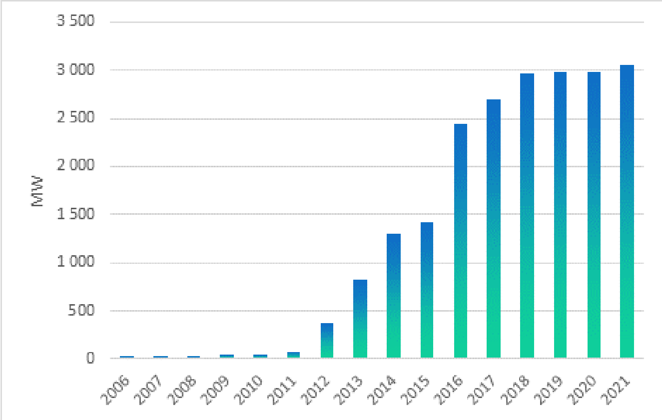
Both natural gas and biogas are likely to be actively developed at the national level in the future. For natural gas, as stated in the Gas Plan 2018, exploration and production will be actively promoted to increase self-sufficiency for future demand growth in Thailand. Biogas is also expected to be actively developed for power and heat generation in the future, as mentioned in the PDP 2018 and AEDP 2018.

B. Water Electrolysis

(1) Solar PV

Thailand's solar installations began to expand in earnest in 2012, following the installation of 30 MW in 2006. By 2021, approximately 3,060 MW of solar capacity had been installed, as reported by IRENA in 2022 and 2023 (Figure 3-x11). From 2006 to 2021, Thailand's solar installations grew at an average annual rate of 36%. Although growth has slowed in recent years, there was still a notable increase of around 2.6% in 2021 compared to 2020.

[Figure 31] Solar PV Capacity in Thailand (Cumulative)



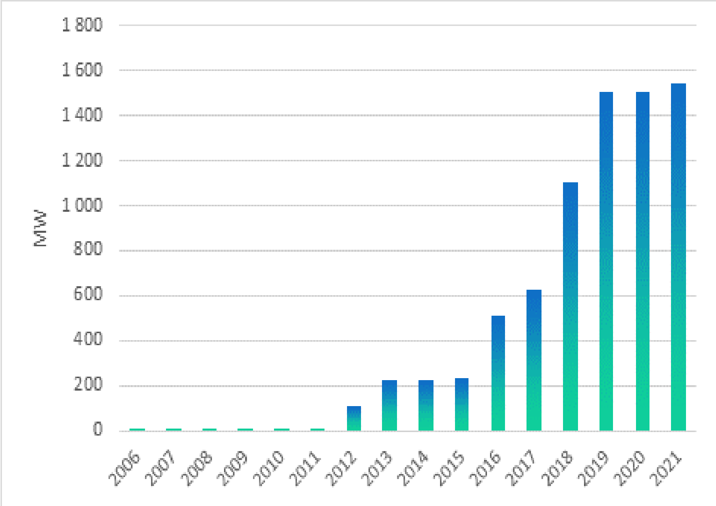
Source: IRENA (2022; 2023)

As of 2021, solar power generation was the third largest renewable energy source in Thailand after biomass power (3,647 MW) and hydropower (3,110 MW), but according to the PDP 2018, solar power aims to become the largest renewable energy source by 2037. The cumulative installed capacity of solar power in Thailand in 2037 is targeted to be 14,754 MW (MOE, 2020b), an increase of about 4.7 times compared to 2021. In order to achieve this goal, the solar power generation capacity will need to expand by 10.3% per year, and Thailand is considered to have a high policy commitment to solar energy development. In particular, the plan includes plans for floating solar facilities (2,725 MW by 2037) in addition to conventional solar facilities (MOE, 2020b), suggesting that the country is trying to diversify its locations to increase the scale of solar power generation.

(2) Wind Power

Currently, Thailand has 1,545 MW of installed wind power capacity, which has expanded rapidly since 0.34 MW was installed in 2006 (IRENA, 2022; 2023). During this period, wind power capacity has grown at an average annual rate of 75%, with particularly rapid expansion in 2013, 2016, 2018, and 2019, as shown in [Figure 3-19].

[Figure 32] Wind Power Capacity in Thailand (Cumulative)



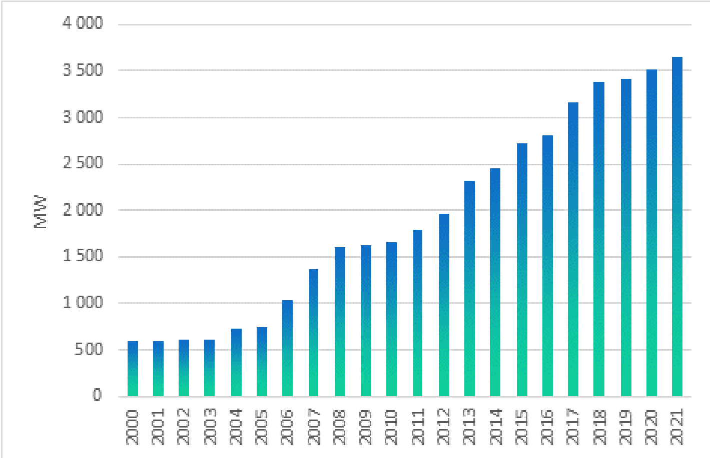
Source: IRENA (2022; 2023)

Thai authorities are aiming to nearly double the size of the country's wind power capacity by 2037. According to the PDP 2018, the targeted wind power capacity in 2037 is 2,989 MW (MOE, 2020b), a 1.9-fold (4.2% CAGR) increase from the 1,545 MW of wind power capacity in 2021. Thus, even though the planned expansion is not as extensive as that of solar power, there is a clear commitment to developing wind resources as a key renewable energy source.

(3) Biomass

Biomass is the largest installed renewable energy source in Thailand as of 2021. The biomass power generation capacity in Thailand demonstrated steady growth, with a compound annual growth rate (CAGR) of 9.0% from 598 MW in 2000 to 3,647 MW in 2021. The latest data for 2021 indicates an increase of around 3.7% compared to 2020 ([Figure 3-20]).

[Figure 33] Biomass Generation Capacity in Thailand (Cumulative)



Source: IRENA (2022; 2023)

According to the PDP 2018, the country aims to expand biomass power generation capacity to 4,694 MW by 2037 (MOE, 2020b), an increase of about 1.3 times compared to 2021. While the growth rate for biomass power may be relatively modest compared to other renewable energy sources leading up to 2037, it is expected to retain its significance as a primary source of electricity generation in Thailand. The country's goal is to have the second-largest renewable energy capacity in 2037, following solar, which is targeted to reach 14,754 MW.

(4) Biogas[63]

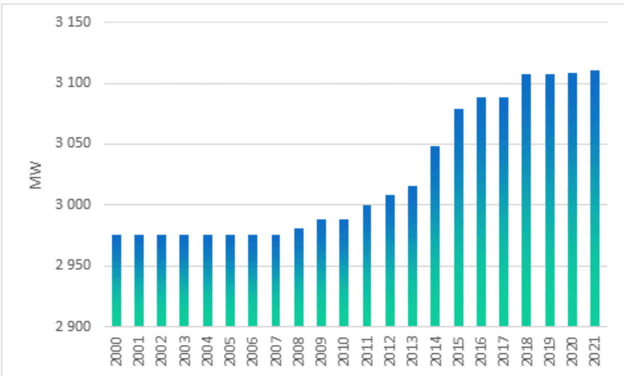
As described in the development status and plans of resources inputs to the SMR process above, biogas power generation has seen significant and rapid growth up to 2021. Moreover, the Thai government is strongly committed to advancing the development of biogas resources.

63 Refer to 3-(A)-(2) in Section 3.2 for the status and plans of biogas power generation.

(5) Hydropower

With 3,110 MW of installed capacity in 2021, Thailand's hydropower sector is the second largest after biomass, with no significant change in capacity from 2000 to 2021 compared to other renewable energy sources ([Figure 3-21]). The PDP 2018 also does not plan to increase the installed capacity of hydropower (2,918 MW) until 2037, with only minor increases planned for hydropower (MOE, 2020b). By 2037, the total installed capacity of hydropower and small hydropower is targeted to be 3,174 MW (MOE, 2020b), which represents an average annual growth rate of 0.1%. Therefore, the Thai government's dedication to hydropower expansion is relatively limited. Nevertheless, it is expected to play an important role in the decarbonization of electricity by having an installed capacity of over 3,000 MW in 2037.

[Figure 34] Hydropower Capacity in Thailand (Cumulative)



Source: IRENA (2022; 2023)

(6) Summary for Water Electrolysis

As outlined in the PDP 2018, there are expansion plans for solar, wind, biomass, biogas, and hydropower generation. A comparison of the five renewable energy generation sources is shown in <Table 3-18>, which shows that solar is poised for the most aggressive and substantial development. This assessment considers both the installed capacity by 2037 and the growth rate in the future. Following solar, biomass and hydropower are expected to be the next largest in terms of scale by 2037. Meanwhile, biogas and wind power, after solar, are forecasted to show the most significant development in terms of growth rate.

