



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



## Deliverable 2

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## Contents

Chapter 1. Introduction .....	1
Section 1. Background and Necessity of Research .....	1
Section 2. Purpose and Method of Research .....	1
Chapter 2. Review of Global Hydrogen Policy and Key Utilization Sectors.....	3
Section 1. Korea.....	3
Section 2. Japan.....	8
Section 3. Germany.....	13
Section 4. United States .....	17
Section 5. Australia.....	20
Section 6. ASEAN Member States .....	23
Section 7. Comprehensive Comparison .....	25
Chapter 3. Selection of Hydrogen Utilization Sector in Thailand.....	27
Section 1. Policy Conformity Review.....	27
Section 2. Review of economic importance .....	31
Section 3. Review of Technical Necessity and Applicability .....	48
Section 4. Review of Energy Consumption Conditions.....	59
Section 5. Comprehensive Comparison and Selection.....	68
Chapter 4. Estimating the Climate Benefits of Hydrogen Utilization in Thailand.....	70
Section 1. Overview of Climate Benefit Estimation.....	70
Section 2. Cement Industry.....	76
Section 3. Oil Refining Business .....	90
Section 4. Road Transport Sector.....	100
Section 5. Power Generation Sector.....	114
Section 6. Comprehensive Comparison.....	129
Chapter 5. Summary and Conclusion .....	131
Reference .....	134

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# **Chapter 1. Introduction**

## **Section 1. Background and Necessity of Research**

The global community has recognized the importance of hydrogen as a means to reduce greenhouse gas (GHG) emissions and achieve carbon neutrality. Many countries, including Thailand, have embraced hydrogen technology and are implementing strategies to transition to a decarbonized society. Thailand has announced its plan to achieve net-zero emissions by 2065 and is investing resources to contribute to this goal. The production and utilization of hydrogen, particularly green hydrogen, are seen as crucial in achieving net-zero emissions. The Thai government acknowledges that green hydrogen can drive economic and industrial growth, and steps are being taken to establish an institutional framework to enhance national competitiveness and lead the industry. Developed countries consider the hydrogen economy as a catalyst for future innovative growth and are investing in relevant infrastructure for power generation, industry, and transportation. Therefore, Thailand needs to develop a pathway towards a hydrogen society by producing and utilizing green hydrogen to meet its national climate targets and achieve net-zero emissions.

## **Section 2. Purpose and Method of Research**

### **1. Research purpose**

This study is conducted as part of a series of tasks to develop the national hydrogen strategy for Thailand. It aims to identify potential hydrogen demand sectors in the country and to justify the development of a national hydrogen strategy by selecting key economic sectors where hydrogen can be utilized, and estimating the Climate Benefit of hydrogen utilization in the selected sectors.

### **2. Research method**

In order to achieve the aforementioned research objectives, the study examines and compares the hydrogen economy policies established by major countries such as Korea, Japan,

Germany, the United States, and Australia, which are competing in the transition to a hydrogen economy in Chapter 2. Based on this, the key areas of economic activity in the hydrogen industry of each country are identified.

Chapter 3 examines the suitability of the hydrogen industry by considering policy coherence, economic conformity, technical necessity, and analyzing the energy consumption status of the economic sector. In Section 1, Thailand's plans for carbon neutrality are reviewed to assess the compatibility and justification of the government's promotion of hydrogen utilization. In Section 2, an analysis of Thailand's economic and industrial structure is conducted to identify the potential for transitioning to a hydrogen economy. Section 3 explores the need and suitability of hydrogen utilization technologies in key industrial sectors, while Section 4 analyzes the energy consumption conditions in each sector. Finally, in Section 5, the findings from the previous sections are synthesized to identify the industrial sectors that could have a significant impact on hydrogen utilization.

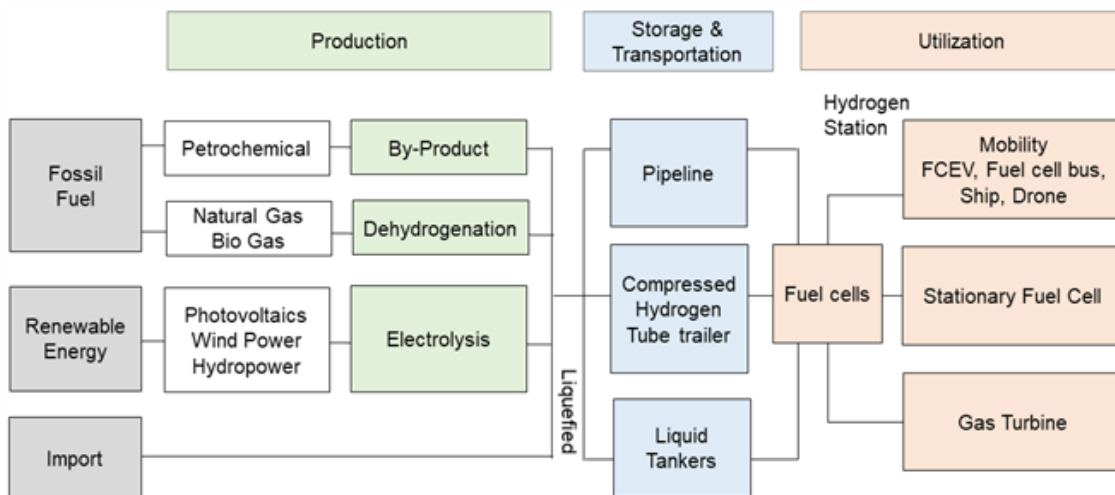
Chapter 4 estimates the climate benefits, such as greenhouse gas (GHG) reduction and economic advantages, which can be achieved through hydrogen utilization in Thailand. Chapter 5 consolidates the above analyses and provides suggestions and potential value propositions for the application and utilization of hydrogen in key industrial sectors in Thailand.

## Chapter 2. Review of Global Hydrogen Policy and Key Utilization Sectors

### Section 1. Korea

In 2019, Korea announced the 「Hydrogen Economy Revitalization Roadmap」, a national strategy for building a hydrogen economy to present the hydrogen economy concept (Figure 2-1) and established policies and plans for the overall hydrogen economy.

[Figure 2-1] The Value Chain of Hydrogen Economy in Korea



Source: Lee & Kim (2021)

In 2021, the world's first hydrogen law, 「Hydrogen Economy Promotion And Hydrogen Safety Management Act」 (enacted on Feb. 4, 2020, enforced on Feb. 5, 2021) secured the legal basis for building a foundation of the hydrogen industry, and based on the provision of formulation a master plan in Article 5 of the Act, the 「1<sup>st</sup> Master Plans for Hydrogen Economy Implementation」 was established and announced jointly with related ministries in November 2021.

In this plan, South Korea set out a short-term, mid-to-long-term plan covering hydrogen

supply and demand plans, institutional operation, financial procurement, and infrastructure creation plans, as well as 4 strategies and 15 tasks to achieve the vision of “leading the clean hydrogen economy by building a full-cycle ecosystem for the hydrogen economy” and the goal of reaching 60% of self-sufficient clean hydrogen production and 100% of clean hydrogen utilization (<Table 2-1>).

<Table 2-1> Korea’s Hydrogen Economy Implementation Master Plan

Value Chain	Present (2020)	2030	2050
Production	<p><b>clean hydrogen Self-sufficiency rate 0%</b></p> <ul style="list-style-type: none"> <li>Supply 0.22Mt - Gray 0.22Mt</li> </ul>	<p><b>clean hydrogen Self-sufficiency rate 34%</b></p> <ul style="list-style-type: none"> <li>Supply 3.9 million tons - Gray 0.94Mt - Green 0.25Mt - Blue 0.75Mt - Overseas 1.96Mt</li> </ul>	<p><b>clean hydrogen Self-sufficiency rate 60%</b></p> <ul style="list-style-type: none"> <li>Supply 27.9Mt - Green 3Mt - Blue 2Mt - Overseas 22.9Mt</li> </ul>
	<ul style="list-style-type: none"> <li>Byproduct Hydrogen extraction production</li> </ul>	<ul style="list-style-type: none"> <li>Blue Hydrogen Production (25~)</li> </ul>	
	<ul style="list-style-type: none"> <li>MW class water electrolysis system demonstration</li> </ul>	<ul style="list-style-type: none"> <li>10MW water electrolysis system commercialization</li> </ul>	<ul style="list-style-type: none"> <li>GW class water electrolysis system commercialization</li> </ul>
	<ul style="list-style-type: none"> <li>Ammonia Overseas production (~25)</li> </ul>	<ul style="list-style-type: none"> <li>Ammonia Overseas introduction (27)</li> <li>Ammonia Stockpiling Base (30)</li> </ul>	<ul style="list-style-type: none"> <li>40 overseas supply chains establishment</li> </ul>
Storage/ Transportation	<ul style="list-style-type: none"> <li>Gas tube trailer operation</li> </ul>	<ul style="list-style-type: none"> <li>Liquefaction · Liquid Tank Lorry (23)</li> </ul>	
	<ul style="list-style-type: none"> <li>Hydrogen filling stations (~70)</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen refueling stations (660)</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen filling more than 2000 stations</li> </ul>

	<ul style="list-style-type: none"> <li>In the natural gas pipeline network co-firing hydrogen demonstration (22)</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen Liquefaction Plant (23)</li> <li>Hydrogen Port (28)</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen pipe network establishment</li> </ul>
Utilization	<p><b>clean hydrogen proportion 0%</b></p> <ul style="list-style-type: none"> <li>Demand 0.22Mt</li> <li>- Transport 0.002Mt</li> <li>- Power generation 0.22Mt)</li> </ul>	<p><b>clean hydrogen proportion 75%</b></p> <ul style="list-style-type: none"> <li>Demand 3.9Mt</li> <li>- Transport 0.37Mt</li> <li>- Power generation 3.53Mt)</li> </ul>	<p><b>clean hydrogen proportion 100%</b></p> <ul style="list-style-type: none"> <li>Demand 27.9Mt</li> <li>- Transport 2.2Mt</li> <li>- Power generation 13.5Mt</li> <li>- Industrial 10.6Mt</li> </ul>
	<ul style="list-style-type: none"> <li>About 10,000 hydrogen vehicles</li> <li>75 hydrogen commercial vehicles</li> </ul>	<ul style="list-style-type: none"> <li>850,000 hydrogen passenger vehicles</li> <li>30,000 hydrogen commercial vehicles</li> </ul>	<ul style="list-style-type: none"> <li>5.15 million hydrogen passenger vehicles</li> <li>110,000 hydrogen commercial vehicles</li> <li>Tram, ship, air</li> </ul>
	<ul style="list-style-type: none"> <li>Hydrogen Fuel Cell Development</li> </ul>	<ul style="list-style-type: none"> <li>20% ammonia mixed firing development (27)</li> <li>50% hydrogen mixed firing Development</li> </ul>	<ul style="list-style-type: none"> <li>100% Ammonia power generation</li> <li>100% Hydrogen power generation</li> </ul>
<b>4 strategies and 15 tasks</b>			
Domestic and international clean hydrogen production lead	Infrastructure building	Widespread Hydrogen Utilization	Enhanced ecosystem base
<ul style="list-style-type: none"> <li>Green Hydrogen production</li> <li>Blue Hydrogen production</li> <li>Overseas clean hydrogen production</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen value chain infrastructure building</li> <li>Hydrogen pipe network build</li> <li>Expanding Hydrogen fueling station</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen power generation expansion</li> <li>Hydrogen Mobility global market leadership</li> <li>Industry hydrogen utilization base preparation</li> </ul>	<ul style="list-style-type: none"> <li>Technology development, human resource development, standardization</li> <li>Leading international cooperation</li> <li>Fostering Hydrogen dedicated companies and promoting finance</li> <li>Expanding Hydrogen cluster, city regulation-free special zone</li> <li>Building policy foundations and</li> </ul>

			increasing public acceptance
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Source: Korean Ministries (2021)

Since the announcement of the hydrogen economy roadmap in 2019, Korea has been receiving steady policy support for the creation of a hydrogen economy. Accordingly, the utilization sectors within the value chain of the hydrogen economy are divided into transportation, household/building, power generation, and gas turbines (Ministry of Industry, 2019). Furthermore, to diversify hydrogen utilization in the hydrogen utilization sector within the basic plan, ① expanding hydrogen power generation in earnest, ② leading the global hydrogen mobility market, and ③ laying the groundwork for hydrogen utilization in the industrial sector were emphasized. First of all, to expand hydrogen power generation, the expansion of fuel cell power generation facilities and the commercialization of 20% coal-fired ammonia (~'27) and hydrogen-fired gas turbines (~'50) were presented as targets. At an early stage of the basic plan, the power generation using grey hydrogen will be replaced by a power generation system using clean hydrogen in the future. Specifically, the government plans to reduce carbon emissions from coal-fired power plants by securing and demonstrating co-firing ammonia with coal and increasing the ammonia blend rate in the future. It also plans to develop and demonstrate technology that blends 50% hydrogen in LNG turbines and commercialize technology that blends hydrogen in gas turbines.

To this end, policy support measures such as the introduction of a mandatory system for clean hydrogen power generation, strengthening the environmental charge system through reforming the tax levy on fuels for power generation, and revising environmental regulations have been proposed.

Second, to lead the mobility market, the goal was to secure production capacity for all types of hydrogen vehicles (passenger vehicles, commercial vehicles, special vehicles, etc.) and expand the application to various mobility such as ammonia and hydrogen ships, drones, and aviation. In response, support measures were put forward to accelerate fuel conversion through intensive subsidy support for commercial vehicles and ships, an eco-friendly vehicle purchase target system, and an increase in the mandatory purchase ratio by public

institutions.

Finally, to lay the foundation for hydrogen utilization in the industrial sector, it was decided to promote hydrogen-based process conversion and fossil fuel/raw material substitution for industries (steel, petrochemical, oil refining, cement, etc.) and old/new industrial complexes that emit large amounts of greenhouse gases. Hydrogen energy is supplied as fuel and raw materials to new industrial complexes, and when replacing facilities in old industrial complexes, LNG and hydrogen co-firing power generation is used to build carbon-free industrial complexes.

In the steel sector, a complete transition of existing blast furnace facilities to hydrogen reduction facilities by 2050, production of high value-added green chemical products using clean hydrogen by replacing heavy oil, the main fuel in the petrochemical process, with hydrogen, etc. will be implemented. In the cement sector, technology development of hydrogen hybrid carbon-free heat sources will be promoted. Based on these goals and strategies, Korea seeks to create new demand by expanding hydrogen utilization in the power generation and industrial sectors and diversifying hydrogen mobility, while maintaining the world's leading technology gap in hydrogen utilization.

## Section 2. Japan

In December 2017, Japan established the 「Basic Hydrogen Strategy」, the world's first national hydrogen industry promotion strategy. Later, 「Hydrogen and Fuel Cell Strategy Roadmap」 in March 2019 and 「Hydrogen and Fuel Cell Technology Development Strategy」 in September 2019 have led to concrete goals of technology development. Also, 「Green Growth Strategy for Carbon Neutrality」 established in December 2020, has led innovation, with a goal of mass hydrogen supply across all sectors to achieve a decarbonized society.

In June 2023, the hydrogen basic strategy was revised once to promote the hydrogen industry's overseas expansion and safety as an essential means for large-scale hydrogen utilization. In addition, the revised strategy supplemented and presented the hydrogen security strategy to enhance the suitability of legal application over the supply chain.

The Basic Hydrogen Strategy includes policy goals and strategies covering all areas of hydrogen supply, storage, transportation, and utilization to solve environmental problems and strengthen energy security, and divides the development stages for the realization of a hydrogen society by 2050 into three stages (present, the late 2020s, around 2040), and separately set goals and key tasks for each stage.

In the first stage, Japan will establish a leading position in the global hydrogen and fuel cell field by expanding the use of stationary fuel cells and fuel cell vehicles (FCVs) and exponential hydrogen utilization. In the second stage, Japan will utilize hydrogen as a new energy source by establishing a large-scale hydrogen supply system, transforming conventional power and heat-centered energy consumption system. The third stage is to establish a CO<sub>2</sub>-free hydrogen supply system. The main contents include 1) establishing a low-cost hydrogen supply system, 2) developing an international hydrogen supply network, 3) expanding the use of hydrogen extracted from renewable energy, 4) hydrogen power generation, 5) hydrogen fuel cell vehicles, 6) fuel cells, and 7) using industrial process heat.

Including the mentioned above, the third stage aims to achieve price competitiveness equal to that of existing energy sources with the hydrogen price reaching 20 yen/Nm<sup>3</sup>, and the power generation capacity is 15~30GW (12 yen/kWh) by replacing gas-fired power generation in 2050 hydrogen society (<Table 2-2>). In the「Hydrogen and Fuel Cell Strategic Roadmap」(2019), the implementation plan for realizing a hydrogen society in the basic hydrogen strategy was specified. Looking at the action plan within the roadmap, it includes specific goals for hydrogen utilization and supply and policy support measures to achieve the goals ([Figure 2-2]).

<Table 2-2> Main Goals of Japan's Hydrogen Basic Strategy (2017)\*

Division		Present	2030	2050
Supply	Type	<ul style="list-style-type: none"> <li>▲ Fossil fuel-based (by-product hydrogen, natural gas modification)</li> <li>▲ demonstration of supply chain establishment, scale-up necessary</li> </ul>	<ul style="list-style-type: none"> <li>▲ International hydrogen supply chain establishment</li> <li>▲ Renewable Energy based hydrogen manufacturing technology established</li> </ul>	<ul style="list-style-type: none"> <li>▲ CO<sub>2</sub>-free hydrogen</li> </ul>
	Scale	<ul style="list-style-type: none"> <li>▲ 0.02 million tons (2017)</li> </ul>	<ul style="list-style-type: none"> <li>▲ 300,000 tons (commercial supply chain scale)</li> </ul>	<ul style="list-style-type: none"> <li>▲ more than 10 million tons (largely rely on power generation consumption)</li> </ul>
	Price	<ul style="list-style-type: none"> <li>▲ 100 yen /Nm<sup>3</sup> (Fueling station price)</li> </ul>	<ul style="list-style-type: none"> <li>▲ 30 Yen /Nm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>▲ 20 Yen /Nm<sup>3</sup></li> </ul>

	Power generation	<ul style="list-style-type: none"> <li>▲ Technology development being underway</li> <li>▲ Hydrogen power generation to be demonstrated in the mid-2020s</li> </ul>	<ul style="list-style-type: none"> <li>▲ (Reference) Hydrogen consumption: 1 million kW with 300,000 tons of generation capacity</li> </ul>	<ul style="list-style-type: none"> <li>▲ (Reference) Hydrogen consumption: 5 to 10 million tons of hydrogen consumption, about 15~30GW in power generation capacity</li> </ul>
Utilization	Mobility	<ul style="list-style-type: none"> <li>▲ Hydrogen 163 fueling stations</li> <li>▲ 3800 FCVs</li> <li>▲ 99 FC buses</li> <li>▲ 250 Forklifts (2020)</li> </ul>	<ul style="list-style-type: none"> <li>▲ Hydrogen 1,000 fueling stations</li> <li>▲ FCV 800,000 units</li> <li>▲ 1,200 FC buses _</li> <li>▲ 10,000 forklifts _</li> </ul>	<ul style="list-style-type: none"> <li>▲ Replacing existing petrol stations with hydrogen fueling stations to improve profitability</li> <li>▲ Replacing gasoline vehicles with hydrogen vehicles through technological advancement and lower cost of the FC stack and FC of heavy-duty vehicles</li> </ul>
	Fuel-cell use	<ul style="list-style-type: none"> <li>▲ Household fuel cell 330,000 units of Enefarm supply</li> </ul>	<ul style="list-style-type: none"> <li>▲ Enefarm 5.3 million units supply</li> </ul>	<ul style="list-style-type: none"> <li>▲ Assumption such as existing energy system hydrogen utilized fuel cell as a system transform</li> </ul>

\* June 2023 revised

Source: METI (Ministry of Economy, Trade and Industry) (2020.11) Future hydrogen policy of review on the propulsion method about; KOTRA (2023) Japan hydrogen industry nurturing policy and industry current situation

Japan's hydrogen utilization sector is largely divided into ① hydrogen power generation, ② transportation, ③ industrial process, and ④ fuel cell technology, with the goal of commercialization by 2030 and securing profitability. Japan's market size is about 150 million dollars (17.5 billion yen) in 2020, and the related market is expected to grow about 268 times by 2035 due to the rapid growth of the power generation sector. Demonstration experiments for ammonia co-fired power generation and hydrogen gas turbine power generation will start in 2024 and 2025, respectively, and it is expected that demand for hydrogen will increase significantly in the power generation sector. According to the Basic Hydrogen Strategy (2023), for hydrogen power generation, the development and demonstration of small gas turbines

and combustors will be carried out by 2030, and the development and demonstration of large gas turbines with more than 30% combustion and combustion burners will be conducted, and ammonia power generation is in the process of realizing more than 50% combustion rate and developing combustion burners.

In the case of transportation, it aims to supply 200,000 hydrogen-powered vehicles by 2025 and 800,000 by 2030. It also aims to supply 1,200 hydrogen buses and 10,000 industrial forklifts by 2030. The hydrogen electric vehicle market is expected to grow more than 100 times by 2030 as infrastructure is expanded, and Japan's Toyota Mirai (2nd generation) continues to dominate the global FCEV market along with Korea's Hyundai Nexo. Japan currently has the largest number of hydrogen fueling stations in the world, and it is promoting related systems and standard maintenance, technology development support, etc. to establish 900 fueling stations by 2030.

In the case of household fuel cells, a demand base is being built with the spread of Ene-Farm, a cogeneration system that can produce electricity and heat in a general house by chemically reacting hydrogen extracted from city gas or LP gas with oxygen in the air. It plans to supply 5.3 million household fuel cells by 2030 for early market independence. In addition, in the field of fuel use, hydrogen-ammonia burner and boiler RD&D and demonstration of hydrogen reduction steelmaking using large-scale blast furnaces will be promoted.

[Figure 2-2] Overview of Quantitative Targets Provided by HFR Japan

		Objectives of the Basic Strategy	Setting targets to aim for	Efforts to achieve the target
Utilisation	Mobility	FCV 200,000 units @ 2025 800,000 units @ 2030	2025 <ul style="list-style-type: none"> <li>● Price difference between FCV and HV (3 M<sup>2</sup> yen → 0.7 M<sup>2</sup> yen)</li> <li>● Cost of FCV system (FC 20,000 yen/kW → 5000 yen/kW) (Hydrogen storage: from 700,000 yen → 300,000 yen)</li> </ul>	<ul style="list-style-type: none"> <li>● Thorough regulatory reform and technological development</li> </ul>
		ST 320 locations @ 2025 900 locations @ 2030	2025 <ul style="list-style-type: none"> <li>● Maintenance and operation costs (Maintenance costs: 350 M<sup>2</sup> yen → 200 M<sup>2</sup> yen) (Operating expenses: 34 M<sup>2</sup> yen → 15 M<sup>2</sup> yen)</li> <li>● ST component cost (Compressor 90 M<sup>2</sup> yen → 50 M<sup>2</sup> yen) (Accumulator: 50 M<sup>2</sup> yen → 10 M<sup>2</sup> yen)</li> </ul>	<ul style="list-style-type: none"> <li>● Expansion of Nationwide ST Network, open on Weekend</li> <li>● Expansion of ST at gas stations and convenience stores</li> </ul>
		Bus 1,200 @ 2030	early 2020s <ul style="list-style-type: none"> <li>● FC Bus Vehicle Price (105 M<sup>2</sup> yen → 52.5 M<sup>2</sup> yen)</li> </ul>	<ul style="list-style-type: none"> <li>● Expansion of bus compatible ST</li> </ul>
Utilisation	Power	Commercialization @ 2030	2020 <ul style="list-style-type: none"> <li>● Power generation efficiency in hydrogen power generation (26% → 27%)</li> </ul>	<ul style="list-style-type: none"> <li>● Development of high-efficiency combustors</li> </ul>
	FC	Grid-parity early realization	2025 <ul style="list-style-type: none"> <li>● Realization of grid parity for commercial and industrial fuel cells</li> </ul>	<ul style="list-style-type: none"> <li>● Technological development of cell stacks</li> </ul>
Supply	Fossil + CCS	Hydrogen cost 30 yen/Nm <sup>3</sup> @ 2030 20 yen/Nm <sup>3</sup> @ future	early 2020s <ul style="list-style-type: none"> <li>● Production: Production cost due to lignite gasification (millions of yen/Nm<sup>3</sup> → 12 yen/Nm<sup>3</sup>)</li> <li>● Storage and transportation: Liquefied hydrogen tank size (thousand m<sup>3</sup> → 50,000 m<sup>3</sup>) Hydrogen liquefaction efficiency (13.6 kWh/kg → 6 kWh/kg)</li> </ul>	<ul style="list-style-type: none"> <li>● Larger and more efficient lignite gasifier</li> <li>● Improvement of heat insulation and enlargement of liquefied hydrogen tanks</li> </ul>
	Reenergized hydrogen	Cost of water electrolysis system 50,000 yen/kW @ Future	2030 <ul style="list-style-type: none"> <li>● Cost of water electrolysis equipment (200,000 yen/kW → 50,000 yen/kW)</li> <li>● Water electrolysis efficiency (5 kWh/Nm<sup>3</sup> → 4.3 kWh/Nm<sup>3</sup>)</li> </ul>	<ul style="list-style-type: none"> <li>● Model area demonstration utilizing Namie demonstration results</li> <li>● Improvement of efficiency and durability of water electrolysis equipment</li> <li>● Building a Hydrogen Supply Chain Utilizing Local Resources</li> </ul>

Source: METI(2021)

### Section 3. Germany

The German federal government considers hydrogen as a key factor in implementing decarbonization. In June 2020, through the establishment of the 「National Hydrogen Strategy (Die Nationale Wasserstoffstrategie)」, the government puts forward a policy to lead the global energy transition and foster competitiveness of the hydrogen industry. Germany, the largest hydrogen economy among EU countries, establishes a concrete form of the EU-level hydrogen strategy (European Commission, 2020) (<Table 2-3>), emphasizing an integration into the European market and regulatory framework and the utilization of hydrogen production and infrastructure.

<Table 2-3> EU's Hydrogen Economy-related Policy

Policy	Detail
renewable energy Guidelines (2019)	<ul style="list-style-type: none"> <li>▲ Mandate to increase the share of renewable energy in final energy consumption to 32% by 2030</li> </ul>
EU Hydrogen Strategy (2020)	<ul style="list-style-type: none"> <li>▲ Published as a follow-up plan to the European Green Deal</li> <li>▲ Evaluates hydrogen as a key enabler for economic revitalization and energy transition</li> <li>▲ Main objectives:               <ul style="list-style-type: none"> <li>▲ 1 million tons of green hydrogen produced by supporting the deployment of 6 GW or more of hydrogen electrolysis (2020-2030);</li> <li>▲ 10 million tons of green hydrogen produced by supporting the deployment of 40 GW or more of hydrogen electrolysis (2030-2050);</li> <li>▲ Widespread use of green hydrogen, even in hard-to-decarbonise sectors (2030-2050).</li> </ul> </li> </ul>
European Clean Hydrogen Alliance	<ul style="list-style-type: none"> <li>▲ EU hydrogen strategy fulfillment for government, industry, civil society, European investment bank Participation</li> </ul>

Source: KOTRA (2022)

In this strategy, Germany defines the scope of the hydrogen economy as “Building up and securing the quality assurance infrastructure for hydrogen production, transport, storage and use, and building trust”, and presents policies related to hydrogen energy, industry, technological innovation, and presents specific action plans covering Germany’s hydrogen-related energy, industrial, technological innovation, and international cooperation policies with an analysis of the current trends.

In addition to the goal, vision, and current status analysis, it also presents an action plan with specific measures. The main goals are ① enhancing competitiveness by reducing hydrogen-related costs, ② developing the hydrogen-related market in Germany, ③ reinforcing hydrogen transport and distribution infrastructure, ④ establishing an international hydrogen market and international cooperation system, and hydrogen demand in Germany is expected to reach about 90-110 TWh in 2030 and up to 380 TWh in 2050. 8 major areas of focus were selected, and the main directions were presented (<Table 2-4>).

**<Table 2-4> 8 focus areas and details of the German Hydrogen Strategy**

Area	Detail
Hydrogen production	▲ Expansion of the domestic market is essential to enable market introduction and export of hydrogen technology, and planned expansion of renewable energy generation capacity, such as wind and solar, is necessary to use hydrogen in a sustainable and economical manner.
Industrial sector	▲ Expansion of the existing hydrogen infrastructure in the chemical industry to other applications such as steel.
Transport	▲ Fuel cells complement battery electric vehicles in public transport such as buses and railways, and in some freight transport.
Heat market	▲ A long-term demand for gaseous fuels, making hydrogen a viable option
Hydrogen as a collaborative project	▲ Opportunities to produce green hydrogen in the long term wind power uses in the North Sea and solar power in Southern Europe, and Europe's gas infrastructure can be used to transport hydrogen
International trade	▲ International trade in hydrogen and derivatives is important as Germany will rely on imports of renewable energy to meet its climate change targets
Transport and distribution infrastructure in Germany and abroad	▲ Building a dedicated hydrogen transport network in addition to using gas infrastructure for hydrogen in the long term
Research, education, innovation	▲ Research funding for responding a new climate course encompassing key technologies and hydrogen value chain

Source : BMWi (2020)

In particular, in the hydrogen utilization sector, it is expected that demand for hydrogen in 2030 will increase by at least 10 TWh in the industrial (chemical, petrochemical, steel) fields, as well as hydrogen fuel cell vehicles and heating/thermal fields. In terms of hydrogen

utilization, even before establishing a national strategy, Germany carried out comprehensive research and development in the field of hydrogen utilization centering on the 「National Innovation Program Hydrogen and Fuel Cell Technology (NIP)」(2007).

As the 1<sup>st</sup> NIP (2007~2016) and 2nd NIP (2016~2026), established large-scale investment plans and proceeded R&D (related to mobility, fuel cells, fueling stations, and so on), field experiments, marketability improvement, etc., this hydrogen strategy also deals heavily with hydrogen application. (<Table 2-5>: Transportation – Measure 5~13, Industry – Measure 14~17, Heat – Measure 18~19).

**<Table 2-5> German’s Hydrogen Strategy Action Plan for Hydrogen Utilization**

Sector	Measure	Detail
Transport	5	<ul style="list-style-type: none"> <li>▲ Increased incentives for hydrogen to meet the EU's Renewable Energy Directive (RED II), among other policies</li> <li>- The German government aims to significantly increase the minimum share of renewable energy consumption in the transport sector above EU regulations by '30, with a target of 2GW of electrolysis capacity.</li> </ul>
	6	<ul style="list-style-type: none"> <li>▲ Expansion of subsidies for eco-friendly mobility and support for hydrogen-related technology development such as fuel cells through continued implementation of NIP.</li> <li>- Use of EKF (Energy and Climate Fund) for energy transition policy in Germany</li> </ul>
	7	▲ Further investment in electricity-based fuel production
	8	▲ Expansion of hydrogen fueling infrastructure supported by EKF
	9	▲ Commitment to advance infrastructure for the commercialization of fuel cells across Europe through guideline amendments.
	10	▲ Support for the development of competitive fuel cell systems such as fuel cell stacks
	11	▲ Support for introducing carbon-free vehicles in the city
	12	▲ Differentiating Collection of Truck Tolls in the EU
	13	▲ Leading international standards for hydrogen fuel cell systems such as fueling standards, hydrogen quality, and hydrogen vehicle types
Industrial sector	14	▲ Hydrogen fuel, in particular, in the chemical and steel industry plays a central role. Therefore, the fund will be provided through the 'Hydrogen Utilization in the Production of Industrial Products ('20-'24)' program

	15	▲ Encouraging the market for hydrogen technology by providing partial government compensation for losses incurred by the chemical and steel industries in operating decarbonized technologies through the Carbon Contracts for Difference (CfD) program.
	16	▲ The German government will continuously review solutions (such as quotas for green raw materials) to enable climate-neutral markets for green products in energy-intensive industries such as chemicals and steel.
	17	▲ A long-term plan will be established in cooperation with on-site stakeholders from energy-intensive industries (chemicals, steel, aviation, logistics, etc.), taking into account industry-specific characteristics.
Heat	18	▲ In the building sector, the Energy Efficiency Incentive Programme (APEE) has been in place since 2016 and will be strengthened to encourage greater use of fuel cells in buildings (with an investment of around €700 million between 2020 and 2024).
	19	▲ The possibility of promoting renewable energies to heat buildings in the long term within the framework of the KWKG (Kraft-Wärme-Kopplungsgesetz).

Source: BMWi (2020)

## Section 4. United States

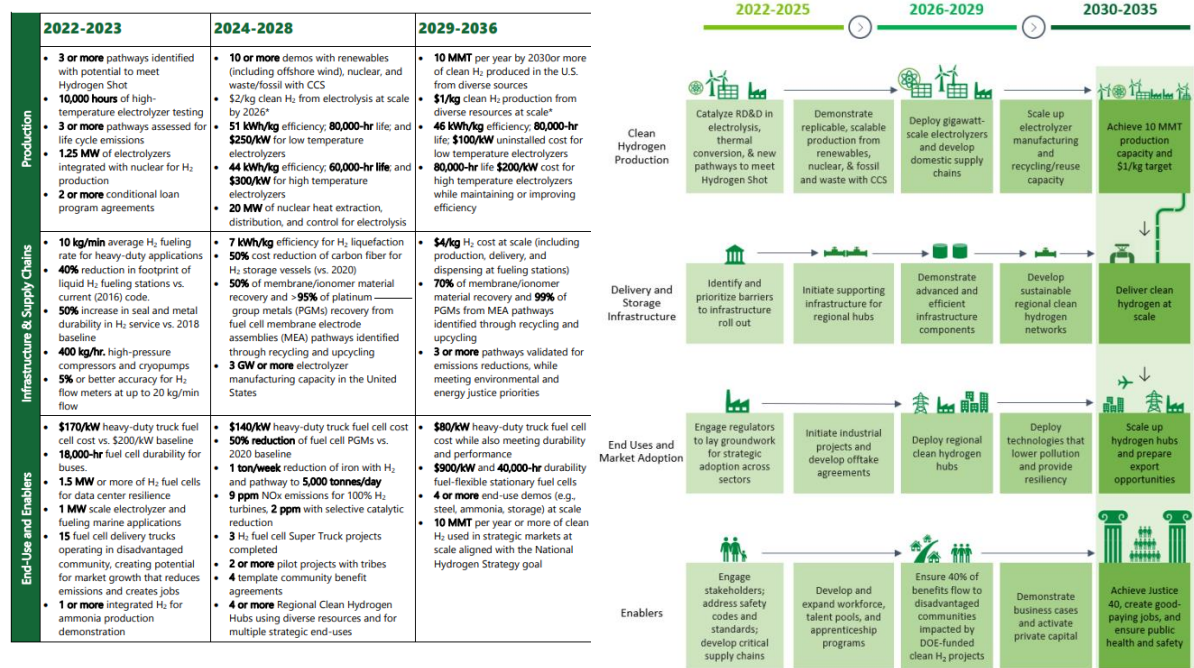
The United States announced the 「US National Clean Hydrogen Strategy and Roadmap」 in June 2023 to promote the production, processing, transportation, storage, and utilization of hydrogen across the entire value chain. The Biden administration sees the affordable and safe use of clean hydrogen as a key enabler of economic and social benefits, and through the development of the Hydrogen Strategy, seeks to establish a comprehensive framework that includes specific goals and action plans for each sector based on the current status and future projections of hydrogen production, transportation, storage, and utilization in the United States.

