博 士 学 位 論 文

Doctoral Dissertation

A Scenario Analysis of the Carbon-Water-Energy Nexus of the Electricity Sector and the Energy Transition of the Transportation Sector in Japan（日本の電力部門における炭素・水・エネルギー・ネクサスと交通部門のエネルギー転換のシナリオ分析）

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Abstract

The United Nations (UN) proposed the Sustainable Development Goals (SDG 17) in 2015, together with The Paris Agreement endorsed by 195 signatories and state parties, to address sustainable development-related issues through ambitious and dynamic actions. The transition of the energy system is at the heart of greenhouse gas (GHGs) mitigation which is required to achieve those goals and the electric sector is the core of energy system of interest while the GHG with the largest contribution to rising temperature is carbon dioxide. As one of the top carbon dioxide (CO_2) emitters in the world, Japan contributed a total CO_2 emission of 1.05 billion tonnes in 2020. The electricity and heat sector, transportation sector, and industry sector, are the three major sources of CO_2 emissions in Japan, accounting for 48.6%, 18.3%, and 17.3%, respectively, of the country's total emissions in 2020. Japan has already proposed the goal of achieving carbon neutrality by 2050. In order to achieve this important milestone and address the severe global climate change issue, the transformation of energy in various industries and sectors is urgently needed. This research therefore focused on the top two carbon emission sectors: the electricity sector and the transportation sector in Japan to analyze the accordingly impacts of energy transition on both the energy system and the natural environment.

For the electricity sector, the transition of the energy sources from fossil fuels to renewable energies is at the heart of GHGs mitigation which is required to achieve those goals and the electricity sector is the core of energy system of interest while the GHG with the largest contribution to rising temperature is carbon dioxide. However, in addition to being centrally relevant for carbon emissions, the electric sector is also an important water consumer. we applied a hybrid life cycle assessment (LCA) model with the disaggregated electric sector to investigate the impacts on carbon emission and water consumption of the energy transition in Japan under the Sixth Strategic Energy Plan. The results indicate that the electricity mix under the Nationally Determined Contribution (NDC) scenario can cut 50% of existing carbon emissions while intensifying the water consumption by 36% from the life cycle perspective in which 30% are foreign water footprints. The Kaya identity analysis confirmed this conclusion and explained the impacts of four driving factors (population, economy, electricity intensity, and electricity mix) qualitatively and

quantitatively showing that the development of technologies and continuous efforts in energy saving can provide a substantial contribution to sustainable development. The results confirmed that the efforts proposed by Japan's NDC for emission reduction through an energy transition in the electric sector can meet the expectation of achieving the Paris Agreement goals but will also pose greater challenges to the future global water demand in the energy system and regional water stress.

For the transportation sector, Japan has been slow to transition its transportation sector to more sustainable energy sources compared to other developed nations. Based on historical data, official reports, white paper, and projections by think tanks, we designed one BAU baseline scenario, four sub-scenarios based on BAU considering different fuel economy, emission standard, and adoption level of EVs, and a combined scenario which considered all the scenarios above under integration of multiple policy impacts. Results showed that the energy consumption in Japan's transportation sector is projected to decline in all examined scenarios. A slight decrease of energy consumption in the BAU scenario can be observed and the Combined scenario showcases the most rapid reduction of a 56% reduction in energy consumption when compared to the baseline BAU scenario by 2050. Besides, even under the ambitious EV promotion scenario the electricity demand increased is also affordable compared with the total electricity demand. Besides, the four types of pollutants mainly emitted in the transportation sector including CO_2, Carbon Monoxide (CO), Methane (CH_4), and Nitrous Oxide (N_2O) were analyzed as well. As for individual scenarios, high EV adoption demonstrates the most substantial reductions, driven by the active promotion of EVs, which shows a 45% reduction compared with BAU. Even in more conservative EV promotion scenarios, noteworthy emission reductions can still be achieved of about 16% reduction, which is a similar contribution as higher fuel economy and stricter emission standards. Furthermore, when multiple policies are integrated in the Combined scenario, a more comprehensive and integrated approach leads to a notable decrease in emissions, with an estimated total of 67% reduction by 2050, only 52 million tons of CO_2 emission. This scenario encompasses a range of measures aimed at reducing carbon emissions from the transportation sector and highlight the potential for significant emission reductions in Japan's transportation sector through various policy interventions.

In addition, we also proposed several policy implications for both sectors based on the simulation results and further discussed the energy transition pathways within each individual sector and also considered the sector coupling between the two sectors through innovative technology such as V2G. Governments can create an enabling environment for V2G technology deployment. This will not only address concerns related to EVs, such as limited driving range and long charging times but also enhance the stability of renewable energy generation by utilizing EVs as mobile energy storage devices. Ultimately, the integration of EVs into the grid through V2G technology holds significant potential in realizing the full benefits of the energy transition and achieving a sustainable and decarbonized society. This research comprehensively analyzed the future energy transition with Japan's electricity and transportation sectors based on scenario assessment and the results can provide meaning reference for the policy implement and environment assessment to achieve the carbon neutral goal.

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Chapter 1. Introduction

1.1 Background and Context

1.1.1 Carbon Dioxide Emission and Global Climate Change

Research about the impact of atmospheric Carbon Dioxide (CO_2) concentration on climate can be traced back to 1896 by Prof. Svante Arrhenius (Arrhenius, 1896). However, it was not until the 1970s that people started to pay attention to the impact of greenhouse gases represented by CO_2 on the climate (Kellogg, 1987). According to the Global Monitoring Laboratory of National Oceanic and Atmospheric Administration (NOAA), the global average CO_2 concentration in 2022 was 417.06 ppm, which is higher than at any time in the past 800,000 years (Galbraith & Eggleston, 2017). The average annual growth rate (AAGR) of global CO_2 in the past 60 years is about 100 times the natural growth rate of the historical period (11,000 to 17,000 years ago), which was less than 1% in the 1960s while it reached 2.48% during 2010 ~ 2022 (Figure. 1-1). The 2015 Paris Agreement endorsed by 195 signatories and state parties aims to prevent the increase in global average temperature from reaching 2 °C (ideally 1.5 °C) above pre-industrial levels and energy transition is one of the most significant parts to effectively fulfill the requirements of the Paris Agreement and achieve the goal of carbon neutrality.

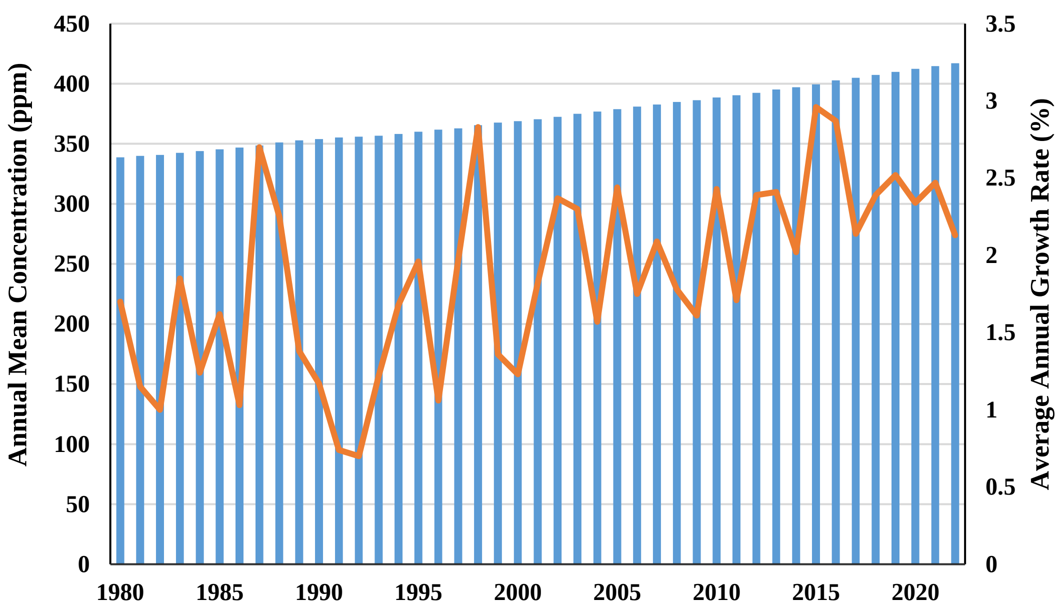


Figure 1- 1. Global Average CO_2 Concentration and Annual Growth Rate

Data source: NOAA ESRL DATA,

Globally averaged marine surface annual mean data

ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_gl.txt

Globally averaged marine surface annual mean growth rates.

ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_gr_gl.txt

Climate change now is one of the most significant challenges facing our world today, and it is widely acknowledged that carbon emissions, especially CO_2 are a leading cause (F. Perera, 2018; S. Solomon et al., 2009). CO_2 emissions, primarily from the burning of fossil fuels, have been linked to rising global temperatures (Friedlingstein et al., 2014), sea level rise (Clark et al., 2016; Ekwurzel et al., 2017), ocean acidification (Feely et al., 2009), biodiversity loss (Bálint et al., 2011; Nagelkerken et al., 2017), and other potentially devastating impacts on the human health as well as societies such as increased air pollution (Jacobson, 2010; Lei et al., 2011), food and water insecurity (Akbar et al., 2018), and extreme weather events (Amirkhani et al., 2022). According to the surface temperature data from GISS Surface Temperature Analysis (GISTEMP v4), since 1900, the global average surface temperature has increased by about 1℃ (Kalnay et al., 1996), most of which occurred after the mid-1970s (Figure 1-2). There is no doubt that global temperature has been accelerating in the past 50 years.

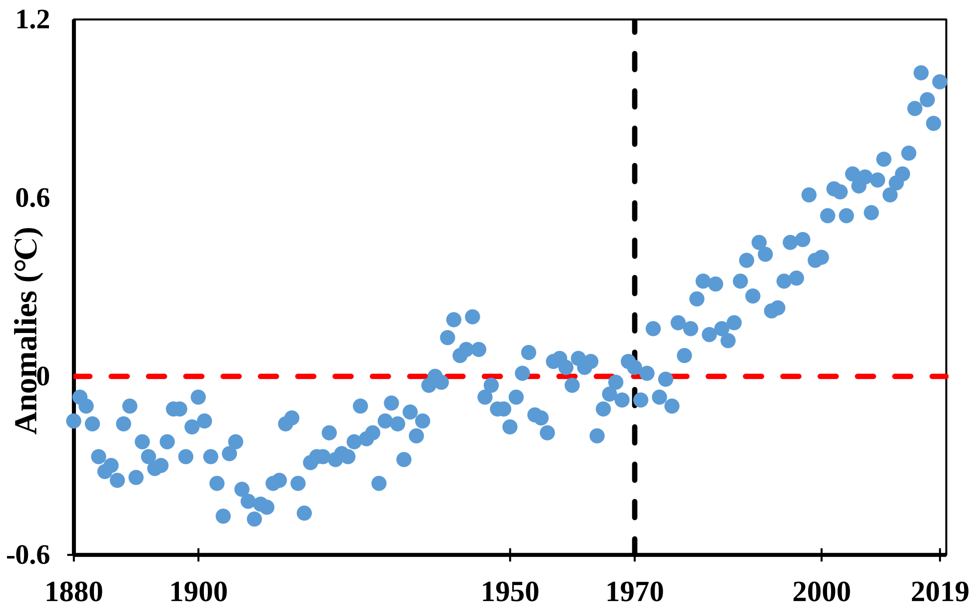


Figure 1- 2. Annual Mean Temperature Anomalies 1880 ~ 2019

Data source: NASA Goddard Institute for Space Studies

GISS Surface Temperature Analysis (GISTEMP), version 4

https://data.giss.nasa.gov/gistemp/

1.1.2 Current Status of Energy and Carbon Dioxide Emissions in Japan

Japan is the world's third-largest economy and is heavily dependent on energy imports, which account for nearly all of its primary energy consumption. In 2019, Japan's total energy consumption was 12 EJ (Figure. 1-3), with fossil fuels, including oil, coal, and natural gas, accounting for approximately 90% of total energy consumption (Ministry of the Environment, Government of Japan, 2023). During Japan's high economic growth period until the 1970s, final energy consumption increased at a higher rate than gross domestic product (GDP). However, in the wake of two oil crises in the 1970s, energy-saving measures, especially in the manufacturing sector, were implemented along with the development of energy-efficient products (Klein, 1980). As a result of these efforts, Japan was able to achieve economic growth while suppressing energy consumption. In the 1990s, energy consumption increased mainly in the household and commercial sectors due to low crude oil prices. However, since the mid-2000s, crude oil prices have risen again, and as a result, final energy consumption has been on a downward trend since the peak in 2005 (Nyga-Łukaszewska & Aruga, 2020). Since 2011, energy consumption has continued to decrease due to an increased awareness of power-saving measures following the Great East Japan Earthquake (Otsuka, 2019), and in 2020, the COVID-19 pandemic caused a decrease in human traffic and a decline in production activities, leading to a real GDP decrease of 4.5% compared to 2019 and a 6.7% decrease in final energy consumption. The trends in final energy consumption and real GDP are shown in figure 1-3. As for energy consumption by sector, the growth from 1973 to 2020 was 0.9 times for the corporate and institutional sectors (10.8 times for the industrial sector, 1.9 times for the commercial sector), 1.9 times for the household sector, and 1.5 times for the transportation sector. In the corporate and institutional sectors, energy-saving measures, especially in the manufacturing sector, have been implemented since the first oil crisis, and this has kept energy consumption at similar levels despite economic growth. On the other hand, in the household and transportation sectors, the widespread use of energy-consuming devices such as home appliances and automobiles has led to a significant increase in energy consumption. As a result, the share of the corporate and institutional, household, and transportation sectors has changed from 74.7%, 8.9%, and 16.4% in 1973 to 61.9%, 15.8%, and 22.3% in 2020. China, the United States, the EU27, India, Russia, and Japan were the top CO_2 emitters globally in 2021. With a combined population of 49.2% of the world's population, these nations account for 62.4% of the world's GDP. Additionally, they generate 67.8% of the world's fossil CO_2 emissions and use 66.4% of the world's fossil fuels (European Commission. Joint Research Centre., 2022). As one of the top CO_2 emitters in the world, Japan contributed a total CO_2 emission of 1.05 billion tonnes in 2020 (Ministry of the Environment, Government of Japan, 2022). The electricity and heat sector, transportation sector, and industry sector are the three major sources of CO_2 emissions in Japan, accounting for 48.6%, 18.3%, and 17.3%, respectively, of the country's total emissions in 2020 (Figure. 1-4). The following elaborates in detail on the top three sectors in terms of emissions.