<Table 3-18> The Summary of Development Status and Plan for Electrolysis

Renewable Power	Capacity (2021, MW) (IRENA, 2022; 2023)	Capacity (2037, MW) (MOE, 2020b)	Annual Growth rate (2021-2037, %)
Solar PV	3,060	14,754	10.3
Wind	1,545	2,989	4.2
Biomass	3,647	4,694	1.6
Biogas	635	1,565	5.8
Hydropower	3,110	3,174	0.1

Source: Authors' calculation based on IRENA (2022;2023) and MOE (2020b)

Section 3. Comprehensive Comparison and Selection

In this section, the hydrogen production method was finally selected based on the results of the technology development conditions in Section 1 and the review of available resources in Section 2. First, considering the climate change response and the availability of fuel and raw materials, water electrolysis technology was deemed a more reasonable hydrogen production method than SMR. When water electrolysis is coupled with renewable energy, no carbon dioxide is emitted during hydrogen production, and renewable energy as a fuel is more abundant that natural gas[64]. However, given the Technology Readiness Level (TRL) and the need to develop large-scale renewable energy resources, it is considered strategic to produce hydrogen through SMR in the short to medium term and hydrogen through water electrolysis technology in the medium to long term.

For technologically mature SMR, it is considered appropriate to utilize natural gas as a fuel and feedstock with high resource potential[65]. To reduce greenhouse gas emissions from hydrogen production, it is crucial to utilize Carbon Capture, Utilization, and Storage (CCUS). Converting the raw material into biogas is required to alleviate the burden of CCUS. For water electrolysis technology as the next technology in SMR, Alkaline and AEM electrolysis method is considered to be the most reasonable given Thailand's technology level, technology development activities and achievements, and technology development capacity.

Given technology level, technology development activities and achievements, and technological development capacities of Thailand, Alkaline and AEM electrolysis methods are the most reasonable for water electrolysis technology as a next-generation technology of

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64 The potential for solar and wind-based electricity is 503,150.02 ktoe and 15,266.53 ktoe, respectively (see Table 3-x16), and the potential for natural gas as a fuel is 8,193.85 ktoe (see Table 3-x5).

65 Based on our analysis of the Gas Plan 2018, PDP 2018, and AEDP 2018, we believe that both natural gas and biogas will be actively developed in the long term.

SMR.

Furthermore, when assessing the most suitable renewable energy source for generating hydrogen through water electrolysis using Alkaline and AEM electrolysis method, it is evident that solar power stands out. Solar power shows the highest capacity for electricity generation in Thailand and is planned to be developed actively and on a large scale. Wind and biomass are also viable options among renewable energy resources, with wind being the superior resource in terms of potential and active national development, while biomass excels in terms of its potential and scale of development. When comparing wind and biomass, wind is deemed as the more favorable choice in terms of availability. This is because wind power does not require the establishment and management of a separate backward industrial supply chain for power generation and has a quicker resource renewal cycle when contrasted with biomass.[66]

In summary, the most appropriate hydrogen production method is to utilize Alkaline and AEM electrolysis method, one of the electrolytic hydrogen production methods, coupled with solar power generation. Nevertheless, in light of the time needed for technology and resource development, it is considered strategic to promote hydrogen production in the following sequence: Starting with SMR hydrogen production method using natural gas (both as fuel and raw materials), then progressing to the SMR hydrogen production method using natural gas as fuel and biogas as raw materials, and finally adopting Alkaline and AEM electrolysis method alongside solar (and wind) power generation.

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[66] While wind power generates electricity by utilizing the wind blowing at a given wind farm location, biomass power generation requires the collection, processing, and delivery of biomass resources to power generation facilities. In addition, the renewal cycle of biomass is dependent on the growth cycle of organisms such as plants.

<Table 3-19> The Summary of Development Status and Plan for Electrolysis

Technology		R&D Environment			Resources Availability	
		Technology Level	R&D Activity and Performance	R&D Capacity	Potential	Status and Plan
Steam Methane Reforming		High	High	High	High (NG-NG), Relatively low (NG-BG)	High (NG, BG)
Electrolysis of Water	Alkaline	Low	Low	Medium	Solar PV >Wind >Biomass >Hydropower >Biogas	Solar PV >Wind, Biomass, Hydropower, Biogas
	PEM	Low	Low	Low		
	AEM	Low	Medium	Medium		
	SOFC	Low	Medium	Low		

Note: NG=Natural Gas; BG=Biogas

Source: Authors

Chapter 4. Region Selection and Economic Analysis

Section 1. Region Selection

1. Site selection criteria[67]

In this section, we first review the factors that should be considered when selecting a location for a hydrogen production demonstration site, regardless of the technology. Then, we review the criteria that need to be considered further for the selected technologies, SMR using biogas and water electrolysis.

A. Common Factors

There are three main criteria to consider when selecting a location for a hydrogen production demonstration site: 1) the current state of local infrastructure, 2) the current state of local hydrogen industry infrastructure and expansion plans, and 3) the acceptability of residents and related laws. First, it is necessary to identify the current status of infrastructure for the supply of electricity, water, and raw materials in the region for the construction of the hydrogen production demonstration center, because the cost of building infrastructure is large when building this hydrogen production demonstration center.

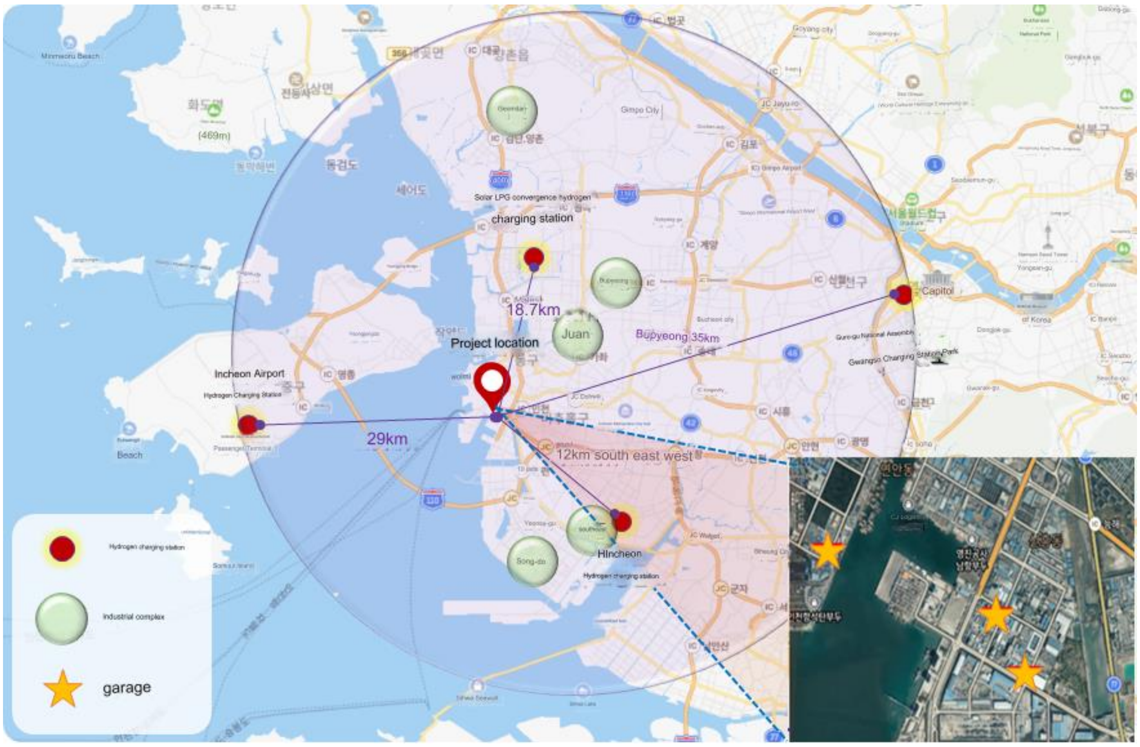
Next, the current status of the hydrogen industry infrastructure and expansion plans in the region should be considered. Given the current status of the hydrogen industry infrastructure and expansion plans in the region, the scale of the hydrogen demonstration complex can be determined, and in connection with this, the appropriate project site area can be calculated and the location can be selected. When building a hydrogen demonstration complex, it is important to select a project site that is easily accessible in consideration of hydrogen production, supply, and utilization considering the demand for hydrogen in the region, as transportation from the project site to the hydrogen production and utilization sites has a

[67] This part is written based on materials provided by Dr. Hyungwoon Song(obtained in September 18, 2023)

large impact on the price of hydrogen.