It will play a crucial role in achieving the Biden administration's goal of 100 % carbon-free electricity supply by 2035 and carbon neutrality by 2050, and forecasts that domestic demand for clean hydrogen production will reach 10 MMT per year by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050, and that total U.S. GHG emissions will be reduced by about 10 % compared to 2005 levels. In addition, the U.S. government has provided the institutional basis to fully support the clean hydrogen industry by allocating approximately \$9.5 billion in investment over five years (2022-2026) to build infrastructure for the hydrogen economy through the Infrastructure Investment and Job Act of 2021 (IIJA) and providing a large-scale subsidy support system for clean hydrogen through the Inflation Reduction Act of 2022 (IRA).

To achieve this goal, the strategy lays out three key strategies: 1) strategic utilization of clean hydrogen, 2) reducing the cost of clean hydrogen, and 3) building regional networks: Through the first core strategy, the government will focus on the use of clean hydrogen to reduce carbon emissions in industries that are difficult to electrify (e.g. chemicals, steel, refining, etc.), heavy-duty transport (trucks and buses, maritime and ports, aviation, railways, etc.), and the power sector; through the second core strategy, the government will support various clean hydrogen production pathways, aiming to reduce the cost of clean hydrogen to \$1/kg, an 80% reduction in about 10 years; and through the third core strategy, the government will build and expand clean hydrogen hubs comprising clean hydrogen producers and regional resources, raw materials, infrastructure, and consumers. To support these three key

strategies, the government also plans to support activities across basic science through Research, Development, Demonstration, and Deployment (RDD&D) over the short-term (2022-2025), medium-term (2026-2029), and long-term (2030-2035) ([Figure 2-3]).

[Figure 2-3] Key Program Targets & Action Plan of Hydrogen Strategy 2022~2036 in the U.S.



Source: DOE (2023)

Hydrogen utilization in the U.S. is largely divided into industry, transportation, and power generation (<Table 2-6>). In the industrial field, chemical, oil refining, and steel fields, which are difficult to decarbonize, were mentioned, and in the transportation field, plans for application to passenger cars, commercial vehicles, ships, and railroads were presented. In the power generation sector, directions for using hydrogen for backup power, power generation, and grid services were suggested.

<Table 2-6> Hydrogen Utilization Sector of the U.S. Hydrogen Strategy

Utilization Sector	Detail
Industry	<ul style="list-style-type: none"> <li>More than half of carbon emissions from industry come from the direct combustion of fossil fuels to generate heat and power for industrial processes, and the use of purified hydrogen to decarbonize these processes</li> </ul>

	<ul style="list-style-type: none"> <li>▲ The use of clean hydrogen in the chemical and steel sectors, particularly in the production of ammonia and methanol, can reduce GHG emissions by more than 90 % and 40-70 % respectively.</li> </ul>
Transport	<ul style="list-style-type: none"> <li>▲ The transportation sector accounts for 33% of U.S. greenhouse gas emissions (2019), 51% of which come from light-duty vehicles.</li> <li>▲ Hydrogen and fuel cells can be used to decarbonize the transport sector for mining equipment, ferries, railways, and other vehicles that need to travel long distances, refuel quickly and carry large, heavy loads.</li> </ul>
Power generation	<ul style="list-style-type: none"> <li>▲ Hydrogen has multiple applications for long-term energy storage, power generation, and grid services, and can provide additional revenue streams as a feedstock or fuel for other sectors</li> </ul>
Government agencies	<ul style="list-style-type: none"> <li>▲ In addition to the commercial market, government agencies are promoting the use of hydrogen for other critical situations, such as restoring energy and water resources for federal facilities during emergencies, backup power for military bases, and other early demonstrations.</li> </ul>

Source: DOE (2023)

Prior to the establishment of this strategy, the United States has been steadily promoting R&D and demonstration projects of hydrogen technology through the Hydrogen Programme Plan (November 2020) and the H2@Scale initiative (March 2019), which integrates R&D and demonstration for the hydrogen economy at the DOE. In particular, through H2@Scale, a fund of about \$64 million was established to promote the establishment of a virtuous cycle system for the national hydrogen economy by utilizing clean hydrogen produced at low prices on a large scale in the power generation sector and to discover areas of application for the hydrogen industry. In addition, it supported projects to develop technology for fuel cell application to commercial vehicles such as medium- and heavy-duty trucks.

## Section 5. Australia

Under its Hydrogen Roadmap (CSIRO, 2018) and National Hydrogen Strategy (COAG, 2019), Australia is pursuing policies to become the world's largest producer and exporter of hydrogen by creating a large-scale hydrogen distribution and export hub (<Table 2-7>).

By supporting the mass production of eco-friendly hydrogen using carbon capture technology, the government has set a goal of reducing the cost of hydrogen production to \$1.39/kg by 2030 and is promoting the establishment of a supply chain to export 75% of total hydrogen production and become one of the top three exporters to Asia by 2050. In addition to these federal policies, Australia's six states and two Territories are also developing state-specific hydrogen strategies.

<Table 2-7> Australian Federal Government Hydrogen Strategy

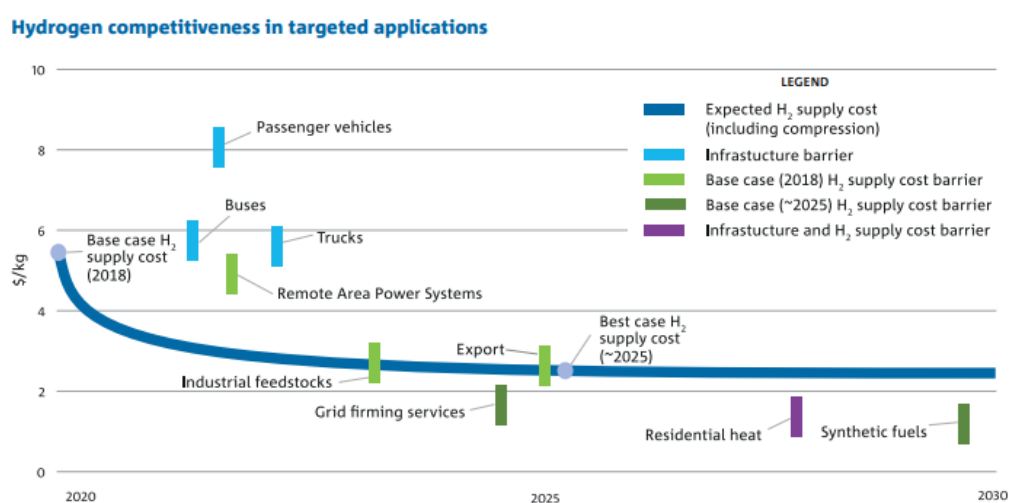
Policy	Detail	
<p>National Hydrogen Roadmap (CSIRO, 2018)</p>		<p> - Provide hydrogen industry stakeholder groups with a step-by-step blueprint for hydrogen production methods, storage and transport, and hydrogen utilization so that the industry can continue to expand.</p>
<p>National Hydrogen Strategy (COAG, 2019)</p>		<ul style="list-style-type: none"> <li>• (Goal) Securing a position as a major player in the global hydrogen sector by 2030</li> <li>• (Direction) Establishing hydrogen hubs, fostering the hydrogen industry by attracting investment, and activating international market formation and trade.</li> <li>• (Implementation process) (2020~2025) Establishment of foundation and demonstration, (2026~2036) Activation of large-scale market</li> <li>• (Major Measures) 21 major measures and 57 detailed tasks are proposed</li> </ul>

Source: CSIRO website ([www.csiro.au](http://www.csiro.au))

Australia's hydrogen industry is dominated by the production side of the market, and the country's local governments are focusing on expanding the use of hydrogen mobility, considering mobility, heating and cooling, and grid electricity as promising areas. In February 2021, the Future Fuel Strategy, which aims to increase the uptake of cleaner vehicles, identified the establishment of charging infrastructure for electric and hydrogen vehicles as a top priority and announced plans to expand pilot projects. There are currently three hydrogen fueling stations in Melbourne, Brisbane, and Canberra, with the Hyundai Nexo and Toyota Mirai vying for a share of the Australian market for FCEVs. The government plans to increase the proportion of eco-friendly vehicles to 30 % (300,000) by 2030, and Australian automotive startup H2X has announced plans to produce hydrogen electric vehicles. In addition, hydrogen trucks for logistics transport and public sector buses have been launched, and research is underway to produce hydrogen fuel cells.

In terms of state-level hydrogen utilization strategies, New South Wales is piloting hydrogen buses in Sydney's inner city, and Victoria has announced a 100 million AUD funding package to boost the hydrogen mobility market through its Zero Emission Vehicle (ZEV) Roadmap. Approximately \$32.6 million of this is for residential and commercial ZEV purchases. The State of Queensland is looking to expand the uptake of ZEVs by building hydrogen fueling stations (2021) and purchasing a Hyundai NEXO for official use.

[Figure 2-4] Trends in hydrogen availability by hydrogen utilization in Australia



Source: CSIRO (2018)

[Figure 2-5] Australia hydrogen utilization sector

VALUE CHAIN ELEMENT	COMMERCIAL	POLICY/REGULATORY	RD&D	SOCIAL
<b>Applications</b>				
<b>Hydrogen fuelled transport</b>	<ul style="list-style-type: none"> <li>Establish refuelling station joint ventures and undertake strategic roll out of stations</li> </ul>	<ul style="list-style-type: none"> <li>Implement emissions standards on vehicles and specific incentives for FCEVs</li> </ul>	<ul style="list-style-type: none"> <li>Demonstrate viability of refuelling stations with 'back to base' vehicles or vehicles with known driving patterns</li> </ul>	<ul style="list-style-type: none"> <li>Improve recognition of FCEVs as electric vehicles</li> <li>Conduct ongoing station safety demonstrations for refuelling stations</li> </ul>
<b>Industrial feedstocks</b>	<ul style="list-style-type: none"> <li>Install new clean hydrogen inlets into facilities during plant shutdowns</li> </ul>	<ul style="list-style-type: none"> <li>Implement incentive schemes regarding use of clean hydrogen as an industrial feedstock</li> </ul>		<ul style="list-style-type: none"> <li>Create awareness of emissions embodied in commodities to help inform consumer choice</li> </ul>
<b>Export (as per production, storage and transport plus)</b>	<ul style="list-style-type: none"> <li>Implement government to government agreements for export to give industry confidence</li> <li>Establish 'take or pay' export offtakes</li> <li>Undertake land appraisal assessments for dedicated renewables</li> <li>Invest in domestic labour force</li> <li>Negotiate favourable tariffs for hydrogen export (including in the existing FTAs)</li> </ul>	<ul style="list-style-type: none"> <li>Implement regulations supporting use of unutilised land for dedicated renewables</li> <li>Engage bodies such as the International Maritime Organisation to ensure appropriate regulatory frameworks for hydrogen shipping</li> </ul>	<ul style="list-style-type: none"> <li>As per hydrogen production, storage and transport</li> </ul>	<ul style="list-style-type: none"> <li>Continue to promote hydrogen as a low emissions export commodity</li> </ul>
<b>Electricity grid firming and RAPS</b>	<ul style="list-style-type: none"> <li>Undertake remote communities appraisal for RAPS</li> </ul>	<ul style="list-style-type: none"> <li>Implement incentives for use of hydrogen in remote mining sites and communities</li> </ul>	<ul style="list-style-type: none"> <li>Continue RD&amp;D into fuel cells to improve capital costs and asset life</li> <li>Demonstrate hydrogen in RAPS in mining activities and remote communities</li> </ul>	<ul style="list-style-type: none"> <li>Develop engagement plans regarding use of hydrogen systems in remote communities</li> </ul>
<b>Heat</b>	<ul style="list-style-type: none"> <li>Invest in 100% hydrogen capable workforce and appliance fitters</li> <li>Coordinate with non-Australian governments to give multinational appliance manufacturers more certainty</li> </ul>	<ul style="list-style-type: none"> <li>Implement clear policy direction for enrichment and subsequent displacement of natural gas</li> <li>Legislate manufacture and use of standardised and easily convertible appliances</li> </ul>	<ul style="list-style-type: none"> <li>Continue R&amp;D in 100% hydrogen appliances</li> <li>Continue trials for natural gas enrichment with hydrogen</li> <li>Undertake feasibility study over designated town for 100% hydrogen</li> <li>Begin development of pilot project for designated town</li> </ul>	<ul style="list-style-type: none"> <li>Undertake hydrogen enriched natural gas demonstrations to familiarise consumers with burning hydrogen</li> </ul>
<b>Synthetic fuels</b>		<ul style="list-style-type: none"> <li>Mandate local and low emissions fuel supply targets</li> <li>Implement incentives for use of synthetic fuels in aviation and shipping industry</li> </ul>	<ul style="list-style-type: none"> <li>Invest in 'power-to-fuels' technologies</li> </ul>	

Source: CSIRO (2018)

## Section 6. ASEAN Member States

While nine of the 10 ASEAN member states, except the Philippines, have declared carbon neutral or net-zero targets (as of June 2022), Singapore is the only country to have a national hydrogen strategy. In October 2022, Singapore's National Hydrogen Strategy announced plans to harness hydrogen to reduce GHG emissions to 60 million tons per year by 2030 and to supply 50% of its electricity generation with hydrogen by 2050. The strategy identifies power generation, industry, and transport as hydrogen utilization sectors to achieve net-zero emissions, which account for the majority of Singapore's GHG emissions, with power generation accounting for 39.8 %, industry 44.4 %, and transport 13.7 % of total emissions in 2020.

In the power generation sector, the plan is to use fuel cells and gas turbines. Unlike fuel cells, which still need to be developed, gas turbines with 30-50% combined cycle gas turbines (CCGTs) are already commercialized, and the goal is to commercialize hydrogen-only gas turbines in 2030. In industry, hydrogen can be used as a feedstock for industrial processes and a fuel for heat, power, and steam generation, particularly in the semiconductor, food, oil refining, and chemical industries.

The transport sector is broadly divided into maritime, air, and road transport, with road transport contributing to domestic GHG reductions. As Singapore is a hub for global maritime and air traffic, the transport sector in Singapore was selected and included as a contributor to global GHG emissions reduction.

The development of ship engines that can burn ammonia or methanol fuel directly, the use of hydrogen fuel cells and liquefied hydrogen in air transport, and the expansion of hydrogen fuel cell vehicles are included in the hydrogen strategy.

Among the other ASEAN member states, Indonesia has been actively investing in hydrogen fuel cell development over the past 15 years and will address the hydrogen sector in its roadmap on energy transition to carbon neutrality, currently being developed by the Ministry

of Energy and Mineral Resources. Hydrogen will be utilized in the power generation sector. The scale of power generation using green hydrogen is expected to gradually grow from 2031 and increase rapidly after 2050.

The Malaysian government is also working on a new national hydrogen economy and technology roadmap, led by the National Nanotechnology Centre under the Ministry of Science, Technology and Innovation. Except for Singapore, ASEAN member states do not have a national hydrogen strategy.

## Section 7. Comprehensive Comparison

As hydrogen is a raw material that can be secured in any region and has the advantages of low GHG emissions and fine dust-free, producing only water as a by-product, countries are establishing strategies and policies to lead the hydrogen economy society in the international community. Therefore, this report comprehensively compares and analyses the current status of hydrogen economy policies in major countries and the direction of hydrogen policies covering the hydrogen utilization sector so that Thailand can benchmark and refer to them when establishing a national hydrogen economy strategy.

The major countries involved are South Korea and Japan, which have established hydrogen strategies early, the United States, which is a global economic powerhouse and leads in technology, Germany, which has major technologies in each sector of the hydrogen economy ecosystem, and Australia, which is a resource-rich country with a huge hydrogen production market potential.

According to <Table 2-8>, all major countries have included a wide range of industries covering the production, storage, transport, and utilization sectors of the hydrogen economy ecosystem in their basic strategies. Priority support areas are identified through the proportion of demand and supply sources in the industrial sector, and the construction of core infrastructure and institutional infrastructure is being promoted together. Major countries such as South Korea, Japan, the United States, and Germany, with the exception of Australia, which focuses on production, have established strategies in the direction of government-led infrastructure deployment for large-scale hydrogen supply and the creation of self-sustaining ecosystems.

<Table 2-8> Key features of hydrogen strategies

Country	Strategy
Korea	▲ Building an ecosystem with a focus on hydrogen mobility and fuel cells

Japan	<ul style="list-style-type: none"> <li>▲ Developing international hydrogen production and supply chains, storage and transport technologies to secure affordable hydrogen supply, and leveraging hydrogen mobility and power generation.</li> </ul>
Germany	<ul style="list-style-type: none"> <li>▲ Securing clean hydrogen production and hydrogen supply chain</li> <li>▲ Establishing a long-term, large-scale investment and technology leadership plan to achieve carbon neutrality</li> </ul>
USA	<ul style="list-style-type: none"> <li>▲ (Key area) Hydrogen production and power generation</li> <li>▲ Strengthening basic research on the hydrogen economy through Ministry of Energy-led R&amp;D research</li> </ul>
Australia	<ul style="list-style-type: none"> <li>▲ Green hydrogen production based on renewable energy</li> <li>▲ Securing hydrogen exporter status by supplying clean hydrogen overseas</li> </ul>

Source: Author

In particular, a summary of common hydrogen applications in the national hydrogen strategies of major countries including Singapore (<Table 2-9>) shows that the transport sector is focusing on the application of hydrogen passenger cars, commercial vehicles, and special vehicle mobility; the power generation sector is using ammonia-fired power generation and hydrogen gas turbine power generation, as well as household fuel cells; and the fuel conversion to hydrogen is being promoted mainly among GHG-intensive emitters such as steel, petrochemicals, refining, and cement industries.

**<Table 2-9> Hydrogen applications in major countries**

Sector	Road Transportation	Power Generation	Iron and steel	Chemical and petrochemical	Refinery	Cement
Korea	○	○	○	○	○	○
Japan	○	○	○	○	○	-
Germany	○	-	○	○	○	○
USA	○	○	○	○	○	-
Australia	○	○	-	-	-	-
Singapore	○	○	-	○	○	-

\* Organized by keywords in each country's hydrogen strategy

Source: Author

## **Chapter 3. Selection of Hydrogen Utilization Sector in Thailand**

### **Section 1. Policy Conformity Review**

In Section 1, the ways to utilize hydrogen in Thailand's major energy policies were reviewed, and the hydrogen utilization sectors consistent with the national policy were identified. Given the need for the development of hydrogen technology worldwide and the immature hydrogen market, active support from the government is required from the initial stage to foster hydrogen demand (hydrogen utilization sector). In this situation, assuming the continuity of government policy, identifying the use of hydrogen that is being considered in the existing government policy is highly likely to be supported by the government in the future, and accordingly, to determine the sector with a high possibility of using hydrogen.

This study examines policy coherence by analyzing four key policies: the National Economic and Social Development Plan (NESDP), Power Development Plan (PDP), Alternative Energy Development Plan (AEDP), and Thailand's Long-term Low Greenhouse Gas Emission Development Strategy (LEDS). The NESDP is a comprehensive 5-year national development plan that covers all sectors of the country, including the economy, environment, and society. It was reviewed to assess hydrogen utilization at the national development plan level. The PDP and AEDP, being core energy plans, were analyzed to evaluate the integration of hydrogen in Thailand's energy development plan. The LEDS, a long-term national strategy for greenhouse gas reduction and carbon neutrality, was reviewed to understand the role of hydrogen in Thailand's greenhouse gas reduction policies. However, since these policies may not explicitly mention hydrogen utilization in specific industries, this study identifies sectors capable of utilizing hydrogen based on the overall policy framework and the industries specified.

#### **1. National Economic and Social Development Plan (NESDP)**

NESDP is Thailand's five-year development plan that has been established since 1961, and

corresponds to the basic guidelines for economic and social development in Thailand to improve the quality of life of Thai people. The most recently announced NESDP is the 13th plan, and the plan period is from 2023 to 2027. The goal of the 13th NESDP is to transform Thailand into a Progressive Society with Sustainable Value-Creating Economy, and a total of 13 development milestones have been set to achieve this goal.

The hydrogen utilization sector included in Thailand's 13th NESDP is the road transportation sector. Although the 13th NESDP did not explicitly organize targets related to hydrogen as a separate milestone, the third milestone (Thailand is the World's Important Electric Vehicle Manufacturing Base) related to zero-emission vehicles set goals related to hydrogen vehicles. The Thai government aims to create domestic consumption and export demand for various types of electric vehicles as one of the targets to achieve the third milestone (Target 1), and the electric vehicle here is a hydrogen vehicle (fuel-cell It is a concept that includes electric vehicle (FCEV). Therefore, Target 1 of Milestone 3 can be said to be a goal that includes the supply plan for hydrogen vehicles, and as a quantitative goal to achieve Target 1, it is planned to supply 282,240 EVs, about 26% of all vehicles, by 2027 (Indicator 1.1).

## **2. Power Development Plan (PDP) and Alternative Energy Development Plan (AEDP)**

The Power Development Plan (PDP) and Alternative Energy Development Plan (AEDP) are plans prepared by Thailand's Ministry of Energy. As the names of the plans suggest, the former is Thailand's power sector plan and the latter is alternative energy such as renewable energy. PDP and AEDP are plans corresponding to the five pillars of Thailand's energy development, so they can be said to be Thailand's core plans. Currently, PDP and AEDP plan from 2018 to 2037, PDP 2018 and AEDP 2018 are the most recent plans, and PDP 2023 and AEDP 2023 will be announced in 2023.

PDP 2018 and AEDP 2018 do not explicitly reveal hydrogen utilization, but PDP 2023 and AEDP 2023, which are currently being prepared, are expected to include hydrogen utilization. PDP 2023 seems to be considering co-fired power generation of natural gas and hydrogen as the type of power plant to be used in the future, so it is believed that Thai authorities are

contemplating the use of hydrogen in the power generation sector. In addition, AEDP 2023 regards heat production and alternative biofuels as hydrogen utilization sources, and sectors that can utilize hydrogen as a heat source (oil refinery, cement industry) and transportation sectors can be major hydrogen utilization sectors.

### **3. Long-term Low Greenhouse Gas Emission Development Strategy (LEDS)**

Thailand's Long-term Low Greenhouse Gas Emission Development Strategy (LEDS) is a report submitted by Thailand to the United Nations and corresponds to a national strategy that contains comprehensive measures for long-term greenhouse gas reduction. Thailand submitted an initial version of the LEDS in 2021, and the initial version sets a scenario of achieving 200 million tons of net greenhouse gas emissions in 2050 and achieving carbon neutrality in 2090 as the base scenario. Meanwhile, the revised version submitted in 2022 sets the scenario of achieving carbon dioxide neutrality by 2050 and greenhouse gas neutrality by 2065 as the base scenario.

As LEDS is a holistic way to achieve carbon neutrality, various ways are examined for hydrogen utilization. First, in the power generation sector, co-fired power generation of natural gas and hydrogen and fuel-fired hydrogen power generation are being considered. In the manufacturing sector, hydrogen will play a key role in areas where carbon reduction is difficult, and supplying high-temperature heat using a hydrogen burner may be studied. The LEDS mentions the iron and steel, aluminum, and cement industries as sectors in which carbon reduction is difficult, and the heavy industry as sectors that require high-temperature heat. However, although not thoroughly highlighted, the petrochemical sector and the oil refinery industry, which require high-temperature heat in the process, can be regarded as major hydrogen utilization areas in terms of difficult carbon reduction. Finally, in the transportation sector, hydrogen-powered FCEVs are stressed as a means of reducing greenhouse gas emissions, and hydrogen utilization in the road transport sector is also being considered.

## 4. Implications

<Table 3-1> provides a summary of the main sectors for hydrogen utilization identified in the four reviewed policies. Among these policies, the road transportation sector is consistently considered across all of them and demonstrates strong policy alignment. In terms of the energy plans (PDP and AEDP) and the greenhouse gas reduction policy (LEDS), the power generation sector, oil refining sector, and cement sector are all consistently examined in these policies. Therefore, these sectors show a high level of conformity with the policies.

<Table 3-1> Analysis of Hydrogen Utilization Sector by Thailand’s Major Policies

Sector	NESDP	PDP	AEDP	LEDS
Iron and steel				○
Chemicals and petrochemicals				○ <sup>2)</sup>
Refinery			○ <sup>1)</sup>	○ <sup>3)</sup>
Power generation		○		○
Cement			○ <sup>1)</sup>	○
Road transportation	○		○	○

Note: Segments are not specified, but 1) hydrogen may be used as a heat source; 2) for sectors where carbon reduction is difficult; 3) Corresponds to sectors requiring high-temperature heat

Source: Author analysis based on NESDC, Office of the Prime Minister (2023), Kurovat (2023), Sinsukprasert (2023), Thailand Government (2022)

## **Section 2. Review of economic importance**

In Section 2, the economic structure in Thailand was analyzed by industry to secure economic consistency in the selection of hydrogen utilization sectors in Thailand. In order to select industry sectors for hydrogen introduction, it is necessary to identify the importance of each industry within the Thai economic structure. The higher the share of a specific industry within the economic structure, the greater the potential climate benefits of that industry through the hydrogen application. Therefore, it is necessary to consider reducing GHG emissions using hydrogen mainly in major industries.

To derive major industrial groups in Thailand, an analysis was conducted in three aspects: Gross Domestic Product (GDP), added value creation, and final product value by dividing into major categories and subcategories using the OECD Input-Output Table. In addition, to derive the importance of each industry in the international market, Thailand's main import and export items and major trading countries were identified, and major industry groups in terms of international trade were derived based on environmental regulation trends in major countries. The higher the probability of being included in the items subject to environmental regulation or directly or indirectly affected by the expansion of the scope of regulation in the future, the more likely it is to preemptively promote greenhouse gas emission reduction based on hydrogen-based eco-friendly and low-carbon conversion for the relevant industry. In the case of major import and export items and trade volume data by major trading countries, data from the Korea Trade Investment Promotion Agency (KOTRA) report based on data from the Ministry of Commerce of Thailand were used. In the case of environmental regulations in major countries, data from the National Assembly Budget Office were used. For reference, the analysis focuses on the regulations of the United States and the European Union, which are leading the global environmental market.

# 1. Production Status by Economic Sector in Thailand

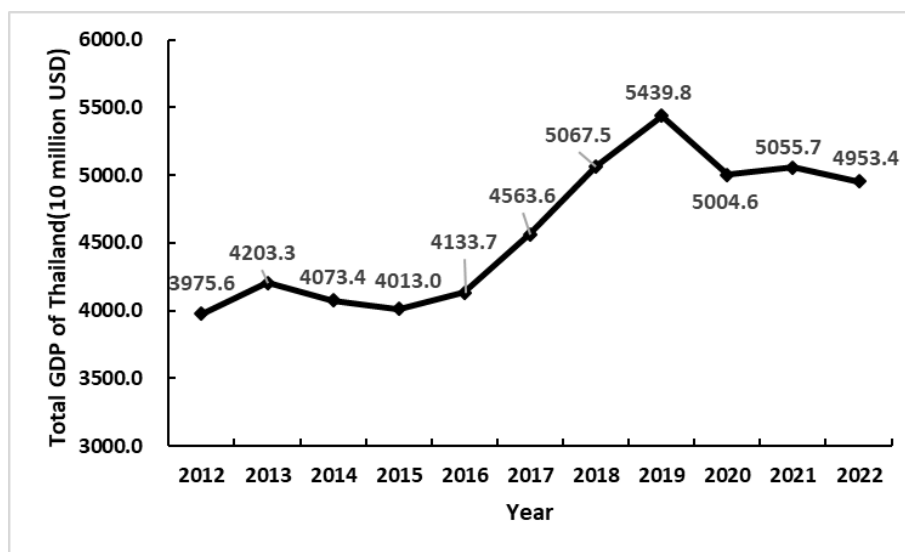
## A. GDP by Major Industry

### (1) Thailand GDP Status

Thailand's national GDP status is shown in the graph below. Since 2012, Thailand's GDP has shown a steady upward trend until 2019. However, the figure has fallen since 2020 due to the coronavirus pandemic, with major Thai and global institutions predicting that the Thai economy will slowly enter a recovery phase. According to the National Economic and Social Development Council (NESDC) of Thailand, employment in the tourism industry and recovery in private consumption are expected to act as major factors for economic growth in Thailand.

Thailand's economic growth beyond 2023 is considered to be rather encouraging. As mentioned above, major domestic institutions such as the Central Bank of Thailand and the National Economic and Social Development Commission, as well as major global institutions such as the World Bank and the International Monetary Fund, expect Thailand's GDP to rise by about 3.6% on average by 2023. Afterward, since the Thai economy is expected to grow continuously, stabilization of the domestic industry and entry into the global market based on this are expected to be major agendas for the next generation.

[Figure 3-1] Thailand National GDP Status (2012~2022)



Source: World Bank Database

## (2) Industry structure

Industries in Thailand can be largely divided into five sectors (service, agriculture, construction, manufacturing, and mining), and among them, the service industry accounts for about 61% of total GDP as of 2020, making it the most important industry. Manufacturing accounts for about 25.2%, agriculture about 8.6%, construction about 2.7%, and mining about 2.1%. However, compared to the industrial structure in 2010, the share of the remaining industries in the domestic GDP has shrunk, excluding the service industry, and therefore the importance of the service industry has increased.

### **B. Status of added value and gross production by major industries**

#### (1) Overview

To identify industries in Thailand that have a significant impact on domestic productivity, the analysis was conducted based on the OECD's industry linkage table. A total of 45 detailed industries were identified as of 2021 based on the Thai Industrial Linkage Table, and these were reclassified into six industries based on the similarity of each industry for analysis. However, in the case of manufacturing and services, the specificity of each industry sector differs significantly, so we divided them into 29 industries by sector.

In analyzing Thailand's major industrial sectors, the five industries mentioned in the industry structure above were added to the vehicle and transport industries, for a total of six industries. In the case of the vehicle and transport sector, we included the manufacturing of vehicles and related, as they are often linked to the transport industry, such as fuel, infrastructure, and parts.

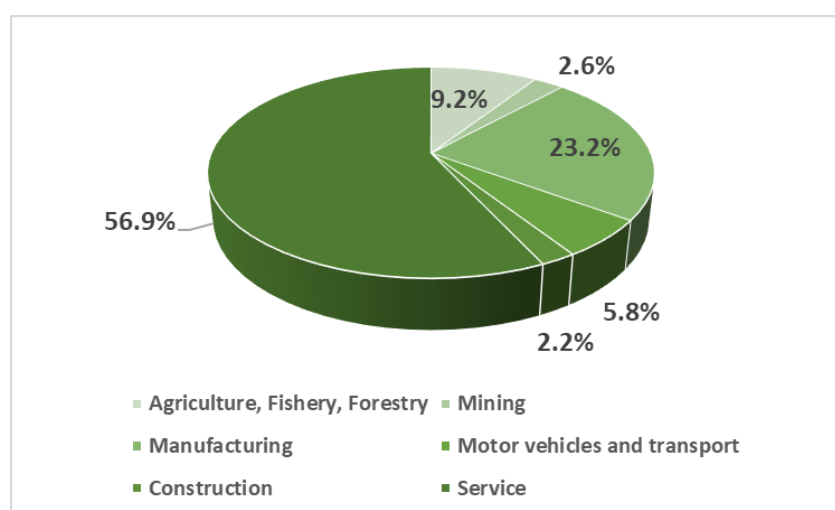
#### (2) Status of added value by industry

The graph below illustrates the value added by major industries in Thailand. Value added represents the difference between the revenue generated from the sale of goods or services and the costs involved, including materials, equipment, and interest. In the industry linkage table, value added is combined with intermediate inputs to calculate the gross output for

each industry's production of goods and services. Industries with high value-added hold significant positions within the economic structure.

When the value added in the Thai economy is categorized into six major sectors—services, agriculture, forestry, and fishing; vehicle and transport; construction; manufacturing; and mining—the services sector demonstrates the highest share of value added at 56.9 %. It is followed by manufacturing at 23.2 %, the vehicle and transport industry at 5.8 %, agriculture, forestry, and fishing at 9.2 %, mining at 2.6 %, and construction at 2.2 %. These proportions align with the share of each industry mentioned in the overall industrial structure, indicating that the Thai economy is predominantly driven by the services and manufacturing sectors.

**[Figure 3-2] Share of value-added by major industries in Thailand**



Source: OECD Database

The table provides a breakdown of value added across 29 detailed industries. The wholesale /retail sector ranks the highest in terms of value added, followed by the agriculture/forestry/fishery sector in second place. Other industries among the top 10 in terms of value added include public administration/defense/social security administration industries, finance and insurance industries, the vehicles and transportation industries, food/beverage/tobacco industries, education industries, electricity/gas/steam supply industries, other service industries, and computer and electronic device industries.

These top 10 industries collectively contribute to approximately 70% of the total value added, indicating that they play a significant role in driving value creation within Thailand's economic and industrial structure.

<Table 3-2> Status of added value by industry in Thailand

(Unit: million dollars)

Main Category	Detailed Classification	Added Value
Agriculture, Forestry, and Fisheries	Agriculture, Forestry, and Fisheries	42,014.4
Mining and related projects	Mining and related projects	11,947.2
Manufacturing	Food products, beverages, and tobacco	2,181.8
	Textiles, textile products, leather and footwear	13,653.9
	Wood and products of wood and cork	1,278.6
	Paper products and printing	2,667.0
	Coke and refined petroleum products, other non-metallic mineral products	8,745.3
	Chemicals and Chemical products	9,875.7
	Pharmaceuticals, medicinal chemicals, and botanicals	1,309.9
	Rubber and plastic products	5,927.4
	Base metal	3,006.6
	Machined metal products	3,445.2
	Computer, electronic, and optical equipment	16,904.1
	Electrical equipment	4,042.0
	Machinery and Equipment, NEC	4,207.6
	Manufactured by NEC; Repair and installation of machinery and equipment	838.2.6
Transportation	Motor vehicle and transport industry	26,525.8
Construction	Construction	10,080.6
Service industry	Supply of electricity, gas, steam, and air conditioning	19,304.7
	Waterworks; Sewerage, waste management, and improvement activities	2,461.1
	Wholesale and retail; car repair	94,589.9
	Accommodation and meal activities	15,047.2
	Telecommunications (publishing, audiovisual and broadcasting activities, telecommunications, IT, and other information services)	10,508.1

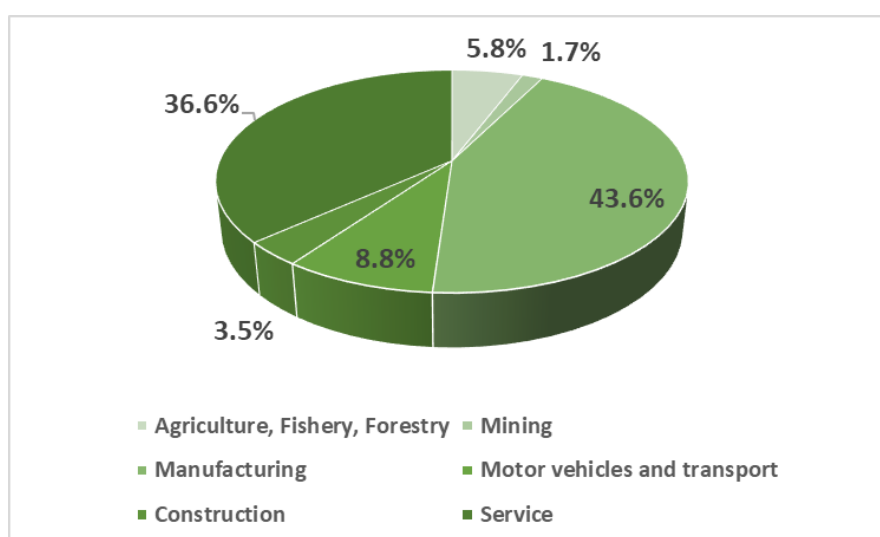
	Financial and insurance activities	28,611.4
	Real estate activity	13,658.5
	Professional, scientific, and technical activities	4,203.0
	Public administration and defense; compulsory social security	29,470.7
	Education	20,573.2
	Health and Social work activities, Arts, Entertainment, and recreation, Administrative and support services, Other service activities	23310

Source: OECD Database

### (3) Total output by industry

The graph below shows the total output according to the production of goods and services by major industrial sectors in Thailand. The gross output here means the difference between the total revenue earned from the sale of goods or services and the amount and interest from materials and equipment. Industries with high gross output can be said to occupy an important position within the economic structure.