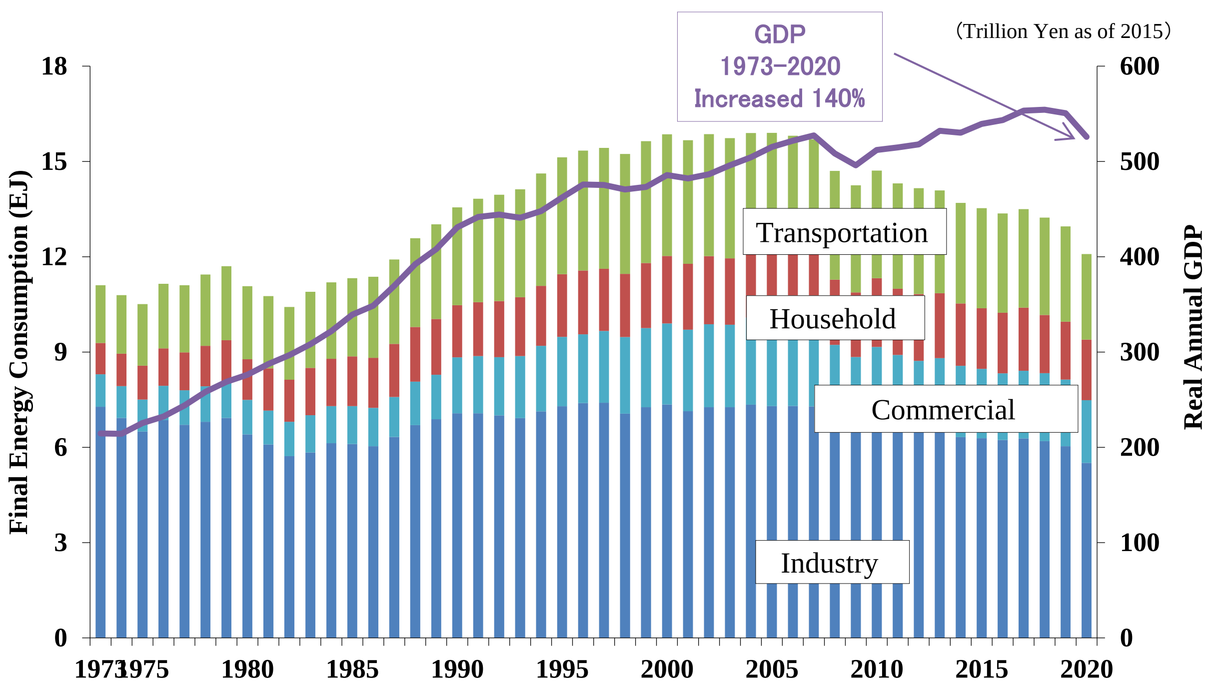


Figure 1- 3. Trends in Final Energy Consumption and Real GDP

Data source: Agency for Natural Resources and Energy

Energy White Paper 2022

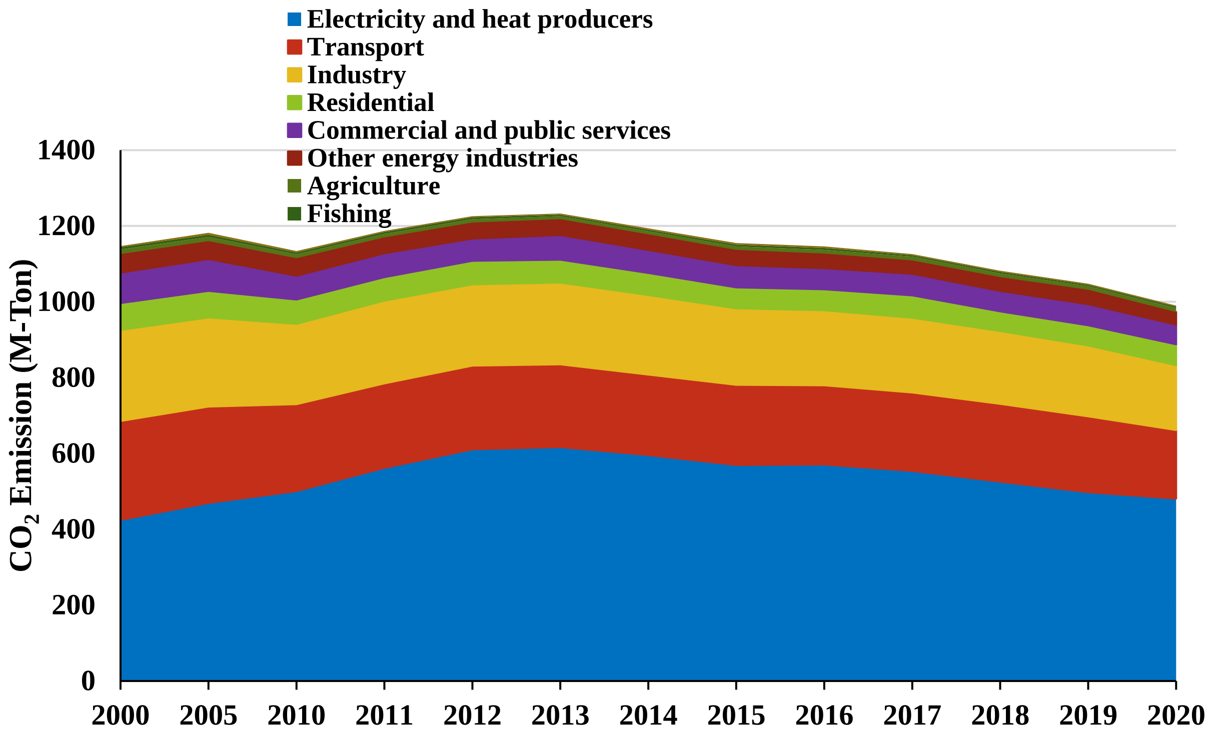


Figure 1- 4. Japan's CO_2 Emission by Sector

Data source: International Energy Agency (IEA)

Energy Statistics Data Browser

https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=JAPAN&fuel=CO2%20emissions&indicator=CO2BySector

(1) The electricity and heat sector

The electricity and heat sector is the largest CO_2 emitting sector in Japan, accounting for approximately half of the country's total emissions. Figure. 1-5 shows the long-term trends of electricity generation and mix in Japan, which steadily increased even after the oil crisis that occurred in the fiscal year 1973, and it increased 2.6 times between the fiscal year 1973 and fiscal year 2007. However, from the fiscal year 2008 to the fiscal year 2009, the economy stagnated due to the global financial crisis, and the electricity supply decreased mainly for corporation use reduction. With the recovery of the economy, electricity supply increased by 4.7% from the previous year in fiscal year 2010, recording

1.15 trillion kWh. However, starting with the Fukushima Daiichi nuclear disaster, the tight supply and demand situation of electricity led to a decrease of 3.7% in fiscal year 2011 compared to the previous year, and this downward trend continued until fiscal year 2015, with the issuance of electricity usage restrictions and the setting of power-saving targets. Fiscal years 2016 and 2017 showed an increase compared to the previous year, but since fiscal year 2018, it again turned to a decrease.

For the electricity mix, this sector is dominated by fossil fuel power generation. Even though the diversification of power sources has been pursued since the first oil crisis in 1973. On the other hand, due to the impact of the Great East Japan Earthquake, nuclear power plants had been shut down since September 2013. However, in August 2015, the No. 1 reactor at Kyushu Electric Power's Sendai Nuclear Power Plant resumed operation, and the restart of nuclear power plants has been gradually progressing. Similarly, the No. 2 reactor at the Sendai Nuclear Power Plant was restarted in October 2015, and Units 3 and 4 at Kansai Electric Power's Takahama Power Plant were restarted in January and February 2016, respectively. Unit 3 at Shikoku Electric Power's Ikata Power Plant was restarted in August 2016, and Units 3 and 4 at Kansai Electric Power's Oi Power Plant were restarted in March and May 2018, respectively. Units 3 and 4 at Kyushu Electric Power's Genkai Nuclear Power Plant were restarted in March and June 2018, respectively, and as of March 2021, a total of 9 reactors have been restarted (Nam et al., 2021). As of 2020, thermal power generation using fossil fuels accounted for 76% of the total, with liquefied natural gas (LNG) being the most used fuel at 39% and coal following at 31%.