Finally, community acceptance and relevant legislation should be reviewed. The simple logic of producing and introducing hydrogen gas may cause local residents to avoid it due to the risk of hydrogen explosion, so it is necessary to ensure that hydrogen production facilities are perceived to be very technically safe. Therefore, local acceptance is very important when considering a site. Currently, the Hydrogen Act has been enforced in Korea, and when building hydrogen facilities, the relevant laws and regulations for the project site are specified, and the appropriate project site must be selected according to the law. In the construction of the hydrogen production demonstration complex, it is very important to identify the status of nearby facilities (schools, railroads, etc.) because the facility is classified as a hazardous facility, and ensuring a safe distance from surrounding facilities is a very important legal consideration.

[Figure 35] Hydrogen demonstration sites in Korea and their accessibility to demand



Source: Dr. Hyungwoon Song

<Table 4-1> **Summary of Hydrogen Production Location Selection Criteria**

Criteria	Description.
Regional Infrastructure Status (electricity, water, raw material supply)	Need to understand the status of building infrastructure for electricity, water, and feedstock supply in the region to build a hydrogen demonstration park
Regional hydrogen industry infrastructure status and expansion plans	When building a hydrogen demonstration complex, select an easily accessible business site that considers hydrogen production, supply, and utilization in light of local hydrogen demand.
Resident acceptance and applicable laws	Ensure that the local population perceives the hydrogen demonstration facility to be very technically safe, rather than the simple logic that hydrogen explosions are a risk when hydrogen is introduced.

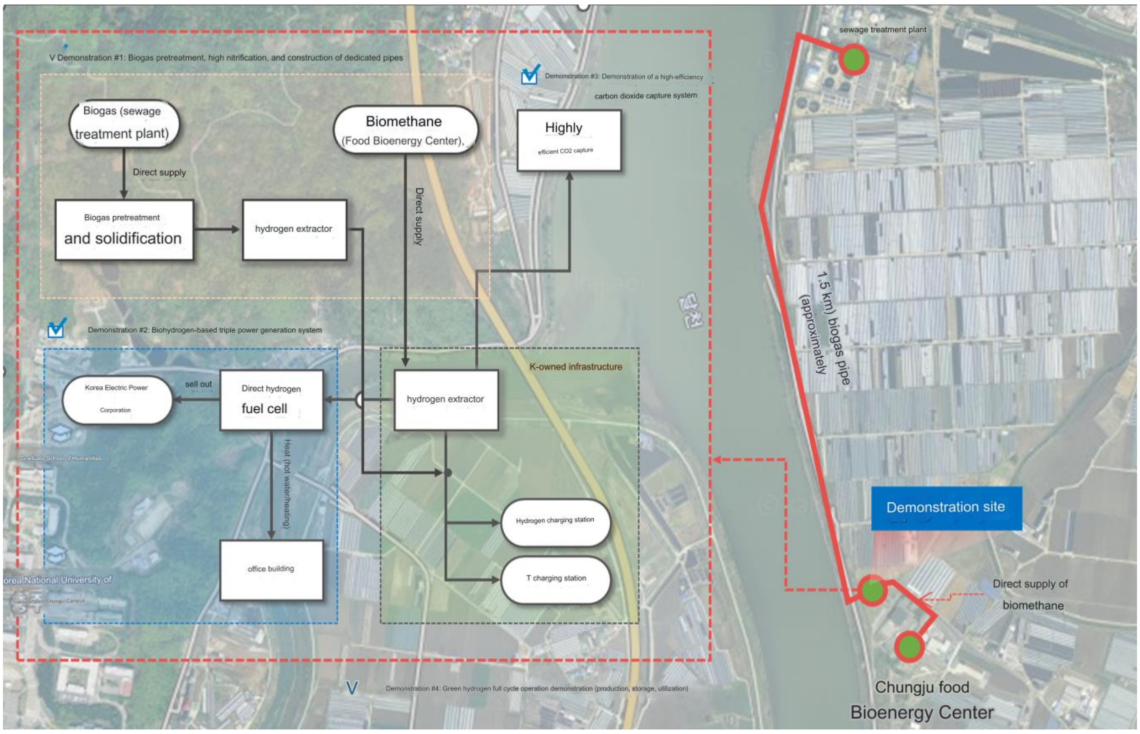
Of the three items summarized in <Table 4-1>, if we assign importance to each item, the first is the current status of local infrastructure, the second is the current status of local hydrogen-related infrastructure and expansion plans, and the third is the review of local acceptance and related laws.

B. Additional considerations for each technology

(1) Steam Methane Reforming (Biogas as feedstock)

Since the SMR hydrogen production demonstration center utilizing biogas needs to be supplied with biogas for hydrogen production, the existence of a nearby biogas plant is a very important consideration factor when selecting a location. For example, in the demonstration facility in Korea, biogas is transported by pipeline from about 1.5 kilometers away and supplied to the hydrogen demonstration complex to demonstrate hydrogen production. (see [Figure 4-2])

[Figure 36] Process and biogas supply infrastructure for a hydrogen demonstration site in South Korea (example)



Source: Dr. Hyungwoon Song

(2) Water Electrolysis

Stable electricity supply is an important consideration for both SMR hydrogen production and water electrolysis hydrogen production, but proximity and connectivity to renewable energy sources (solar, wind, etc.) is crucial for green hydrogen production using water electrolysis. Yet, in order to directly connect renewable energy sources, the volatility of renewable energy must be reliably utilized by the electrolysis facility.

2. Selectin of possible regions in Thailand

First, Thai experts were interviewed to identify the most appropriate regions for each hydrogen production demonstration site. For the SMR hydrogen production utilizing biogas as feedstock, Rayong and Saraburi provinces were recommended, and for the electrolysis hydrogen production, Rayong province and Nakhon Ratchasima province, located in the northeast, were recommended. Therefore, in this part of the report, we applied the location criteria selected above for these regions to find out which regions are more suitable for the installation of the hydrogen production demonstration complex.

A. Steam Methane Reforming (Biogas as feedstock)

As shown in <Table 4-2> below, the two regions of Rayong and Saraburi are compared based on the criteria. Here, "◎" indicates that the criterion is very well met, "△" indicates that the criterion is partially met, and "N/A" indicates that the criterion cannot be judged.

First, the assessment results for the common criteria show that both Rayong and Saraburi are well equipped in terms of local infrastructure, namely electricity and water supply, etc. Next, in terms of the infrastructure of the local hydrogen industry and its expansion plans, Rayong seems to be better than Saraburi based on the expert interviews. Rayong already has well-developed infrastructure, such as gray hydrogen production and hydrogen refueling stations in the nearby Pattaya area, as well as plans for future expansion, while Saraburi does not seem to have such infrastructure and plans yet. Regarding the review of legislation related to the acceptability of residents, we have not yet received specific information on this in either area, so we reserve judgment.

When looking at the presence of biogas plants by technology specialization, we can see that both Rayong and Saraburi provinces have biogas plants. This could be an important factor in promoting projects related to green hydrogen production in the region.

In conclusion, the two regions can be considered to be at the same level in terms of basic infrastructure and the presence of biogas plants. However, in terms of existing hydrogen industry infrastructure and expansion plans, Rayong province is included in the Eastern Economic Corridor (EEC) and has many industrial parks, so the demand for hydrogen utilization is expected to be high in the future, while Saraburi province has only a cement industry and transportation difficulties, so there is some doubt about the effectiveness of installing hydrogen production facilities.

<Table 4-2> Selection of the location for the SMR (Biogas as feedstock)

Category	Criteria	Rayong	Saraburi
Common Criteria	Regional Infrastructure Status (electricity, water, etc.)	◎	◎
	Regional hydrogen industry infrastructure status and expansion plans	◎	△
	Review resident acceptability and applicable laws	N/A	N/A
Technical Specialization Criteria	Biogas plant presence	◎	◎

Source: Author based on interviews

B. Water Electrolysis

As shown in <Table 4-3> below, we compared two regions, Rayong and Nakhon Ratchasima, based on the criteria. Here, "◎" indicates that the criterion is very well met, "○" indicates that the criterion is met moderately, "△" indicates that the criterion is partially met, and "N/A" indicates that the criterion cannot be judged.

Looking at the results of the assessment against the common criteria, it can be seen that the current state of regional infrastructure, specifically electricity and water supply, is somewhat lacking compared to Rayong, although Nakhon Ratchasima has recently accelerated its infrastructure development by promoting the construction of a smart city[68].

Next, in terms of the infrastructure of the local hydrogen industry and its expansion plans, Rayong province was evaluated as having a well-developed infrastructure, with gray hydrogen production already taking place as described above and hydrogen refueling stations being installed in nearby Pattaya, as well as well-developed plans for future expansion. However, in the Nakhon Ratchasima area, there were concerns from experts that there are not many places to utilize the hydrogen produced nearby, so the cost of transportation would be high. Regarding the review of legislation related to the acceptability of residents, similarly, no specific information was provided for both provinces, so the assessment was reserved.