**[Figure 3-3] Share of total output by Thailand's major industries**



Source: OECD Database

The total output of products and services by industry in the Thai economy was divided into

six industries, including service, agriculture/forestry/fishing, vehicles, construction, manufacturing, and mining, as analyzed above. The service industry recorded the highest total output share at 48.6%, and the manufacturing industry showed the second-highest total output share at 36.6%. It was followed by the motor vehicles industry with 8.8%, agriculture/forestry/fishery with 5.8%, construction with 5.8%, and mining with 1.7%. This shows similar results to the above value-added analysis, and in the case of the construction industry, the intermediate input amount was relatively high, resulting in a high total output compared to the mining industry. In terms of gross output, the service and manufacturing sectors are also judged to be the most important industries in Thailand.

The table below shows the total output divided into 29 detailed industrial sectors. The wholesale and retail industries ranked the highest total output, followed by motor vehicles and the transport industry. Subsequently, the computer and electronic device industries, food, beverage, and tobacco industries, agriculture, forestry, fishing, coke, petroleum refining, and other non-metallic product industries, electricity, gas, steam supply, lodging and restaurants, textiles, leather, clothing, and public administration, defense, and social security administration. Unlike the top 10 industries from a value-added perspective, three new sectors were included in the top 10 industries: coke, petroleum refining, and other non-metallic products, lodging and restaurants, and textiles, leather, and clothing. This is believed to have caused a difference in the final output ranking as the intermediate input from raw materials, raw materials, and facilities in the three industries has relatively high value. The top 10 sectors account for about 65% of the total value-added share, which can be seen as driving the most value creation in the Thai economic and industrial structure.

**<Table 3-3> Total Output by Industry in Thailand**

(Unit: million dollars)

Main Category	Detailed Classification	Gross Output
Agriculture, Forestry, and Fisheries	Agriculture, Forestry, and Fisheries	67,804.4
Mining and related support projects	Mining and related support projects	19,662.5
Manufacturing	Food products, beverages, and tobacco	88886.8

	Textiles, textile products, leather and footwear	44833.8
	Wood and products of wood and cork	3955.0
	Paper products and printing	8667.3
	Coke and refined petroleum products, other non-metallic mineral products	38354.1
	Chemicals and chemical products	54730.4
	Pharmaceuticals, medicinal chemicals, and botanicals	4,085.9
	Rubber and plastic products	26,516.2
	Base metal	11,921.4
	Machined metal products	12,674.9
	Computer, electronic, and optical equipment	94,169.9
	Electrical equipment	16,400.4
	Machinery and Equipment, NEC	17,023.1
	Manufactured by NEC; Repair and installation of machinery and equipment	36,173.7
Transportation	Motor vehicle and transport industry	103161.8
	Transport by land and pipeline	26058.1
	Water transport	10327.4
	Air transport	12678.8
	Storage and support activities for transportation	960.9
Construction	Construction	40834.1
Service industry	Supply of electricity, gas, steam, and air conditioning	52827.7
	Waterworks; Sewerage, waste management, and improvement activities	3661.7
	Wholesale and retail; car repair	122598.1
	Postal and courier activities	3117.2
	Accommodation and meal activities	46051.7
	Telecommunications (publishing, audiovisual and broadcasting activities, telecommunications, IT, and other information services)	22011.5
	Financial and insurance activities	40466.4
	Real estate activity	16709.2
	Professional, scientific, and technological activities	10277.3
	Management and Support Services	11637.7
	Administration and defense; compulsory social security	41589.6
	Education	27270.6
	Human health and social work activities	16672.0
	Arts, Entertainment, and Recreation	1949.3
	Other Volunteer Activities	9648.1
Employment in the neighborhood	Household activity as an employer; Undifferentiated goods and services production activities	2890.1

Source: OECD database

#### (4) Overall status

When looking at the current status of added value and total output comprehensively, the main industrial sectors in the Thai economic structure are shown in the table below. Among the top 10 industries, seven sectors, including Wholesale and retail, Agriculture, Forestry and Fisheries, Motor vehicles and transport industry, Public administration, national defense, social security administration, Food, Beverage, and Tobacco, Electricity, gas, steam supply, and Computer and electronics, are common.

<Table 3-4> Thailand's 10 major industries

Industry Classification	Value Added Ranking	Gross Output Rank
Wholesale and retail	1st place	1st place
Agriculture, Forestry, and Fisheries	2nd place	5th place
Public administration, national defense, social security administration industry	3rd place	10th place
Motor vehicles and transport industry	5th place	2nd place
Food, Beverage and Tobacco Industry	6th place	4th place
Electricity, gas, steam supply industry	8th place	6th place
Computer and electronics industry	10th place	3rd place
Coke · Petroleum Refinery · Other non-metal product industry	-	6th place
Lodging and catering	-	8th place
Textile / leather / clothing industry	-	9th place
Finance and insurance industry	4th place	-
Education industry	7th place	-
Other service business	9th place	-

Source: Author

Major industries in Thailand include distribution, transportation, public sector, primary industry, manufacturing, and energy. In particular, in the case of manufacturing, it was analyzed that the computer and electronic device industries have high value. Therefore, in order to realize a sustainable social economy through eco-friendly and low-carbon policies in the future, it is necessary to select transportation and energy fields and high-carbon manufacturing fields as major industrial fields to attempt a low-carbon transition.

## 2. Export/Import Status by Economic Sector in Thailand

### A. Import and export status in Thailand

#### (1) Current status of national import and export

As of 2022, Thailand's export and import performance over the past five years is shown in the table below. While going through the COVID-19 pandemic, both imports and exports decreased, but after 2021, they switched to an upward trend, showing higher trade than before the pandemic. In 2022, Thailand's exports were about \$287.1 billion and imports were about \$303.2 billion, up 5.5% and 13.6% from the previous year, respectively. As a result, in 2022, Thailand recorded the largest trade value ever, but in terms of trade balance, it showed a deficit in 8 years. This can be attributed to the rise in global energy and raw material prices and the rise in exchange rates mentioned in the above economic situation.

<Table 3-5> 5-Year Export/Import in Thailand

(Unit: billion dollars, %)

Division	2018	2019	2020	2021	2022
Export	253.0	246.3	231.6	272.0	287.1
Export growth rate	-	-2.6	-6.0	17.4	5.6
Income	248.2	236.3	206.2	266.9	303.2
Income change rate	-	-4.8	-12.7	29.4	13.6
Total trade	501.2	482.6	437.8	538.9	590.3
Balance of trade	4.8	10.0	25.4	5.1	-16.1

Source: Author analysis based on data from KOTRA (2023b)

#### (2) Export/Import Status by Major Items

In the case of Thailand, 15 items both export and import account for the majority of total exports. In the case of exports, the 15 major export items recorded a total of 16.3 billion dollars in 2022, accounting for 56.7% of total exports, and in the case of imports, a total of 22.2 billion dollars, which corresponds to 73.2% of total imports. The detailed main items and total amount are shown in the table below.

<Table 3-6> Export value and growth by 15 major commodities in 2022

Product classification	Total exports (million dollars)	Growth rate (%)
Automobile	28,214	-3.5
Computer parts	20,664	-6.2
Bijouterie	15,106	50.3
Rubber products	13,862	-4.2
Ethylene	10,683	-5.0
Refined oil	10,105	14.2
Chemicals	9,572	-3.1
Semiconductor electronics	9,320	9.4
Mechanical parts	8,744	7.2
Air purifying machine parts	7,044	8.6
Steel	7,006	1.5
Other industrial products	6,173	6.0
Frozen food	5,652	-7.1
Mobile phone parts	5,412	71.5
Rubber products	5,160	-7.7
Sum	162,717	4.0

Source: Author analysis based on data from KOTRA (2023b)

<Table 3-7> Import value and growth by 15 major items in 2022

Product classification	Gross Income (million USD)	Growth rate (%)
Crude oil	37,396	59.1
Chemicals	21,023	1.8
General machinery	20,779	-0.7
Electronic machine	20,241	5.1
Semiconductor electronics	19,041	25.7
Steel	15,581	-5.2
Jewelry	15,561	29.8
Other steel	13,515	4.3
Natural gas	12,718	115.7
Computer	9,034	-10.9
Vegetables	8,785	-4.2
Automotive Parts	8,270	-2.7
Home Appliances	8,156	-9.4
Fish oil	5,991	11.9
Science experiment tool	5,707	20.9
Total	221,797	12.9

Source: Author analysis based on data from KOTRA (2023b)

Overall, Thailand mainly exports industrial products such as automobiles and computer parts, and mainly imports raw materials and raw materials. As of 2022, Thailand's total exports and total imports increased overall, but the increase in imports was even greater due to the depreciation of currency and the increase in prices of major raw materials, ultimately recording a deficit.

## B. Major trading partners and related status

### (1) Import and export status of 10 major trading partners

According to data from 2022, Thailand's top three trading partners are China, the United States, and Japan, collectively accounting for \$230.3 billion in trade volume. This represents approximately 39% of Thailand's total trade volume. The table below displays the trade volumes and major trading partners based on Thailand's imports and exports over the past five years. The ranking of major trading countries was determined by analyzing import and export figures from 2022, revealing that the United States and ASEAN countries were the primary trading partners for Thailand.

<Table 3-8> 5-year export/import for major trading countries

(Unit: billion dollars)

Ranking	Nation	2018	2019	2020	2021	2022
1	China	80.2	79.4	76.9	103.8	105.4
2	USA	43.0	48.6	49.2	56.3	65.6
3	Japan	60.2	57.7	50.5	60.6	59.3
4	Malaysia	24.9	23.1	18.9	24.1	27.2
5	Vietnam	18.7	17.6	16.6	19.5	21.2
6	UAE	13.0	9.8	7.4	12.0	20.8
7	Indonesia	18.2	16.3	13.4	17.0	20.0
8	Singapore	17.0	16.5	17.0	16.4	18.5
9	Australia	16.6	14.2	13.1	17.2	18.4
10	India	12.5	12.1	9.8	15.0	17.7

Source: Author analysis based on data from KOTRA (2023b)

### (2) Thailand's trade strategy

In the case of Thailand, trade with the top 10 countries accounts for about 63% of the total trade volume. As a result, establishing strong relationships and response strategies with these key trading partners is considered crucial. It is important to foster stable and increased trade through agreements and trade system alignment with these major partners. One notable agreement is the Regional Comprehensive Economic Partnership (RCEP), which took effect in January 2022. RCEP is a multilateral free trade agreement involving 10 ASEAN countries (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam) and 15 other countries, including South Korea, China, Japan, Australia, and New Zealand. As the world's largest FTA, covering approximately 30% of global trade, population, and gross domestic product, its impact is expected to be significant.

In the case of Thailand, in the first year of RCEP implementation, trade volume with RCEP member countries increased by 5.19% compared to 2021. The share of trade value with RCEP countries accounted for about 55.4% of Thailand's total trade, indicating a substantial impact. Consequently, it is anticipated that trade volume will continue to grow as a result of the agreement's influence.

### **C. Current status of import regulations and systems in major trading partners**

#### **(1) International trends**

As protectionism rises globally in the aftermath of the COVID-19 pandemic, many developed countries are implementing policies to safeguard their industries and stimulate economic recovery. Supply chain disruptions caused by lockdowns and logistical challenges have further exacerbated the situation, leading countries to impose restrictions on industrial activities. China, a major exporter, experienced significant disruptions in production and logistics due to a simultaneous decline in demand and supply. Consequently, many countries are now exploring measures to diversify their supply chains and strengthen trade ties, particularly with the ASEAN region.

Furthermore, the increasing impact of the climate crisis has prompted the formulation of various policies and strategies for green and low-carbon transitions worldwide. Among the

key issues in international trade, the emergence of "carbon trade barriers" is of significant importance. Carbon trade barriers refer to trade restrictions imposed by applying domestic carbon emission regulations to imported goods and reflecting them in prices. This approach aims to establish a trading system that promotes sustainability and fairness in major developed countries. The United States and Europe, leading the global environmental agenda, are currently shaping international carbon trade barriers. Consequently, countries seeking to export to these markets must align their domestic systems with the carbon regulations of the United States and Europe to mitigate carbon trade barriers.

From Thailand's perspective, it is crucial to enhance domestic systems that align with US regulations to ensure export stability, as the United States is one of its major trading partners. Although European Union (EU) is not currently among the major trading partners, Thailand has expressed its intent to resume negotiations on a free trade agreement with the EU in March 2023, with the goal of completing the negotiations within two years. This demonstrates the Thai government's strong determination to enter the EU market. Consequently, Thailand must establish a national strategy and reform its systems proactively to address potential EU carbon trade barriers.

## (2) US

The United States began providing national support to cope with the climate crisis by implementing the Inflation Reduction Act (IRA) in January 2023. This legislation aims to raise funds by increasing corporate taxes to support energy security, climate crisis response, and medical assistance. Approximately \$369 billion, half of the total funding, will be allocated to energy security and climate change response. As the largest climate legislation in U.S. history, the implementation of the IRA demonstrates the country's commitment to addressing climate change at the national level.

Furthermore, the United States is planning to introduce the Clean Competition Act (CCA), which will impose carbon taxes on 12 imports starting in 2024. These imports encompass a wide range of products, including fossil fuels, petroleum refining, petrochemicals, fertilizers, hydrogen, adipic acid, cement, steel, aluminum, glass, pulp and paper, and ethanol. This

regulation covers a broader array of products compared to the six items restricted by the European Union's Carbon Border Adjustment Mechanism (CBAM) and differs in that it imposes a fixed rate per unit of carbon emissions. The table below provides an overview of the main contents of the proposed Clean Competition Act.

<Table 3-9> Major contents of the U.S. Clean Competition Act

<b>Carbon price</b>	Scheduled to charge \$ 55 per ton (planned to increase by 5% in consideration of inflation)
<b>Applied industry</b>	① Fossil fuels, ② Petroleum products, ③ Petrochemical products, ④ Fertilizers, ⑤ Hydrogen, ⑥ Adipic acid, ⑦ Cement, ⑧ Steel, ⑨ Aluminum, ⑩ Glass, ⑪ Pulp and paper, ⑫ Ethanol
<b>Application Criteria</b>	Applied based on carbon weight for high-carbon product manufacturing countries (except for least developed countries)
<b>Application method</b>	$[(\text{The average emission intensity of U.S. industry}) - (\text{The average emission intensity of manufactured country's industry})] \times \text{price per ton}$
<b>Action plan</b>	2024: To be piloted in some industries 2026: Include imported finished goods containing more than 500 pounds of energy-intensive primary products 2028: Lower raw material standards to at least 100 pounds
<b>Revenue utilization</b>	Support for decarbonization of relevant industries (75%) and support for decarbonization of least developed countries (25%)

Source: National Assembly Budget Office Korea(2023b)

Major Thai industries covered by the U.S. CCA include cokes, petroleum products, and other non-metallic products. Furthermore, there is scope for the inclusion of many product groups in the 15 major exports, including steel, chemicals, ethylene, refined petroleum products, and chemicals. In addition, the motor vehicles and transport industry is likely to be affected in the future by fossil fuel utilization, although this is not directly stated. Also, the electricity, gas, and steam supply industries can be constrained by the application of indirect emission allowances to exports. Therefore, in order to resolve the US carbon trade barrier and target the local market, the Thai government needs to prepare policies and strategies for an eco-friendly electricity production system and promote sustainable conversion policies for high-carbon emitting industries such as steel, petroleum well products, and petrochemicals.

(3) Europe

Europe is one of the most committed countries to the Kyoto Protocol and the Paris Agreement and has shown a strong commitment to tackling climate change, even exceeding its initial commitments. The European Union's strong commitment to addressing climate change is evident in its policy framework, including the launch of the EU Green Deal in 2019 to become the world's first climate-neutral country by 2050, and the announcement of 'Fit for Package 55', a legislative and policy package to address the climate crisis to achieve interim goals.

The EU's Fit for Package 55 includes the Carbon Border Adjustment Mechanism (CBAM) as one of its 12 key pillars. To prevent carbon leakage when goods are exported to the EU from countries with absent or lax greenhouse gas emission controls, CBAM is a system that applies the same carbon emission controls as the EU and reflects the difference in import prices. The EU will pilot the scheme from October 2023 to 2025, with mandatory certificate submission from 2026 onwards. There are currently six major product groups that will be regulated under the CBAM: cement, steel, steel products, aluminum, fertilizers, electricity, and hydrogen.

Thailand's main industries within the scope of the EU CBAM are the electricity, gas, and steam supply industries, and there is scope for steel products to be included in the top 15 exports. As steel does not account for a large proportion of exports, and the electricity, gas, and steam supply industry are at the bottom of the list of 10 major industries, it can be concluded that the impact of CBAM will not be significant, but it is necessary to prepare more extensive policies and institutions to preemptively respond to the planned expansion of the system and preempt the market. In particular, in the case of the vehicle and transportation industry, the Thai government can increase the share of Thai products in the export market by using green hydrogen. Also, in the case of the electricity industry, the government can benefit from direct and indirect trade benefits through clean energy production using hydrogen and renewable energy. Therefore, in order to overcome the European carbon trade barrier and enter the European market, the Thai government must prepare policies and strategies for an eco-friendly electricity production system and promote sustainable conversion policies for energy, steel, and transport-related industries. Furthermore, although Europe is not currently among Thailand's major trading partners, it has the potential to emerge as one of the key trading partners through the new free trade agreement. Thus far, proactive policy and institutional

development can contribute significantly to the country's future entry into the European market.

### **3. Implications**

Looking at Thailand's economic structure, the main industries that account for the largest share are distribution, transport, utilities, primary industry, manufacturing, and energy-related industry, which are similarly reflected in the country's major exports and imports. As Thailand's manufacturing and service sectors account for a large proportion of its exports, the country mainly exports manufactured goods such as automobiles and computer components, and imports raw materials and raw materials for these products. Therefore, it is expected that the introduction of hydrogen for green and low-carbon transformation in the above product groups and industries will bring the greatest potential environmental benefit.

The eco-friendly and low-carbon transition in major industries is considered an urgent national task when analyzing the trends of international environmental regulation. In particular, as the era of carbon trade barriers is in full swing, it is essential to identify and proactively respond to regulations in key countries such as the United States and the European Union, which are leading the way. In the case of Thailand, if a hydrogen conversion strategy to reduce carbon emissions is prepared and implemented on a pilot basis for the automotive and transportation industry and the industries related to petroleum refining and petrochemical products, it is expected to enhance its competitiveness in the international market.

In addition, industries that are not currently major players in Thailand's economic structure, but are related to products that are included in the regulations of key countries, should be considered as one of the industries to be piloted when preparing a hydrogen strategy. For example, common product groups in the US CCA and European CBAM include cement, steel, fertilizer, and hydrogen. Considering the utilization of hydrogen in these industries could have a positive impact on Thailand's international market share in the future.

## **Section 3. Review of Technical Necessity and Applicability**

In this section 3, technological options using hydrogen for each sector were reviewed. Subsequently, their applicability to Thailand was analyzed based on such as 1) the existence of infrastructure, 2) alternative possible technological options to reduce GHGs, and 3) the possibility of investment from the Thai government and/or business in the sector.

### **1. Iron and Steel**

#### **A. Technology option**

##### **(1) Hydrogen gas blast furnace blowing technology**

Hydrogen gas blast furnace injection technology allows hydrogen to partially replace the carbon reduction role by injecting a gas that contains a certain %age of hydrogen into the blast furnace. By introducing hydrogen gas such as COG (Cokes Oven Gas), it is possible to reduce the consumption of coke and PCI coal, the existing reducing materials, and reduce GHG emissions. As verified through the COOLSTAR project, the GHG emissions that can be reduced by blast furnace blowing of COG are expected to be about 3.7 %.

##### **(2) HBI blast furnace technology**

Hot briquetted iron (HBI) technology is a method of melting HBI agglomerated with direct reduced iron (DRI) in an electric furnace instead of melting conventional iron ore in a blast furnace. To melt HBI in a blast furnace, existing blast furnaces for melting conventional iron scrap cannot be used, and a dedicated DRI/HBI blast furnace needs to be developed. If the HBI utilization furnace technology is commercialized, it is expected to reduce greenhouse gas emissions by 60-70% compared to the traditional blast furnace method.

##### **(3) Hydrogen Reduced Iron**

Hydrogen reduction steelmaking is a steelmaking technique that uses hydrogen instead of carbon as a reducing agent in the process of making iron by separating oxygen from iron oxide. Currently, hydrometallurgy can be broadly divided into the Shaft Furnace method and the

HyREX method. The shaft furnace method uses the same type of shaft furnace as the DRI manufacturing process such as MIDREX, but differs in that it uses green hydrogen as the reducing gas, and the DRI produced by the shaft furnace is melted in an electric melting furnace to produce molten steel. The HyREX process combines the fluidized reduction method of the FINEX process with an electric furnace dedicated to DRI and uses green hydrogen as the reducing gas. If successfully commercialized, hydrogen-reduced steelmaking is expected to reduce most of the greenhouse gases generated in the steelmaking process.

## B. Applicability to Thailand

According to 2022 data from the Iron and Steel Institute of Thailand, 15 and 13 companies in Thailand use EAF (Electric Arc Furnace) and IF (Induction Furnace) to produce long products, respectively, and 2 companies use EAF to produce flat products ([Figure 3-4]). Based on this, it can be assumed that there are no producers using BF-BOF (Blast Furnace Steelmaking).

[Figure 3-4] Thailand steel industry Structure in 2022

### Thailand steel industry structure 2022

Steelmaking		Finishing & Coating			Forming & Fabrication	End Users	
<b>Long Product</b>							
<b>Melting &amp; Casting</b> <b>EAF ~ 15 Mills</b> - Millcon - TATA - NTS - SYS - BLSW - Etc.  <b>IE ~ 13 Mills</b> - SKY - Chow - Linan - SINGHA THAI - Etc.  <b>Prod : 3.29 mT (excl. IF)</b> <b>Im : 1.2 mT</b> - Oman 62% - Japan 11% - Indonesia 8%  <b>Ex : 0.3 mT</b> - Philippines 73% - Taiwan 13% - Indonesia 13% <b>Demand: 4.19 mT</b>	<b>Hot-Forming</b> <b>Bar ~ 34 Mills</b> - TATA - Millcon - BLSW - BSIARSM - Etc. <b>HR Section ~ 8 Mills</b> - SYS (Heavy Section) - Triumph - ZUBB - TATA - Etc.  <b>Bar &amp; HR Section</b> <b>Prod : 3.64 mT</b> <b>Im : 0.7 mT</b> - Japan 43% - China 33% - Korea 13% <b>Ex : 0.7 mT</b> - Malaysia 26% - Philippines 17% - Hong Kong 8% - Vietnam 13% <b>Demand: 3.64 mT</b>  <b>Wire rod ~ 7 Mills</b> - TYCN - TATA - BMS - ZUBB - Etc. <b>Prod : 0.9 mT</b> <b>Im : 1.1 mT</b> - Japan 16% - China 33% - Vietnam 13% <b>Ex : 0.04 mT</b> - Indonesia 43% - Vietnam 23% - Malaysia 13% <b>Demand: 1.96 mT</b>  <b>Piercing Seamless pipe</b> ~ 2 Mills - Boly Pipe - WSP Pipe <b>Prod : N/A</b> <b>Im : 0.4 mT</b> <b>Ex : 0.1 mT</b>	<b>Cold-Forming</b> <b>Cold drawn bar &amp; Steel Wire</b> <b>Low carbon steel</b> ~ 50 Mills - TYCN - Kriangkai - ChiaoPao - Bangkok Fastener - Etc.  <b>High carbon steel</b> ~ 12 Mills - TWP - Bangkok Steel Wire - Siam Wire - Thana Inter - Etc.  <b>Stainless steel</b> ~ 10 Mills - Menam - Thai Seisen - SKJ Metal - ABP Stainless - Etc.  <b>Cold drawn bar</b> <b>Prod : N/A</b> <b>Im : 0.1 mT</b> - Japan 40% - China 18% - Taiwan 14% <b>Ex : 0.01 mT</b> - Myanmar 33% - Indonesia 20% - Singapore 18%  <b>Steel Wire</b> <b>Prod : N/A</b> <b>Im : 0.3 mT</b> - China 52% - Japan 13% - Russian 11% <b>Ex : 0.1 mT</b> - Taiwan 24% - Malaysia 10% - Indonesia 9%	<b>Coating</b> <b>Galvanized</b> ~ 20 Mills - TWP - Sin Thani - Etc.  <b>Bronze coated</b> ~ 2 Mills - Siam Michelin - Rayong Wire - Etc.  <b>Prod : N/A</b> <b>Im : 0.04 mT</b> - China 79% - Malaysia 8% - Korea, South 4% <b>Ex : 0.01 mT</b> - India 36% - Singapore 33% - Myanmar 24%	<b>&gt; 1,000 Mills</b> - Roll forming - Machining - Bending - Cutting - Welding - Forging - Heat Treatment - Etc.	<b>Construction</b> 57%  <b>Automobiles and parts</b> 22%  <b>Electrical Appliances</b> 8%  <b>Machinery and Industrial Products</b> 7%  <b>Packaging</b> 6%  <b>Other</b> 1%		
<b>Flat Products</b>							
<b>Melting &amp; Casting</b> <b>EAF ~ 2 Mills</b> - G Steel - GJS  <b>Prod : N/A mT</b> <b>Im : 1.31 mT</b> - Japan 42% - Oman 36% - Malaysia 10%  <b>Ex : 0.0004 T</b> - Myanmar 96% - Cambodia 2% - Lao Republic 0.4%	<b>Hot-Forming</b> <b>HRC</b> ~ 4 Mills - G Steel - GJ Steel - SSI - Prime steel  <b>Prod : 2.3 mT</b> <b>Im : 1.48 mT</b> - Japan 73% - S.Korea 14% - China 6% - Ex : 0.05 T - Vietnam 46% - Spain 21% - Malaysia 17% <b>Demand: 3.73 mT</b>  <b>HRP</b> ~ 2 Mills - LPH - SPM <b>Prod : 0.14 mT</b> <b>Im : 0.3 mT</b> - China 42% - Japan 36% - Indonesia 8% <b>Ex : 0.004mT</b> - Myanmar 21% - Indonesia 16% - Lao Republic 11% <b>Demand: 0.43 mT</b>	<b>CR-Sheet Steel</b> ~ 5 Mills - NS-SUS - TKRSS - NS BlueScope - Starcore  <b>Prod : 2.1 mT</b> <b>Im : 1.54 mT</b> - Japan 44% - S.Korea 32% - China 11% <b>Ex : 0.2 mT</b> - Malaysia 19% - USA 15% - Indonesia 15% <b>Demand: 3.44 mT</b>  <b>CR-Sheet Stainless Steel</b> - POSCO-Thalnox <b>Prod : N/A</b> <b>Im : 0.01 mT</b> - China 48% - India 40% - Malaysia 4% <b>Ex : 0.01 mT</b> - Myanmar 69% - Laos 15% - Cambodia 11%	<b>CF-Sections</b> ~ N/A Mills - Neastern - T.S.K. - Millcon - Stealex - Etc.  <b>Prod : N/A</b> <b>Im : 0.01 mT</b> - China 48% - S.Korea 15% - Vietnam 12% <b>Ex : 0.2 mT</b> - USA 55% - Canada 9% - Cambodia 6%	<b>Welded Pipe</b> ~ N/A Mills - Cotco - Pacific - Saha-Thai - Samchai - Etc.  <b>Prod : N/A</b> <b>Im : 0.2 mT</b> - China 32% - S.Korea 15% - Vietnam 12% <b>Ex : 0.2 mT</b> - USA 55% - Canada 9% - Cambodia 6%	<b>GI</b> ~ 8 Mills - TIW - BSI & RSH - Posco-Tcs - Sangkasi Thai - Etc.  <b>Prod : 0.21 mT</b> <b>Im : 1.4 mT</b> - China 66% - S.Korea 12% - Japan 12% <b>Ex : 0.02 mT</b> - Myanmar 32% - Laos 18% - Bangladesh 17% <b>Demand: 1.59 mT</b>  <b>GA</b> ~ 3 Mills - NS-SUS - JSCT - POSCO-TCS  <b>Prod : 0.74 mT</b> <b>Im : 0.1 mT</b> - Taiwan 23% - Japan 69% - China 5% <b>Ex : 0.02 mT</b> - Malaysia 25% - Taiwan 23% - Indonesia 21% <b>Demand: 1.44 mT</b>  <b>Zn-Al-Mn</b> ~ 1 Mills - NS BlueScope <b>Prod : N/A</b> <b>Im : 0.1 mT</b> - China 51% - Cambodia 51% - Myanmar 38% - Vietnam 7% <b>Ex : 0.001 mT</b> - China 99.9% - Japan 0.1% <b>Ex : 0.00001 mT</b> - Maldives 99% - Laos 1%	<b>EG</b> ~ 1 Mills - TCS  <b>Prod : N/A</b> <b>Im : 0.1 mT</b> - China 51% - Cambodia 51% - Myanmar 38% - Vietnam 7% <b>Ex : 0.001 mT</b> - China 99.9% - Japan 0.1% <b>Ex : 0.00001 mT</b> - Maldives 99% - Laos 1%	<b>IP/TF</b> ~ 2 Mills - TTP - STP  <b>Prod : 0.3 mT</b> <b>Im : 0.2 mT</b> - China 59% - S.Korea 28% - Japan 7% <b>Ex : 0.001 mT</b> - Vietnam 47% - UAE 17% - Myanmar 15% <b>Demand : 0.5 mT</b>

Source: Iron and Steel Institute of Thailand

**<Table 3-10> Applicability for technology options in Thailand**

technology option	related facility	Applicability
Blast Furnace Gas Injection Technology	BF-BOF	Limited due to lack of BF-BOF production
EAF Technology using HBI	EAF	Limited due to the requirement of new EAF as well as HBI
Hydrogen Direct Reduced Iron	BF-BOF	Limited due to lack of BF-BOF production

Source: Author

In this regard, for the applicability of each technology option in Thailand as shown in <Table 3-10> above, it can be concluded that all three hydrogen utilization technologies have very limited applicability to the Thai steel industry. Firstly, both Blast Furnace Gas Injection Technology and Hydrogen Direct Reduced Iron are technologies that can be used when steel production is carried out in BF-BOF facilities. In Thailand, as discussed earlier, long products and flat products are not produced using BOF, so the applicability of these technologies is not possible. Second, even in the case of HBI using EAF technology, it is necessary to introduce new EAF equipment to utilize the technology. This is usually considered a measure to reduce GHG emissions from the production of high-grade steel using the BF-BOF method, so it can be expected that the applicability of this technology to Thailand is not high. In addition, the technology requires a continuous supply of HBI, so all of these factors make it difficult to implement in the Thai steel industry.

## **2. Chemicals and Petrochemicals**

### **A. Technology options**

#### **(1) Utilization of Hydrogen as Feedstock (MTO)**

The petrochemical industry relies on the naphtha cracking process, which involves breaking down crude oil-based naphtha using high heat. This process contributes significantly to carbon dioxide emissions, mainly from naphtha, by-product gas, and electricity usage. To minimize GHG emissions, feedstock substitution involves replacing conventional fossil fuel naphtha with methane to olefin (MTO) by utilizing hydrogen. This approach entails combining by-product gas from petrochemical processes with hydrogen to produce methanol and

subsequently olefin products.

## (2) Utilization of Hydrogen as Fuel

In the pyrolysis process of NCCs in the petrochemical industry, petroleum-based fuels are used as the heat source in the furnace to pyrolyze naphtha into hydrocarbon compounds at a high temperature of over 800°C. Thus, fossil fuels injected into the NCC can be converted into hydrogen to reduce carbon dioxide generation. The main technologies that utilize hydrogen in fuel conversion are hydrogen co-combustion and hydrogen NCC. Hydrogen co-firing is a strategy to reduce greenhouse gas emissions by replacing some of the by-product methane and crude oil previously used as input fuels for NCC with green hydrogen but combusting hydrogen with existing energy sources. Hydrogen NCC, on the other hand, is a technology that converts all fuel inputs to the NCC process to green hydrogen. In the case of hydrogen blending, existing NCC facilities are modified and utilized, but in the case of hydrogen NCC, new facilities must be developed to operate NCC entirely with hydrogen fuel.

## B. Applicability to Thailand

In addition to the two hydrogen technologies above, there are many other carbon-neutral technologies in the petrochemical industry, including plastic recycling, the use of biomass-derived raw materials, and the use of electrothermal cracking processes (see <Table 3-11> below).

**<Table 3-11> Alternative carbon neutral technology options other than hydrogen  
(Petrochemical Industry)**

Alternative technology options	Details
Plastic recycle	Reducing carbon by reusing waste plastics as petrochemical feedstock through mechanical and chemical recycling technologies
Biomass origin raw material / material use	Reducing carbon by using biomass-derived raw materials and materials instead of fossil fuels
Electric heating naphtha Decomposition process	Direct heating with electricity to replace the fossil fuel-based naphtha pyrolysis process.

Source: Author rewriting based on Jo Yong-won et al. (2021)

Plastic recycling is one of the first carbon-neutral technologies in the petrochemical sector to be commercialized, and in Thailand, SCG Chemical has built a demonstration plant at the Rayong Complex to provide recycled feedstock for its upstream petrochemical plants in 2021. In addition, the use of biomass-derived raw materials and material use is also being actively promoted in Thailand due to the abundance of biomass resources.