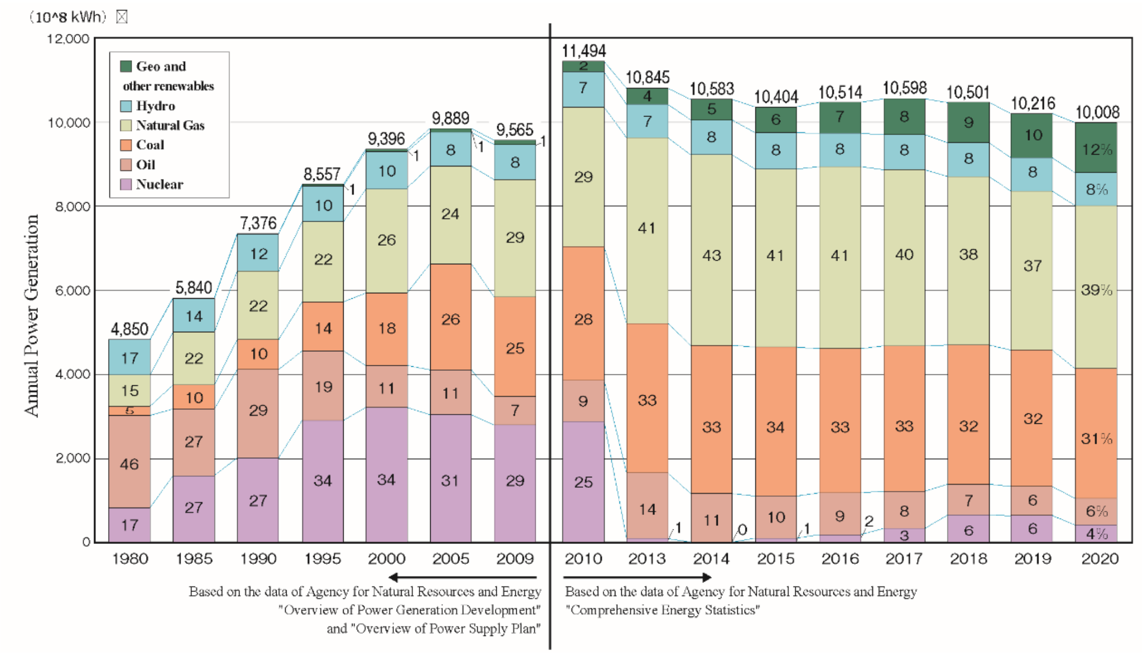


Figure 1- 5. Trends of Electricity Generation and Mix in Japan

Data source: Agency for Natural Resources and Energy

Energy White Paper 2022

However, Even compared to the efficiency of thermal power generation in other countries, Japan's thermal power generation efficiency is top-notch. However, in order to achieve an energy mix, further improvements in efficiency and decarbonization are necessary. The self-set aim for Japan's electric sector to reduce CO_2 emissions during the first commitment period of the Kyoto Protocol was roughly 0.34 kg-CO_2/kWh (Ministry of the Environment, Government of Japan, 2023), which represents a reduction of about 20% from the level in 1990. In comparison to other nations, Japan had maintained a low CO_2 emission coefficient by 2011. However, since nuclear power reactors were shut down following the Fukushima disaster, the CO_2 emission coefficient has dramatically increased (Kharecha & Sato, 2019). Subsequently, the electricity supply and demand structure for the fiscal year 2030 was presented in the long-term energy supply and demand outlook, and in accordance with this, a voluntary framework for the electricity industry, in which major operators participated, was announced in July 2015 (with a target CO_2 emission coefficient of 0.37 kg-CO_2/kWh that is consistent with the national energy mix and CO_2 reduction targets). In February 2016, the Electricity Business Low Carbon Society Council was established, and mechanisms and rules for formulating reduction plans for individual companies and conducting PDCA for the entire industry were announced (Ministry of the Environment, Government of Japan, 2023).

(2) The transportation sector.

The following 2nd emitter is the transportation sector. The transportation industry produced 260 million tons, or 18.6%, of Japan's 1.18 billion tons of carbon dioxide emissions in 2019 (Ministry of the Environment, Government of Japan, 2022). The transportation sector, which includes the automotive industry, was accountable for 86.1% (16.0% of the total emissions in Japan), with freight vehicles accounting for 36.8% (6.8% of the total emissions in Japan) and passenger vehicles providing 49.3% (9.2%) of the emissions (Figure. 1-6).

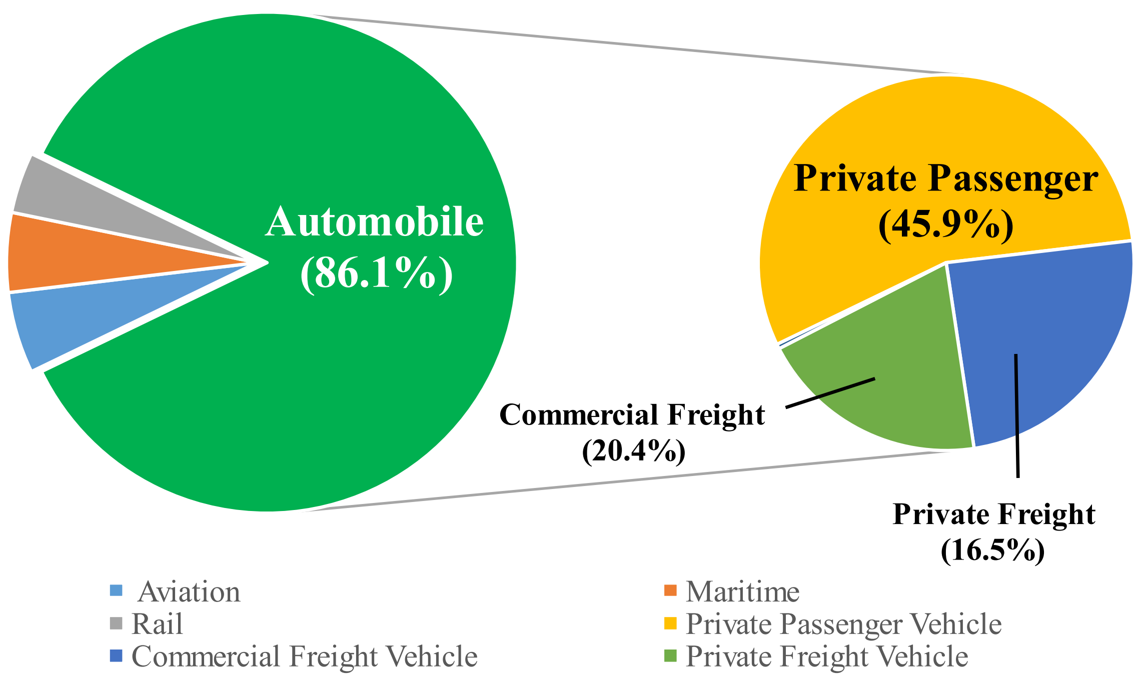


Figure 1- 6. CO_2 Emission of Japan's Transportation Sector

Derived from: Ministry of Land, Infrastructure, Transport and Tourism (MLIT)

https://www.mlit.go.jp/sogoseisaku/environment/sosei_environment_tk_000007.html

In terms of the total number of vehicle stock, the number of cars in Japan has been increasing year by year. The growth rate has gradually slowed down since surpassing 80 million units in 2013, and as of 2021, the total number of vehicles is approximately 82 million. Passenger cars account for about 75% of the total, while freight vehicles account for about 17% but contributed 38.6% of total emissions in the transportation sector (Figure. 1-7).