When looking at proximity to renewable energy sources by technology specialization, we see solar in Rayong province and both solar and wind in Nakhon Ratchasima.

Based on the results of this evaluation, it is possible to conclude that the Rayong region is the preferred location for the water electrolysis hydrogen production demonstration site based on a comprehensive consideration of the advantages and disadvantages of both regions.

<Table 4-3> Selection of the location for Water Electrolysis

Category	Criteria	Rayong	Nakhon Ratchasima
Common Criteria	Regional Infrastructure Status (electricity, water, etc.)	◎	△

[68] https://www.citydata.in.th/nakhonratchasima/en/homepage/

	Regional hydrogen industry infrastructure status and expansion plans	◎	X
	Review resident acceptability and applicable laws	N/A	N/A
Technical Specialization Criteria	Proximity to renewable energy sources	○	◎

Source: Author based on interviews

Section 2. Economic Analysis

In this section, we have briefly reviewed the items for CAPEX (Capital expenditures) and OPEX (Operational Expenditure) calculation. However, when applying this to real-world data in the local context of Thailand, several intricacies must be taken into account. The collection and integration of data will be feasible once the demonstration site is finalized, and thus, this aspect was not encompassed in the present report.

1. Steam Methane Reforming (Biogas as feedstock) [69]

A. CAPEX

The relevant processes for producing hydrogen using biogas generated by anaerobic treatment of organic waste (food waste, livestock manure, sewage sludge, etc.) as raw materials are organized as follows.[70]

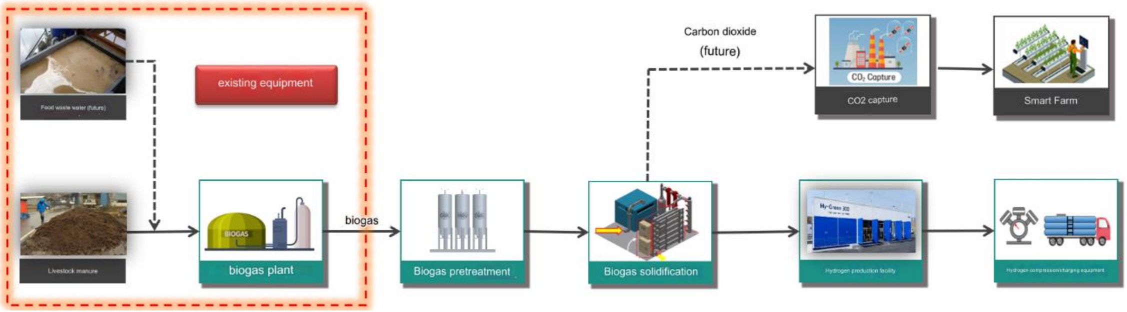
[69] This part is written based on materials provided by Dr. Hyungwoon Song

[70] Organizes only the process from biogas to hydrogen production and shipment

<Table 4-4> Facility Capacity of Steam Methane Reforming (Biogas as feedstock)

Item	Capacity
Biogas Utilization	4,000 Nm3-Biogas/day
Biogas Composition	60% methane, 40% carbon dioxide
Hydrogen Production	500 kg-H2/day

[Figure 37] Process configuration of a hydrogen demonstration complex in South Korea



<Table 4-5> CAPEX indicator items and example costs for SMR hydrogen production demonstration complex (Biogas as feedstock)

Item	Details	Details	Quantity	Cost (millions KRW)	Cost (thousands USD)
Design/ Authorizations	Authorizations	KGS Technical Review	1	50	37
	Fundamentals and Architectural Design (with supervision)	Production Facility Design	1	250	185
Civil/ Construction Work	Civil/ Construction Work	TT charging stations, office buildings	1	1,500	1,110

Biogas Refining	Refining/ Upgrading	Refining/Upgrading	1	2,500	1,850
Electrical/ Plumbing	Electricity	Primary Electricity	1	150	111
	Plumbing	Facility Connection Piping	1	200	148
Hydrogen Extraction System	Hydrogen Extractor	Hydrogen Extraction Facilities	1	3,400	2,516
		Utilities	1		
		Commissioning	1		
Hydrocompression Storage/ TT Charge	Hydrogen compressors	Compressors (7->200bar)	2	1,000	740
	Storage containers	BufferTank	1	50	37
		Medium Pressure Vessels	2	200	148
	TT Charging Facilities	Electrical/Plumbing Connections	1	150	111
		TT Charging Panel	1	50	37
Deployment cost subtotal				9,500	7,030

Source: Dr. Hyungwoon Song

B. OPEX

Factors that should be considered in the economic analysis of the operation of this biogas utilization SMR hydrogen production demonstration complex include facility size and utilization rate, cost of sales, and operating costs. Facility size and utilization rate should consider the number of hours (days) and utilization rate of the facility, hydrogen production, and hydrogen sales price. For cost of sales, you can consider biogas tariffs and industrial electricity rates. Operating costs include capex depreciation and maintenance, labor, and general and administrative costs.

<Table 4-6> Operating conditions of SMR hydrogen production demonstration complex (Biogas as feedstock)

Item	Condition
Hydrogen Sales Price	5,500 KRW/kg-H2
Operations staffing	5 people (1 team leader, 4 drivers)
Operation days	330 days/year

<Table 4-7> OPEX indicator items and example costs for SMR hydrogen production demonstration complex (Biogas as feedstock)

Item	Amount (millions KRW)	Amount (thousands USD)
Sales	907	671
TubeTrailer	907	671
Selling, general, and administrative expenses	710	525
Labor costs	180	133
Electricity costs	250	185
Maintenance fees	200	148
General and administrative expenses	80	59
Operating Profit	197	146

2. Water Electrolysis

A. CAPEX

The CAPEX of a water electrolysis hydrogen production complex is focused on the water electrolysis equipment (electrolyzer) and is usually expressed as the price of the stack or system per kilowatt-hour. It depends mainly on material prices, current density, processing/fabrication costs, etc. and is a widely used metric for economic evaluation and comparison of different types of electrolysis. Typically, the cost of an electrolysis plant ranges from $500 to $1,400/kW for alkaline and $700 to $2,100/kW for PEM, with PEM electrolysis being about 30% to 40% higher than alkaline. [71] The main reason for the difference in CAPEX between alkaline and PEM electrolysis is the cost of the materials used. Alkaline electrolysis uses relatively low-cost nickel (Ni) based materials, while PEM electrolysis uses titanium (Ti), which is difficult to replace expensive catalyst materials such as iridium oxide (IrOx) and platinum (Pt). Although the material price of titanium is relatively cheaper than precious metals, it is difficult to process, so the processing/manufacturing cost is expected to be high.

In addition to these hydrogen electrolysis facilities, other CAPEX metrics include utilities, water switching facilities, emergency hydrogen treatment facilities, civil/architectural, foundation, permitting, control room (office building), and hydrogen storage and shipping facilities (if needed).

B. OPEX

The OPEX cost of a water electrolysis facility (electrolyzer) is most commonly modeled as part of the original CAPEX and is modeled as independent of the type of electrolyzer, with most studies setting this value between 1-3% of the electrolyzer CAPEX. In Christensen (2020), it was calculated as a fixed OPEX cost of $40/kW in the US and $50/kW in the EU. Other OPEX

[71] Christensen, A. 2020. "Assessment of hydrogen production costs from electrolysis: United States and Europe."

indicators[72] include labor, electricity, other utility costs, maintenance and repair costs (materials, waste disposal, subsidies and incentives, royalties, replacement costs over the life of the stack), and overhead (taxes, insurance, etc.).

[72] This part is written based on materials provided by Dr. Suhyun Kim

Chapter 5. Summary and Conclusion

The purpose of this report is to identify the optimal hydrogen production method for Thailand based on the methods discussed in Chapter 2. While hydrogen production technologies are globally standardized, this study evaluates them in terms of their technical merits and relevance to the Thai context. The ultimate goal is to identify technologies that will either support internal development in Thailand or pave the way for external technology transfer.

The selection process includes a review of Thailand's current technology development, available resources, and investments in hydrogen production. We assess technology development conditions such as technology level, R&D activities, performance and capacity, as well as resource potential and development plans. Through a comparative analysis of these factors, the study focuses on the most appropriate production method for Thailand.

The methods considered are steam methane reforming (SMR) and water electrolysis, both thermochemical processes discussed in Chapter 2. Internationally, SMR is considered a blue hydrogen production method, while electrolysis is considered a green hydrogen production method. Both technologies are under active research in Thailand. Biological and photoelectrochemical hydrogen production, while promising, are still in their infancy on a global scale. Their potential limitations for Thailand's immediate hydrogen needs and potential technology transfer challenges make them less relevant for this study.