As the technology is characterized by a relatively short development period due to oil extracted from biomass being used without significant modifications to the existing naphtha process and the importance of the stability of raw material procurement to achieve GHG reduction (Choi Soo-won et al., 2021), its adoption and utilization in Thailand is expected to be high. From the above, it can be seen that there are many alternative technologies in the petrochemical sector other than carbon reduction technologies using hydrogen and that there are two technology options that are particularly easy to apply in Thailand. Therefore, it can be concluded that there is a possibility of introducing hydrogen utilization technology in the petrochemical industry, but competition from alternative technologies is high.

### **3. Refinery**

#### **A. Technology Options**

##### **(1) Conversion of conventional hydrogen to clean hydrogen**

The refining industry has been producing hydrogen by reforming LNG and utilizing it in the desulphurization process. In the process of replacing hydrogen production facilities, the refining industry can reduce GHGs by gradually converting grey hydrogen used in the desulfurization process into clean hydrogen. An example of large-scale green hydrogen production and its use to decarbonize refinery processes is the EU-funded REFHYNE (Clean Refinery Hydrogen for Europe) project. The project ran from 2018 to 2022, intending to install and operate a 10 MW electrolyze using renewable energy at a refinery in Germany.

##### **(2) Replacement of LNG with hydrogen or hydrogenated green fuels**

To achieve hydrogen utilization, the substitution of heat sources in refining processes with

hydrogen or hydrogenated green fuels is necessary to decrease carbon emissions. This requires the development and implementation of combustion systems that enable the conversion of refinery processes to operate on hydrogen fuel.

## **B. Applicability to Thailand**

Globally, the refining industry is expected to experience a gradual decline in crude oil demand due to the strengthening of carbon neutrality policies. The share of crude oil and renewable energy in global energy consumption is expected to change from 33.2 % and 4.5 % in 2018 to 14.3 % and 44.3 % in 50 years, respectively, leading to a fundamental shift in the energy consumption landscape in the long term.

PTT Group, a leading company in the Thai refining industry, participated in the installation of hydrogen fueling stations with Toyota and Bangkok Industrial Gas Company Limited (BIG) in 2022, and later announced an investment of USD 7 billion in April 2023 with ACWA Power, a Saudi Arabian renewable energy company, to produce green hydrogen. Therefore, PTT's efforts to enter the hydrogen industry are visible in the Thai refining industry, and there is potential for the application of demand-related technologies that utilize green hydrogen in existing processes.

## **4. Power generation**

### **A. Technology Options**

#### **(1) Fuel cell for hydrogen power generation**

A fuel cell is a direct power generation method that produces water, electricity, and heat by combining the chemical energy (hydrogen) in fuel with oxygen in the air in an electrochemical way. Among them, fuel cells for hydrogen power generation can be said to be a highly efficient and eco-friendly hydrogen fuel power generation technology that directly converts electricity and heat using electrochemical reactions of hydrogen-based fuel and oxygen. In general, fuel cells for power generation include low-temperature fuel cells such as PEMFC (Polymer Membrane Fuel Cell) and PAFC (Phosphoric Acid Fuel Cell), and high-temperature fuel cells

such as MCFC (Molten Carbonate Fuel Cell) and SOFC (Solid Oxide Fuel Cell). PAFCs, MCFCs, and SOFCs are used for distributed power generation.

## (2) Hydrogen gas turbine

Hydrogen and ammonia can be used as fuel for gas turbines in two ways: blending by replacing some of the existing LNG fuel with hydrogen or ammonia, and all-electricity generation by hydrogen or ammonia. In the field of hydrogen gas turbines, active research and development, and demonstration commercialization are being carried out by major manufacturers (GE, Siemens, Mitsubishi Power, etc.) in the United States, Europe, and Japan. From the first-generation diffusion flame method with low efficiency and large NO<sub>x</sub> generation to the second-generation premixed gas turbine method with high efficiency and low NO<sub>x</sub> generation, research and demonstration commercialization of hydrogen power generation methods are being carried out, and the third-generation porous gas turbine combustor technology for high-concentration hydrogen mixing or hydrogen electrolysis is being developed.

## **B. Applicability to Thailand**

Thailand uses fossil fuels such as oil and natural gas along with renewable energy sources such as solar, wind, biomass, and hydropower. According to the International Renewable Energy Agency's (IRENA) 'Renewable Energy Statistics 2022', Thailand is experiencing an average annual growth rate of 8 % in its major renewable energy sources - hydropower, wind power, solar thermal and solar photovoltaic, and bioenergy - and as of 2021, the country's capacity has doubled from 2012. The share of renewables in total electricity generation capacity also increased from 17.1 % in 2012 to 21.7 % in 2021.

Despite these other power industry options, Thailand's Energy Policy and Planning Office (EPPO) has announced that it is planning to launch a pilot project to generate electricity using hydrogen at a gas power plant in the Wang Noi district owned by the Electricity Generating Authority of Thailand (EGAT) on 4 July 2023. The EPPO hopes that hydrogen, which is a by-product of refineries, will be mixed with gas and injected into the power plant, and that the

share of hydrogen as a power generation fuel will reach 20 % in the future. To summarize, despite the presence of other technology options such as renewable energy in Thailand, the potential for hydrogen technology in the power industry is large enough to warrant policy support from the Thai government.

## **5. Cement**

### **A. Technology Options**

#### **(1) New heat source technology using hydrogen fuel**

Cement manufacturing requires more than 1800 degrees of heat to melt limestone into cement. Currently, a lot of carbon is generated by burning waste materials such as coal and waste tires to generate heat. By using hydrogen energy, which is clean energy, we can contribute to carbon neutrality.

### **B. Applicability to Thailand**

The greenhouse gas emissions from the cement industry are composed of CO<sub>2</sub> (Process CO<sub>2</sub>) generated from the thermal decomposition of limestone used as a raw material for cement, which accounts for about 60%, and CO<sub>2</sub> (Combustion CO<sub>2</sub>) generated from the combustion of fossil fuels used for clinker production, which accounts for about 40%. Since no substitute for limestone, which is used as a raw material for cement, has been developed, the cement industry generates more GHGs than other industrial sectors, and it is difficult to expect significant GHG reduction effects.

In addition, there are alternative carbon-neutral technology options other than hydrogen, as shown in <Table 3-12> below, Siam Cement Group (SCG), the largest cement company in Thailand, is developing low-carbon cement products with reduced clinker and limestone alternatives. The company also says it is developing an eco-friendly cement that utilizes biomass as a fuel and waste heat from the production process as an alternative energy source. In conclusion, it can be said that there is a possibility of introducing hydrogen utilization technology in the cement sector in the medium to long term, but in the short term, the

introduction of alternative technologies is prioritized.

**<Table 3-12> Alternative carbon neutral technology options other than hydrogen (cement industry)**

hydrogen except how technology option	explanation
Increased use of waste synthetic resin	Utilizing the fuel, coal, by converting it into waste resin
Biomass utilization	Using biomass as a heat source instead of coal as a fuel
Limestone alternative raw material use	Using industrial by-products containing calcium oxide instead of limestone, replacing some of the clinker in the mix, or using blast furnace slag, a by-product of the steel process, or coal ash (fly ash), a by-product of thermal power plants.
Mixture use	Using coal ash instead of limestone

Source: Author organized based on Marmier (2023)

## 6. Road transport sector

### A. Technology Options

#### (1) Hydrogen fuel cell electric vehicles

Hydrogen fuel cell electric vehicles (FCEVs) use hydrogen fuel cells, which react with oxygen in the air to produce electricity and heat by supplying hydrogen extracted from oil and gas as fuel, instead of batteries or in conjunction with batteries or supercapacitors, to power the on-board motor.

### B. Applicability to Thailand

Other than hydrogen vehicles, the other technology option for the road transport sector is electric vehicles, and the Thai government aims to increase the share of electric vehicles in new vehicles produced in Thailand to 30 % by 2030. To achieve this, the Thai government has approved tax breaks and subsidy policies, and Chinese electric vehicle companies BYD, Toyota

of Japan, China's Great Wall Motors (GWM), SAIC Motor, and MG Car have benefited from the Thai government's supportive policies.

Despite the high proportion of electric vehicles, there is still potential for the introduction of hydrogen vehicles, with the recent introduction of hydrogen vehicles and the installation of hydrogen fueling stations. In December 2022, the Japanese automotive industry, led by Toyota, signed a joint business agreement with Thailand's CP Group to extract hydrogen from biogas from agricultural waste, and CP Group will introduce hydrogen trucks to use it as fuel. In addition, PTT Oil and Retail, a subsidiary of PTT, together with Bangkok Industrial Gas, Toyota Daihatsu Engineering & Manufacturing, and Toyota Motors, installed a hydrogen fueling station in the Eastern Economic Corridor of Chonburi, Thailand.

## **7. Comparison of the hydrogen utilization technology applicability across the sectors**

The main hydrogen utilization technologies and alternatives in the six industrial sectors reviewed above, as well as their applicability to Thailand, are summarized in <Table 3-13>. First of all, it can be concluded that hydrogen utilization technologies are difficult to apply in the steel sector due to the lack of BF-BOF facilities. In the petrochemical industry, there are many carbon-neutral countermeasures such as plastic recycling, the use of biomass-derived raw materials and materials, and the electrolysis process in addition to hydrogen utilization technology, so it is possible to introduce hydrogen utilization technology in the petrochemical industry, but it is difficult to achieve in a short time. In the oil refining industry, PTT's efforts to enter the hydrogen industry are underway, so it can be expected that clean hydrogen utilization technology can be applied to existing processes. In the cement sector, the introduction of hydrogen utilization technology is likely to be possible in the medium to long term, but in the short term, the introduction of alternative technologies will be prioritized. In the power industry, hydrogen technology is expected to have a high potential for adoption if the Thai government's policy efforts and commitment are increased. Finally, in the road transport sector, although the market share and policy support for electric vehicles is very large, the recent introduction of hydrogen vehicles and hydrogen fueling stations suggests that the potential for hydrogen vehicle technology adoption is also quite large.

**<Table 3-13> Analysis of hydrogen utilization technologies by economic sector and their applicability to Thailand**

Sector	Hydrogen technology options	Alternative technology options	Applicability to Thailand
Iron and steel	<ul style="list-style-type: none"> <li>▲ Blast furnace gas injection</li> <li>▲ Hydrogen Direct Reduced Iron</li> </ul>	-	X <sup>1)</sup>
Chemicals and petrochemicals	<ul style="list-style-type: none"> <li>▲ Use of Methane to Olefin (MTO) as feedstock</li> <li>▲ Use of hydrogen as fuel</li> </ul>	<ul style="list-style-type: none"> <li>▲ Use of recycled plastic as feedstock</li> <li>▲ Use of bio-naphtha as alternative naphtha</li> <li>▲ Electrically heated naphtha cracking process</li> </ul>	○
Refinery	<ul style="list-style-type: none"> <li>▲ Conversion from conventional hydrogen to clean hydrogen</li> <li>▲ Substitution of LNG fuel with hydrogen or eco-friendly fuel supplemented with hydrogen</li> </ul>	-	◎
Power generation	<ul style="list-style-type: none"> <li>▲ Fuel cells for hydrogen power generation</li> <li>▲ Hydrogen Gas Turbine</li> </ul>	<ul style="list-style-type: none"> <li>▲ Hydropower</li> <li>▲ Wind power</li> <li>▲ Solar thermal and solar photovoltaic</li> <li>▲ Bioenergy power generation</li> </ul>	◎
Cement	<ul style="list-style-type: none"> <li>▲ New heat source technology using hydrogen fuel</li> </ul>	<ul style="list-style-type: none"> <li>▲ Increase in the use of waste synthetic resin as fuel</li> <li>▲ Use of biomass as fuel</li> <li>▲ Use of alternative materials to replace limestone</li> <li>▲ Use of blended materials to replace limestone</li> </ul>	○
Road transportation	<ul style="list-style-type: none"> <li>▲ Hydrogen Fuel Cell Electric Vehicle</li> </ul>	<ul style="list-style-type: none"> <li>▲ Electric Vehicle</li> </ul>	◎

Note: \*X as Limited, ○ as Possible with mid-to-long-term perspective, ◎ as Possible in a shorter term; 1) due to lack of BF-BOF production

Source: Author

## **Section 4. Review of Energy Consumption Conditions**

Section 4 reviews the energy consumption of each economic sector in Thailand. As hydrogen is a means of reducing GHGs to achieve carbon neutrality, the higher the share of fossil fuel consumption in each economic sector, the more it is necessary to actively consider reducing GHGs using hydrogen. On the other hand, if the share of electricity<sup>1</sup> and renewable energy consumption in the economic sector is high, the importance of GHG reduction is relatively low compared to other economic sectors because the final energy consumption structure is decarbonized. Therefore, in Section 4, we examine the energy consumption by economic sectors in Thailand to identify sectors that require active GHG reduction efforts.

To compare energy consumption by economic sector, it is necessary to have energy consumption data on the same basis for each economic sector. Energy consumption data for Thailand can be found in the Energy Statistics and Energy Balance published by the Ministry of Energy, but it is difficult to use this data in this study because energy consumption is not disaggregated by the detailed economic sector. Therefore, this study compared energy consumption by economic sector based on the United Nations Statistics Division (UNSD) Energy Balance for Thailand, which has a relatively detailed economic sector breakdown. The share of non-fossil energy in the UNSD Energy Balance is calculated as the share of electricity, renewable, and heat input (consumption) in total energy input (consumption), and the share of fossil energy is calculated as the proportion occupied by total energy input (consumption) minus the input (consumption) of electricity, renewable, and heat.

### **1. Iron and Steel**

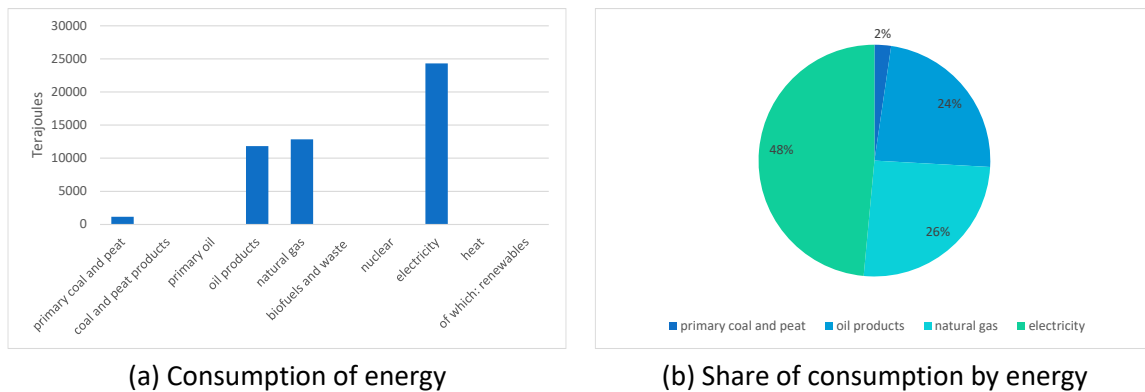
According to the final energy consumption of the UNSD Energy Balance, the Iron and Steel sector in Thailand consumed a total of 50,147 TJ of energy in 2020. The largest share of energy consumed is electricity, which totaled 24,329 TJ in 2020, accounting for approximately 48.5

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<sup>1</sup> In the case of electricity, the fuel used for power generation determines greenhouse gas emissions at the national level. However, in this study, only direct emissions were considered. In addition, as replacing fossil fuels with electricity (electrification) in final consumption is one of the means to reduce greenhouse gas emissions, it was judged that the importance of greenhouse gas reduction was low.

% of the iron and steel sector's final energy consumption (see [Figure 3-5]). Electricity was followed by natural gas (25.6 %), petroleum products (23.6 %), and coal and charcoal (2.3 %), with no renewable energy consumption. Therefore, the share of non-fossil fuel consumption in the Thai iron and steel sector is 48.5%, while the share of fossil fuel consumption is 51.5%.

**[Figure 3-5] Current status of final energy consumption in the iron and steel sector (2020)**



Source: Author based on UNSD Energy Balance

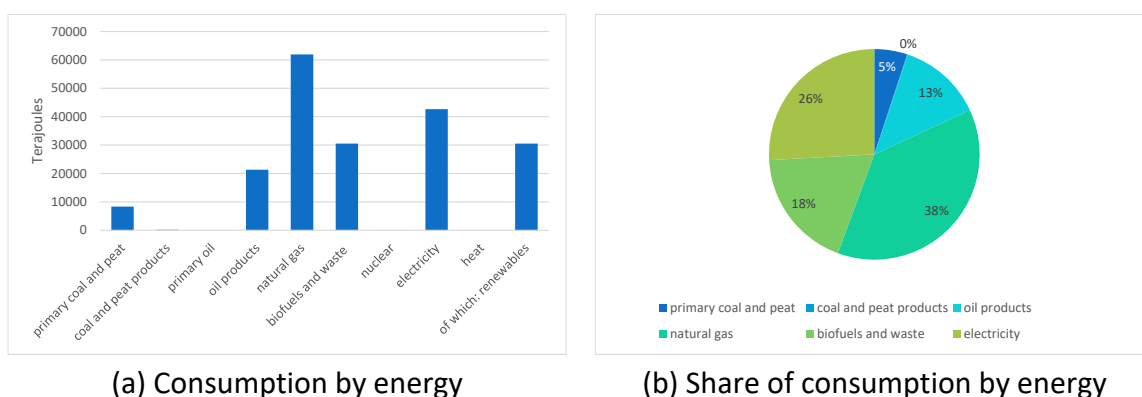
On the other hand, in the case of the iron and steel sector, depending on the production process of crude steel, energy commodity is consumed not only as a fuel, but also as material (or feedstock), which is recorded in the transformation row in the energy balance. For example, in the production of primary crude steel from iron ore via the BF-BOF (blast furnace-basic oxygen furnace) process, coke is produced from coal in a coke oven, which is then fed into the blast furnace as a reducing agent for steel production. In the case of hydrogen in particular, the inputs of energy commodities as raw materials need to be mainly examined, as hydrogen is considered a substitute for coke-reducing agents in the iron and steel sector. However, the UNSD Energy Balance does not have data in the rows for coke ovens and blast furnaces in the transformation row. Statistics from the World Steel Association show that steel production method in Thailand appears to be the electric arc furnace process, which utilize ferrous scrap to produce secondary steel.

## 2. Chemical and petrochemical

According to the data on Thailand's final energy consumption in 2020, the chemical and petrochemical sector accounted for 164,963 TJ. Among the energy consumed by this sector,

natural gas was the primary source, accounting for the largest portion. In 2020, natural gas consumption reached 61,940 TJ, representing approximately 37.5% of the sector's total energy consumption. Natural gas, electricity, and biofuels, and waste, were the next significant energy commodities. Specifically, electricity consumption amounted to 42,678 TJ, accounting for 25.9% of the sector's energy consumption, while biofuels and waste accounted for 30,509 TJ, representing 18.5%. On the other hand, Thailand's chemical and petrochemical sector is considered to be a large consumer of renewable energy. According to the UNSD energy balance, the chemical and petrochemical sector consumed 30,509 TJ of renewable energy in 2020, accounting for about 18.5% of total final energy consumption ([Figure 3-6]).

**[Figure 3-6] Current status of final energy consumption in the chemical and petrochemical sector (2020)**



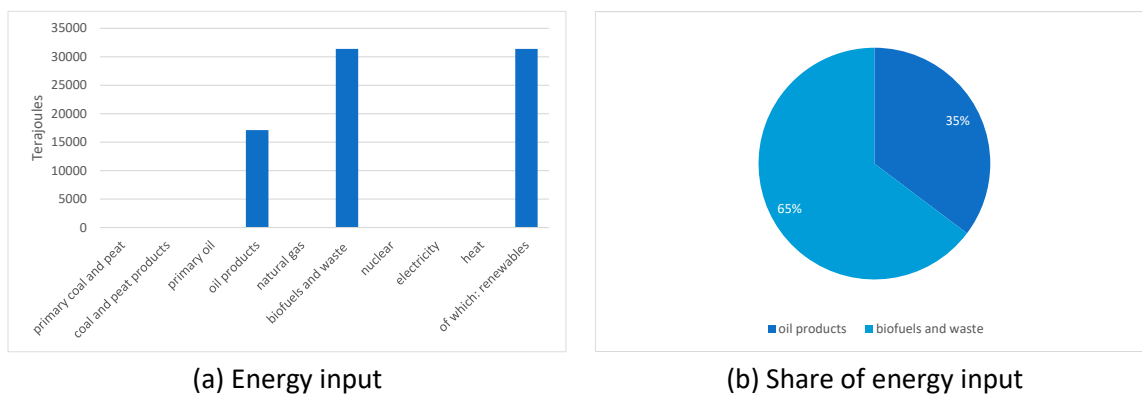
Source: Author based on UNSD Energy Balance

In the case of petrochemical sector, which involves the production of petroleum products, it is important to consider not only the consumption of energy commodities as fuels but also their consumption as a raw material for the transformation processes and non-energy consumption. As in the iron and steel sector, in the petrochemical sector, transformation of raw materials using hydrogen is a key reduction strategy, so it is necessary to understand the current status of energy products being input as raw materials. However, the transformation row of the UNSD Energy Balance does not show the petrochemical sector but the sector is included in other transformation categories. Additionally, while the transformation sectors typically present inputs and outputs of energy commodities, denoted by a +/- sign, the 2020

Energy Balance only shows inputs for all in other transformation sectors<sup>2</sup>.

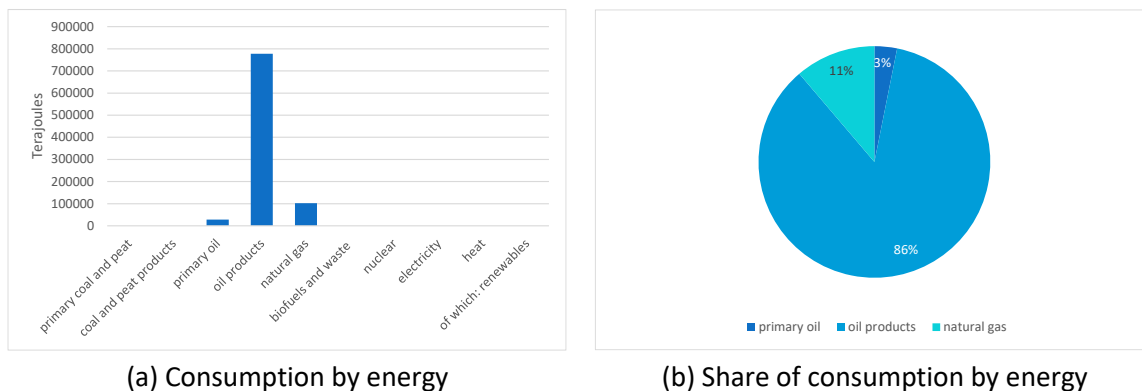
Moreover, the Energy Balance does not provide a detailed breakdown of items or industries consumed as chemical raw materials in the final non-energy consumption sector. Despite these limitations, to obtain a rough estimate of the proportion of fossil and non-fossil energy commodity consumption as raw materials, we calculated the energy input shares based on the energy commodity inputs in the other transformation sector and the final non-energy consumption part of the UNSD Energy Balance. The analysis revealed that fossil energy inputs accounted for 35.3% of the total energy inputs in the other transformation sector ([Figure 3-7]), while fossil energy constituted 100% of the final non-energy consumption ([Figure 3-8]).

[Figure 3-7] Other transformation sector energy product input status (2020)



Source: Author based on UNSD Energy Balance

[Figure 3-8] Energy commodity inputs in the Other transformation sector



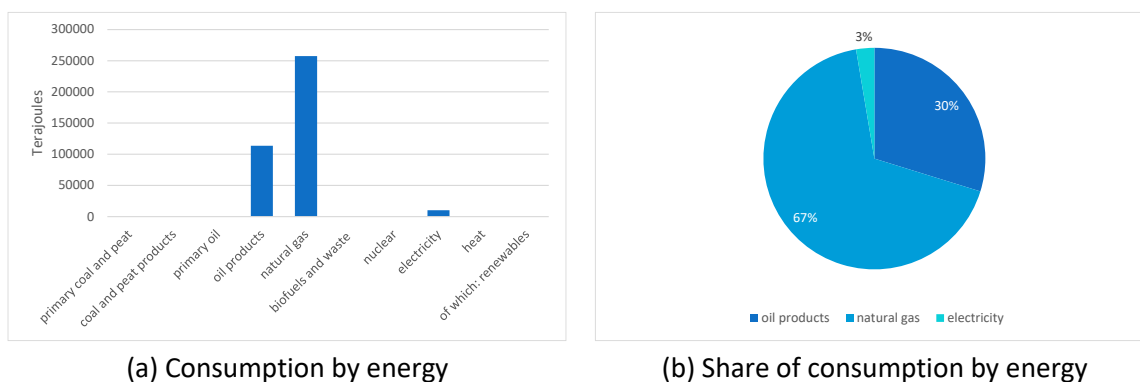
<sup>2</sup> It is believed that this is because the classification of fuels in the UNSD Energy Balance is not detailed.

Source: Author based on UNSD Energy Balance

### 3. Refinery

In the energy balance, energy consumption as a fuel in the refining sector is categorized as energy industry own use within the transformation part, rather than being classified under final consumption. The breakdown of energy industry own use by industry is provided in the detailed energy balance, but the UNSD energy balance does not offer this specific breakdown. Despite this limitation, to calculate a rough share, the proportion of energy consumption is calculated using the data recorded in the energy industry's use part. Out of the total energy consumption of 381,130 TJ in 2020, natural gas accounted for 67.6 % (257,505 TJ), followed by petroleum products at 29.8 % and electricity at 2.6 %<sup>3</sup> ([Figure 3-9]).

[Figure 3-9] Energy consumption by the energy industry own use sector (2020)



Source: Author based on UNSD Energy Balance

The refinery sector is a sector that produces secondary energy commodities such as petroleum products by inputting energy commodities such as crude oil, so it consumes energy commodities not only as fuel but also as raw materials. Due to the production characteristics of the refinery sector, the input energy commodity (raw material) is expected to be fossil energy, and in fact, only crude oil is written as an input in the UNSD energy balance. Therefore, the consumption of energy commodities as raw materials in the refining sector is all fossil

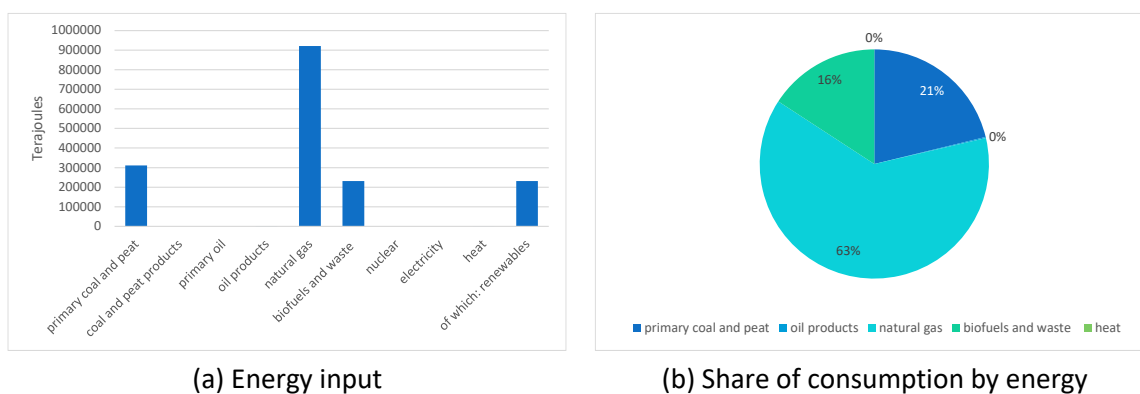
<sup>3</sup> As described later in Chapter 4, Section 2, based on the fuel consumption of Thai Oil Public Company Limited in 2022, natural gas (65.3%) is consumed the most, and non-fossil energy consumption such as electricity and renewable energy as a refining fuel is considered to be non-existent.

energy.

#### 4. Power generation

Energy consumption in the power sector of the UNSD Energy Balance is recorded in the transformation sector, rather than in the final consumption sector of the energy balance, where the inputs of fuels used for power generation and the amount of electricity produced are recorded. According to the UNSD Energy Balance, fuel inputs in the power sector in 2020 were 1,465,490 TJ, with natural gas accounting for the largest share of inputs at 62.8 % followed by primary coal and charcoal at around 21.2 %, as shown in Figure 3-10. Meanwhile, heat and renewable energy are also used for power generation, accounting for 0.0 % and 15.8 %, respectively. Therefore, based on the UNSD Energy Balance, fossil fuel inputs in the Thai power sector account for 84.2 % of total inputs, while non-fossil energy inputs account for the remaining 15.8 %<sup>4</sup>.

**[Figure 3-10] Current status of energy product input in the power generation sector (2020)**



Source: Author based on UNSD Energy Balance

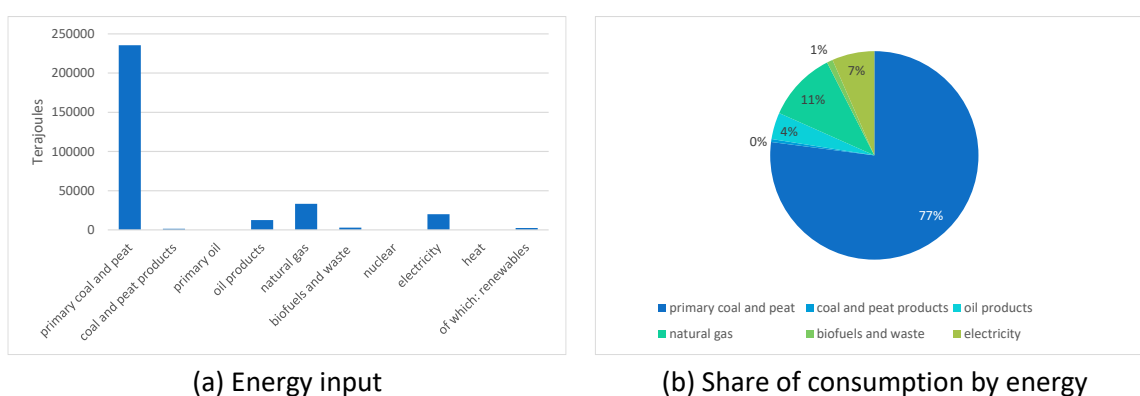
#### 5. Cement

While the cement industry is included in the final energy consumption sector in the energy balance, the UNSD Energy Balance does not classify the cement industry separately, but only

<sup>4</sup> As described later in Chapter 4, Section 4, based on the 2022 fuel consumption of the Electricity Generating Authority of Thailand, a power generation company in Thailand, natural gas (68.7%) has the highest share, followed by lignite (29.2%) and diesel (1.9%).

records final energy consumption for the top economic sector, non-metallic minerals manufacturing. In 2020, final energy consumption in non-metallic minerals manufacturing totaled 305,622 TJ, with primary coal and peat accounting for the largest share of final energy consumption at 77.1 % (see [Figure 3-11]). After primary coal and peat, natural gas (10.8 %), electricity (6.6 %), and oil products (4.1 %) were consumed. The non-metallic minerals manufacturing sector consumed 2,346 TJ of renewable energy or 0.8 % of total energy consumption.

**[Figure 3-11] Current state of final energy consumption in the non-metallic minerals manufacturing sector (2020)**



Source: Author based on UNSD Energy Balance

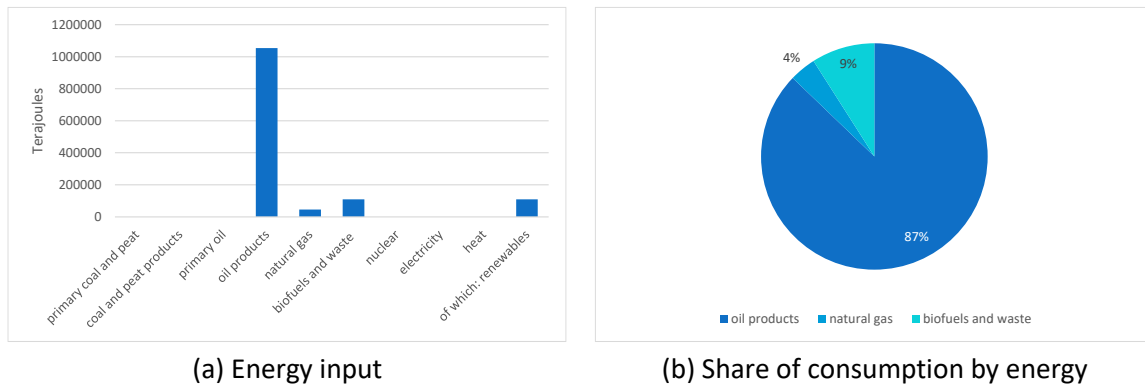
## 6. Road transportation

Based on the UNSD Energy Balance, the final energy consumption of the road transport sector in Thailand in 2020 was recorded at 1,208,402 TJ. Due to the nature of modern road transport vehicles, petroleum products were found to be the largest consumer in Thailand's road transport sector, with a total consumption of 1,053,621 TJ, accounting for 87.2% of the final energy consumption (see [Figure 3-12]). The consumption of petroleum products was followed by biofuels and waste (9.0%) and natural gas (3.8%), while no consumption of electricity was recorded<sup>5</sup>. Therefore, the final energy consumption of the road transport

<sup>5</sup> As analyzed in Section 3 of Chapter 4, according to the Monthly Report on Petroleum and Electricity Consumption of Thailand's Energy Planning and Policy Office, electricity consumption in the road transport sector in 2022 is 53.0 TJ, which is little energy consumption compared to petroleum products such as gasoline and diesel

sector in Thailand is analyzed to be approximately 91.0% from fossil fuels and 9.0% from non-fossil fuels.

**[Figure 3-12] Final Energy Consumption in Road Transportation (2020)**



Source: Author based on UNSD Energy Balance

<Table 3-14> based on the UNSD Energy Balance, presents the energy consumption structure across various economic sectors, comparing the proportion of fossil energy consumption to non-fossil energy consumption. The findings indicate that fossil energy consumption is predominant across sectors. In particular, the road transport sector exhibits a high reliance on fossil fuel energy, with a share of 91.0%. This sector is found to require active measures to transition to alternative transportation fuels. Similarly, the refinery sector (97.4%) and cement sector (92.7%) also demonstrate substantial dependence on fossil energy consumption and are deemed as sectors in urgent need of alternative fuels.

While the chemical and petrochemical sector exhibits a relatively lower share of fossil energy consumption as fuel compared to other sectors, it has a significant reliance on fossil energy consumption as raw materials. Therefore, it is crucial to prioritize a shift from existing fossil energy-based raw materials to low-carbon alternatives in this sector.

The power generation sector, although having a lower proportion of fossil fuel consumption compared to other sectors, still exceeds 80%. This sector requires fuel switching to

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and natural gas.

decarbonize the electricity consumed by other sectors.