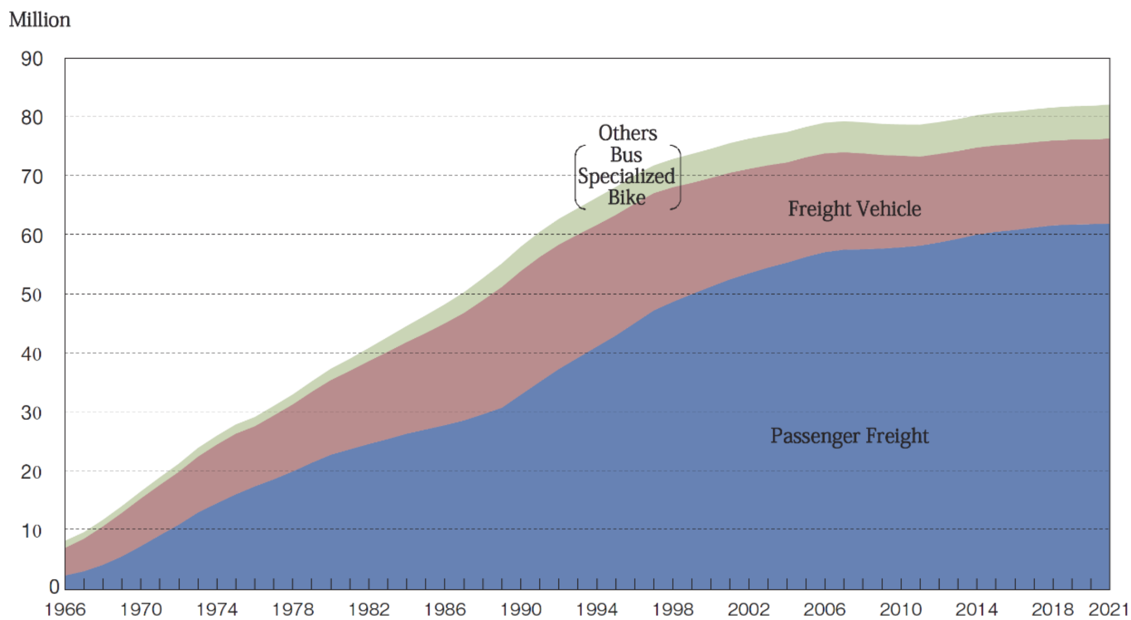


Figure 1- 7. Trends of Vehicle Stock in Japan

Data source: Automobile Inspection & Registration Information Association

https://www.airia.or.jp/

1.1.3 Carbon Neutral and Global Initiatives

The notion of "carbon neutral" varies from country to country. Currently, it is understood to mean "efforts to achieve a net-zero balance between greenhouse gas emissions such as CO_2 and their absorption" (Gössling, 2009). It is challenging to stop greenhouse gas emissions, nevertheless. To achieve a balance between production operations and environmental preservation, efforts are being made to deploy renewable energy and greenhouse gas recovery technologies while reducing emissions. Carbon neutral is defined by the Japanese Ministry of the Environment as "achieving a balance between greenhouse gas emissions and their absorption". Since greenhouse gases, like CO_2, are equally spread throughout the atmosphere, their concentration is essentially the same everywhere. Therefore, the location of emissions or reductions has no bearing on the amount of greenhouse gases present or their effects on the planet. As a result, decreases elsewhere can be used to offset local emissions. This can be done, for instance, by preserving forests, reforestation, and the development of renewable energy sources.

Carbon neutral does not imply that there are no carbon emissions. A net-zero balance between CO_2 emissions and absorption is what is meant by "carbon neutrality." The term "net-zero" refers to attaining a balance in which CO_2 emissions are balanced by CO_2 absorbed by carbon sinks, such as forests. Zero carbon emissions, on the other hand, relate to goods that do not release any carbon dioxide during the processes of manufacturing, providing, and operation. The entire supply chain, including all raw materials, shipping, and packaging, is affected by this. In fact, there are not any instances of things that are carbon-free yet. The main factor driving nations to become carbon neutral is the serious threat that climate change, brought on by greenhouse gas emissions, poses to human society at large. There are many kinds of greenhouse gases, with carbon dioxide making up the majority of emissions (73%). Despite the COVID-19 pandemic, global restrictions, and legislation that significantly reduced energy demand in 2020, the world's energy-related CO_2 emissions nevertheless totaled 31.5 billion tons. Therefore, excessive CO_2 emissions are the primary contributor to global warming, which has a range of negative effects on human production and our way of life, including melting glaciers, rising sea levels, heat waves, and ecological degradation. The most pressing task to combat climate change is to achieve global carbon neutral, which is also a crucial step toward the world's sustainable development (F. Wang et al., 2021). This objective will call for international collaboration across national boundaries, resulting in an energy revolution and an industrial revolution. We need to cool the globe and address the issues brought on by 200 years of human progress over the next 30 to 40 years. This will necessitate a radical, unprecedented, and extensive overhaul of global manufacturing practices.

Carbon dioxide, which accounts for the largest amount of greenhouse gases, appears to be decreasing in advanced countries while increasing in emerging and developing countries (M. Khan & Ozturk, 2021). Looking at the regional breakdown of CO_2 emissions from energy sources, emissions are decreasing in European countries, South Africa, North America, and Russia, while increasing in Asian countries, the Middle East, and South America. The 2015 Paris Agreement set a goal of achieving net-zero by the second half of this century. Governments are increasingly incorporating this goal into national strategies and setting visions for a carbon-free future. 125 nations and 1 region, including the United States, the European Union, the United Kingdom, and Japan, have made the commitment to become carbon neutral by the year 2050 as of April 2023 (Table 1-1). These nations generate 37.7% of the world's CO_2 emissions (Ministry of the Environment, Government of Japan, 2023).