Chapter 3 discusses the development status of SMR and water electrolysis in Thailand and analyzes the resource requirements for both. The chapter concludes by recommending the most appropriate hydrogen production technology for Thailand. The ideal hydrogen production method for Thailand is derived by consolidating the results of the technology readiness and resource assessments. Initially, water electrolysis coupled with renewable sources emerges as the long-term preference due to its environmental advantages and resource abundance, outweighing SMR. However, for the immediate future, SMR using natural gas as both fuel and feedstock is considered strategic. The importance of reducing emissions leads to a shift towards biogas for SMR. As a successor to SMR, alkaline and AEM electrolysis are identified as the most suitable based on Thailand's technological framework. Among the renewable energy sources, solar energy is highlighted as the first choice for these electrolysis methods due to its large capacity and growth plans, while wind energy is also recognized for its efficient renewability. The recommended progression is to start with SMRs using natural gas, move to biogas, and finally adopt alkaline and AEM electrolysis, supported by solar and wind sources.

In Chapter 4, we evaluate the ideal site for a hydrogen production demonstration in Thailand. After considering general site factors, we further evaluate specific criteria for SMR with biogas and water electrolysis. Consultations with Thai experts highlighted Rayong and Saraburi provinces for biogas-based SMRs, while Rayong and Nakhon Ratchasima were considered suitable for electrolysis. Rayong ultimately emerged as the preferred site. Although the chapter provides an overview of CAPEX and OPEX considerations, the real-world application in the Thai context introduces additional complexities, with detailed data integration required until final site selection.

In conclusion, Thailand stands at the precipice of a transformative energy journey, with hydrogen production technologies paving the way for a more sustainable future. This report, based on thorough research and contextual assessment, underscores the dynamic landscape of hydrogen production in Thailand. While the immediate path points to harnessing the capabilities of SMR, particularly with biogas, the long-term vision converges on water electrolysis, supported by Thailand's solar and wind resources. Our findings underscore Rayong as a strategic location for a demonstration project, reflecting its potential and suitability. The synergy of technological readiness, resource assessments, and local expertise provides Thailand with the knowledge to make informed decisions. As the world increasingly turns to cleaner energy alternatives, it is our fervent hope that this report will serve as a guiding document for Thailand's hydrogen strategy, facilitating the nation's progress toward energy independence and a greener future.

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Appendix: Hydrogen storage and transportation technology review[73]

Hydrogen can be stored physically and chemically.[74] Physical-based hydrogen storage is divided into compressed hydrogen method (gaseous storage) and liquified hydrogen at low temperature method (liquid storage). Chemical-based hydrogen storage includes adsorbents for solid storage and metal hydrides, organic hydrides, and inorganic hydrides for material conversion and storage. Stored hydrogen can be transported as a gas, liquid, or solid via pipeline, trailer, or ship.

Based on the review of various hydrogen storage and transportation technologies in this appendix, gaseous hydrogen storage and transportation via tube trailer is likely to be utilized in Thailand due to the lack of infrastructure for its initial introduction.

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73 References for the Appendix can be found in the Reference section

74 Kim, Hoon, 2021, Hydrogen Story Part 5: Hydrogen Storage Technology and Problems to be Addressed, 6 June 2021, <https://www.safety1st.news/news/articleView.html?idxno=1600> (in Korean)

<Table 1> Modes of Hydrogen Storage and Transporation

<table>
<tr><td colspan="5">Modes of Hydrogen Storage and Hydrogen Form</td><td>Transportation</td></tr>
<tr><td rowspan="3">Physical</td><td rowspan="4">No material transfor-mation</td><td colspan="3">Gas</td><td>Pipeline or Tube Trailer</td></tr>
<tr><td colspan="3">Liquid</td><td>Tube Trailer or Ship</td></tr>
<tr><td rowspan="3">Solid</td><td colspan="2">The simple physical or chemical adsorption of hydrogen onto a solid material.</td><td rowspan="3">Tube Trailer</td></tr>
<tr><td rowspan="5">Chemical</td><td colspan="2">Metal hydrides: store hydrogen as it enters the crystal lattice of a substance</td></tr>
<tr><td rowspan="4">Material transfor-mation</td><td colspan="2">Transition metal hydrides: A metal absorbs hydrogen and turns into an ion or covalent compound.</td></tr>
<tr><td rowspan="3">Liquid</td><td rowspan="2">Organic compound (organic hydride or liquid organic hydrogen carrier (LOHC))</td><td>The use of Toluene (hydrogenation catalyst) and save it as MCH</td><td rowspan="3">Tube Trailer or Ship</td></tr>
<tr><td>Others</td></tr>
<tr><td>Inorganic compound</td><td>Ammonia etc</td></tr>
</table>

Section 1. Hydrogen Storage Technologies

1. Major hydrogen storage technologies

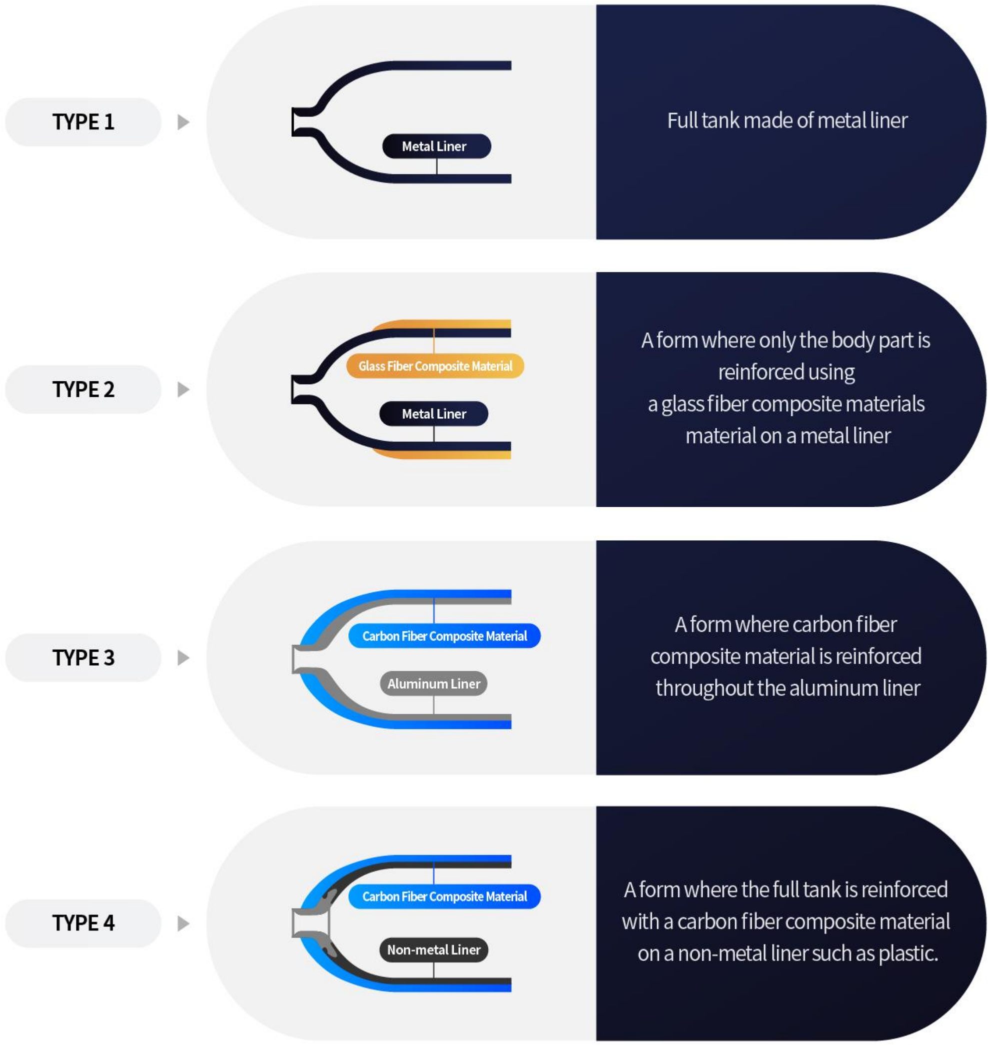
A. Physical method

(1) Gaseous hydrogen storage[75]

The primary method for hydrogen storage is through gaseous hydrogen storage, where hydrogen is contained at room temperature in high-pressure and ultra-lightweight tanks, typically at pressures ranging from 20 to 70MPa. There are 4 types of vessels for hydrogen storage. Type 1 is a pressure vessel of metal material such as steel and aluminum. Type 2 is an upgraded Type 1 with its body part made of composite materials. Type 3 is a container consisting of an internal metal liner reinforced with composite materials. Type 4 is a vessel of non-metal liner reinforced with composite materials.(See [Figure 1])

[75] Sohn, Hiesang, Technology Trends in Hydrogen Storage Materials, Chemical Engineering and Materials Research Information Center (CHERIC), <https://www.cheric.org/research/ip/ipview.php?code=p202105> (in Korean)

[Figure 1] Pressure Tank/Vessel for Hydrogen Storage Type 1~4



(2) Liquid hydrogen storage

Liquid hydrogen storage technology involves cooling hydrogen to low temperatures and converting it into a liquid form. It is possible to store hydrogen about 240 times more than gaseous storage technology by cooling liquid hydrogen to cryogenic temperatures of below –252.8 ℃. Liquid hydrogen storage technology can reduce the volume by about 1/800 compared to gaseous the hydrogen storage method at the same pressure, resulting in 800 times the volumetric energy density of gaseous hydrogen.