**<Table 3-14> Fossil energy consumption by the economic sector in Thailand (2020)**

Sector		Fossil energy (%)	Non-fossil energy (%)
Iron and steel	Fuel	51.5	48.5
	Material	-	-
Chemicals and petrochemicals	Fuel	55.6	44.4
	Material	35.3 <sup>1)</sup> 100.0 <sup>2)</sup>	64.7 <sup>1)</sup> 0.0 <sup>2)</sup>
Refinery	Fuel <sup>3)</sup>	97.4	2.6
	Material	100.0	0.0
Power generation		84.2	15.8
Cement <sup>4)</sup>		92.7	7.3
Road transportation		91.0	9.0

Note 1) Other transformation standards; 2) Based on final non-energy use; 3) Energy industry own use standards;

4) Based on non-metallic minerals

Source: Author analysis based on UNSD Energy Balance

## **Section 5. Comprehensive Comparison and Selection**

Section 5 compares different economic sectors in Thailand by integrating the analysis of policy compatibility, economic importance, technology applicability, and energy consumption conditions discussed above. <Table 3-15> provides a summary of these four categories of analysis.

In Section 1 (policy conformity), four policies, namely NESDP, PDP, AEDP, and LEDS were examined. After evaluating sectors for hydrogen utilization specified in these policies, it was revealed that the road transportation sector aligns the most with the policies. Additionally, the electric power, oil refinery, and cement sectors also exhibit high policy compatibility.

With consideration of various indicators reviewed in Section 2 (review of economic importance), an overall comparison based on the value-added ratio by industry in Thailand was conducted. The analysis revealed that the petrochemical, electric power, cement, and road transportation sectors possess a value-added ratio of 0.3 or higher, indicating their significant economic importance.

Regarding technology applicability, the refinery, electric power, and road transportation sectors demonstrate the highest suitability for adopting hydrogen technology. While alternative technologies are available in the petrochemical and cement sectors, hydrogen technology appears viable in the medium to long term.

Lastly, in terms of energy consumption conditions, the refinery, electric power, cement, and road transportation sectors heavily rely on fossil energy, accounting for over 80% of their energy consumption. Consequently, these sectors necessitate transformation towards utilizing decarbonized fuels and raw materials such as hydrogen.

Based on the comprehensive assessment of these four factors, the research suggests prioritizing the introduction of clean hydrogen in the following sectors: 1) road transportation, 2) power, 3) cement, and 4) refinery.

<Table 3-15> Comprehensive comparison and Final Selection of economic sectors

Sector	Policy Coherence	Economic Importance	Technological Assessment	Energy Consumption	Final Selection
Iron and steel	△	○	X	○	Not selected
	▲ LEDS	▲ Value added ratio > 0.15	▲ Lack of BF-BOF production	▲ Fossil energy (%) > 50	
Chemicals and petrochemicals	△	◎	○	○	Not selected
	▲ LEDS	▲ Value added ratio > 0.3	▲ Strong presence of alternative technology options	▲ Fossil energy (%) > 50	
Refinery	○	△	◎	◎	Selected
	▲ AEDP ▲ LEDS	▲ Value added ratio < 0.15	▲ Technological readiness with initiatives	▲ Fossil energy (%) > 80	
Power generation	○	◎	◎	◎	Selected
	▲ PDP_ ▲ LEDS	▲ Value added ratio > 0.15	▲ Technological readiness with initiatives	▲ Fossil energy (%) > 80	
Cement	○	◎	○	◎	Selected
	▲ AEDP ▲ LEDS	▲ Value added ratio > 0.3 <sup>1)</sup>	▲ Strong presence of alternative technology options	▲ Fossil energy (%) > 80	
Road transportation	◎	◎	◎	◎	Selected
	▲ NESDP ▲ AEDP ▲ LEDS	▲ Value added ratio > 0.3	▲ Technological readiness with initiatives	▲ Fossil energy (%) > 80	

Note: \* △ as Low Applicability, ○ as Moderate Applicability, ◎ as High Applicability; 1) Summed result of Other non-metallic mineral products

Source: Author

## Chapter 4. Estimating the Climate Benefits of Hydrogen Utilization in Thailand

### Section 1. Overview of Climate Benefit Estimation

#### 1. Purpose and significance of climate benefit estimation

Chapter 4 aims to quantitatively estimate the climate benefits of hydrogen utilization for the hydrogen utilization sectors in Thailand selected in Chapter 3. Climate benefit can be defined as the positive impact that a country, group of people, or individuals can obtain in terms of climate through GHG reduction and climate change adaptation activities. In the context of climate change mitigation, hydrogen is usually considered as a means of reducing GHG emissions. Thus, the climate benefits of hydrogen utilization estimated in this study are redefined as the positive impacts of Thailand's efforts to reduce GHG emissions through hydrogen utilization.

Estimating climate benefits requires establishing a scope for "greenhouse gases" and defining the "positive impacts" of GHG reduction efforts. According to the 1997 Kyoto Protocol, there are six major greenhouse gases: carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ( $\text{SF}_6$ ). As of 2019, Thailand's carbon dioxide emissions were 329,891.41 thousand tons, accounting for about 88.5% of the 372,716.86 thousand tons of greenhouse gas emissions excluding LULUCF, and this study only considers carbon dioxide, which is the largest emission source in Thailand<sup>6</sup>.

While there are various positive effects of GHG reduction efforts<sup>7</sup>, the direct output that can occur in the 'climate change mitigation aspect' is GHG reduction, and the resulting benefits to a country, group of people, or individuals can be referred to as positive impacts. Benefits

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<sup>6</sup> Greenhouse gas referred to in this report refers to carbon dioxide unless otherwise specified.

<sup>7</sup> The effects of greenhouse gas reduction efforts can occur in various ways, such as not only greenhouse gas reduction, which will be described later, but also air pollutant reduction (co-benefit), economic growth contribution effect by creation of new industries, and employment effect.

from GHG reductions occur through complex pathways for different actors. In this study, given that greenhouse gas reduction is a national goal, the benefits from greenhouse gas reduction are limited to those that can be obtained by society as a whole. Furthermore, the benefits are assumed to be calculated by the reduction of costs to be borne by society as a whole in accordance with the amount of greenhouse gas reduction.

The expected climate benefits of hydrogen utilization will be a key contributor to the establishment of Thailand's national hydrogen strategy and climate change response strategies and policies. The climate benefits estimated in this study are the 'expected' benefits of hydrogen utilization in specific sectors in Thailand, allowing us to measure the effects of GHG reduction activities. Building on the climate benefits, more effective and efficient climate actions are possible with revised and supplemented national GHG reduction strategies and policies.

## **2. Methods of estimating climate benefits**

There are three main steps to estimate the climate benefits of hydrogen utilization. The first step is to estimate the GHG emissions that could occur when current activities in each economic sector continue in the long term. The second step is to estimate the GHG emissions when using hydrogen in each economic sector and to calculate the emissions that can be reduced compared to the results of the first step. The third step is to estimate the benefits by converting the avoided GHG emissions into a monetary value. The main contents and issues of climate benefits estimation are as follows:

### **A. Step 1: Estimation of GHG emissions baseline**

The first step is to calculate a baseline (baseline emissions) to estimate the GHG reductions of hydrogen utilization, which is an estimation of GHG emissions that could be expected when economic activities continue without hydrogen utilization. In other words, the first step is to estimate the Business-As-Usual (BAU) of GHG emissions.

Since estimating future GHG emissions from current activities is a long-term projection, the

choice of projection methodology is a key issue. There are various methods for forecasting GHG emissions, ranging from simple time trend lines to time series models to macro and micro models. This study used Kaya Identity for projection, considering data availability and the ease of analysis, modification, and supplementation. Kaya Identity is a simple mathematical framework that the total GHG emissions can be expressed as four factors that affect the level of emissions, the most common form of which is shown in Equation 4-1.

$$C = C/E \times E/G \times G/P \times P \text{ (Equation 4-1)}$$

Where C indicates GHG emissions, E indicates energy consumption, G indicates GDP, and P indicates population. Therefore, according to Kaya Identity, GHG emissions (C) can be expressed as the product of GHG intensity (C/E), defined as the number of GHGs emitted per unit of energy consumed, and the energy intensity of a country's economy (E/G), GDP per capita (G/P), and population (P), and as the right-hand side of Equation 4-1 shows, when all of these factors are multiplied together, only GHG emissions (C) remain, so Equation 4-1 always holds.

Projecting GHG emissions using Kaya Identity boils down to forecasting each factor of Kaya Identity, and then multiplying the projections for each factor to estimate future GHG emissions. If we assume that GHG intensity (C/E) is the GHG coefficient that is a fixed value over the long term, three factors in Equation 4-1 need to be projected. Furthermore, when using the projections of GDP per capita (G/P) and population (P) already projected in various national plans, an energy intensity (E/G) projection is needed. In the case of energy intensity, it is possible to estimate macroeconomic models using econometric techniques by utilizing energy intensity data from the past to the present.

This study utilizes Kaya Identity to reflect the characteristics of each economic sector as shown in Table 4-1. Since the GHG emissions of the economic sector depend on the type and proportion of fuel used, this study considers GHG emissions by fuel and the level of consumption by fuel, unlike Kaya Identity. In addition, as the power generation sector is included in this study, only direct emissions from fuel consumption were considered when

estimating the GHG emissions of each economic sector. However, in terms of the cement industry that emits carbon dioxide from the raw materials, Emissions from industrial processes and product use (IPPU) were also considered. A detailed description of the GHG emission equations, variables, and factors for each economic sector is presented in each section of Chapter 4.

The year for estimating GHG was set to 2050. Thailand aims to achieve Nationally Determined Contribution (NDC) by 2030, with a goal of carbon neutrality by 2050 and GHG neutrality by 2065. Since the GHG to be estimated in this study is carbon dioxide, and it is not realistic to utilize hydrogen in the short term in the selected economic sectors, the year of 2050 when Thailand aims to accomplish carbon neutrality was set as the time frame for estimating carbon dioxide emissions and GHG reductions.

**<Table 4-1> GHG emission equation utilized by economic sectors in Thailand**

Sectors	Identity	Variables
Cement	$C = C_E + C_{IPPU}$ $C_E = \sum C_i / E_i \times E_i / E \times E / Q \times Q$ $C_{IPPU} = C_{IPPU} / Q_{clinker} \times Q_{clinker} \times CKD$	<p><math>C_E</math>: Carbon dioxide emissions from energy consumption  <math>C_{IPPU}</math>: Carbon dioxide emissions from industrial processes  <math>C_i</math>: Carbon dioxide emissions from fuel i  <math>E_i</math>: Consumption of fuel i  <math>E</math>: Total fuel consumption  <math>Q</math>: Cement production  <math>Q_{clinker}</math>: Clinker Production  <math>CKD</math>: Cement Kiln Dust Correction Factor</p>
Oil Refinery	$C = \sum C_i / E_i \times E_i / E \times E / Q \times Q$	<p><math>C_i</math>: Carbon dioxide emissions from fuel i  <math>E_i</math>: Consumption of fuel i  <math>E</math>: Total fuel consumption  <math>Q</math>: Crude Oil Inputs</p>
Road Transportation	$C = \sum C_i / E_i \times E_i / V_i \times V_i / V \times V / G \times G / P \times P$	<p><math>C_i</math>: Carbon dioxide emissions from fuel i  <math>E_i</math>: Consumption of fuel i  <math>v_i</math>: Number of i-fuel vehicles  <math>V</math>: Total number of vehicles  <math>G</math>: GDP  <math>P</math>: Population</p>
Power Generation	$C = \sum C_i / E_i \times E_i / Elec_i \times Elec_i / Elec \times Elec / Con \times Con / G \times G / P \times P$	<p><math>C_i</math>: Carbon dioxide emissions from fuel i  <math>E_i</math>: Consumption of fuel i  <math>Elec_i</math>: i Fuel power generation  <math>Elec</math>: Total electricity generation</p>

		Con: Power consumption G: GDP P: Population
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Source: Author

## B. Step 2: Calculation of GHG reduction by hydrogen utilization

The amount of GHG reduction by hydrogen utilization in each economic sector can be calculated as the difference between the 2050 GHG emissions estimated in Step 1 and the 2050 GHG emissions when using hydrogen. The 2050 GHG emissions from hydrogen utilization were estimated using the same adjusted Kaya Identity as in Step 1, as shown in <Table 4-1>.

As described in Step 1, Kaya Identity consists of multiplied factors that determine GHG emissions, and by adjusting the factors related to hydrogen utilization, the GHG emissions from hydrogen utilization can be estimated. For example, GHG emissions from increased hydrogen utilization in the cement and oil refining industries can be estimated by increasing the hydrogen consumption in the consumption share ( $E_i/E$ ) of each fuel. By increasing the hydrogen vehicles in the share of vehicles by fuel ( $V_i/V$ ) in the case of road transportation and by increasing the share of hydrogen power generation in power generation by fuel ( $Elec_i/Elec$ ) in the case of power generation, GHG emissions from increased hydrogen utilization can be estimated. Changes in factors not directly related to hydrogen utilization (cement production, crude oil inputs, GDP per capita, population, etc.,) were assumed to be the same as those used to estimate GHG emissions in Step 1. In practice, increased hydrogen utilization may affect endogenous variables such as industrial capacity, industrial outputs, and macroeconomic variables, which in turn may cause changes in other factors. However, in this study, the change in GHG emissions by other factors was controlled, assuming that there was no change in other factors for the simplification of the analysis.

The main issue in Step 2 is to set the share of hydrogen in consumption by fuel (cement, oil refining), vehicle types by fuel (road transportation), and power generation by fuel (power generation) in 2050. The proportion of hydrogen utilization in each economic sector can be estimated through national policies and industrial targets, but it is difficult to find an officially

announced hydrogen target in Thailand. Furthermore, as this study is part of establishing Thailand's national hydrogen strategy, it is necessary to estimate climate benefits under various scenarios to set national goals. Therefore, this study calculated the GHG reductions and climate benefits of each scenario by setting a scenario for the proportion of hydrogen utilization in each economic sector in 2050.

### **C. Step 3: Calculation of GHG reduction benefits**

In Step 3, the GHG reductions calculated in Step 2 are translated into benefits, and the final climate benefits are identified. As explained above, this study defines the climate benefits of hydrogen utilization as the reduction of costs to be borne by the whole society corresponding to GHG emission reductions. Therefore, the climate benefits can be calculated by multiplying the "social costs saved per unit of GHG emission reduction" by the GHG emission reduction calculated in step 2.

However, accurately estimating the social cost per unit of GHG reduction is complicated, and it is usually used by replacing the price of GHG (carbon price) data expressed in market value, such as the price of emissions. As the carbon price is the cost to be paid when one unit of carbon is emitted, the price represents the costs that can be reduced by the corresponding GHG reduction when multiplying the carbon price by the amount of GHG reduction. Therefore, this study utilizes Thailand's 2050 carbon price as the social cost per unit of GHG reduction.

However, the key issue with Step 3 is that projections of carbon prices vary widely across prior research, leading to differences in climate benefits depending on the carbon price choice. According to Guivarch and Rogelj(2017), carbon price projections under the 2-degree scenario range from \$45 to \$1,000 per ton in 2050, which is likely due to differences in the structure of the models used to project carbon prices and the socioeconomic variables used as inputs. Thailand's Mid-century, Long-term Low Greenhouse Gas Emission Development Strategy submitted to the United Nations predicts that the country's carbon price will reach \$368 per

ton in 2050 under its greenhouse gas reduction policies<sup>8</sup>. On the other hand, Rajbhandari et al.(2023) analyzed that for Thailand to achieve carbon neutrality in 2050, the carbon price would need to be \$734/ton in 2050. Meanwhile, the International Energy Agency (IEA) used a carbon price of \$180 per ton in 2050 for other emerging markets and developing economies in its Global Energy and Climate Model analysis under the Net Zero Emissions by 2050 Scenario. In this study, the carbon price of \$ 734 per tonne was analyzed by Rajbhandari et al.(2023), whose carbon price estimate is clear and reflects Thailand's carbon-neutral target.

## Section 2. Cement Industry

### 1. Setting up an equation

In this study, Kaya Identity was adjusted and utilized for the cement industry in Thailand as shown in Equation 4-1.

$$C = C_E + C_{IPPU} \text{ (Equation 4-1-a)}$$

$$C_E = \sum C_i/E_i \times E_i/E \times E/Q \times Q \text{ (Equation 4-1-b)}$$

$$C_{IPPU} = C_{IPPU}/Q_{clinker} \times Q_{clinker} \times CKD \text{ (Equation 4-1-c)}$$

For the cement industry, unlike other economic sectors, carbon dioxide emissions are calculated by dividing them into emissions from energy combustion ( $C_E$ ) and industrial processes and product use ( $C_{IPPU}$ ). This is because carbon dioxide is generated by the consumption of limestone in the production of clinker, the raw material for cement, as explained earlier. Limestone is a raw material composed primarily of calcium carbonate ( $CaCO_3$ ), and carbon dioxide is generated during calcination to produce clinker (Equation 4-2). Carbon dioxide emissions from the industrial process can fundamentally be reduced through raw material substitution, so it is difficult to see that it is largely related to the use of hydrogen in the cement industry. However, in order to consider the total carbon dioxide emissions of the cement industry, carbon dioxide emissions from the industrial processes and

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<sup>8</sup> It is judged that the carbon price derived under the scenario of achieving net GHG emissions of 200 MtCO<sub>2eq</sub> in 2050 and net zero in 2090.

product use were also considered.



Emissions from energy combustion ( $C_E$ ) in the cement industry were categorized into carbon dioxide intensity factor ( $C_i/E_i$ ), fuel composition factor ( $E_i/E$ ), energy intensity factor ( $E/Q$ ), and production factor ( $Q$ ). The carbon dioxide intensity factor was defined as the carbon dioxide emissions from each fuel  $i$  ( $C_i$ ) relative to its consumption ( $E_i$ ). The fuel composition factor is expressed as the ratio of specific fuel consumption ( $E_i$ ) to total fuel consumption ( $E$ ), and all else being equal, a higher share of more carbon-intensive fuels will result in higher carbon dioxide emissions. The energy intensity factor refers to the ratio of total fuel consumption ( $E$ ) to cement production ( $Q$ ), which means the total energy consumption when producing a unit of cement. Therefore, with all other factors being equal, the more energy-intensive the cement is, the greater the amount of carbon dioxide emitted in its production. Finally, the production factor ( $Q$ ) is the amount of cement produced, and when the effects of other factors are fixed, an increase in cement production will lead to an increase in carbon dioxide emissions.

In the cement industry, emissions from industrial processes ( $C_{IPPU}$ ) were estimated using the IPCC's estimation equation (Tier 2: Emission based on clinker production data). According to the IPCC's estimation equation, carbon dioxide emissions from clinker production can be estimated as the product of the weight of clinker produced, the emission factor for clinker, and the emission correction factor for cement kiln dust<sup>9</sup> (CKD). Therefore, in this study, an equation consists of a clinker carbon dioxide intensity factor ( $C_{IPPU}/Q_{clinker}$ ), clinker production factor ( $Q_{clinker}$ ), and cement kiln dust factor (CKD), as shown in Equation 4-1-c, where  $Q_{clinker}$  is the clinker production amount, and CKD is the cement kiln dust correction factor.

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<sup>9</sup> Cement kiln dust is dust generated in the production process of clinker. If cement kiln dust is not recycled in the kiln, carbon dioxide emissions from cement kiln dust must be considered (IPCC, 2006), and the correction factor is used for this purpose.

## 2. Data

To estimate the baseline GHG emissions of the cement industry and the GHG reduction from hydrogen utilization, data and long-term projections are needed for each of the variables and factors in Equation 4-1. However, for some variables and factors, there was limited publicly available data for the cement industry, so we indirectly obtained and utilized variable and factor data.

### A. Carbon dioxide intensity factors

For the carbon dioxide intensity factor ( $C_i/E_i$ ), which refers to the amount of carbon dioxide emitted per unit of fuel consumption, the carbon dioxide emission factor by fuels was used based on the IPCC's 2006 guidelines, and it was assumed to be constant until 2050. In order to utilize fuel-specific carbon dioxide emission factors, the identification of fuel types used in the cement industry is a priority. In this study, the classification of fuels follows the energy classification of the United Nations Statistics Division (UNSD) Energy Balance, which will be used as a source of fuel-specific consumption ( $E_i$ ). However, the UNSD Energy Balance does not distinguish cement manufacturing as a separate sector like ISIC 2394, so the non-metallic manufacturing sector, which includes cement manufacturing, was used to identify the fuel types.

As mentioned above, according to the UNSD Energy Balance, the energy consumed in Thailand's non-metallic mineral manufacturing sector is: (1) primary coal and peat, (2) coal and peat products, (3) oil products, (4) natural gas, (5) biofuels and waste, and (6) electricity<sup>10</sup>. However, the fuel classification in the IPCC Emission Factor Guidelines is more detailed than the fuel classification in the UNSD Energy Balance, so the two do not correspond one-to-one. Therefore, in this study, the fuel classification of UNSD Energy Balance was linked to IPCC emission coefficient values with reference to non-metallic mineral manufacturing fuel consumption in Korea and the EU, where their detailed energy balance data are available. For

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<sup>10</sup> UNSD Energy Balance classifies energy commodities into 9 categories: primary coal and peat, coal and peat products, primary oil, oil products, natural gas, biofuels and waste, nuclear, electricity, and heat. Among these, consumption corresponding to renewable energy is also presented.

biofuels and waste, industrial wastes such as waste oil and waste tires are used in cement production. It seems possible to use industrial waste emission factors, but the emission factor for other primary solid biomass values was applied based on the structure of the UNSD Energy Balance<sup>11,12</sup>. In addition, since this study only calculates the direct emissions of carbon dioxide, GHG emissions from electricity use were not considered. Moreover, GHG emissions from hydrogen utilization were not also considered when calculating the amount of GHG reductions in Step 2.

**<Table 4-2> Thailand's emission coefficient for the non-metallic mineral manufacturing sector**

Fuel (UNSD Energy Balance)	Representative fuels (IPCC 2006 guidelines)	Carbon Dioxide _ Emission Factor (IPCC 2006 guidelines)
Primary Coal and Peat	Other Bituminous Coal	94,600kgCO <sub>2</sub> /TJ
Coal and peat products	Brown coal	97,500kgCO <sub>2</sub> /TJ
Petroleum Products	Average gas/diesel oil and residual fuel oil	75,750kgCO <sub>2</sub> /TJ
Natural Gas	Natural gas	56,100 kgCO <sub>2</sub> /TJ
Biofuels and waste	Other primary solid biomass	100,000 kgCO <sub>2</sub> /TJ
Electricity	-	-

Source: IPCC (2006)

## B. Fuel composition

For the fuel composition factor ( $E_i/E$ ), it was assumed that the fuel composition for the cement industry in Thailand is similar to that of non-metallic mineral manufacturing. Accordingly, based on the consumption by fuel of non-metallic mineral manufacturing of UNSD Energy Balance, the consumption proportion of each fuel was calculated and utilized.

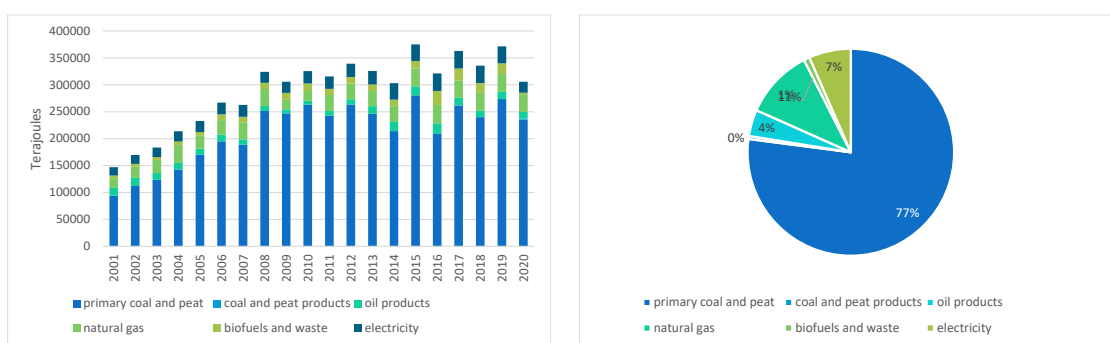
<sup>11</sup> In the UNSD Energy Balance, the consumption of biofuels and waste energy in non-metallic mineral manufacturing for the period 2001 to 2019 is consistent with the consumption of renewable energy in the same sector. Among the six types of energy described above, it is judged that there is no fuel that can be classified as renewable energy consumption except for biofuels and waste.

<sup>12</sup> Korea and the EU are also consuming primary solid biomass as biofuel in the non-metallic mineral manufacturing sector.

Fuel-specific consumption ( $E_i$ ) is the consumption of each energy consumed in non-metallic mineral manufacturing described above, and total fuel consumption ( $E$ ) is the sum of  $E_i$ . The fuel consumption trend for non-metallic mineral manufacturing in Thailand is illustrated in Figure 4-1-(a), and the fuel consumption ratio in 2020 is depicted in [Figure 4-1-(b)].

Furthermore, this study assumes that the fuel composition in 2050 remains the same as that in 2020 in terms of projecting the baseline GHG emissions for the cement industry<sup>13</sup>. In other words, the GHG emission levels in 2050 was estimated based on the current fuel usage practices, and then assessed the change in GHG emissions when hydrogen is adopted and there is a shift in the fuel composition in the future.

**[Figure 4-1] Fuel consumption trends and share of non-metallic minerals manufacturing sector (2020)**



(a) Trend of fuel consumption by year

(b) Share of consumption by fuel in 2020

Source: Author based on UNSD Energy Balance

### C. Energy Intensity and Production Factor

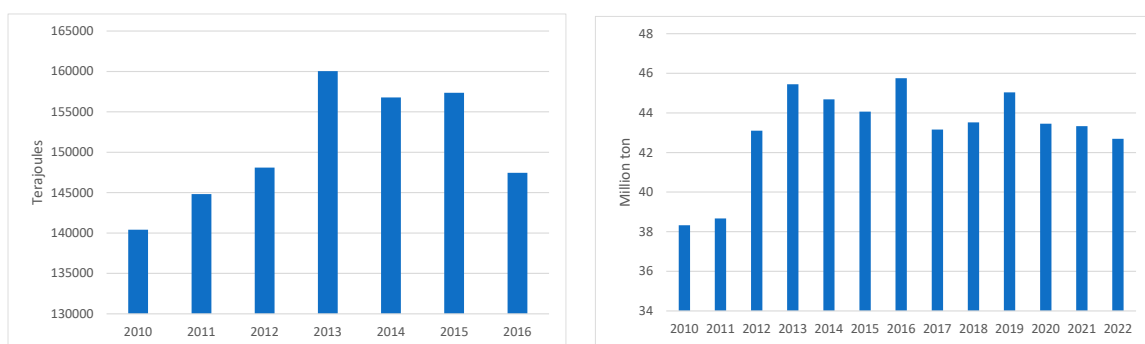
The energy intensity factor ( $E/Q$ ) was calculated by considering the total fuel consumption and cement production in the cement industry, and the cement production was utilized for the production factor ( $Q$ ). It is important to note that the total fuel consumption should correspond specifically to the cement industry, not the overall non-metallic mineral manufacturing sector as mentioned above. Utilizing the total fuel consumption of the non-

<sup>13</sup> Currently, the most up-to-date data available for Thailand in the UNSD Energy Balance database is for 2020.

metallic mineral manufacturing sector could lead to an overestimation of fuel consumption per unit of cement.

The total fuel consumption (E) of the cement industry was utilized by converting the energy consumption (ktoe) from 2010 to 2016 calculated by Vorayos et al. (2020) into terajoules. For cement production (Q), the values from 2010 to 2015 were taken from Vorayos et al. (2020), and the values from 2016 to 2022 were taken from the annual data of cement production from the Monthly Industry Statistics published by the Office of Industrial Economics<sup>14</sup>. The trend in total fuel consumption for the Thai cement industry on a yearly basis is illustrated in Figure 4-2-(a), while the cement production trend is depicted in [Figure 4-2-(b)]. Additionally, based on this data, the energy intensity of the cement industry is calculated and shown in [Figure 4-3].

**[Figure 4-2] Fuel consumption and production trend of the cement industry**



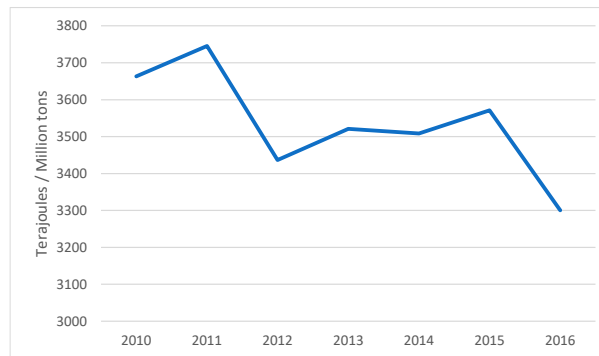
(a) Total fuel consumption trend by year

(b) Trend of cement production by year

Source: Vorayos et al. (2020) and by the author based on The Office of Industrial Economics

<sup>14</sup> The sum of codes 10 (Portland cement), 20 (Mixed cement), and 30 (Various kinds of cement) of TSIC 23941 (Manufacture of cement) were used.

**[Figure 4-3] Energy intensity trends in the cement industry**



Source: Vorayos et al. (2020) and author calculations based on The Office of Industrial Economics data

In this study, the energy intensity factor ( $E/Q$ ) and the production factor ( $Q$ ) were modeled and estimated using econometric techniques, and projections were made for the values in 2050 based on the estimated models. To estimate the production factor ( $Q$ ), which represents cement production, based on the monthly production from January 2016 to March 2023, it was assumed that the decreasing trend during the period follows a logistic function with a left-right symmetry in production over time, as shown in Equation 4-3.

$$Q_t = L / (1 + \exp(-b(\text{time}_t - c))) + u_t \text{ (Equation 4-3)}$$

Where  $Q_t$  is the monthly cement production,  $u_t$  is the disturbance term, and  $L$ ,  $b$ , and  $c$  are the coefficients to be estimated.  $\text{time}_t$  is the independent variable in the logistic function and can take values from 1 to 87<sup>15</sup>.  $L$  is the upper limit of the logistic function,  $b$  is the logistic growth rate, and  $c$  is the midpoint of the logistic function. In this study, the logistic function is estimated assuming that the upper bound of the logistic function is fixed at the Thai cement production capacity<sup>16</sup> (5.71 million tons) to reflect the characteristics of Thai cement production. The results of the logistic function estimation show that all coefficients are statistically significant at the 5% level of significance (<Table 4-3>).

<sup>15</sup> When estimating the logistic function, time was coded as 1 from January 2016, and the total number of observations is 87 by March 2023.

<sup>16</sup> This corresponds to the latest monthly cement production capacity (value for March 2023) presented in Monthly Industry Statistics published by The Office of Industrial Economics.

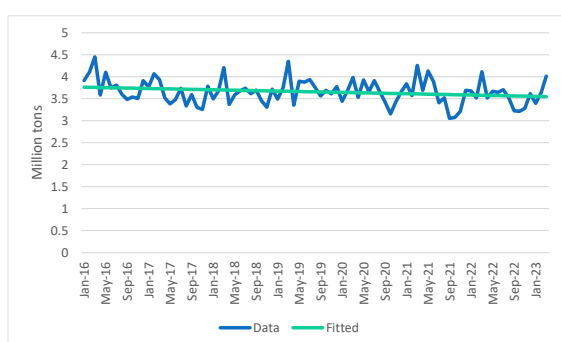
<Table 4-3> Result of Thailand cement production function estimation

Coefficient	Estimated value	Standard Error	t-statistics	P-value	R-squared
b	0.002	0.001	2.11	0.038	0.9945
c	-348.222	144.605	-2.41	0.018	

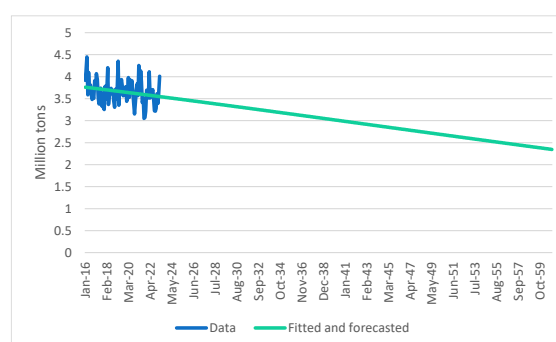
Source: Author analysis

The results of performing long-term projections based on the estimated cement production function are shown in [Figure 4-4]. Monthly cement production is expected to be around 2.7million tons in 2050, and total cement production in 2050 is expected to be around 32 million tons, a decrease of around 10 million tons compared to the production in 2022.

[Figure 4-4] Long-term projection for cement production in Thailand



(a) Comparison between data and estimation model



(b) Long-term trends in cement production

Source: The Office of Industrial Economics data and author analysis

The energy intensity factor (E/Q) in this study is assumed to follow a learning curve for cumulative cement production, representing the learning effect or increased efficiency in energy usage as Thailand continues to produce cement. Equation 4-4 describes this relationship:

$$(E/Q)_t = a \times Q_{cum,t}^b + u_t \quad (\text{Equation 4-4})$$

In the equation,  $(E/Q)_t$  represents the energy intensity by year,  $Q_{cum,t}$  is the cumulative cement production by year, and  $u_t$  is the disturbance term. The coefficients 'a' and 'b' are to be estimated, with b representing the learning rate.

To estimate the learning curve, actual energy intensity data from 2010 to 2016, as well as projected energy intensity for 2030 and 2050, were considered. Projections from the European Cement Research Academy indicate an expected thermal energy consumption of 3,300 to 3,400 MJ per ton of clinker produced in 2030, and 3,150 to 3,250 MJ in 2050. Additionally, electricity consumption is projected to be 96 kWh per ton of cement in 2030, and 86.4 to 91.2 kWh in 2050. Based on these figures, the median values were used, resulting in projected energy intensities of 3,548.6 TJ per ton in 2030 and 3,378.1 TJ per ton in 2050<sup>17</sup>. This study assumed that Thailand also has this trend in long run, and used the energy intensity of 2030 and 2050 for model estimation.

The results of estimating the learning curve for energy intensity based on cumulative cement production are presented in Table 4-4. Coefficient a is significant at the 1% level of significance, while coefficient b is significant at the 10% level. The long-term forecasts using the estimated learning curve are illustrated in Figure 4-5. However, a limitation of this study is the relatively limited number of observations for estimating the learning curve, which affects the reliability of the results. Obtaining more reliable estimation results would be possible with a larger dataset of total monthly fuel consumption for the Thai cement industry.

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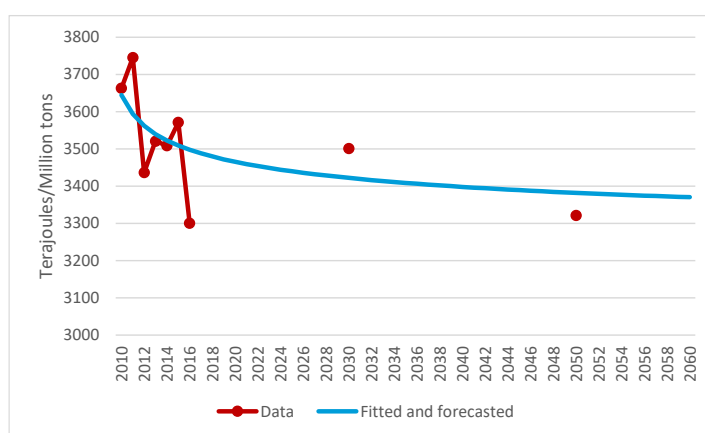
<sup>17</sup> When converting clinker production into cement production, a clinker-to-cement ratio of about 0.7 to 0.8 is usually used. For example, consuming energy as much as A in producing 1 ton of clinker can be said to be equivalent to consuming energy as much as A\*clinker-to-cement ratio in producing 1 ton of cement. However, in Thailand, not all of the clinker produced is used for domestic cement production, but some production is exported, so it is judged that the clinker production and cement production statistics do not follow the normal clinker-to-cement ratio. In this study, in order to reflect the fuel consumed when producing clinker to be exported overseas, the ratio of clinker production to cement production, 0.95 as of 2022, based on clinker production and cement production statistics was used.