Table 1- 1. Timetable of mid-term greenhouse gas reduction targets and achieving carbon neutral (CN) for major emitting countries/international organizations

U. S.	Mid-term Goal	50-52% reduction from 2005 levels by 2030
	Year of Achieving CN	2050
EU	Mid-term Goal	55% reduction from 1990 levels by 2030
	Year of Achieving CN	2050
U. K.	Mid-term Goal	78% reduction from 1990 levels by 2030
	Year of Achieving CN	2050
Japan	Mid-term Goal	46% reduction from 2013 levels by 2030
	Year of Achieving CN	2050
China	Mid-term Goal	GHGs peak out by 2030
	Year of Achieving CN	2060

Japan wants to achieve carbon neutral by 2050. In a recent compilation of Japan's greenhouse gas emissions for FY2020, the Ministry of the Environment and the National Institute for Environmental Studies (NIES) found that the total emissions (Note 2) for FY2020 were 1.15 billion tons (carbon dioxide (CO2) equivalent), down 5.1% from the previous year. On the other side, 44.5 million tons were absorbed by forests and other sinks in FY2020. When the "amount absorbed by forests and other sinks" is subtracted from the "total emissions," the result is 1,106 million tons, which is 60 million tons fewer than the previous year and 303.6 million tons (30.5%) less than the total emissions in FY2013. The development of a novel coronavirus illness caused a drop in manufacturing output, and a drop in passenger and freight transit volume resulted in a drop in energy consumption, all of which contributed to the decrease from the previous fiscal year (National Institute for Environmental Studies, 2022). The world community should work together to confront the significant challenge of climate change. Since 1995, the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), which is based on the UNFCCC, has been convened annually. Since 1995, the COP has taken place annually, and there have been heated discussions on how to reduce greenhouse gas emissions globally. Intense debates have taken place at the COP in an effort to reduce greenhouse gas emissions globally. The Global Stock take, a method for evaluating the global level of implementation every five years, was established by the Paris Agreement. Climate change has caused an upsurge in natural disasters worldwide since 2021, and biodiversity has had a profound effect on human society. A temperature increase of 2.7 degrees Celsius is anticipated by 2100, even if all nations' currently submitted nationally determined contributions (NDCs) for greenhouse gas reductions are added together, according to a report by the international environmental think tank NGO Climate Action Tracker (Climate Action Tracker, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), the Paris Agreement's goal of limiting temperature increase to 1.5°C by 2030 will require a 45% decrease in world average emissions (relative to 2010 levels).

Japan, the third-largest economy in the world and one of the biggest carbon emitters, is essential to the fight against climate change and the goal of becoming carbon neutral. Reducing carbon emissions at their source is the key to achieving carbon neutral, and for Japan it is critical to continue promoting energy transition in the two sectors with the highest CO_2 emissions, which are the electricity sector and the transportation sector. The Japanese government has proposed numerous policies to encourage energy transition in these two sectors, such as continuously reducing electricity demand, gradually increasing the proportion of renewable energy in the electricity sector through technological advancements and strengthening power conservation, as well as promoting the electrification transition of vehicles in the transportation sector through subsidies and other means, but the specific effects of these policies on the whole energy system and the environment are still unknown.

1.2 Research Question and Significance

Two fundamental research questions can be raised based on the background and context we summarized in section 1.1, which are:

(1) What policies Japan has proposed and what scenarios can be designed based on the current and future possible policies?

(2) What impacts on both energy system and carbon emission will be made under these scenarios?

The answers to these questions are crucial for policymakers to further deploy energy transition plans at the sectoral level, as well as for our general understanding and participation in the comprehensive energy transition.

1.3 Research Objectives

To answer the above questions, the main objective of this research is to:

(1) Design several energy transition scenarios for the electricity and transportation sector in Japan based on current polices and determinations.
(2) Analyze the impact of energy transition on both energy system and natural environment under different scenarios.
(3) Draw policy implications and references based on the results above.

1.4 Dissertation Outline

This dissertation consists of six main chapters. The following is the structure of each chapter and its contents:

Chapter 1: Introduction

This chapter provides an introduction and overview of the background and context of the research topic and presents the research questions, significance, as well as objectives of the study.

Chapter 2: Literature Review

This chapter provides a comprehensive review of not only the relevant literature on the topics of energy transition and sustainable development from its historical evolution to future pathways but also the literature concerning the sectoral energy transition process especially from the perspective of Carbon-Water-Energy nexus within the electricity sector and the perspective of scenario design within the transportation sector. Furthermore, policies and initiatives in Japan's electricity sector and transportation sectors are also reviewed. The chapter then identifies the research gaps of previous research and propose the originality of this research.

Chapter 3: Materials and Methodologies

This chapter describes the theoretical framework, data sources, and methodologies used in the study. Data used for the analysis of both the electricity sector and the transportation sector are introduced and the main methodologies used, including the environmentally extended input-output analysis (EEIOA) approach for the electricity sector and the system dynamics approach for the transportation sector are explained.

Chapter 4: Carbon-Water-Energy Nexus of the Electricity Sector

This chapter presents the results and analysis in the electricity sector, including electricity mix of under the base year (2015) and NDC scenarios (2030), and the life cycle carbon emissions and water consumption of different electricity generation technology sources are calculated. Then the accordingly disaggregated environmental impact of different driving factors on CO_2 emissions and water consumption are analyzed. The chapter also discusses the implications of the results and analysis for policymakers and stakeholders.

Chapter 5: Energy Transition in the Transportation Sector

This chapter presents the results and analysis in the transportation sector, including a detailed design of six scenarios and a comprehensive dynamics approach of the LEAP model. The results of model analysis cover the demand of four types of energy sources and the emission of four pollutants under different scenarios. The chapter also discuss the future potential and impact of energy transition within the whole transportation sector to be linked to the global EV transition trends.

Chapter 6: Conclusion and Recommendations

This chapter provides a summary of the main findings and conclusions of the study and proposes recommendations for future research and policy implications in not only Japan's electricity sector and transportation sector, but also the whole industry and society. The chapter also reflects on the limitations and strengths of the study and suggests areas for further research.

Chapter 2. Literature Review

2.1 Energy Transition Research

2.1.1 Development of Energy Transition

Energy transition is another name for "energy structural transition," which refers to a fundamental shift in the energy structure that results in the conversion and replacement of major energy sources. The human society has experienced several energy transition processes in history. During the firewood and coal eras, the first energy transition took place, and coal gradually supplanted firewood as the main energy source. The second energy transition happened during the coal and oil ages, and oil finally displaced coal as the major energy source and the third energy transition that the world is currently experiencing is intimately tied to the suppression of climate change. To combat global warming and its irreversible ecological repercussions, clean energy sources releasing minimal greenhouse gases will eventually replace fossil fuels as the primary energy source of the future (B. D. Solomon & Krishna, 2011). An environmental think tank proposed the concept of energy transition with the goal of renewable energy dominance in 1980, primarily referring to the transition from a high-pollution fossil energy system to a zero or low-pollution renewable energy system (Strunz, 2014) in order to achieve "growth and prosperity without oil and uranium" (Schmitz & Voß, 1980). Some scholars define "energy transition" as a systematic evolution of the energy structure, primarily demonstrated by the substitution of dominant energy sources, namely the substitution of renewable energy for high-carbon energy and the reform of high-carbon energy structures, ultimately achieving human society's sustainable development (Bogdanov et al., 2021; Kabeyi & Olanrewaju, 2022). The development of renewable energy systems includes not only the development of specific renewable energy sources such as wind, solar, geothermal, and biomass fuels, but also the clean utilization of fossil energy through the development of new technologies and materials such as hydrogen extraction, dimethyl ether (DME), methanol, and so on. Furthermore, the efficient and comprehensive use of energy resources, as well as energy conservation (such as distributed energy, smart grids, and so on), are viewed as critical components in the transition to a renewable energy system (Dahlgren, 2022; Styring et al., 2021).