[Figure 2] Storage Capacity: Gaseous versus Liquid Hydrogen

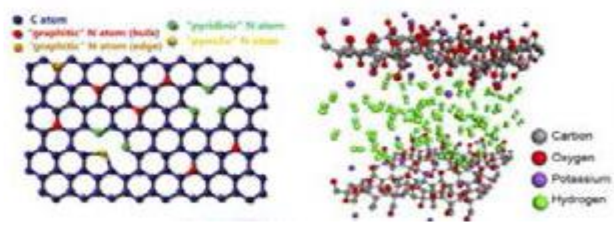
B. Chemical method

(1) Non-material conversion adsorbent method (solid hydrogen alloy storage)[76]

Non-material conversion adsorbent method stores hydrogen at low pressure inside or on the surface of solid materials and releases the stored hydrogen when needed. Solid hydrogen storage technology has seen limited investment in technological development, primarily due to its lower hydrogen storage density per unit of weight, restricting its applications to mobility where weight is an important factor. However, it is becoming increasingly necessary as renewable energy is expanding and energy grid efficiency is becoming more important. MOF (Metal Organic Framework) or Zeolite are typically used for solid materials. MOF is crystalline materials with a structure formed by linking metal ion, organic molecules. Hydrogen is stored both on the structure surface and within its nanopores. Zeolites feature porous structures with substantial surface areas, allowing for the storage of significant quantities of hydrogen.

[76] *Ibid.*

[Figure 3] Porous Materials for Hydrogen Storage[77]

	Add K-ion to two-dimension material in order to enhance hydrogen absorption
	Attach catecholate inside the porous material (MOF) in order to enhance hydrogen absorption

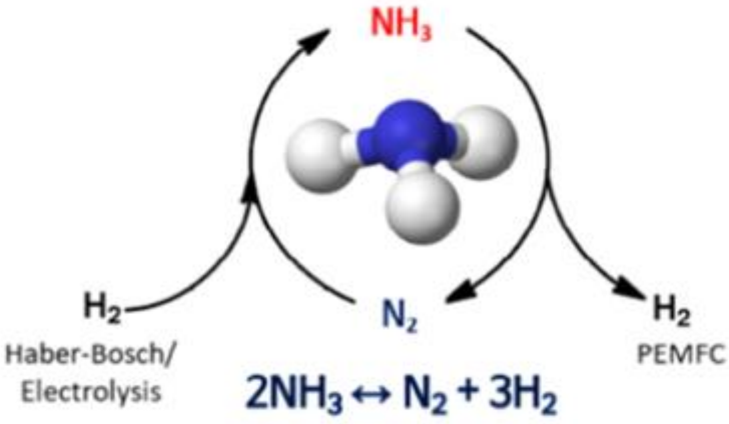
(2) Material conversion methods (solid hydrogen alloys, liquid hydrogen storage)[78]

Conversion storage methods are categorized into metallic hydrides, organic hydrides, and inorganic hydrides. Metal hydride is a method of storing hydrogen in light metals such as Palladium, Magnesium, Lanthanum, Aluminum, etc. Organic hydrides store hydrogen by combining it with toluene and converting it to methylcyclohexane. Inorganic hydrides store hydrogen by using carbon-free inorganic compounds such as ammonia, ammonia borane, hydrazine, etc.

77 Moon, Hoi Ri, 2019, Study on Porous Materials for Overcoming the Limit of Hydrogen Storage System, Ulsan National Institute of Science and Technology, Aug. 2019. 2019, <https://scienceon.kisti.re.kr/srch/selectPORSrchReport.do?cn=TRKO202000002187> (in Korean)

78 Sohn, Hiesang, Technology Trends in Hydrogen Storage Materials, Chemical Engineering and Materials Research Information Center (CHERIC), <https://www.cheric.org/research/ip/ipview.php?code=p202105> (in Korean)

[Figure 4] Haber Process (Ammonia Manufacturing) - The Engineering Concepts[79]



<Table 2> Hydrogen Storage/Transport Technologies of Major Global Companies[80]

Country	Field	Company	Stage	Technology
Japan	High-Pressure Hydrogen Vessel	Japan Steel Works (JWS)	Commercialization	High-pressure storage tanks (990bar) and vessels
	Liquefaction	Iwatani	Demonstration to commercialization	Cryogenic (-253℃) hydrogen liquefaction
	Liquefied/liquefaction transport	Chiyoda	Demonstration to commercialization	Toluene-based Liquid Organic Hydrogen Carriers (LOHC)
	Liquefaction transport	Kawasaki Heavy Industries	Research	Hydrogen liquefaction carrier and liquefaction, hydrogen tank
Europe	High-Pressure Vessel, Liquefaction	Linde/ Air Liquide	Commercialization	Supplies the global market with its original high-pressure vessel, liquefaction technology

79 Yoo, Young Don, 2019, Hydrogen Storage, Transport, and Charging, Technology and Innovation, Special Issue 02, <http://webzine.koita.or.kr/201909-specialissue/02-%EC%88%98%EC%86%8C%EC%9D%98-%EC%A0%80%EC%9E%A5-%EC%9A%B4%EC%86%A1-%EB%B0%8F-%EC%B6%A9%EC%A0%84> (in Korean)

80 MOTIE (Ministry of Trade, Industry and Energy, Korea), 2019a, Hydrogen Economy Roadmap of Korea, Jan. 2019 (in Korean)

	Liquefaction	Hydrogenious	Commercialization	Dibenzyl Toluene-based Liquid Organic Hydrogen Carriers (LOHC)
US	Liquefaction/ liquefied	Air Products	Commercialization	Original liquefaction technology Ethyl-Carbazol-based Liquid Organic Hydrogen Carriers (LOHC)
	High-Pressure Vessel	Hexagon Composites/ Lincoln Composite Materials	Commercialization	Storage tank, tube trailer(500bar)
	Liquefaction	Praxair	Liquefaction	Original hydrogen liquefaction technology

2. Advantages and Disadvantages of Hydrogen Storage Technologies

A. Physical method

(1) Gaseous hydrogen storage[81]

In storing gaseous hydrogen, even the slightest impact carries significant risks, and the development of pressure vessels capable of withstanding pressures of approximately 150 atmospheres is essential. This results in high energy consumption costs for hydrogen compression. Type 1 is heavy with constraints imposed by the choice of materials for the hydrogen storage container. Type 2 is a container made by reinforcing only the body part of the Type 1 with composite materials, resulting in weight reduction through the decreased thickness of the metal container walls. Type 3 is a container consisting of an internal metal liner reinforced with composite materials, which is lighter in weight compared to metal containers, but not as durable for large diameter containers. Type 4 is a vessel of non-metal liner reinforced with composite materials. The vessel exhibits the lowest weight, highest

81 Sohn, Hiesang, Technology Trends in Hydrogen Storage Materials, Chemical Engineering and Materials Research Information Center (CHERIC), <https://www.cheric.org/research/ip/ipview.php?code=p202105> (in Korean)

durability, and is readily producible in large quantities for hydrogen storage.

(2) Material conversion methods (solid hydrogen alloys, liquid hydrogen storage)[82]

Liquid hydrogen can be stored at atmospheric pressure, which enhances its safety for storage and reduces the likelihood of explosions compared to gaseous hydrogen. It also has the highest energy storage density and can be utilized immediately by simply vaporizing it, with no other process required to utilize it. However, hydrogen liquefaction is expensive and requires maintaining the temperature during transportation.

B. Chemical method

(1) Solid hydrogen alloy storage method: metal hydride method[83]

Solid materials can play a pivotal role in developing safe, efficient, and space-efficient hydrogen storage technology. R&D areas include metallic substances, complex materials, carbon-based materials, and porous materials.

Storing hydrogen in a hydrogen storage alloy allows hydrogen to be stored at a higher hydrogen density than gaseous or liquid hydrogen, and it is highly stable due to its high purity and the fact that it does not need to be made at high pressure and low temperature. However, commonly known storage alloys, such as LaNi5, TiFe, and Mg2Ni, are important resources with high prices. In addition, the weight of the alloy itself reduces a storage rate per weight. It stores between 2-4% hydrogen by weight, making them impractical.