<Table 4-4> Estimated energy intensity learning curve for cement production in Thailand

Coefficient	Estimated value	Standard Error	t-statistics	P-value	R-squared
a	3920.332	222.839	17.59	0.000	0.9991
b	-0.020	0.010	-1.92	0.096	

Source: Author analysis

[Figure 4-5] Long-term outlook for energy intensity of cement production in Thailand



Source: Vorayos et al. (2020), The Office of Industrial Economics data and author analysis

#### D. Clinker carbon dioxide intensity factor

The clinker carbon dioxide intensity factor (CIPPU/Qclinker) is a carbon dioxide emission factor for clinker production, similar to the carbon dioxide intensity factor for energy combustion (Ci/Ei). According to the IPCC 2006 guidelines, the default emission factor for clinker production is 0.5071 tons of carbon dioxide emitted per ton of clinker produced. This study assumes that this emission factor remains constant until 2050.

#### E. Clinker Production Factor

The clinker production factor ( $Q_{clinker}$ ) is the clinker production volume. Monthly data on clinker production from the Monthly Industry Statistics published by The Office of Industrial Economics is used to calculate the annual clinker production volume. Long-term projections of clinker production are not estimated separately using econometric techniques, but are based on the projected cement production.

As discussed in footnote above, clinker production can be estimated by multiplying cement production by the clinker-to-cement ratio if all domestically produced clinker is utilized in domestic cement production. However, since Thailand not only utilizes clinker for domestic cement production, but also exports it, applying a typical clinker-to-cement ratio could underestimate clinker production and, consequently, underestimate carbon dioxide emissions from the industrial process. Data from the Monthly Industry Statistics indicate that the ratio of clinker production to cement production ranges from 0.81 to 1.00.

This study estimates clinker production using the ratio of clinker production to cement production rather than the clinker-to-cement ratio, and assumes that the 2022 value of 0.95 is constant in the long term. This implies that as cement production in Thailand decreases, clinker production in Thailand will also decrease at a constant rate.

#### F. Cement Kiln Dust Factor

The cement kiln dust factor (CKD) accounts for the impact of cement kiln dust generated during clinker production on carbon dioxide emissions. The default value of 1.02 provided in the 2006 IPCC guidelines is used as the cement kiln dust correction factor and assumed to remain constant until 2050, similar to the fuel-specific carbon dioxide emission factors and clinker carbon dioxide emission factors.

### **3. Hydrogen Utilization Scenario**

A total of five scenarios for hydrogen utilization in the cement industry were developed, considering the varying rates of hydrogen substitution for coal ranging from 20% to 100%. Based on the data from 2020, coal consumption accounts for approximately 77% of the total fuel consumption in Thailand's non-metallic mineral manufacturing industry. Therefore, this study identifies coal as the most critical fuel to be replaced to reduce GHG emissions in the Thai cement industry, and the scenarios were developed accordingly. The share of consumption by fuel in the cement industry based on the hydrogen utilization scenarios is presented in <Table 4-6>.

**<Table 4-5> Hydrogen Utilization Scenarios in Thailand's Cement Industry**

Scenario Number	Description
CS1	By 2050, hydrogen replaces primary coal and peat by 20%.
CS2	By 2050, hydrogen replaces primary coal and peat by 40%.
CS3	By 2050, hydrogen replaces primary coal and peat by 60%.
CS4	By 2050, hydrogen replaces primary coal and peat by 80%.
CS5	By 2050, hydrogen replaces primary coal and peat by 100%.

Source: Author

**<Table 4-6> Fuel Consumption Proportion (%) by Hydrogen Utilization Scenario in Thailand's Cement Industry**

Scenario	Hydrogen	Primary coal and peat	Coal and peat products	Oil products	Natural Gas	Biofuels and waste	Electricity
Base	-	77.06	0.46	4.13	10.85	0.92	6.58
CS1	15.41	61.65	0.46	4.13	10.85	0.92	6.58
CS2	30.83	46.23	0.46	4.13	10.85	0.92	6.58
CS3	46.24	30.82	0.46	4.13	10.85	0.92	6.58
CS4	61.65	15.41	0.46	4.13	10.85	0.92	6.58
CS5	77.06	0	0.46	4.13	10.85	0.92	6.58

Source: Author

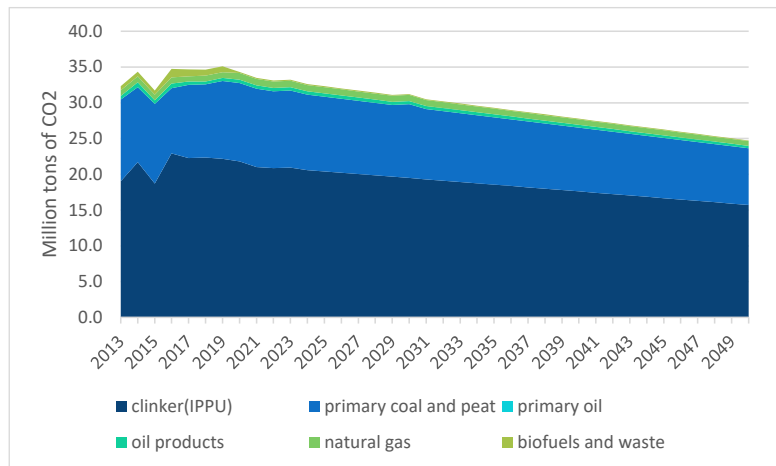
#### **4. Climate Benefit Estimation**

##### **A. The result of GHG emission threshold estimation**

Based on the above equation and the available data, the results of GHG emission baseline estimation in the Thai cement industry are presented in Figure 4-6. It is anticipated that carbon dioxide emissions from the industry will continue to decline, primarily due to a decrease in cement production and improvements in energy intensity. In 2013, the industry emitted a total of 32.3 million tons of carbon dioxide, consisting of 13.3 million tons from fuel combustion and 19.0 million tons from industrial processes. By 2050, it is projected that the

industry will emit a total of 24.8 million tons of carbon dioxide, with 9.1 million tons from fuel combustion and 15.7 million tons from industrial processes<sup>18</sup>.

**[Figure 4-6] Forecasts of carbon dioxide emissions from Thailand's cement industry (BAU)**



Source: Author

## B. GHG reduction and climate benefit estimation results

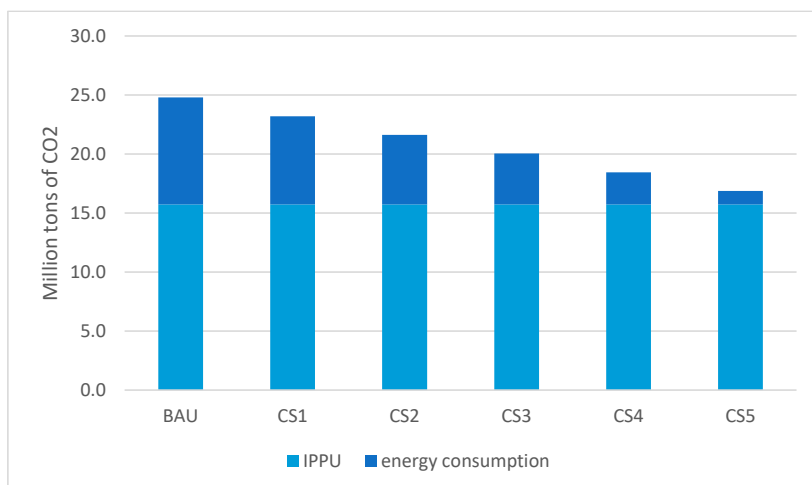
The carbon dioxide emissions by 2050 according to the hydrogen utilization scenario in the cement industry are shown in Figure 4-7, and the carbon dioxide reduction and climate benefits are summarized in Table 4-7. Not surprisingly, total carbon dioxide emissions decrease as the share of hydrogen utilization in the cement industry increases. Hydrogen replacing coal by 20% would result in a reduction of 1.6 million tons of carbon dioxide in 2050 compared to the baseline, equating to a 6.4% decrease in carbon dioxide emissions. Conversely, completely replacing coal with hydrogen would lead to a reduction of approximately 7.9 million tons (31.9%).

In terms of climate benefits, if hydrogen replaces 20% of coal in 2050, the estimated value amounts to around 37,179 million Baht (\$1,162 million). Similarly, if hydrogen replaces 100%

<sup>18</sup> According to Thailand's Fourth Biennial Update Report submitted by Thailand to the UNFCCC in 2022, IPPU emissions from cement production as of 2019 were 18.5 million tons. Thus, the 22.2 million tons of IPPU emissions in 2019 in this study were overestimated by about 3.7 million tons.

of coal, the estimated climate benefits are approximately 185,893 million Baht (\$58.11 million).

**[Figure 4-7] GHG emissions from hydrogen utilization in the cement industry (2050)**



Source: Author

**<Table 4-7> GHG reduction and climate benefits of hydrogen utilization in the cement industry (2050)**

Scenario	Emissions (million tons of CO <sub>2</sub> )			Reduction (million tons of CO <sub>2</sub> , %)		Climate benefit (million)	
	energy consumption	IPPU	Total	Amount	ratio	Baht*	USD*
Bow	9.1	15.7	24.8	-	-	-	-
CS1	7.5	15.7	23.2	1.6	6.4	37,179	1,162
CS2	5.9	15.7	21.6	3.2	12.8	74,357	2,324
CS3	4.3	15.7	20.0	4.8	19.2	111,536	3,487
CS4	2.7	15.7	18.4	6.3	25.6	148,714	4,649
CS5	1.2	15.7	16.9	7.9	31.9	185,893	5,811

\* Exchange rate: 31.9907 THB/USD (as of 2021)

Source: Author

## Section 3. Oil Refining Business

### 1. Setting up the equation

To estimate the GHG emission threshold of the Thai refinery industry, this study utilized the adjusted Kaya Identity as shown in Equation 4-5.

$$C = \sum C_i/E_i \times E_i/E \times E/Q \times Q \text{ (Equation 4-5)}$$

The carbon dioxide emissions (C) of the refinery industry are divided into four factors: carbon dioxide intensity factors ( $C_i/E_i$ ), fuel composition factor ( $E_i/E$ ), energy intensity factor ( $E/Q$ ), and throughput factor (Q). Similar to the cement industry, the carbon dioxide intensity factor is defined as the ratio of carbon dioxide emissions ( $C_i$ ) to fuel consumption ( $E_i$ ) for each fuel. The fuel composition factor represents the proportion of fuel consumption ( $E_i$ ) for each fuel relative to the total fuel consumption (E). The energy intensity factor ( $E/Q$ ) is the total energy consumption per unit of crude oil processed (Q) in the Thai refinery industry. When other factors remain constant, an increase in energy consumption per unit of crude oil processed leads to an increase in carbon dioxide emissions. The throughput factor (Q) represents the scale of crude oil processing mentioned above.

### 2. Data

To estimate GHG emissions from the refinery industry, it is necessary to project the variables and factors outlined in Equation 4-5. Similar to the cement industry, limited data were available for some variables and factors, requiring the use of indirect estimates.

#### A. Carbon dioxide intensity factor

The carbon dioxide intensity factor ( $C_i/E_i$ ) utilizes fuel-specific carbon dioxide emission factors from the IPCC 2006 guidelines and assumes no change in emission factors until 2050. The types of refinery fuels used in the industry were taken from the Sustainability Report and Performance Summary of Thai Oil Public Company Limited (Thaioil), and it was assumed that the entire Thai refinery industry uses these types of fuels.

Thaioil reports the use of eight fuels in their refinery: natural gas, fuel oil, fuel gas, coke, LPG, diesel, gasoline, and ethanol<sup>19</sup>. The emission factors for each fuel are based on those provided in the IPCC guidelines (<Table 4-8>). Among Thaioil's fuels, fuel gas was linked to refinery gas, which is the most consumed petroleum product in the industry in the Korean and EU cases. Additionally, coke and ethanol were associated with petroleum coke and ethane, based on the EU cases.

**<Table 4-8> Emission Factors in Thailand's Oil Refining Sector**

Fuel (Thaioil)	Representative Fuel (IPCC 2006 Guideline)	CO2 Emission factor (IPCC 2006 Guidelines)
natural gas	natural gas	56,100kgCO <sub>2</sub> /TJ
fuel oil	residual fuel oil	77,400kgCO <sub>2</sub> /TJ
fuel gas	refined gas	57,600kgCO <sub>2</sub> /TJ
Cola	petroleum coke	97,500kgCO <sub>2</sub> /TJ
LPG	LPG	63,100kgCO <sub>2</sub> /TJ
diesel	gas/diesel oil	74,100kgCO <sub>2</sub> /TJ
Gasoline	Motor gasoline	69,300 kgCO <sub>2</sub> /TJ
Ethanol	Ethane	61,600 kgCO <sub>2</sub> /TJ

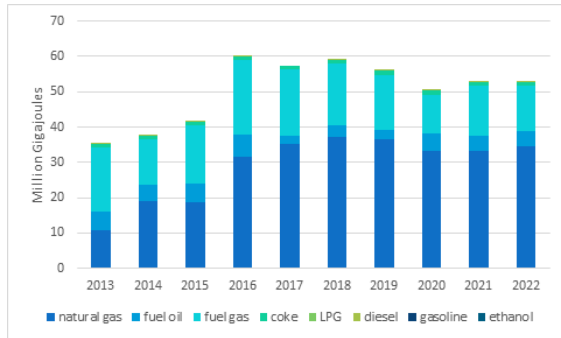
Source: IPCC (2006)

## B. Fuel Composition Factor

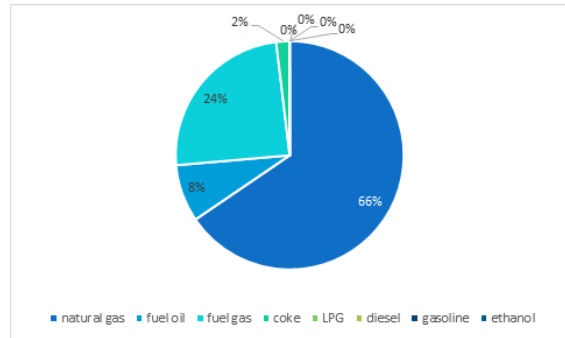
The fuel composition ( $E_i/E$ ) of Thailand's refinery GHG emissions was assumed to be the same as Thaioil's fuel composition as described above, and Thaioil's fuel consumption ( $E_i$ ) was used to calculate the share of each fuel. Thaioil's fuel consumption by year is shown in [Figure 4-8-(a)], and the fuel composition in 2022 is shown in Figure 4-8-(b). This study assumes that the fuel mix in 2022 will remain the same until 2050 to project GHG emissions from the refinery.

<sup>19</sup> However, as described in the fuel composition factors, gasoline, ethanol, and LPG are used less than other fuels according to thaioil's report, so their fuel composition ratio is 0%.

**[Figure 4-8] Fuel Consumption Trend and Share in the Oil Refining Industry (Thaioil) (2022)**



(a) Trend of fuel consumption by year



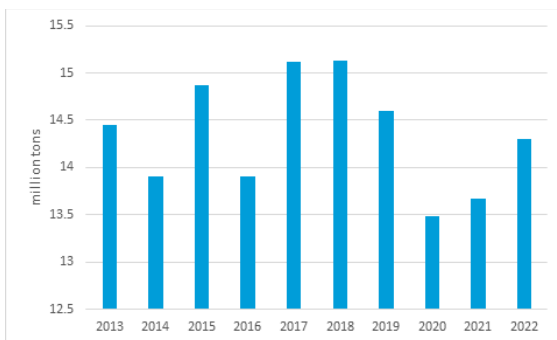
(b) Share of consumption by fuel in 2022

Source: Author based on Thaioil (2014; 2018; 2022)

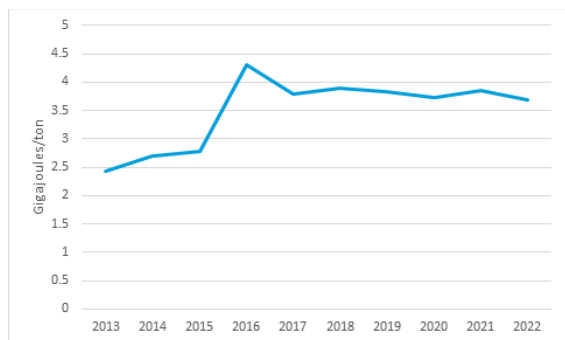
### C. Energy Intensity Factor and Throughput Factor

The energy intensity factor ( $E/Q$ ) is derived by dividing Thaioil’s total fuel consumption ( $E$ ) by its crude oil throughput. It is assumed that the energy intensity of the Thai refinery industry follows the energy intensity pattern observed in Thaioil. Thaioil’s total fuel consumption is determined based on the previously described consumption data for each fuel type, while Thaioil’s crude oil throughput is obtained from their Sustainability Report and Performance Summary. Figure 4-9 illustrates Thaioil’s crude oil throughput and the corresponding energy intensity over the years.

**[Figure 4-9] Thaioil’s crude oil throughput and energy intensity**



(a) Crude oil throughput by year



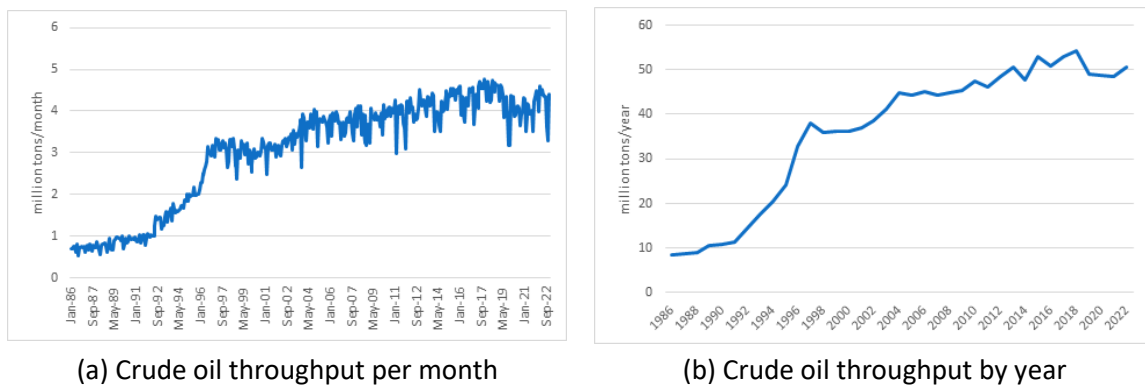
(b) Energy intensity trend

Source: Author based on Thaioil (2014; 2018; 2022)

Meanwhile, the total crude oil throughput ( $Q$ ) of the Thai refining industry can be found in

Petroleum Statistics from the Energy Policy and Planning Office of the Thai Ministry of Energy. Petroleum Statistics provides Thailand's crude oil material intakes by month and year. The statistics provide crude oil throughput in barrels per day, and this study converts monthly and yearly crude oil throughput into mass units (million tons/month and million tons/year). Thailand's monthly crude oil throughput and annual crude oil throughput are shown in [Figure 4-10].

[Figure 4-10] Trends in crude oil throughput in Thailand



Source: Author based on Petroleum Statistics

Similar to the cement industry, we used econometric techniques to estimate models describing energy intensity ( $E/Q$ ) and crude oil throughput ( $Q$ ) for the refining industry and projected values for 2050. Crude oil throughput ( $Q$ ) was assumed to have an upward trend from January 1986 to December 2022, as shown in [Figure 4-10-(a)], and to follow a logistic function over time as shown in Equation 4-6.

$$Q_t = L / (1 + \exp(-b(\text{time}_t - c))) + u_t \text{ (Equation 4-6)}$$

In Equation 4-6,  $Q_t$  is the monthly crude oil throughput of Thai refineries,  $\text{time}_t$  is an independent variable with values ranging from 1 (January 1986) to 444 (December 2022), and  $u_t$  is the disturbance term. The coefficients to be estimated are  $L$ ,  $b$ , and  $c$ . However, the upper bound of the logistic function,  $L$ , is assumed to be fixed at the refining capacity of Thai refineries. According to the Energy Policy and Planning Office, Thailand's refining capacity in 2023 is 1,243,600 bbl/day, which translates to about 61.7 million tons of annual capacity in mass units. This study assumes that the annual capacity of 61.7 million tons divided by 12 is

the upper limit of the amount of crude oil that can be processed per month, that is L. It is assumed that there is no expansion or reduction of the capacity in the long run. The results of the logistic function estimation are shown in Table 4-9, with all coefficients estimated to be significant at the 1% level of significance.

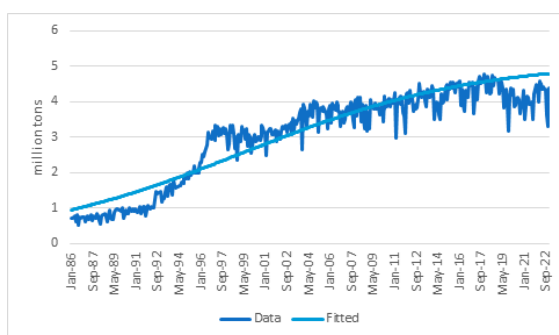
<Table 4-9> Results of Thai crude oil throughput function estimation

Coefficient	Estimated value	Standard Error	t-statistics	P-value	R-squared
b	0.009	0.000	41.64	0.000	0.9819
c	161.103	2.350	68.56	0.000	

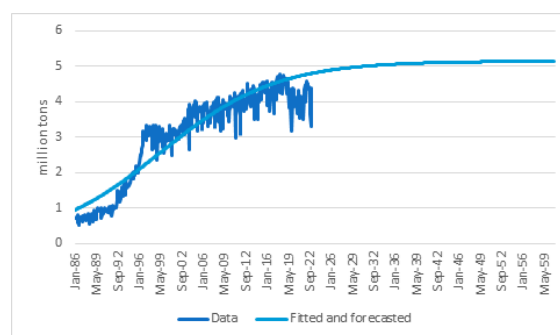
Source: Author analysis

The results of long-term forecasting using the estimated crude oil throughput function are shown in [Figure 4-11]. Thailand's monthly crude oil processing capacity in 2050 is expected to be about 5.1 million tons, an increase of about 0.3 million tons from the level of 4.8 million tons in 2022, and the annual crude oil processing capacity is expected to be about 61.5 million tons.

[Figure 4-11] Long-term outlook for oil refinery throughput in Thailand



(a) Comparison between data and estimation model



(b) Long-term trend of refinery throughput

Source: The Office of Industrial Economics data and author analysis

The energy intensity factor (E/Q) of the refinery industry is assumed to be the same as that of the cement industry, with a decreasing energy intensity due to the learning effect of

cumulative crude oil processing. As shown in [Figure 4-9-a], the energy intensity of the refinery industry increased until 2016, after which it decreased with a low slope. This study assumes that the energy intensity (E/Q) of refining follows a learning curve after 2016. The learning curve model for cumulative crude oil throughput ( $Q_{cum,t}$ ) is shown in Equation 4-7, where  $u_t$  is the disturbance term and  $a$  and  $b$  are the coefficients to be estimated.

$$(E/Q)_t = a \times Q_{cum,t}^b + u_t \text{ (Equation 4-7)}$$

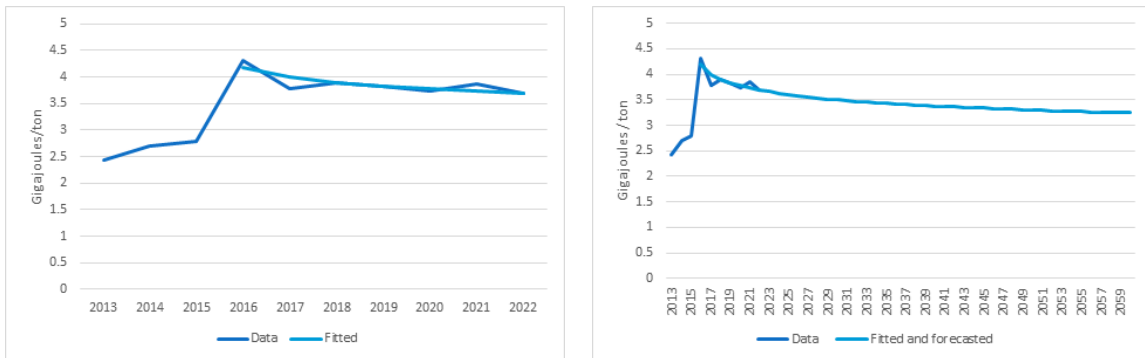
The result of estimating Equation 4-7 is shown in <Table 4-10>. The coefficients  $a$  and  $b$  are estimated to be significant at the 1% and 5% significance levels, respectively, and the energy intensity of the refining industry is found to decrease by about 6.5% for a 1% increase in cumulative crude oil throughput. If Thailand's refinery throughput projections are converted to annualized values and the estimated learning curve is used to project energy intensity through 2050, the projections are shown in Figure 4-12. However, the learning curve for energy intensity in the refining industry is estimated from a considerably sparse set of observations, making the estimation somewhat unreliable. More reliable results would be obtained if sufficient information on historical energy intensity were available or if monthly fuel consumption data were available.

**<Table 4-10> Result of estimating the energy intensity learning curve of Thailand's oil refining industry**

Coefficient	Estimated value	Standard Error	t-statistics	P-value	R-squared
a	5.389	0.519	10.41	0.000	0.9993
b	-0.065	0.019	-3.46	0.018	

Source: Author analysis

[Figure 4-12] Long-term Forecasts for Energy Intensity in Thailand's Oil Refining Industry



(a) Comparison between data and estimation model

(b) Long-term trends in energy intensity

Source: Author writing and analysis based on Thairoil (2014; 2018; 2022)

### 3. Hydrogen Utilization Scenario

A total of five hydrogen utilization scenarios for the refinery industry were developed according to the substitution rate of hydrogen for natural gas (20% to 100%) (see <Table 4-11>). Based on Thairoil's fuel consumption, the share of natural gas consumption in 2022 is the main fuel, accounting for about 65% of the total fuel consumption. Therefore, to reduce the proportion of natural gas consumption to reduce GHG emissions in the Thai refinery industry, this study constructed a scenario in which part of the natural gas input is replaced with hydrogen, and a mixture of natural gas and hydrogen can be utilized. The consumption shares of each fuel according to hydrogen utilization in the refinery industry are shown in <Table 4-12>.

<Table 4-11> Hydrogen Utilization Scenarios in the Thai Oil Refining Industry

Scenario Number	Description
RS1	By 2050, hydrogen replaces natural gas by 20%.
RS2	By 2050, hydrogen replaces natural gas by 40%.
RS3	By 2050, hydrogen replaces natural gas by 60%.
RS4	By 2050, hydrogen replaces natural gas by 80%.
RS5	By 2050, hydrogen replaces natural gas by 100%.

Source: Author

**<Table 4-12> Fuel Consumption Proportion (%) according to Hydrogen Utilization Scenarios  
in Thai Oil Refining Industry**

Scenario	Hydrogen	Natural gas	Fuel oil	Fuel gas	Coke	LPG	Diesel	Gasoline	Ethanol
Base	-	65.28	8.10	24:40	1.86	0.00	0.04	0.00	0.00
RS1	13.05	52.23	8.10	24:40	1.86	0.00	0.04	0.00	0.00
RS2	11.26	39.17	8.10	24:40	1.86	0.00	0.04	0.00	0.00
RS3	39.17	26.11	8.10	24.40	1.86	0.00	0.04	0.00	0.00
RS4	52.22	13.06	8.10	24.40	1.86	0.00	0.04	0.00	0.00
RS5	65.28	0.00	8.10	24.40	1.86	0.00	0.04	0.00	0.00

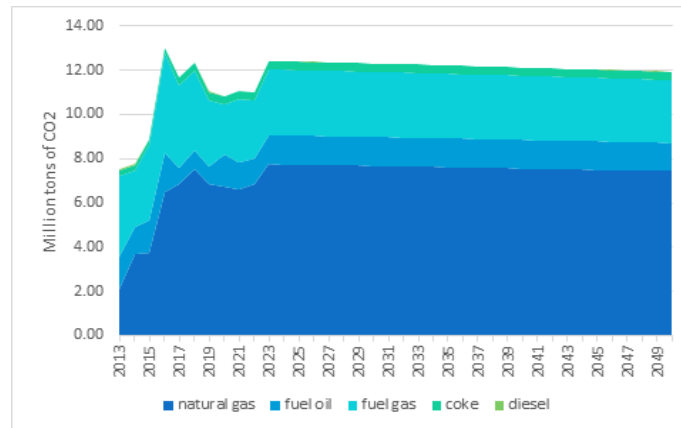
Source: Author

#### **4. Climate benefit estimation results**

##### **A. GHG Emissions Threshold Estimation Results**

Based on the equation for carbon dioxide emissions from the refining industry described above and the long-term projections of each factor and variable, the results of estimating the threshold for carbon dioxide emissions from the refining industry are shown in Figure 4-13. Carbon dioxide emissions from refineries in Thailand increased by about 46.6% from about 7.5 million tons in 2013 to about 11.0 million tons in 2022. From 2023 to 2050, carbon dioxide emissions from the refinery industry are expected to decrease slowly but gradually, reaching about 11.9 million tons of carbon dioxide in 2050, an increase of about 8.6% from 2022.

[Figure 4-13] Forecasts for carbon dioxide emissions from oil refining in Thailand (BAU)



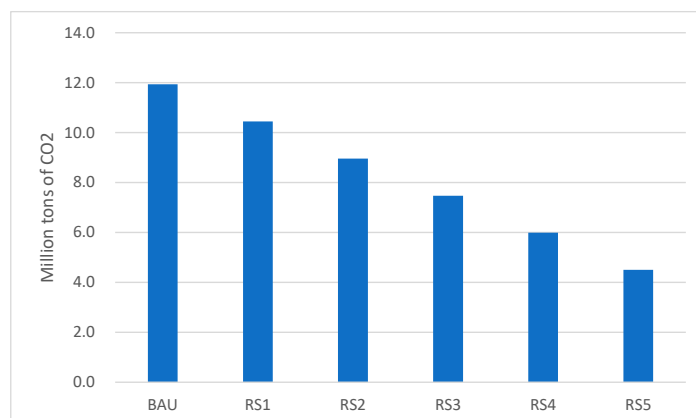
Source: Author

## B. GHG Reduction and Climate Benefit Estimation Results

The carbon dioxide emissions in 2050 for each hydrogen utilization scenario in the refining industry are shown in Figure 4-14, and the reduction amount, reduction rate, and climate benefits for each scenario are summarized in Table 4-12. If hydrogen replaces 20% of the natural gas used in refining, it is expected to reduce GHG emissions by about 1.5 million tons (12.5%). In this case, the climate benefit is estimated to be about 34,918 million baht (US\$10,092 million). Furthermore, the full replacement of natural gas with hydrogen is expected to reduce GHG emissions by 7.4 million tons (62.3%), with an estimated climate benefit of 174,592 million baht (\$5,458 million)<sup>20</sup>.

<sup>20</sup> According to Thailand's Fourth Biennial Update Report, emissions from petroleum refining in 2019 were 9.5 million tons, and the 11.0 million tons of oil refining emissions in 2019 in this study were overestimated by about 1.5 million tons.

**[Figure 4-14] GHG Emissions from Hydrogen Utilization in the Oil Refining Industry (2050)**



Source: Author

**<Table 4-13> Greenhouse gas reduction and climate benefits according to hydrogen utilization in the oil refinery (2050)**

Scenario	Emissions (million tons of CO <sub>2</sub> )	Reduction (million tons of CO <sub>2</sub> , %)		Climate Benefit (millions)	
	Total	Amount	Rate	in THB*	in USD*
BAU	11.9	-	-	-	-
RS1	10.4	1.5	12.5	34,918	1,092
RS2	9.0	3.0	24.9	69,837	2,183
RS3	7.5	4.5	37.4	104,755	3,275
RS4	6.0	5.9	49.8	139,673	4,366
RS5	4.5	7.4	62.3	174,592	5,458

\* Exchange rate: 31.9907 THB/USD (in 2021)

Source: Author

## Section 4. Road Transport Sector

### 1. Setting up the equation

This study utilizes the adjusted Kaya Identity for the road transportation sector in Thailand as shown in Equations 4-8.

$$C = \sum C_i/E_i \times E_i/V_i \times V_i/V \times V/G \times G/P \times P \text{ (Equation 4-8)}$$

The carbon dioxide emission (C) of the road transportation sector is established by an equation with five factors: carbon dioxide intensity factor ( $C_i/E_i$ ), fuel consumption factor by vehicle type ( $E_i/V_i$ ), vehicle type composition factor ( $V_i/V$ ), vehicle intensity factor ( $V/G$ ), economic growth factor ( $G/P$ ), and population factor (P). The carbon dioxide intensity factor ( $C_i/E_i$ ) is defined as the ratio of carbon dioxide emissions ( $C_i$ ) to consumption ( $E_i$ ) of each fuel in the road transport sector, the same as in the cement and oil refining industries. The fuel consumption factor by vehicle type is the amount of fuel consumed ( $E_i$ ) per vehicle ( $V_i$ ) that consumes fuel i. When other factors are constant, carbon dioxide emissions increase as the amount of fuel consumed per vehicle increases. The vehicle type composition factor ( $V_i/V$ ) is the proportion of vehicles, that consume fuel i, in the Thai road transportation sector. As the proportion of fossil fuel vehicles increases, carbon dioxide emissions will increase. The vehicle intensity factor ( $V/G$ ) is defined as the total number of vehicles (V) relative to GDP (G), a factor that indicates the number of vehicles relative to the scale of Thailand's economy. All other factors being equal, a higher number of vehicles relative to the scale of the economy will result in higher carbon dioxide emissions. The economic growth factor ( $G/P$ ) refers to Thailand's GDP per capita and reflects the phenomenon that as Thailand's economy grows, the demand for road transportation services increases, which in turn increases carbon dioxide emissions. Finally, the population factor (P) is the population of Thailand, and as the population grows, the number of people using road transportation services increases, resulting in an increase in carbon dioxide emissions from the road transportation sector.

### 2. Data

In order to estimate the baseline GHG emissions of the road transport sector and the GHG reduction by utilizing hydrogen, the data and long-term projections for each variable and factor in Equation 4-8 were constructed as follows.