Overall, "energy transition" refers to a fundamental transformation of the energy structure, characterized by the replacement of existing energy sources (mainly fossil fuels) with renewable energy sources and the enhancement of energy usage. The goal of today's energy transition is to establish a sustainable usage of clean, widely dispersed, and efficient energy, with a focus on replacing traditional energy sources with renewable ones and improving energy consumption. Regarding the relationship between energy and socioeconomic production processes, energy, as a tactical resource, is crucial for sustaining social production, communication, and daily existence in society (Palle, 2021). A social-industrial revolution known as an energy transition affects every step of the energy production process, from energy supply and distribution to final consumption. By 2050, the low-carbon energy transition sector will have invested more than 3.2 trillion US dollars annually, making up about 2% of the global GDP, with a total investment of more than 95 trillion US dollars, creating more than 100 million job opportunities (IRENA, 2020). The economic structure, technology, and system are all faced with continuous and systematic issues as a result of this process, necessitating government participation to assure fairness throughout (Pegels et al., 2018). Some scholars also argue that energy transition is a "creative destruction", where technological change will create new winners and losers. Therefore, social and technological transformation is fundamentally a political process (Bjerkan et al., 2021; David, 2017; Kivimaa & Kern, 2016). Although the switch from technology based on fossil fuels to technology based on renewable energy may result in new market winners in the form of niche market entrants, it will also encounter political resistance because it poses a challenge to current interests (Geels, 2014).

Furthermore, the term "energy transition" is used to particularly refer to the fundamental transformation of the present energy system (full abandonment of fossil fuels and nuclear energy) in response to concerns about climate change and nuclear energy dangers. The energy mix, on the other hand, is a more pragmatic approach to energy system reform based on tackling climate challenges and energy affordability (Leipprand et al., 2017). Nuclear energy use is controversial, although both sides concur that "energy transition" and "climate change response" should be seen as intertwined ideas. To effectively promote the energy transition and work to increase their nationally determined contributions, economic entities should use the Paris Agreement's provisions on limiting global warming to 2 degrees Celsius as a starting point and set goals for comprehensive changes to energy production and consumption from this baseline.

In conclusion, these considerations imply that, in the modern environment, the definition of "energy transition" is constantly shifting, moving from a straightforward economic issue to a complex issue including social, technological, and political areas. Governments and nations take the lead in this process, ensuring the fairness of the transition and working to match the development of the energy transition with the aspirations of the international community to combat climate change.

2.1.2 Energy Transition Policy Research

With the rapid development of the energy industry, academia is actively researching innovative policies for energy transition industries. It is widely recognized that policies and policy combinations play a key role in transitioning towards a non-fossil fuel energy society, as they can accelerate social and technological transformation (Kern & Rogge, 2016). In terms of research topics, comparing policies at the national and global levels is popular for academics studying new policies for the energy transition industry. For instance, Zander et al. (2019) employed a selection model to assess the likelihood of households installing solar energy in the future under the influence of financial incentives in Australia, a nation with high sun radiation. The findings demonstrated that household energy transition installation is positively impacted by policy awareness, education, and income. In terms of multi-country policy comparisons, Dusonchet & Telaretti (2015) used economic analysis to study innovative policies in the energy transition industry in the UK, France, Germany, Italy, and other countries with developed energy transition industries. They found that electricity compensation mechanisms can effectively promote the development of the energy transition industry. Polo & Haas (2014) discovered that government subsidies are efficient tools for promoting energy transition and advancing the self-generation and self-use of new energy based on their research on international policies for energy transition and grid interconnection, as well as thorough comparisons of energy transition and grid interconnection policies in some European, Asian, and the US countries.

In terms of research content, scholars mainly focus on evaluating policy effectiveness.

Li et al. (2019)conducted a qualitative analysis of China's energy transition poverty alleviation projects and found that although individual information disclosure policies or incentive policies promoted the implementation of energy transition poverty alleviation projects, the combination of these two policies had a more significant stimulating effect on the energy transition industry. The favorable impact produced by R&D policies supporting the development, demonstration, and deployment of renewable energy generation technologies has also been identified by several academics as a crucial component in the cost decrease of these technologies. They argue that similar policy combinations may be necessary to stimulate innovation in other important technologies (Kavlak et al., 2018; Nemet, 2019). Other scholars, however, argue that while public policies are helpful in promoting technological advancements, current policies are still insufficient to achieve the goals of energy transition and propose a disconnection between the goals and the policy combination (Mata et al., 2020). Furthermore, several scholars are concerned about the challenge of integrating energy policies which entails addressing cross-sectoral policy challenges while taking into account the main functions of various departments in the context of an overarching policy strategy. They examine the degree of policy integration using policy integration theory and suggest that the cross-sectoral character of energy transition necessitates coordination of interests between the government and other stakeholders from other sectors with distinct energy policy aims (Park & Youn, 2017; Spijkerboer et al., 2019).

2.2 Carbon-Water-Energy Nexus Research

Carbon, water, and energy are environmental indicators of the level of sustainable development and have a significant impact on the sustainable development. Changes in one factor cause changes in the other two, research on the carbon-water-energy nexus is necessary and beneficial for promoting sustainability (Vera & Langlois, 2007; Winston & Pareja Eastaway, 2008). For example, published in 2006, The Singapore Green Plan 2012 outlined broad goals and tactics with the ultimate goal of achieving environmental sustainability (Tortajada & Joshi, 2014). The Government of Mexico City has included mitigating water, climate change, and energy pressures in the city ’s sustainable development goals (Shen et al., 2011). The massive energy consumption of mega cities has caused a series of air pollution and greenhouse gas emissions, threatening human health and asset security (Pachauri et al., 2014). In this context, alleviating urban energy, water and other resource pressures and controlling carbon emissions are important aspects of urban sustainable development (Kılkış, 2019). The basic framework of Carbon-Water-Energy Nexus is shown in figure. 2-1.

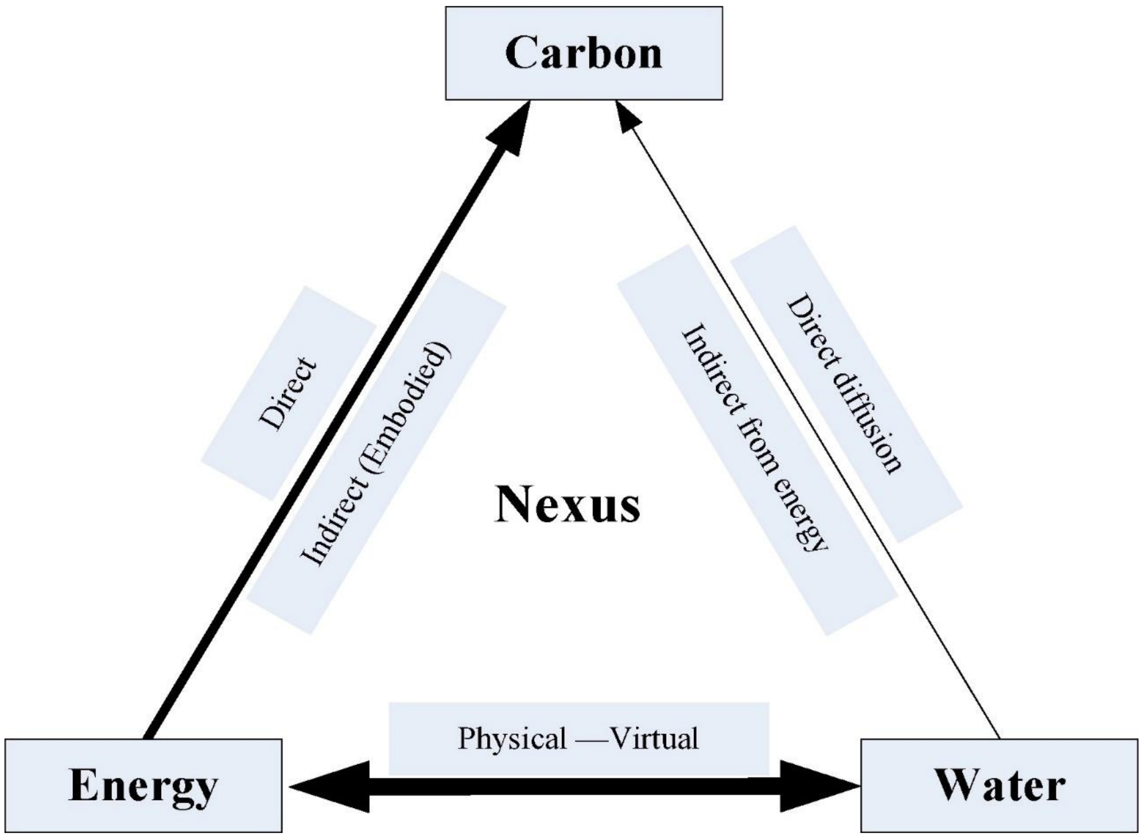


Figure 2- 1. Framework of Carbon-Energy-Water Nexus

* The width of connecting lines represents the content of nexus between the two elements.