Hydrogen-absorbing alloys react reversibly with hydrogen to produce metal hydrides. At room temperature, hydrogen absorption typically occurs in exothermic reactions, and hydrogen release takes place when the hydrogen absorbing alloy is heated. The density of

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[82] Sohn, Hiesang, Technology Trends in Hydrogen Storage Materials, Chemical Engineering and Materials Research Information Center (CHERIC), <https://www.cheric.org/research/ip/ipview.php?code=p202105> (in Korean)

[83] *Ibid.*

hydrogen atoms in the metal hydride is approximately 90 kg-H2/m3 or more, which is higher than the density of liquid hydrogen (70.8 kg-H2/m3), making it applicable to space-constrained vehicles and energy storage system. However, the continuous utilization of hydrogen-absorbing alloys poses challenges since the stored hydrogen is not fully utilized, and, in part, permanent binding of the stored hydrogen occurs.

<Table 3> Main Types of Metal Hydride Hydrogen Storage

Type of metal hydride	Affiliation	Occluded hydrogen (in weight)	Type of metal hydride	Affiliation	Occluded hydrogen (in weight)
AB5	LaNi5 etc.	1	BCC	Ti-Mn-V series, Ti-Cr-V series, V-Ti-Cr series	up to 3
AB2	TiCr1.8, ZrMn2	up to 2			
AB	TiFe	up to 2	Mg series (A2B)	Mg2Ni, Mg2Cu	up to 4

(2) Liquid hydrogen storage method: organic hydride method[84][85]

Organic hydride transfer utilizes an aromatic organic compound as a hydrogen transporter. Compared to the high-pressure state, the volume is about 1/500, and it can be liquidized and used in chemical tankers or chemical lorries. On the other hand, hydrogen addition

[84] Gas News, 2008, Organic Hydride Transports Hydrogen, 25 Feb. 2008, <http://www.gasnews.com/news/articleView.html?idxno=37089> (in Korean)

[85] Integral, 2019, The Future of Hydrogen (Part 2), 19 Jan. 2019, <https://www.integralkorea.com/?p=23440> (in Korean)

(hydrogenation) is an exothermic reaction, and hydrogen removal (dehydrogenation) is an endothermic reaction.

The commercialization of methylcyclohexane (MCH) toluene is being promoted in the aspects of safety and convenience. While the hydrogenation reaction and transfer performance are currently established, there are issues concerning the conversion rate and longevity of the dehydrogenation reaction step. Nevertheless, a highly durable and selective dehydrogenation catalyst has been recently developed in Japan, raising the possibility of practical application. Chiyoda Corporation, a leading Japanese company, is looking at toluene, benzene, and naphthalene as aromatic hydrocarbons to hold hydrogen, but toluene is currently the most advanced in its commercialization.

(3) Liquid hydrogen storage method: inorganic hydride method[86]

Ammonia contains 17.8% of hydrogen and is easily liquefiable at low temperatures below 10bar. Ammonia is a basic chemical and is produced in large quantities as a fertilizer ingredient. Global ammonia production is about 200 million tons/year, mainly in the United States, Russia, China, and India. Typically, ammonia is synthesized by the Haber-Bosch method (reaction of hydrogen and nitrogen in an iron-catalyzed atmosphere at 100 to 250 bar and 520 to 820 °C). Ammonia is a stable substance and can be used as a carrier for hydrogen. Direct dehydrogenation (cracking) of ammonia requires the use of lithium-based catalysts, which react at high temperatures above 670 °C.The commercialization of methylcyclohexane (MCH) toluene is being promoted in the aspects of safety and convenience. While the hydrogenation reaction and transfer performance are currently established, there are issues concerning the conversion rate and longevity of the dehydrogenation reaction step. Nevertheless, a highly durable and selective dehydrogenation catalyst has been recently developed in Japan, raising the possibility of practical application.

[86] Sanupin, 2020, Ammonia a Solution for Transport and Utilization of Hydrogen, 18 Nov. 2020, <https://www.sanupin-news.kr/news/articleView.html?idxno=697> (in Korean)

Chiyoda Corporation, a leading Japanese company, is looking at toluene, benzene, and naphthalene as aromatic hydrocarbons to hold hydrogen, but toluene is currently the most advanced in its commercialization.

3. Applications of Hydrogen Storage Technology

A. Technology development trends and recent status[87]

In the field of physical storage, the United States, Japan, and Europe have commercialized high-pressure gas storage vessels and hydrogen liquefaction plants. Meanwhile, Korea is developing a high-pressure vessel (〉 900 bar) made of composite materials and has begun developing a liquefaction plant. In the field of chemical storage, Germany, the United States, and Japan are pursuing small-scale demonstrations of liquid and solid hydrogen storage. In Korea, both liquid and solid hydrogen storage remain at the basic and fundamental research level.

Regarding hydrogen transportation, the United States and Europe have achieved commercialization in land transportation with tube trailers, pipelines, and tank trucks. Meanwhile, Japan is actively demonstrating various methods for transporting liquid hydrogen and liquid organic hydrogen carrier (LOHC) in marine applications. In Korea, efforts are underway to advance technology and enhance the transportation capacity of tube trailers and pipelines for land transportation, with marine transportation still in its nascent stage of technology development.

Hydrogen, due to its considerable volume at room temperature, necessitates the development of technologies that can enable large-scale storage and transportation for cost reduction. Apart from storage and transportation of compressed hydrogen, other methods are still in the development stages. Currently, domestic companies such as HYCHANGWON

[87] MOTIE (Ministry of Trade, Industry and Energy, Korea), 2019b, Roadmap for Hydrogen Technology Development, Oct. 2019 (in Korean)

CO., LTD, SK, and Hyosung Group are engaged in the construction and demonstration of liquid hydrogen plants in collaboration with multinational companies such as Linde and Air Liquide. However, basic research has been underway to develop original technology in Korea. It is important to note that challenges still exist, including the cost and technical complexities of maintaining extremely low temperatures at -253°C for liquid hydrogen storage.

On the other hand, Liquid Organic Hydrogen Carrier (LOHC) technology has recently gained attention as a promising method for storing substantial quantities of hydrogen. LOHC offers advantages such as high hydrogen storage capacity, ease of use, and compatibility with existing infrastructure such as pipelines and transport tanks.

B. Diversification and Advancement of hydrogen storage methods

Gaseous storage is a suitable for the storage and transportation of high-pressure hydrogen. There is a proven technology for high-pressure storage vessels (tube trailers) above 500bar. Therefore, it may be beneficial to consider relaxing regulations on pressure standards to facilitate the use of gas storage.

To store and supply significant quantities of liquefied hydrogen, it is crucial to focus on developing and localizing key technologies. While hydrogen liquefaction plants are operational in the United States, Europe, and Japan, Korea is still working on establishing both commercial and research-oriented hydrogen liquefaction facilities.

The liquid-solid storage method requires increased R&D support for safe and stable supply. The liquid storage method converts into organic compounds such as toluene and ammonia, enabling the storage and transportation of hydrogen in large quantities under ambient temperature and pressure.

Continuous support is needed to expand the development of original technologies for the liquid storage method. In contrast, the solid-state method involves the secure and efficient storage and transportation of hydrogen in solid form, either within or on the surface of hydrogen storage alloys. Since this approach is still in the early stage of global development, expanded support is required to establish the technology for long-term viability.

C. Establishment of Key Technology Development Strategy

First, in the development of key technologies, it is imperative to enhance gas storage and transportation technologies to increase the volume of hydrogen transport capacity. Simultaneously, liquid hydrogen and Liquid Organic Hydrogen Carrier (LOHC) storage and transportation technologies that can reliably handle substantial hydrogen volumes.

Given the large-scale infrastructure construction requirements for each technology, it is necessary to conduct economic and environmental analysis before technology demonstration. Building on this, priority technologies should be reevaluated after establishing a national hydrogen supply strategy. Second, gas storage and transportation technologies should be advanced, such as reducing the price of storage containers for vehicles. Lastly, it is essential to secure original technologies in the field of LOHC, which is an areas of active research in other countries such as the United States, Japan, and Germany. Promoting product development within the liquid hydrogen domain should also be a key priority.

Section 2. Hydrogen Transportation Technologies

1. Major hydrogen transportation technologies

A. Pipeline[88]

Pipelines can be used to transport large amounts of hydrogen over land. In Japan, a low-pressure hydrogen pipeline is installed inside the Kombinat, but in Europe, large-scale, long-distance hydrogen pipelines or high-pressure hydrogen pipelines are installed and operated. For example, Air Liquide in France operates a total of 830 kilometers of hydrogen pipelines near the borders of France, Belgium, and the Netherlands. Similarly, Germany’s North Rhine-Westphalia state has 240 kilometers of pipelines, while Germany's Linde maintains a 140-kilometer pipeline network near Leipzig. Germany has established a hydrogen supply value chain centered on Power to Gas (P2G), where hydrogen is produced from abundant renewable energy and delivered through the existing gas grid.