#### A. Carbon dioxide intensity factor

For the carbon dioxide intensity factor ( $C_i/E_i$ ), the emission factors specified in the IPCC emission factor guidelines were applied, the same as for the cement and oil refinery analysis cases, and no change in emission factors was assumed until 2050. The types of fuels consumed in Thailand's road transportation sector are based on the Monthly Report on Petroleum and Electricity Consumption published by the Energy Policy and Planning Office of Thailand, which classifies vehicle fuels as gasoline, diesel, LPG, natural gas, and electricity. The IPCC basic emission factors for the above fuels are summarized in <Table 4-14>. Since this study only calculates direct emissions from fuel consumption, it does not consider GHG emissions from electricity use.

**<Table 4-14> Emission Factors for Road Transport in Thailand**

Fuel (EPPO)	Representative Fuel (IPCC 2006 Guideline)	CO <sub>2</sub> Emission factor (IPCC 2006 Guideline)
Gasoline	Motor Gasoline	69,300 kgCO <sub>2</sub> /TJ
Diesel	Gas/diesel oil	74,100 kgCO <sub>2</sub> /TJ
LPG	Liquefied petroleum gas	63,100 kgCO <sub>2</sub> /TJ
Natural gas	Natural gas	56,100 kgCO <sub>2</sub> /TJ
Electricity	-	-

Source: IPCC (2006)

#### B. Fuel Consumption Factor by Vehicle Type

To build the fuel consumption factor ( $E_i/V_i$ ) data by vehicle type, consumption by fuel ( $E_i$ ) and number of vehicles by fuel ( $V_i$ ) are required. In the case of fuel consumption ( $E_i$ ) data for the road transportation sector, it can be found in the Monthly Report on Petroleum and Electricity Consumption published by the Energy Policy and Planning Office mentioned above, and the

consumption expressed in kTOE was converted to terajoules. Consumption of fuel in Thailand's road transportation sector is shown in [Figure 4-15-a].

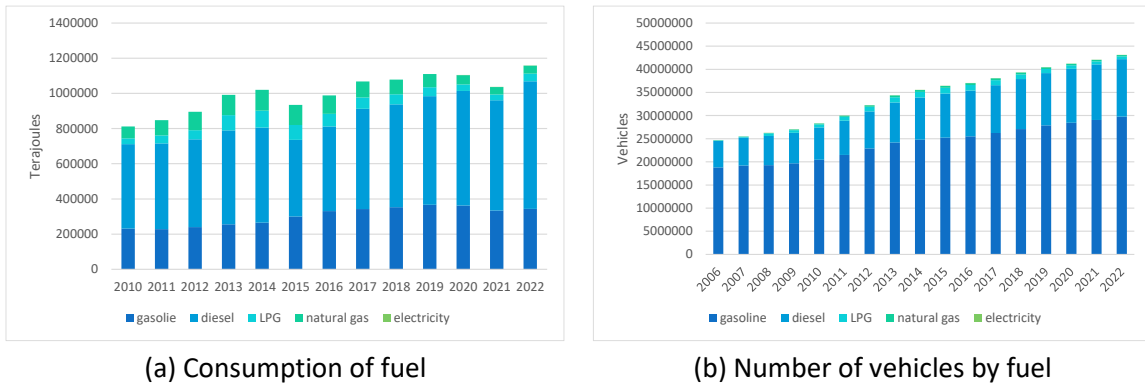
The number of vehicles ( $V_i$ ) by fuel is taken from the vehicle statistics provided by the Department of Land Transport (DLT) in Thailand, using the cumulative number of vehicles at the end of each year. The DLT statistics provide a detailed breakdown of vehicles by fuel type, which needs to be reclassified into the fuel categories of this study: gasoline, diesel, LPG, natural gas, and electricity. This study reclassifies the Department of Land Transport statistics by referring to the number of vehicles by fuel, which is partially provided by the Monthly Report on Petroleum and Electricity Consumption, and the reclassification criteria are shown in Table 4-14. The number of vehicles by fuel in Thailand's road transportation sector based on this study's reclassification is shown in [Figure 4-15-b].

**<Table 4-15> Vehicle Type Reclassification by Fuel**

Fuel	Vehicle (Department of Land Transport)
Gasoline	<ul style="list-style-type: none"> <li>▲ (-2016) Gasoline</li> <li>▲ (2017-2019) Gasoline, Gasoline-Electric, Gasoline-E20, Benzene-Ethanol</li> <li>▲ (2020-2021) Gasoline, Gasoline-Electric, Gasoline-Electric Plug-In, Gasoline-E20, Benzene-Ethanol</li> <li>▲ (2022) gasoline, gasoline-electric, gasoline-electric plug-in, benzene-ethanol</li> </ul>
Diesel	<ul style="list-style-type: none"> <li>▲ (-2016) diesel</li> <li>▲ (2017-2019) diesel, diesel-electric</li> <li>▲ (2020-2022) diesel, diesel-electric, diesel-electric plug-in</li> </ul>
LPG	<ul style="list-style-type: none"> <li>▲ (-2016) LPG, LPG-gasoline, LPG-diesel</li> <li>▲ (2017-2019) LPG, LPG-gasoline, LPG-diesel, LPG-gasoline-electric, LPG-diesel-electric</li> <li>▲ (2020-2022) LPG, LPG-gasoline, LPG-diesel, LPG-gasoline-electric, LPG-diesel-electric, LPG-diesel-electric plug-in</li> </ul>
Natural gas	<ul style="list-style-type: none"> <li>▲ (-2016) CNG, CNG-gasoline, CNG-diesel</li> <li>▲ (2017-2019) CNG, CNG-Gasoline, CNG-Diesel, CNG-LPG, CNG-LPG-Gasoline, CNG-LPG-Diesel, CNG-Gasoline-Electricity, CNG-Diesel-Electricity</li> <li>▲ (2020-2021) CNG, CNG-Gasoline, CNG-Diesel, CNG-LPG, CNG-LPG-Gasoline, CNG-LPG-Diesel,</li> <li>▲ (2022) CNG, CNG-Gasoline, CNG-Diesel, CNG-LPG, CNG-LPG-Gasoline, CNG-LPG-Diesel, LNG</li> </ul>
Electricity	<ul style="list-style-type: none"> <li>▲ (2017-2022) Electricity</li> </ul>
Note	Vehicles classified as non-fuel, not-specified, hybrid, other are excluded.

Source: Author

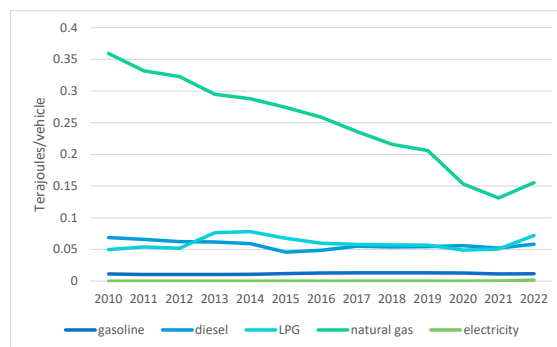
[Figure 4-15] Consumption by Fuel and Number of Vehicles in Road Transport in Thailand



Source: Author based on EPPO and DLT data

[Figure 4-16] shows the fuel consumption factors ( $E_i/V_i$ ) by vehicle type using the consumption amount by fuel ( $E_i$ ) and the number of vehicles by fuel ( $V_i$ ) in Thailand's road transport sector. In this study, it was assumed that the amount of fuel consumed per vehicle would be constant until 2050 with the value in 2022. This means that the characteristics of each vehicle type (place of use and transportation distance, etc.) do not change significantly compared to the current characteristics.

[Figure 4-16] Fuel Consumption Factors by Vehicle Type in Road Transport in Thailand



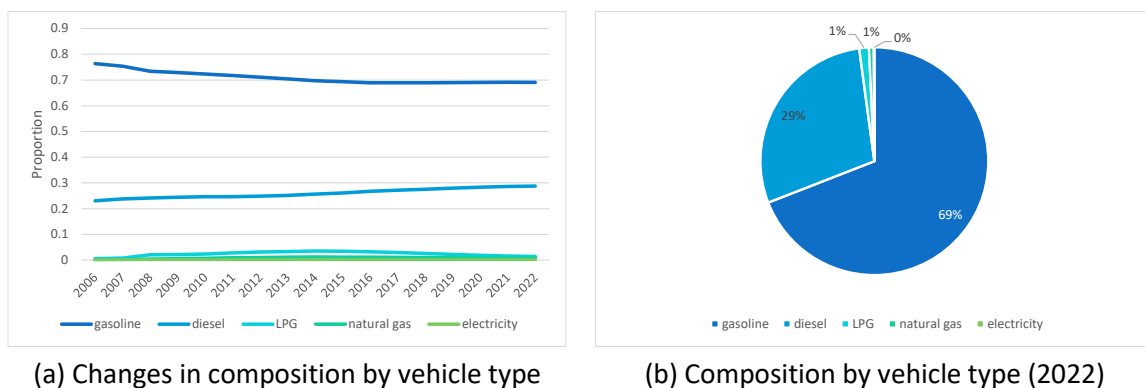
Source: Author calculation based on EPPO and DLT data

### C. Vehicle Type Factor

The vehicle type composition factor ( $V_i/V$ ) can be constructed by utilizing the data reclassified using Table 4-14 based on the statistical data of DLT described above. In this study, non-fuel,

not-specified, hybrid, and other in the statistics were excluded when reclassifying the DLT data, and therefore, when constructing the vehicle type composition ( $V_i/V$ ) data, the excluded vehicle types were excluded to calculate the share of each vehicle type. [Figure 4-17] shows the share of vehicles by fuel type in Thailand's road transportation sector. In projecting the 2050 GHG emission standard, this study assumes that the vehicle type composition will remain the same as the current level, although the total number of vehicles will increase. The vehicle type composition is a key factor in the hydrogen use scenarios for the road transport sector and was used as a factor that changes with the proportion of hydrogen vehicles substituted.

**[Figure 4-17] Composition by vehicle type in Thailand's road transport sector**

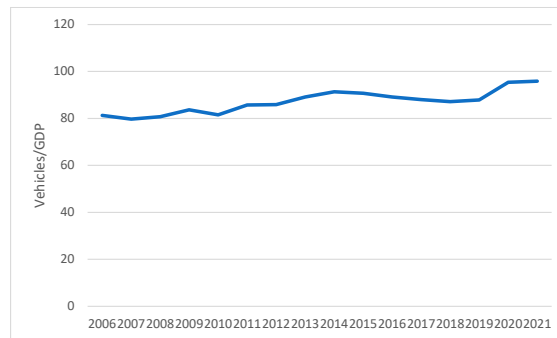


Source: Author calculation based on DLT data

#### D. Vehicle intensity, economic growth, and demographic factors

The vehicle intensity factor ( $V/G$ ) was constructed using data on the total number of vehicles and GDP in Thailand's road transport sector. DLT statistics were used for the total number of vehicles in Thailand's road transport sector, and Thailand's GDP (million US dollars, 2015) data provided by the World Bank was used for GDP. [Figure 4-18 shows vehicle intensity factors based on the two data.

**[Figure 4-18] Trends in vehicle intensity in Thailand**



Source: Author calculation based on DLT and World Bank data

The projections of the vehicle intensity factor (V/G) are based on econometric estimation of a model related to vehicle intensity. The study assumes that the number of vehicles per capita can be expressed as a logistic function of GDP per capita, which is shown in Equation 4-9.

$$(V/P)_t = L / (1 + \exp(-b((G/P)_t - c))) + u_t \text{ (Equation 4-9)}$$

In Equation 4-9, (V/P)<sub>t</sub> is the number of vehicles per capita per year, and (G/P)<sub>t</sub> is GDP per capita. In addition, L, b, and c correspond to the coefficients we want to estimate in the model. After identifying the relationship between the number of vehicles per capita (V/P) and GDP per capita (G/P) through the model in Equations 4-9, this study forecasts the number of vehicles per capita based on the long-term forecast of GDP per capita. Finally, we calculated vehicle intensity (V/G) by dividing the projected number of vehicles per capita by GDP per capita. Therefore, the process of projecting the vehicle intensity factor involves projecting the economic growth factor (G/P) and the population factor (P).

First, the data and estimation results for estimating Equations 4-9 are as follows. GDP per capita is calculated using World Bank's Thailand GDP and Thailand's population as described above (million USD/person), and the number of vehicles per capita is calculated using DLT's vehicle statistics and the population (vehicle/person). The results of estimating Equations 4-9 based on the above data are shown in Table 4-14, where L and b are significantly estimated at the 1% significance level and a is significantly estimated at the 5% significance level. However, the estimation results of the number of vehicles per capita function in Thailand are

estimated using a small number of observations (2009-2021 annual data), so the reliability of the estimation results is somewhat lacking. It is expected that more reliable estimation results can be obtained when sufficient time series data can be constructed.

**<Table 4-16> Result of estimating the number of vehicles per capita in Thailand**

Coefficient	Estimated value	Standard Error	t-statistics	P-value	R-squared
L	0.710	0.093	7.66	0.000	0.9989
a	891.516	370.396	2.41	0.037	
b	0.005	0.000	25.79	0.000	

Source: Author analysis

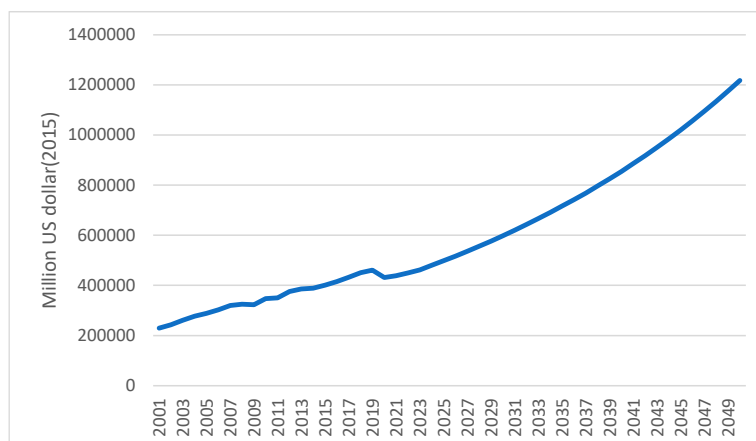
Next, to forecast the number of vehicles per capita, the forecast for GDP per capita is needed, and this study made a forecast using the projections for GDP growth rate and population growth rate. According to Thailand's Office of the National Economic and Social Development Council (NESDC), the economic growth rate in 2022 is expected to be 2.6% and the economic growth rate in 2023 will be 2.7%. In addition, the annual economic growth rate from 2024 to 2037 used the projections used when establishing the Ministry of Energy's Energy efficiency plan 2018 (EEP 2018) and Thailand power development plan 2561 – 2580 (PDP 2018). The economic growth rate from 2038 was assumed to be constant with the projected economic growth rate (3.6%) for 2037, the last planning year of EEP 2018 and PDP 2018 (<Table 4-17>). Thailand's GDP projections are shown in [Figure 4-19].

**<Table 4-17> Forecasts for Thailand's economic growth rate (%)**

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
2.6	2.7	3.87	3.8	3.73	3.76	3.69	3.71	3.71	3.75
2032	2033	2034	2035	2036	2037	2038-			
3.72	3.66	3.65	3.6	3.62	3.6	3.6			

Source: NESDC (2023), MOE (2020a; 2020b)

**[Figure 4-19] Forecasts for Thailand's GDP**



Source: Author calculation based on World Bank, NESDC (2023), MOE (2020a; 2020b) data

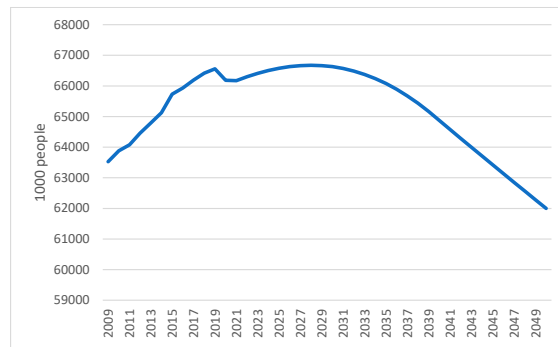
Meanwhile, NESDC's population projection was used for Thailand's population growth rate. In this study, the annual population growth rate was calculated using the registered population data based on the medium fertility assumption in the NESDC's population projections, and the population forecast was prepared by applying the annual population growth rate to Thailand's population statistics. The population forecast prepared was used as the projection of the population factor (P). According to NESDC, Thailand's population is expected to increase until 2028 and then decrease (<Table 4-18>), and is expected to reach 61,998 thousand in 2050 ([Figure 4-20]).

**[Table 4-18] Thailand's population growth rate (%) projections**

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0.19	0.17	0.14	0.11	0.08	0.05	0.02	-0.02	-0.05	-0.09
2032	2033	2034	2035	2036	2037	2038	2039	2040	2041-
-0.13	-0.16	-0.20	-0.24	-0.29	-0.33	-0.37	-0.41	-0.45	-0.45

Source: Author calculation based on NESDC (2019)

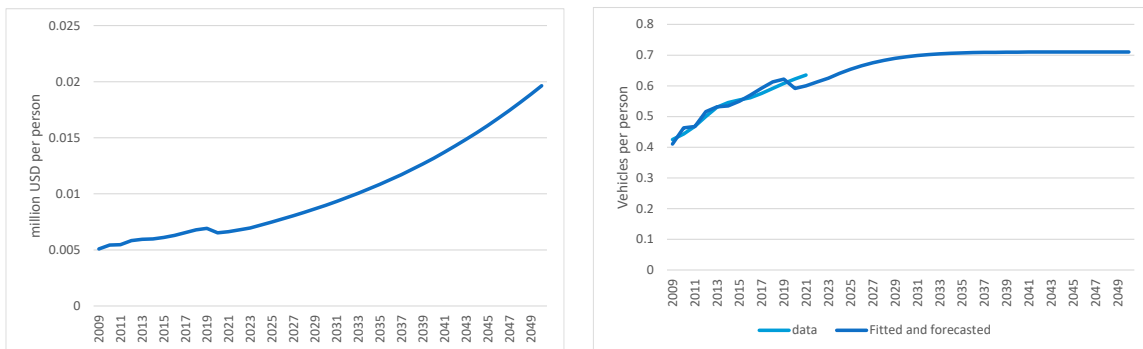
**[Figure 4-20] Population Forecasts in Thailand**



Source: Author calculation based on Provincial Administration data and NESDC (2019)

The results of forecasting GDP per capita and forecasting the number of vehicles per capita using the logistic function estimated as shown in <Table 4-16> are shown in [Figure 4-21]. The forecasted GDP per capita is used as a projection for the economic growth factor ( $G/P$ ). Also, the forecasted GDP per capita and the number of vehicles per capita are used to calculate the projection for the vehicle intensity factor ( $V/G$ ), as shown in [Figure 4-22].

**[Figure 4-21] Forecast of per capita GDP and number of vehicles per capita**

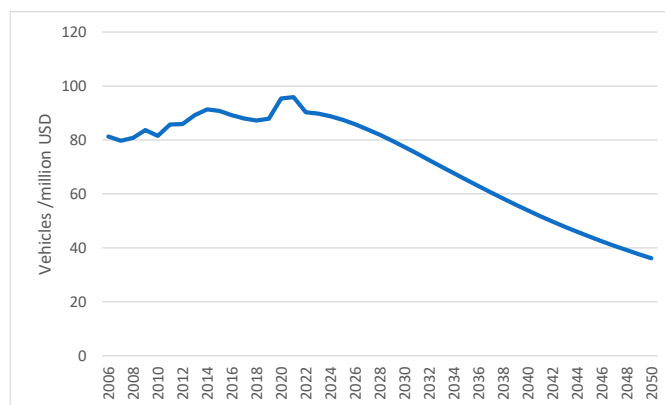


(a) GDP per capita

(b) number of vehicles per capita;

Source: World Bank, Department. Author analysis based on data of Provincial Administration, NESDC (2019; 2023), MOE (2020a; 2020b)

[Figure 4-22] Forecasts for Vehicle Intensity in Thailand



Source: Author calculation

### 3. Hydrogen Utilization Scenario

A total of 10 scenarios for hydrogen utilization in the road transport sector were considered based on the percentage of hydrogen vehicles replacing conventional vehicles (see <Table 4-19>). As shown in [Figure 4-17-(b)], diesel vehicles account for about 29% and gasoline vehicles account for about 69% of the total vehicles in the road transport sector in 2022, making diesel and gasoline vehicles a total of 98% of the vehicles. Since hydrogen vehicles can replace both passenger and commercial vehicles, this study includes five diesel vehicle replacement scenarios and five gasoline vehicle replacement scenarios. The share of vehicles by fuel for each scenario in the road transportation sector is shown in <Table 4-20> and <Table 4-21>.

<Table 4-19> Hydrogen Utilization Scenarios in Thailand's Road Transport Sector

scenario number	explanation
TS1-1	Hydrogen cars will replace 20% of diesel cars by 2050
TS1-2	Hydrogen cars will replace 40% of diesel cars by 2050
TS1-3	Hydrogen cars will replace 60% of diesel cars by 2050
TS1-4	Hydrogen cars will replace 80% of diesel cars by 2050
TS1-5	Replacing 100% of the share of hydrogen cars and diesel cars by 2050
TS2-1	By 2050, hydrogen cars and gasoline cars will replace 20% of the market share

TS2-2	By 2050, hydrogen cars and gasoline cars will replace 40% of the market share
TS2-3	By 2050, hydrogen car replaces gasoline car's share by 60%
TS2-4	By 2050, hydrogen car replaces gasoline car's share by 80%
TS2-5	By 2050, hydrogen car replaces gasoline car's share by 100%

Source: Author

**<Table 4-20> Share of Vehicles by Fuel in Road Transport in Thailand (%): Diesel Vehicle Replacement Scenario**

Scenario	Hydrogen	Gasoline	Diesel	LPG	natural gas	Electricity
Base	-	69.08	28.79	1.37	0.68	0.07
TS1-1	5.77	69.08	23.03	1.37	0.68	0.07
TS1-2	11.52	69.08	17.28	1.37	0.68	0.07
TS1-3	17.28	69.08	11.52	1.37	0.68	0.07
TS1-4	23.04	69.08	5.76	1.37	0.68	0.07
TS1-5	28.79	69.08	-	1.37	0.68	0.07

Source: Author

**<Table 4-21> Share of Vehicles by Fuel in Road Transport in Thailand (%): Gasoline Vehicle Replacement Scenario**

Scenario	Hydrogen	Gasoline	Diesel	LPG	natural gas	Electricity
Base	-	69.08	28.79	1.37	0.68	0.07
TS2-1	13.83	55.26	28.79	1.37	0.68	0.07
TS2-2	27.64	41.45	28.79	1.37	0.68	0.07
TS2-3	41.46	27.63	28.79	1.37	0.68	0.07
TS2-4	55.27	13.82	28.79	1.37	0.68	0.07
TS2-5	69.08	-	28.79	1.37	0.68	0.07

Source: Author

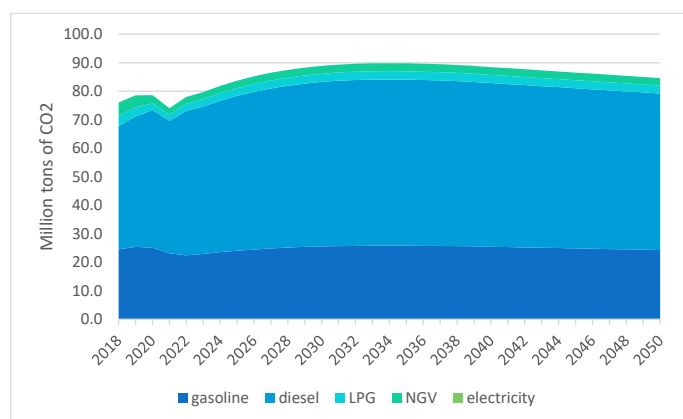
## 4. Climate benefit estimation results

### A. GHG emission baseline estimation results

Using the above equation for the road transport sector and the long-term projections of each factor and variable, the results of estimating the baseline carbon dioxide emissions of the

road transport sector by 2050 are shown in Figure 4-21. Carbon dioxide emissions from the road transport sector in Thailand are projected to increase from 78.0 million tons in 2022 to 89.8 million tons in 2034 and then continue to decline until 2050, reaching 84.6 million tons. This is an increase of 6.6 million tons compared to 2022, representing an estimated 8.5% increase in emissions compared to 2022 carbon dioxide emissions.

**[Figure 4-23] Forecasts for carbon dioxide emissions from road transport in Thailand (BAU)**



Source: Author

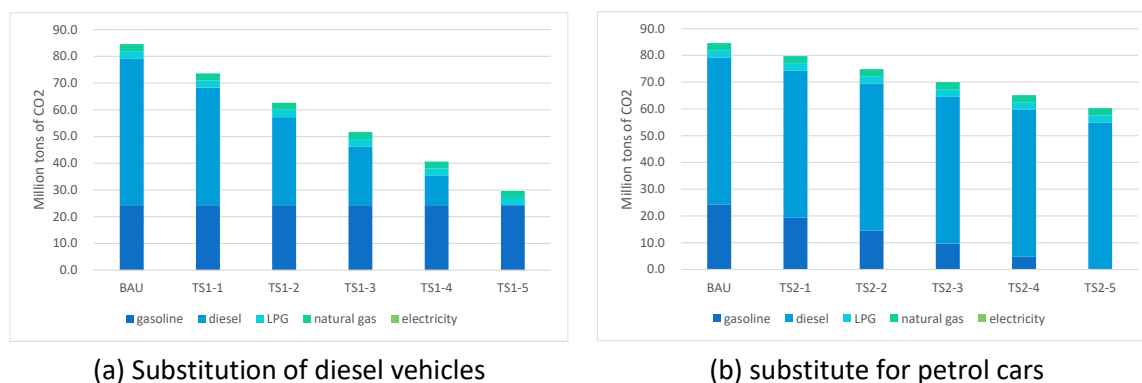
## B. GHG Reduction and Climate Benefit Estimation Results

The carbon dioxide emissions in 2050 according to the hydrogen utilization scenarios in the road transport sector are shown in Figure 4-22, and the reduction amount, reduction rate, and climate benefits by scenario are summarized in Table 4-20 and Table 4-21. If hydrogen vehicles replace 20% of diesel vehicles in Thailand's road transport sector, about 11.0 million metric tons (13.0%) of GHG emissions could be reduced, with climate benefits of 257,948 million baht (\$8,063 million). If hydrogen vehicles were to replace the entire diesel vehicle fleet, 54.9 million tons (64.9%) of carbon dioxide could be reduced, with climate benefits of 1,289,739 million baht (\$40,316 million).

On the other hand, if hydrogen vehicles replace gasoline vehicles, a 20% replacement of gasoline vehicles would reduce GHGs by 4.9 million tons (10.3%) and generate climate benefits of 114,147 million baht (\$3,568 million). Furthermore, if hydrogen vehicles replace the entire gasoline vehicle fleet, it is estimated that 24.3 million tons (51.4%) of GHGs will be

reduced and 570,736 million baht (\$17,841 million) in climate benefits will be achieved.

**[Figure 4-24] GHG Emissions from Hydrogen Utilization in Road Transport (2050)**



Source: Author

**<Table 4-22> GHG Reductions and Climate Benefits (2050) by Hydrogen Utilization in Road Transport: Diesel Vehicle Replacement Scenario**

Scenario	Emissions (million tons of CO <sub>2</sub> )	Reduction (million tons of CO <sub>2</sub> , %)		Climate Benefit (millions)	
	Total	Amount	Rate	in THB*	in USD*
BAU	84.6	-	-	-	-
TS1-1	73.6	11.0	13.0	257.948	8.063
TS1-2	62.6	22.0	26.0	515.896	16.126
TS1-3	51.6	33.0	39.0	773.843	24.190
TS1-4	40.7	43.9	51.9	1,031,791	32.253
TS1-5	29.7	54.9	64.9	1,289,739	40,316

\* Exchange rate: 31.9907 THB/USD (in 2021)

Source: Author

**<Table 4-23> Greenhouse Gas Reduction and Climate Benefits (2050) by Hydrogen Utilization in Road Transport: Gasoline Vehicle Replacement Scenario**

Scenario	Emissions (million tons of CO <sub>2</sub> )	Reduction (million tons of CO <sub>2</sub> , %)		Climate Benefit (millions)	
	Total	Amount	Rate	in THB*	USD*

Bow	84.6	-	-	-	-
TS2-1	79.7	4.9	10.3	114,147	3,568
TS2-2	74.9	9.7	20.6	228,294	7,136
TS2-3	70.0	14.6	30.8	342,441	10,704
TS2-4	65.2	19.4	41.1	456,588	14,273
TS2-5	60.3	24.3	51.4	570,736	17,841

\* Exchange rate: 31.9907 THB/USD (in 2021)

Source: Author

## Section 5. Power Generation Sector

### 1. Setting up the equation

For the power generation sector in Thailand, this study utilizes the adjusted Kaya Identity as shown in Equation 4-10.

$$C = \sum C_i/E_i \times E_i/Elec_i \times Elec_i/Elec \times Elec/Con \times Con/G \times G/P \times P \text{ (Equation 4-10)}$$

The equation for the carbon dioxide emissions (C) of Thailand's power generation industry is constructed using seven factors: carbon dioxide intensity factor ( $C_i/E_i$ ), fuel use inefficiency factor ( $E_i/Elec_i$ ), generation mix factor ( $Elec_i/Elec$ ), electricity self-sufficiency factor ( $Elec/Con$ ), electricity consumption intensity factor ( $Con/G$ ), economic growth factor ( $G/P$ ), and population factor (P). The carbon dioxide intensity factor ( $C_i/E_i$ ), similar to the equation for other economic sectors, is the carbon dioxide emissions per fuel consumption ( $C_i$ ) relative to the fuel consumption ( $E_i$ ) in power generation. The fuel use inefficiency factor ( $E_i/Elec_i$ ) is the amount of fuel used ( $E_i$ ) relative to the amount of electricity generated ( $Elec_i$ ) by fuel  $i$ , and is the inverse of the efficiency of electricity generation by fuel  $i$ . In other words, the inverse of fuel efficiency ( $E_i/Elec_i$ ) is a factor that shows the inefficiency of fuel use, and when other factors are constant, an increase in the fuel use inefficiency factor leads to an increase in fuel use and carbon dioxide emissions. The power generation mix factor ( $Elec_i/Elec$ ) is defined as  $i$  fuel generation ( $Elec_i$ ) relative to total power generation ( $Elec$ ) in Thailand and shows how Thailand's power mix is organized based on power generation. All other factors being equal, increasing the share of electricity generation from fossil fuels will increase carbon dioxide emissions. The electricity self-sufficiency factor ( $Elec/Con$ ) is calculated as Thailand's electricity generation ( $Elec$ ) relative to Thailand's electricity consumption ( $Con$ ) and shows the extent to which Thailand's electricity demand can be met by domestic electricity production. When Thailand's electricity self-sufficiency rate is high, the country's power system is considered to be excellent from an energy security perspective, but it also means that the country has to generate a lot of electricity domestically, which increases carbon dioxide emissions. The electricity consumption intensity factor ( $Con/G$ ) refers to the amount of electricity consumed relative to the size of Thailand's economy and can be calculated by

dividing electricity consumption (Con) by GDP (G). All other factors being equal, a higher electricity consumption relative to the size of Thailand's economy will result in higher carbon dioxide emissions from the power generation industry. The economic growth factor (G/P) and population factor (P) are defined as GDP per capita and population, respectively, and as these factors increase, electricity demand tends to increase, which is expected to increase carbon dioxide emissions due to increased power generation.

## 2. Data

In order to estimate the baseline GHG emissions of the Thai power generation sector and the GHG reduction by hydrogen utilization, the data and long-term projections for each variable and factor in Equations 4-10 are constructed as follows.

### A. Carbon dioxide intensity factor

The carbon dioxide intensity factor ( $C_i/E_i$ ) is assumed to be constant until 2050, applying the 2006 IPCC emission factor guidelines as in the other economic sector analyses. The types of fuels consumed by the power generation sector in Thailand were categorized according to the Energy Statistics of Thailand, power generation by fuel (GWh), published by the Ministry of Energy. According to Energy Statistics, there are eight types of power generation fuels: natural gas, lignite, coal, fuel oil, diesel, hydro, and renewable. In this study, the eight types of power generation fuels are linked to the IPCC's fuel classification, and the IPCC's emission factors, which are provided in kgCO<sub>2</sub>/TJ, are converted to kgCO<sub>2</sub>/GWh (see <Table 4-24>). On the other hand, this study assumes that the GHG emission factors of hydro and renewable are zero.

<Table 4-24> Thailand's Power Generation Sector Emission Factor

Fuel(Ministry of Environment)	Representative fuel (IPCC 2006 Guidelines)	Carbon dioxide_ emission factor (IPCC 2006 Guidelines)	Carbon dioxide_ emission factor
Natural gas	Natural gas	56,100kgCO <sub>2</sub> /TJ	201,960
Lignite	Lignite	101,000kgCO <sub>2</sub> /TJ	363,600
Coal	other bituminous coal	94,600 kgCO <sub>2</sub> /TJ	340,560
fuel oil	Residual fuel oil	77,400 kgCO <sub>2</sub> /TJ	278,640

Diesel	Gas/diesel oil	71,900 kgCO <sub>2</sub> /TJ	258,840
Hydro	-	-	-
Renewable	-	-	-

Note: 1 kWh = 3,600,000 Joules

Source: IPCC (2006)

## B. Fuel Inefficiency Factor

To calculate the fuel use inefficiency factor ( $E_i/Elec_i$ )<sup>21</sup>, we need data on fuel consumption and generation by fuel in the Thai power sector. The data on fuel-specific generation for the entire Thai power sector is available in the Energy Statistics described above, but the data on fuel-specific consumption is only available for the Electricity Generating Authority of Thailand (EGAT), a power generation company in Thailand. Therefore, this study calculates the inefficiency factor ( $E_i/Elec_i$ ) of fuel use based on EGAT's data and assumes that the figures are representative of the entire Thai power generation sector. In addition, according to Energy Statistics, EGAT generates electricity using lignite but does not generate electricity using coal. Therefore, this study assumes that the inefficiency of EGAT's use of lignite is the same as the inefficiency of the Thai power sector's use of coal.

EGAT's fuel-specific generation (GWh) and fuel-specific consumption data, expressed in physical units of individual fuels, are converted to terajoules<sup>22</sup>, and plotted in [Figure 4-25]. Dividing “the power generation by fuel” by “the consumption by fuel” gives the power generation efficiency value, and the inverse of the power generation efficiency is the inefficiency factor of fuel use that we want to build in this study. However, if the power generation efficiency is calculated using the above method, the power generation efficiency of fuel oil in 2019 and 2020 exceeds 1, which is theoretically impossible<sup>23</sup>. Therefore, this

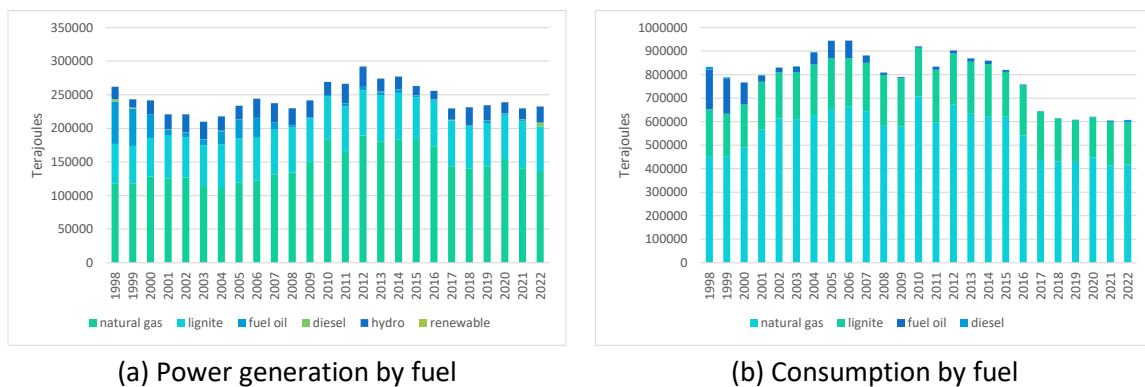
<sup>21</sup> The inefficiency factor of fuel use was calculated only for natural gas, lignite, coal, fuel oil, and diesel with non-zero emission factors.

<sup>22</sup> Consumption by fuel was converted using the conversion factor presented in MOE (2023). However, for natural gas with multiple conversion coefficients, 1.03 MJ/SCF, which is the middle value of wet natural gas (1.04 MJ/SCF) and dry natural gas (1.02 MJ/SCF), was used for conversion. In addition, for lignite, 12.995 MJ/kg, which is the median value of LI (18.42 MJ/kg), KRABI (10.88 MJ/kg), MAE MOH (10.47 MJ/kg), and CHAE KHON (15.11 MJ/kg), was applied.

<sup>23</sup> The fuel oil consumption in 2019 and 2020 is 556.78TJ and 1153.33TJ, respectively, and the power generation

study did not use the 2019 and 2020 fuel oil power generation efficiency calculated from Energy Statistics and interpolated the 2019 and 2020 values with the 2018 and 2021 values. EGAT's generation efficiency and fuel use inefficiency ( $E_i/Elec_i$ ) by fuel are shown in [Figure 4-26].

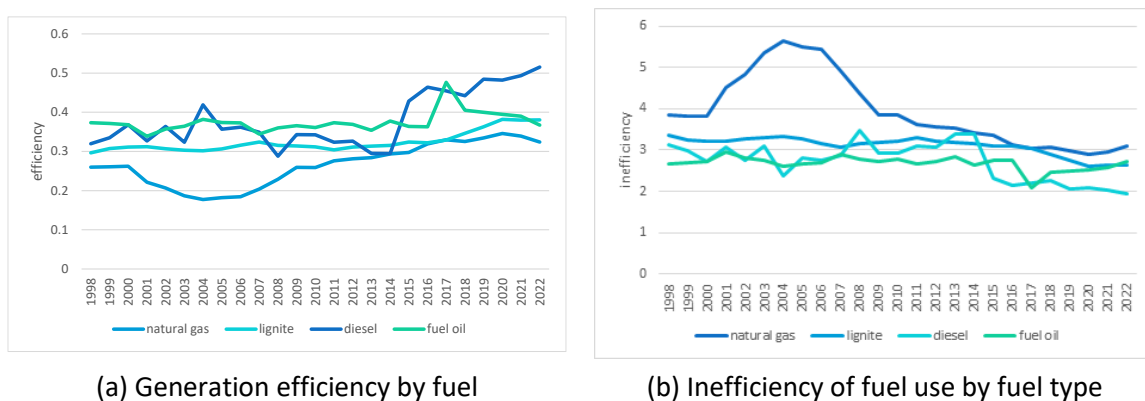
**[Figure 4-25] EGAT power generation by fuel and consumption by fuel**



Note: renewable is the sum of renewable and geothermal in MOE (2023)

Source: Author based on MOE (2023)

**[Figure 4-26] EGAT's power generation efficiency by fuel and inefficiency of fuel use**



Note: 2019 and 2020 values for fuel oil are interpolated using the nearest values.

Source: Author based on MOE (2023)

The forecast of the inefficiency factor ( $E_i/Elec_i$ ) of fuel use was estimated by estimating the learning curve that can explain the decreasing trend of fuel use inefficiency, and then using

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is calculated as 3551.87TJ and 2246.69TJ, respectively.

the estimated learning curve. In this study, it is assumed that the inefficiency of fuel use forms a learning curve for the cumulative power generation by fuel as shown in Equation 4-11.

$$(E_i/Elec_i)_t = a \times Elec_{i,cum,t}^b + u_t \text{ (Equation 4-11)}$$

In Equation 4-11,  $(E_i/Elec_i)_t$  is the inefficiency of fuel use in year  $i$ ,  $Elec_{i,cum,t}$  is EGAT's cumulative generation by fuel in petajoules,  $u_t$  is the disturbance term, and  $a$  and  $b$  are the parameters of the model to be estimated. The dependent variable, fuel use inefficiency, can be constructed as shown in Figure 4-24-(b) in the manner described above, and the cumulative generation by fuel of EGAT is utilized from the Ministry of Energy's Energy Statistics.

On the other hand, this study estimates the learning curve in Equation 4-11 for natural gas, lignite, and diesel only, respectively. In the case of fuel oil, the fuel use inefficiency value in 2022 was assumed to be constant until 2050 without estimating a separate learning curve because there was no clear trend except for 2019 and 2020. For natural gas, the learning curve was estimated using annual data from 2003 to 2022, which shows a clear decreasing trend in fuel use inefficiency, and for lignite and diesel, it was estimated using full observation (1998-2022).

The results of estimating the learning curve for fuel use inefficiency are shown in Table 4-23. The results show that the parameters of the learning curve are significant at the 1% level for natural gas, lignite, and diesel. However, the learning curve estimates are based on limited observations, and more reliable estimates can be obtained by extending the time series or using monthly data.

**<Table 4-25> Estimation result of fuel use inefficiency learning curve in the power generation sector in Thailand**

Natural gas					
Coefficient	Estimated value	Standard Error	t-statistics	P-value	R-squared
a	118.258	23.179	5.10	0.000	0.9967
b	-0.456	0.027	-17.07	0.000	

Lignite					
Coefficient	estimated value	standard error	t-statistic	P-value	R-squared
a	4.306	0.346	12.43	0.000	0.9971
b	-0.051	0.013	-4.06	0.000	
Diesel					
Coefficient	estimated value	standard error	t-statistic	P-value	R-squared
a	4.698	0.793	5.93	0.000	0.9809
b	-0.246	0.076	-3.22	0.004	

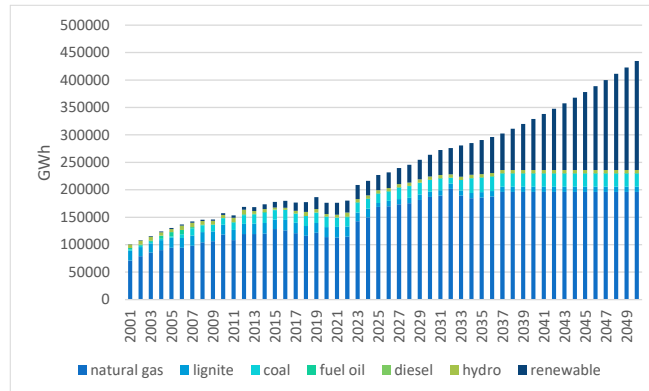
Note: 2003-2022 for natural gas; 1998-2022 for lignite and diesel.

Source: Author analysis

In order to perform a long-term projection based on the learning curve estimation results in <Table 4-23>, the cumulative generation forecast of EGAT by fuel is required. The Ministry of Energy's Thailand power development plan 2561-2580 (PDP 2018) presents fuel-specific power generation by year through 2037, separated by power generation companies, and this study utilizes EGAT's fuel-specific power generation data (2023-2037) from PDP 2018 as a forecast.

On the other hand, EGAT's power generation from 2038 to 2050 is projected based on the power generation of the entire Thai power generation sector, and the share of EGAT's power generation. First, we assumed that the total power generation by fuel for the Thai power sector as a whole will follow the projections of PDP 2018 from 2023 to 2037, but from 2038, the power generation by other fuels except renewable energy will be constant until 2050. In this case, renewable energy power generation is assumed to be equal to the total power generation minus the power generation by other fuels, i.e., from 2038, there will be no increase in other power generation facilities except renewable energy, and only renewable energy power generation facilities will be added to meet the power demand. To calculate the amount of renewable energy generation under these assumptions, a forecast of total electricity generation from 2038 to 2050 is required, and this study calculated the forecast of total electricity generation by multiplying the forecast of electricity self-sufficiency factor (Elec/Con) by the forecast of electricity consumption (Con) as described later. The forecast of electricity generation by fuel for Thailand's power sector through 2050 is shown in [Figure 4-27].

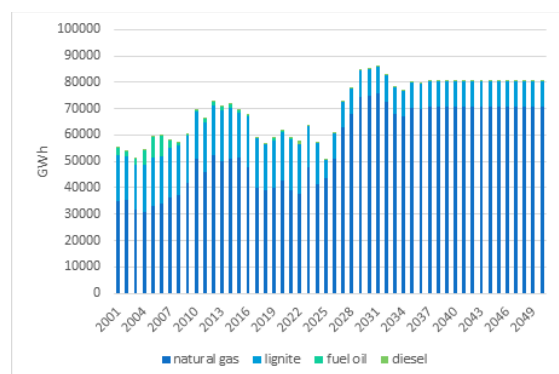
**[Figure 4-27] Forecast of power generation by fuel in Thailand's power generation sector**



Source: Author based on MOE (2023), MOE (2020b)

The forecast for the share of EGAT (Electricity Generating Authority of Thailand) in the total power generation within the power generation sector from 2038 to 2050 was made in this study. The assumption was that the share of EGAT in 2037, the last year predicted by PDP 2018, would remain constant throughout the period. Based on the data for 2037, the projected share of EGAT's power generation for natural gas, lignite, fuel oil, and diesel power generation are estimated to be 36.0%, 100%, 0%, and 27.5% respectively. By multiplying these shares with the power generation by fuel in Thailand's power generation sector from 2038 to 2050, the projected power generation by fuel for EGAT can be calculated ([Figure 4-28]).

**[Figure 4-28] EGAT's forecast for natural gas, lignite, fuel oil, and diesel power generation**

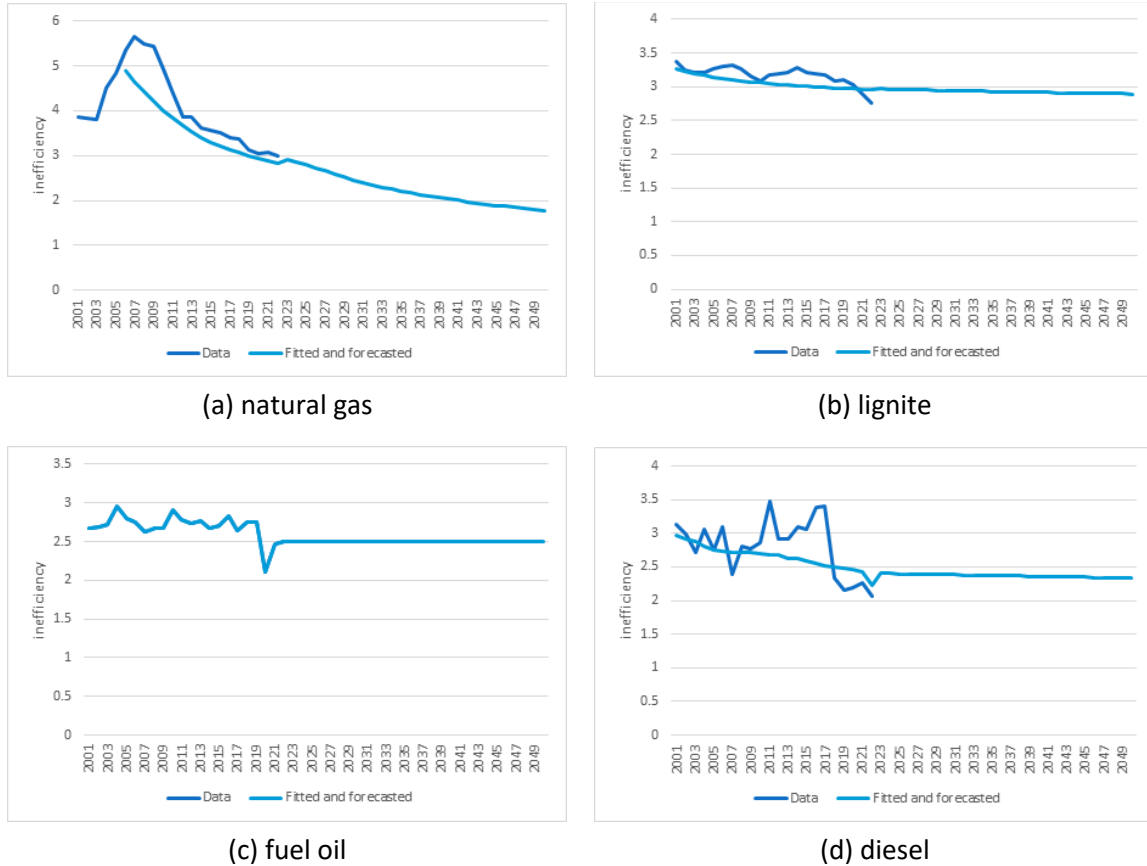


Source: Author based on MOE (2023), MOE (2020b)

[Figure 4-29] illustrates the inefficiency factor of fuel utilization by fuel, based on the

generation forecasts calculated by EGAT.

[Figure 4-29] Forecasts for fuel use inefficiency factors of EGAT



Source: Author analysis based on MOE (2023), MOE (2020b)

### C. Generation Mix Factor

The generation mix factor (Elec/Elec) can be calculated by utilizing the forecasted generation by fuel for the entire Thai power sector described above. As explained above, it is assumed that from 2038 onwards, only renewable energy generation will increase in line with the increase in total generation (Elec). While this is a fairly strong assumption, it does not achieve the 74% renewable electricity share in 2050 targeted in Thailand’s LEDS. Therefore, while the renewable electricity growth assumption is a strong assumption, it is more conservative than Thailand’s policy target for 2050. Thailand’s 2022 fuel mix and 2050 fuel mix are shown in [Figure 4-30].

[Figure 4-30] Forecasts for Power Generation Mix in Thailand's Power Sector



(a) Share of power generation in 2022

(b) Share of power generation in 2050

Source: Author analysis based on MOE (2023), MOE (2020b)

#### D. Power self-sufficiency factor

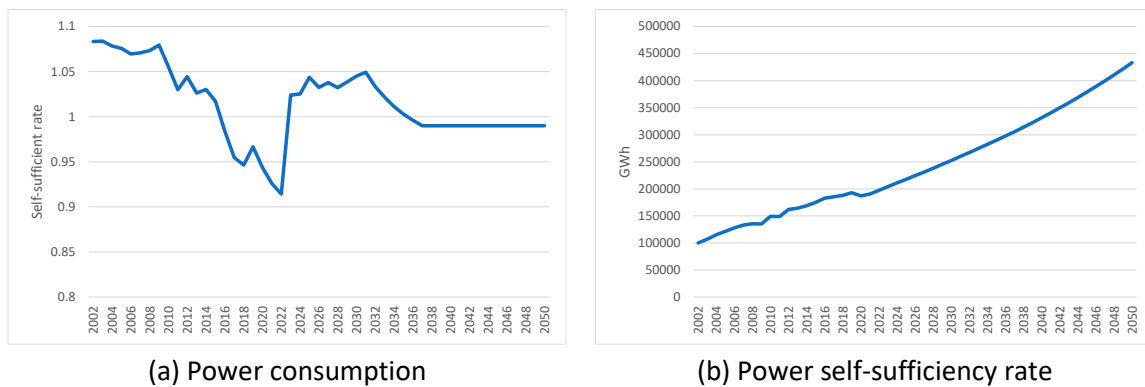
The electricity self-sufficiency factor (Elec/Con) was calculated by utilizing the total electricity generation (Elec) of the Thai power sector and the electricity consumption (Con) data provided by Energy Statistics. Gross electricity generation was projected as described in the previous section on fuel use inefficiency factors, and electricity consumption (Con) was calculated by multiplying the annual consumption growth rate (2023-2037) projected in PDP 2018 (see <Table 4-26>) by the electricity consumption from Energy Statistics. The electricity consumption growth rate from 2038 to 2050 was assumed to be constant at the 2037 electricity consumption growth rate (2.7%) to project the 2050 electricity consumption value. [Figure 4-31] shows the electricity consumption projections for Thailand and the resulting electricity self-sufficiency projections.

<Table 4-26> Forecasts for Thailand's power consumption growth rate (%)

2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
3.44	3.42	3.15	3.14	2.93	2.98	3.09	2.91	2.93	2.79
2033	2034	2035	2036	2037	2038-				
2.83	2.70	2.70	2.70	2.72	2.72				

Source: Author calculation based on MOE (2020b)

**[Figure 4-31] Forecasts for electricity consumption and electricity self-sufficiency in Thailand**

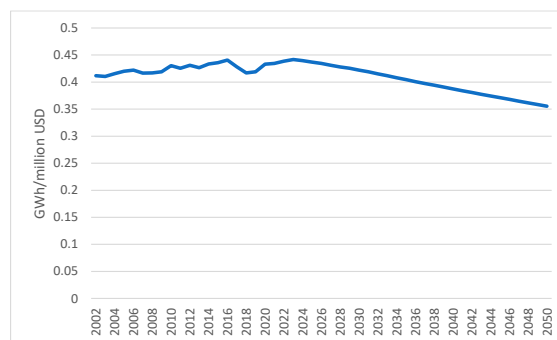


Source: Author analysis based on MOE (2023), MOE (2020b)

### E. Power Consumption Intensity Factor

The electricity consumption intensity factor (Con/G) was projected using Thailand's electricity consumption forecast divided by the GDP forecast. The GDP forecast is the same forecast used in the analysis of the road transportation sector in Section 3 (see [Figure 4-19]). The projected electricity consumption intensity for Thailand is shown in [Figure 4-32].

**[Figure 4-32] Outlook on electricity consumption intensity in Thailand**



Source: Author analysis based on World Bank, NESDC (2023), MOE (2020a; 2020b; 2023)

### F. Economic Growth and Population Factors

The economic growth factor (G/P) and population factor (P) projections for Thailand are the same as those used in the analysis of the road transport sector in Chapter 4, Section 3. The economic growth factor and population factor projections are shown in [Figures 4-21] and [4-20], respectively.

### 3. Hydrogen Utilization Scenarios

The hydrogen utilization scenarios for Thailand's power generation sector were created by building 10 scenarios, five each for replacing the share of coal and lignite generation and the share of natural gas generation. As shown in Figure 4-28, natural gas generation accounts for 64% of Thailand's power generation in 2022, the highest share, followed by lignite (10%) and coal (9%). Although the share of coal-based power generation in Thailand is relatively low compared to the share of natural gas power generation, it is the second highest after natural gas power generation, and the GHG emission factors of coal and lignite are large, so a hydrogen utilization scenario was prepared. The hydrogen utilization scenario for Thailand's power generation sector is shown in <Table 4-27>, and the share of power generation by fuel under the alternative scenario of coal and lignite generation and the alternative scenario of natural gas generation are shown in <Tables 4-28 and 4-29>, respectively.

**<Table 4-27> Thailand's Power Sector**

Scenario No.	Detail
PS1-1	By 2050, hydrogen will replace coal and lignite by 20% each.
PS1-2	By 2050, hydrogen will replace coal and lignite by 40% each.
PS1-3	By 2050, hydrogen will replace 60% of the share of coal and lignite.
PS1-4	By 2050, hydrogen will replace 80% of the share of coal and lignite.
PS1-5	By 2050, hydrogen will replace 100% of each share of coal and lignite.
PS2-1	By 2050, hydrogen will replace 20% of natural gas's share.
PS2-2	By 2050, hydrogen will replace 40% of natural gas's share.
PS2-3	By 2050, hydrogen replaces natural gas's share by 60%
PS2-4	By 2050, hydrogen replaces natural gas's share by 80%
PS2-5	By 2050, hydrogen replaces natural gas's share by 100%

Source: Author

**<Table 4-28> Power Generation Share (%) by Fuel According to Hydrogen Utilization Scenarios in Thailand's Power Generation Scenario: Alternative Scenarios for Coal and Lignite Power Generation**

Scenario	Hydrogen	Natural	Lignite	Coal	Fuel oil	Diesel	Hydro	Renewable
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		gas						
Base	-	45.74	2.26	5.71	0.00	0.02	1.39	44.88
PS1-1	1.59	45.74	1.81	4.57	0.00	0.02	1.39	44.88
PS1-2	3.18	45.74	1.36	3.43	0.00	0.02	1.39	44.88
PS1-3	4.78	45.74	0.91	2.28	0.00	0.02	1.39	44.88
PS1-4	6.38	45.74	0.45	1.14	0.00	0.02	1.39	44.88
PS1-5	7.97	45.74	-	-	0.00	0.02	1.39	44.88

Source: Author

**<Table 4-29> Share of generation (%) by fuel in Thailand's power sector under different hydrogen utilization scenarios: Natural gas generation substitution scenario**

Scenario	Hydrogen	Natural gas	Lignite	Coal	fuel oil	diesel	hydro	renewable
Base	-	45.74	2.26	5.71	0.00	0.02	1.39	44.88
PS2-1	9.15	36.59	2.26	5.71	0.00	0.02	1.39	44.88
PS2-2	18.29	27.45	2.26	5.71	0.00	0.02	1.39	44.88
PS2-3	27.44	18.30	2.26	5.71	0.00	0.02	1.39	44.88
PS2-4	36.59	9.15	2.26	5.71	0.00	0.02	1.39	44.88
PS2-5	45.74	-	2.26	5.71	0.00	0.02	1.39	44.88

Source: Author

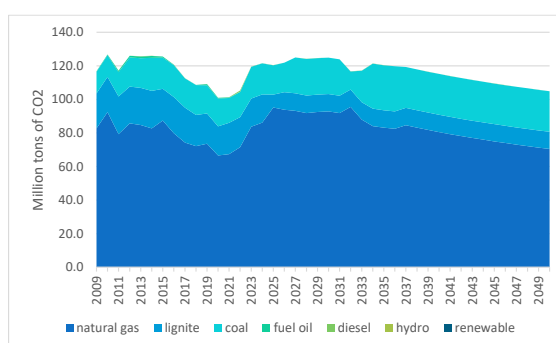
## 4. Climate benefit estimation results

### A. GHG emission baseline estimation results

Using the GHG emission equation and the long-term projections of each variable and factor, the results of estimating the GHG emission baseline for the power sector in Thailand by 2050 are shown in [Figure 4-31]. Carbon dioxide emissions from Thailand's power sector are projected to increase from 105.3 million tons in 2022 to 125.0 million tons in 2027. After 2027, carbon dioxide emissions show a declining trend, and in 2050, the Thai power sector is

expected to emit 104.9 million tons of carbon dioxide<sup>24</sup>.

**[Figure 4-33] Forecasts for carbon dioxide emissions from power generation in Thailand (BAU)**



Source: Author

## B. GHG Reduction and Climate Benefit Estimation Results

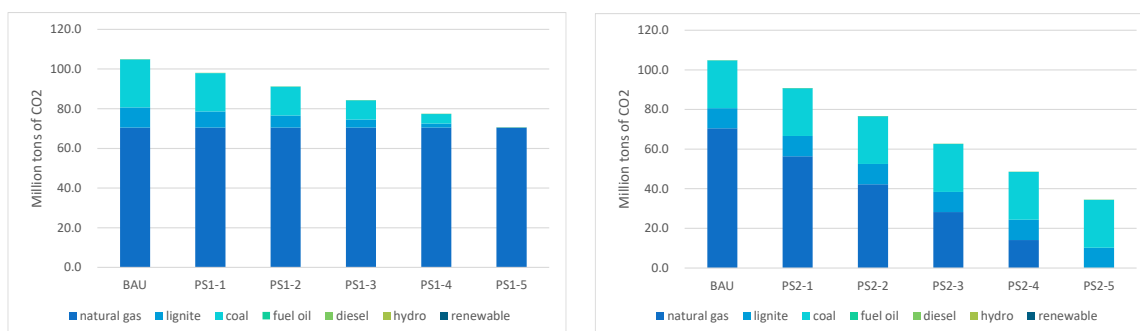
The carbon dioxide emissions in 2050 according to the hydrogen utilization scenarios in the Thai power sector are shown in [Figure 4-34], and the tables summarizing the main results by scenario are shown in <Tables 4-30 and 4-31>. First, in the scenario where hydrogen is used to replace coal and lignite generation, a 20% replacement of coal and lignite generation (PS1-1 scenario) is expected to reduce a total of 6.9 million tons of carbon dioxide, resulting in a climate benefit of 161,291 million baht (US\$5,042 million). If the entire share of coal and lignite generation is replaced with hydrogen generation (PS1-5 scenario), the carbon dioxide reduction is estimated to be 34.3 million tons with a climate benefit of 806,456 million baht (\$25,209 million).

Replacing a higher share of natural gas generation in Thailand with hydrogen generation would result in more carbon dioxide reductions and greater climate benefits under each scenario. Under the scenario of replacing 20% of natural gas generation (PS2-1), 14.1 million

<sup>24</sup> According to Thailand's Fourth Biennial Update Report, emissions from main activity electricity and heat production in 2019 were 93.0 million tons, and the 109.2 million tons of oil refining emissions in 2019 in this study were overestimated by about 16.2 million tons.

tons of carbon dioxide could be reduced, resulting in climate benefits of THB 330,951 million (USD 10,345 million). Replacing all-natural gas generation with hydrogen generation (PS2-5) is expected to reduce 34.4 million tons of carbon dioxide and generate 1,654,753 million baht (\$51,726 million) in climate benefits.

**[Figure 4-34] GHG Emissions from Hydrogen Utilization in Power Generation (2050)**



(a) Substitution of coal and lignite generation

(b) Substitution of natural gas generation

Source: Author analysis

**<Table 4-30> GHG emissions and climate benefits of hydrogen in power generation (2050):  
Coal and lignite generation replacement scenario**

Scenario	Emissions (million tons of CO <sub>2</sub> )	Reduction (million tons of CO <sub>2</sub> , %)		Climate Benefit (Millions)	
	Total	Amount	Rate	in THB*	in USD*
BAU	104.9	-	-	-	-
PS1-1	98.0	6.9	6.5	161,291	5,042
PS1-2	91.1	13.7	13.1	322,582	10,084
PS1-3	84.3	20.6	19.6	483,873	15,125
PS1-4	77.4	27.5	26.2	645,165	20,167
PS1-5	70.5	34.3	32.7	806,456	25,209

\* Exchange rate: 31.9907 THB/USD (in 2021)

Source: Author

**<Table 4-31> GHG emissions and climate benefits of hydrogen in power generation (2050):  
Natural gas power generation replacement scenario**

Scenario	Emissions (million tons of	Reduction (million tons of CO <sub>2</sub> , %)	Climate Benefit (millions)
----------	-------------------------------	--	----------------------------

	CO <sub>2</sub> )				
	Total	Amount	Rate	in THB*	in USD*
BAU	104.9	-	-	-	-
PS2-1	90.8	14.1	13.4	330,951	10,345
PS2-2	76.7	28.2	26.9	661,901	20,690
PS2-3	62.6	42.3	40.3	992,852	31,036
PS2-4	48.5	56.4	53.8	1,323,802	41,381
PS2-5	34.4	70.5	67.2	1,654,753	51,726

\* Exchange rate: 31.9907 THB/USD (in 2021)

Source: Author

## Section 6. Comprehensive Comparison

<Table 4-32> summarizes the estimated GHG emission reductions and climate benefits of hydrogen utilization in the cement, refining, road transportation, and power sectors selected for this study. Based on the second hydrogen utilization scenario for each economic sector, the largest GHG reduction from hydrogen utilization is in the power sector, which is expected to reduce about 28.2 million tons of carbon dioxide. It is also expected to have the largest climate benefits from GHG reductions. In terms of the GHG reduction rate, the power generation sector is analyzed to reduce the largest proportion of GHGs at 26.9%, and the road transportation sector (26.0%) is also expected to reduce a large proportion of GHGs. In the case of cement, the GHG reduction rate is not as high as in other sectors. This is likely due to the fixed IPPU emissions of the cement industry.

If the effects of hydrogen utilization in the cement, oil refining, road transportation, and power sectors are combined, a total of 56.4 million tons (24.9%) of GHG reductions are expected. According to Thailand's Fourth Biennial Update Report, carbon dioxide emissions in 2019 were 329.9 million tons, and GHG reductions from hydrogen utilization in the cement, refinery, road transport, and power sectors are equivalent to 17.1% of carbon dioxide emissions in 2019. Furthermore, the 56.4 million tons of GHG reductions are estimated to generate climate benefits of THB 1,321,991 million (USD 41,323 million) for Thailand. This climate benefit is equivalent to approximately 9.4% of Thailand's 2021 GDP of \$438,481 million.

<Table 4-32> GHG emissions and climate benefits of hydrogen utilization by economic sector (2050)

	Cement	Refinery	Road transport	Power	Total
BAU emission (million tons of CO <sub>2</sub> )	24.8	11.9	84.6	104.9	226.2
Replacement	primary coal consumption	natural gas consumption	diesel and gasoline vehicle	coal·lignite and natural gas generation	-

Scenario for comparison		CS2	RS2	TS1-2 (replacing diesel vehicle)	PS2-2 (replacing natural gas power generation)	-
Reduction (million tons of CO <sub>2</sub> , %)	Amount	3.2	3.0	22.0	28.2	56.4
	Ratio	12.8	24.9	26.0	26.9	24.9
climate benefits (million)	In THB *	74,357	69,837	515,896	661,901	1,321,991
	in USD *	2,324	2,183	16,126	20,690	41,323

\* Exchange rate: 31.9907 THB/USD (in 2021)

Source: Author

## **Chapter 5. Summary and Conclusion**

This study aims to identify the economic sectors that could potentially utilize hydrogen in Thailand and estimate the climate benefits of hydrogen utilization in these sectors to formulate a national hydrogen strategy for Thailand. In order to identify the sectors for hydrogen utilization in Thailand, Chapter 2 reviews hydrogen policy examples from major international countries to determine which sectors of the economy are being targeted for hydrogen utilization. Then, in Chapter 3, the cases of hydrogen utilization in developed countries were reviewed from various aspects of policy, economy, technology, and energy consumption to determine which economic sectors can be utilized in Thailand, and finally, hydrogen utilization sectors in Thailand were identified. Finally, in Chapter 4, the carbon dioxide emissions and climate benefits of hydrogen utilization in each economic sector were estimated.

The main findings of this study are as follows A review of the hydrogen policies of major international economies shows that they consider the iron and steel, chemical and petrochemical, cement, refinery, power generation, and road transport sectors as the main sectors for hydrogen utilization. Of the above six sectors, four sectors have been identified as key economic sectors for hydrogen utilization in Thailand, namely cement, refinery, power generation and road transport, based on a comprehensive consideration of Thailand's existing policies, industrial production, technology options and applicability, and fossil fuel consumption.

To estimate the carbon dioxide reduction from hydrogen utilization, the cement sector was assumed to use hydrogen to replace coal, with a minimum carbon dioxide reduction of 1.6 million tons and a maximum of 7.9 million tons depending on the scenario in 2050. The climate benefits were estimated to be a minimum of 37,189 million baht (US\$1,162 million) and a maximum of 185,893 million THB (US\$58.11 million). The refinery sector assumes the replacement of natural gas used as fuel with hydrogen, which is expected to reduce carbon dioxide by between 1.5 million tons and 7.4 million tons depending on the scenario, resulting

in climate benefits of THB 34,918 million (US\$1,092 million) to THB 174,592 million (US\$5,458 million). For the road transport sector, a diesel vehicle replacement scenario and a petrol vehicle replacement scenario were assumed. In the diesel vehicle substitution scenario, the introduction of hydrogen vehicles could reduce GHG emissions by 11.0 million tons to 54.9 million tons, with benefits ranging from 257,948 million baht (\$8,063 million) to 1,289,739 million baht (\$40,316 million). Meanwhile, in the petrol vehicle substitution scenario, the introduction of hydrogen vehicles is expected to reduce GHG emissions by 4.9 million tons to 24.3 million tons, with climate benefits of THB 114,147 million (US\$3,566 million) to THB 570,736 million (US\$17,814 million). For the power generation sector, a coal and lignite substitution scenario and a natural gas substitution scenario were also constructed, and it was analyzed that up to 34.3 million tons of GHGs could be saved in the coal and lignite substitution scenario and up to 70.5 million tons of GHGs could be saved in the natural gas substitution scenario. In this case, the maximum climate benefits for Thailand are expected to reach 806.456 million baht (\$25.209 million) (coal and lignite substitution) and 1,654.753 million baht (\$51.726 million) (natural gas substitution), respectively.

Based on the comparison of the second hydrogen utilization scenario in each economic sector, it is found that the power generation sector can reduce the largest amount of carbon dioxide emissions and obtain the largest climate benefits, followed by road transport, cement, and oil refining. Combining the four sectors analyzed in this study, the GHG emission reduction from hydrogen utilization in 2050 is estimated to be 56.4 million tons, with a climate benefit of 1,321,991 million baht (\$41,323 million). This is a reduction of 17.1 percent of Thailand's 2019 carbon dioxide emissions, and the climate benefits are equivalent to about 9.1 percent of GDP in 2021.

Based on the above analysis, there are several key takeaways. First, hydrogen production facilities in Thailand need to be geographically located to ensure that hydrogen can be smoothly supplied to the cement, refinery, road transport, and power generation sectors. The hydrogen applications selected in this study are sectors with large-scale demand for hydrogen, and the location of the demand sector is essential to consider when planning hydrogen production facilities on the supply side for an efficient hydrogen value chain. In

particular, unlike vehicles in the road transport sector, which are mobile sources of emissions, cement production facilities, refineries, and power generation facilities are stationary sources of emissions, and the location of hydrogen production facilities and related infrastructure should be designed so that large amounts of hydrogen can be efficiently supplied to these production facilities and facilities.

Second, in terms of GHG emission reductions and climate benefits, the utilization of hydrogen in Thailand appears to have some justification. According to the results of this study, based on the second scenario for each economic sector, it is analyzed that 17.1% of the carbon dioxide emission level in 2019 can be reduced and climate benefits of about 9.1% of GDP in 2021 can be obtained. Although there is no absolute criterion for determining the feasibility of hydrogen utilization, and the cost of hydrogen utilization must be considered at the same time, hydrogen utilization in the cement, refinery, road transport and power generation sectors can contribute significantly to national GHG reduction. Therefore, hydrogen utilization in Thailand can be a major means of reducing GHG emissions in response to climate change.

This study's significance lies in its identification of hydrogen utilization sectors in Thailand and its quantitative estimation of GHG emission reductions and climate benefits within each sector, providing a key demand-side basis for the development of a national hydrogen strategy. On the other hand, this study has limitations due to data constraints, such as the use of various assumptions in some analyses and the unreliability of some estimates. Therefore, when establishing hydrogen strategies and policies at the national level, it is expected that more effective national strategies and policies can be established if additional data are reviewed and analyses are revised and supplemented based on this study.

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