In the United States, Air products has a hydrogen pipeline network totaling 560 kilometers in length in California, Texas, and Louisiana. Meanwhile, domestic hydrogen transportation accounts for 88% of pipeline transportation and 12% of tube trailer transportation. In Korea, specifically in the industrial complexes of Ulsan, Daesan, Yeosu, and Banwon-Sihwa, hydrogen pipeline networks are 200-kilometer long.[89]

B. Tube Trailer - High Pressure Gas Hydrogen Transportation

When transporting hydrogen onshore, it is common to transport it by compression. Typically, hydrogen is compressed to 196 bar, filled into cylinders, strapped down, and transported in curdles. For larger quantities of hydrogen, hydrogen trailers are used, which are a collection

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[88] Deloitte, 2022, Analysis of Supporting Policies and Demonstration Projects of Leading Countries in Hydrogen Development, The Rise of Climate Tech and Hydrogen Economy (Part 2), Deloitte Insights No.24, <https://www2.deloitte.com/content/dam/Deloitte/kr/Documents/insights/deloitte-korea-review/24/Deloitte-Insights-no.24-part2-3.pdf> (in Korean)

[89] Gas News, 2016, Byproduct Hydrogen: Current Status and Utilization, 18 May 2016, <http://www.gasnews.com/news/articleView.html?idxno=73661> (in Korean)

of large cylinders over 6 meters long.

When supplying hydrogen to a hydrogen station, the hydrogen is high-pressurized during transportation to increase the amount of hydrogen supplied at a time and minimize pressure booster issues at the hydrogen station. In Japan, New Energy and Industrial Technology Development Organization (NEDO) has conducted a demonstration of a 450 bar hydrogen trailer and adopted composite cylinders to reduce weight due to high pressure.[90] In Korea, Iljin Hydrogen has successfully developed a 450 bar (Type 4) trailer utilizing composite materials.[91]

In Japan, compressed hydrogen is widely used in industrial sectors. The primary consumers of compressed hydrogen include the semiconductor, liquid crystal, and electronic component industries, followed by the metal, chemical, and glass industries.

[Figure 5] 450 bar (Type 4) tube trailer

[90] Global Auto News, 2014, Japan's Policies for a Hydrogen Society and its Implications, 16 Sep. 2014, <http://global-autonews.com/bbs/board.php?bo_table=bd_035&wr_id=97> (in Korean)

[91] Money Today, 2021, Iljin Hysolus' Factory in Wanju North Jeolla Province, 11 Jul. 2021, <https://news.mt.co.kr/mtview.php?no=2021071109282162120> (in Korean)

C. Vessel - Liquid hydrogen transfer[92]

As hydrogen demand expands, it is essential to introduce liquefied hydrogen, which is optimized for high volume storage and transportation. Hydrogen liquefies at -253℃and shrinks to 1/800th of its volume.

Only Air Liquide (France), Linde (Germany), and Air products (USA) have the original technology to design and build large-scale liquefaction plants. Japan and China have inherited this technology from these companies and focus on constructing and operating medium-sized hydrogen plants. In the U.S., liquid hydrogen accounts for about 80% of hydrogen transportation on land, and there is an ongoing development of four 30-ton-per-day liquid hydrogen plants to address increasing demand for hydrogen.

Liquefied hydrogen vessels employ the cylindrical vacuum heat-insulating technique, featuring a double-walled structure. The inner vessel is enclosed in a vacuum to prevent heat intrusion. Additionally, a multilayered metal reflector and insulation sheet is utilized within the vacuum space to minimize both radiation and heat conduction.

Nevertheless, heat intrusion does occur, resulting in Boil Off Gas (BOG), and the BOG rate of recently developed vessels is less than 1% per day.

On the other hand, hydrogen carriers are utilized when liquefied hydrogen is imported. Japan's Kawasaki Heavy Industries has obtained approval from Nippon Kaiji Kyokai General Incorporated Foundation (the Japan Maritime Association) as an accredited cargo containment facility for liquefied hydrogen carriers, demonstrating the world's first liquefied hydrogen carrier. [93]

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[92] MOLIT (Ministry of Land, Infrastructure and Transport, Korea), 2018, Development of Core Technologies in Commercial Liquid Hydrogen Plant <https://www.codil.or.kr/filebank/original/RK/OTKCRK190025/OTKCRK190025.pdf?stream=T> (in Korean)

[93] Global Economic, 2021, The World First Liquefied Hydrogen Carrier Developed by Japan to Depart for Australia, 27 Dec. 2021, <https://news.g-enews.com/article/Global-Biz/2021/12/20211227115253412391af309431_1?md=20211227124716_U> (in Korean)

2. Advantages and Disadvantages of Hydrogen Transportation Technologies

A. Pipeline

Pipelines are the most effective means of transporting large quantities of gaseous hydrogen. However, there is an initial CAPEX burden (1 billion KRW/1 kilometer) for pipeline installation. The reliability of pipeline hydrogen transfer has been verified through domestic and international demonstrations. Various studies on the material properties of pipelines (hydrogen embrittlement) are underway, and a stable and organic supply system through the pipeline network can be established when new economical materials are introduced.

B. Tube Trailer

Basically, charging by tube trailer has the advantage of low initial CAPEX, but it has the disadvantage of low operating efficiency when demand expands in the long run. Recently, the domestic natural gas industry is considering adding hydrogen reforming facilities at Compressed Natural Gas (CNG) stations to address these limitations.

C. Others

(1) Solid hydrogen transportation

Hydrogen transfer by hydrogen absorption alloy is a new industry, and various research and development programs are underway. The hydrogen absorption alloy method offers the advantage of large storage capacity per unit volume, making hydrogen utilization convenient. However, its heavy weight poses challenges for land transportation. Hydrogen fuel stored in hydrogen absorption alloy does not deteriorate, allowing for long-term storage. Furthermore, since it does not involve combustion, there are no installation limitations dictated by fire regulations, which make it easily deployable as an emergency power source in the city center.

(2) Liquid hydrogen transportation

The advantage of liquefied hydrogen is that it is 1/800th the volume of gaseous hydrogen. This enables efficient transportation in large quantities within a single trip, reducing transportation costs. It can be stored and supplied in large quantities, making it easier to use land for hydrogen refueling stations. The pressure is similar to atmospheric pressure, ensuring stable and secure transportation.

(a) Toluene (organic hydride)

Toluene, one of the organic hydrides, is converted to methylcyclohexane (MCH) by fixing three molecules of hydrogen. The toluene-MCH system has the advantage of being able to remain liquid over a wide temperature range of 95°C to 100°C, eliminating the need for solvents everywhere.

Fixing three molecules of hydrogen to benzene gives cyclohexane, and fixing five molecules of hydrogen to naphthalene gives decaline. However, the use of benzene is constrained by temperatures around 5~6℃ due to its carcinogenic characteristics, which restricts its applicability based on location. In addition, naphthalene is a solid at room temperature, requiring continuous dissolution in a solvent, which is not convenient.

The synthesis of MCH with hydrogen molecules anchored to toluene is relatively easy and well established industrially. However, the process of stripping the hydrogen from MCH and returning it to toluene is more technically challenging.

(b) Ammonia (inorganic hydrogen)

The cost of hydrogen contained in ammonia is 20-35 Yen/Nm3 based on CIF prices, making ammonia a low-cost source of hydrogen. Ammonia uses propane infrastructure and has the advantage of high energy density. On the other hand, ammonia's odor and toxicity require careful handling, and research is needed for commercialization.

3. Applications of Hydrogen Transportation Technology

A. Promotion Plan

(1) Streamlining hydrogen transportation

Expanding the application of tube trailers will enhance liquid transportation in high-pressure gas transportation. Specifically, it is possible to reduce transportation costs and expand hydrogen supply areas by increasing hydrogen storage capacity and transportation and making trailers lighter. In the long term, transportation efficiency can be improved by utilizing tank lorries for liquid hydrogen transportation.

Pipelines currently centered on primary demand hubs can be expanded across the country. Pipelines should be installed in major demand hubs first, but in the medium to long term, main pipelines should be built to connect with large-scale supplies such as LNG production and hydrogen receiving bases. Currently, there are only about 200 kilometers of hydrogen pipelines in the country, and it is necessary to improve the supply pressure and develop materials to increase the operational lifespan.

(2) Development and Utilization of Hydrogen Transport Carriers

Hydrogen carriers are needed to store overseas hydrogen in liquid or liquefied (organic compound) form and transport it in bulk in preparation for the long-term mass hydrogen consumption. To this end, our objective is to successfully achieve the development and demonstration of hydrogen carriers in conjunction with overseas hydrogen production and import by the year 2030. In terms of technology, hydrogen cargo hold technology has been developing since 2016 and technological developments related to design, cryogenic temperature management, insulation and safety assessments are in progress. In particular, we are focusing on supporting the core technology of liquefied hydrogen transportation vessels and conducting long-term basic research on liquid organic compound carriers. To this end, the three shipbuilding companies are leading the development of core technologies, and furthermore, they should actively collaborate with equipment manufacturers to establish a win-win industrial ecosystem.