At present, many scholars have emphasized the coupling relationship (nexus) of energy flow, water flow, and other material flows in the system (Pandit et al., 2017). As one of the largest CO_2 emitter and water consumer within the industry, the Carbon-Water-Energy Nexus research has now become a popular field to understand the environmental impact of the energy transition process in the electricity sector.

2.2.1 Energy-Water Nexus Research

Research on energy-water nexus mainly focus on single sector of the energy sector or the water industry. For the energy sector research, the main attention is paid to water consumption in the energy extraction and the power generation industry (L. Liu et al., 2015). For research in the water industry, it can be refined into energy consumption in water resources mining, water supply, water distribution, and wastewater treatment. (Hamiche et al., 2016; Nogueira Vilanova & Perrella Balestieri, 2015). On the one hand, energy extraction and processing consume a lot of water resources, such as coal mining, refining, and transportation (Bian et al., 2010), crude oil mining and refining process (Ali & Kumar, 2017), exploit of natural gas and oil shale (Gregory et al., 2011). In addition, some researchers have studied the energy-water nexus in biofuel production and proposed that the cooling process is the main driving force for water consumption in the biofuel production process (Martín & Grossmann, 2015). On the other hand, the consumption of water resources caused by different power generation methods in the power industry has also attracted the attention of a large number of scholars (Ackerman & Fisher, 2013; L. Liu et al., 2015) such as thermal power (DeNooyer et al., 2016), hydropower (Hennig, 2016), wind power (J. Yang & Chen, 2016), nuclear power (Khamis & Kavvadias, 2012), solor power (X. D. Wu & Chen, 2017) and so on. In addition, water supply, distribution, and wastewater treatment also consume a lot of energy. It is estimated that about 3% of electricity consumed in the U.K. is used in the water supply sector (Ainger et al., 2009) and about 4% of electricity consumed in the U.S. is used for water treatment and transportation (EPRI, 2022). In conclusion, the water-energy nexus has received a great deal of attention over the past decades, and many scholars have stressed the significance of comprehending how interdependent water and energy systems are. The studied literature emphasizes the interconnectedness and complexity of the water-energy nexus as well as the necessity of interdisciplinary cooperation and integrated management strategies.

2.2.2 Energy-Carbon Nexus Research

Energy-carbon nexus research mainly covers CO_2 emissions related to energy use. In recent years, researchers have discussed the energy-carbon or energy-greenhouse gas nexus relationship at the global level (Nejat et al., 2015; Wiebe et al., 2012), national and regional levels (Lin & Raza, 2019; Y. Liu et al., 2016; Long et al., 2015; Y.-J. Zhang & Da, 2015), city level (X. Chen et al., 2017; Jing et al., 2018; J. Liu et al., 2011; Meng et al., 2016), industry and sector level (Du & Lin, 2018; J.-C. Feng et al., 2018; Griffin et al., 2016; Malmodin & Lundén, 2018, pp. 2010–2015; Robaina-Alves et al., 2016; Y. Yu et al., 2021), and product level (Hassard et al., 2014). For example, Ang & Su (2016) calculated the CO2 emission intensity of global power generation and found that improvements in thermal efficiency of generation were the main driver of reduction in aggregate carbon intensity (ACI), while the impact of fuel switching and increased use of non-fossil energy sources was relatively less significant. Irandoust (2016) analyzed the coupling relationship between renewable energy and CO_2 in four Nordic countries and concluded that there is a one-way causal relationship between renewable energy in Denmark and Finland and CO_2 emissions, and two-way causality in Sweden and Norway. At the industrial level, the scope of research involves the metal industry (C. Feng et al., 2018; Song et al., 2018), construction industry (K. Wang et al., 2018), transportation sector (W. Chen & Lei, 2017), tourism industry (Robaina-Alves et al., 2016) and so on.

Furthermore, urban energy-carbon nexus has gradually become a hot research issue. In addition to accounting for CO_2 emissions from energy consumption at the city scale (Jing et al., 2018). There are also scholars who have established a time series-based carbon and energy flow database that contains 66 city samples with different geographic and economic conditions. The time span is as early as 1865 considering the city size and population density to assess the energy consumption and correlation between carbon emissions (X. Chen et al., 2017).

2.2.3 Carbon-Water-Nexus Research

Water-Carbon nexus research are relatively fewer compared to the former two parts and can be divided into single industry and multi-industry research. Single industry research emphasizes the nexus within the water systems (L. Wu et al., 2015) or the energy system (Shaikh et al., 2017; J. Zhang et al., 2018). For example, a study of the Zhikong Hydropower Station in Tibet shows that for every 1 kg of greenhouse gas emission reductions achieved, it will consume 0.704 m^3 of water, the reservoir will have 0.126 m^3 water lost due to evaporation for every cubic meter of water stored (J. Zhang et al., 2018). Research based on multiple industries mainly assesses the water consumption and CO_2 emission levels of different industries. Studies have shown that the overall water intensity of the China's primary, secondary, and tertiary industries is significantly positively correlated with the intensity of CO_2 emissions (Cai et al., 2016). Another study explained the water-carbon nexus flow path of the economic system to get the key industry nodes in the coupled water-carbon flow based on the calculation of the embodied water consumption and embodied CO_2 emissions of various economic sectors (Meng et al., 2019). Furthermore, because the carbon capture and storage process involve many water-related difficulties, the carbon capture stage necessitates a large amount of water to cool the equipment, and the regeneration of chemical and physical adsorbents consumes water resources. As a result, key international organizations are devoting themselves to researching the water-carbon nexus relationship in the process of carbon capture and storage, as well as resolving water-related issues. (Klapperich et al., 2014).

2.2.4 Carbon-Water-Energy Nexus Research

The research on the carbon-water-energy nexus comes last. It is the most intricate and thorough research that examines the entire nexus system. However, it is also the one that has received the least attention since it is the most complex and comprehensive. Due to the complexity of the system and the high precision of the data requirements, even though the research fervor in energy-carbon-water nexus has steadily grown in recent years and the related research literature has expanded significantly, the number of such studies is still not comparable to the aforementioned categories. At present, there are relatively few studies on energy-water-carbon nexus, and they are mainly divided into two categories: single-industry and multi-sectoral energy-water-carbon nexus in urban systems. Researchers analyze the linkage between energy, water, and CO_2 in different systems by accounting water consumption and CO_2 emissions in the energy system, or energy consumption and carbon emissions in the water system.

There has been some research on Energy-Water-Carbon nexus within single industry. For instance, energy consumption in Ontario, Canada in 2015 was 153.7 TWh, causing water consumption 1.34 billion cubic meters, producing about 11.58 million tons of greenhouse gas emissions and it is expected to reach an energy demand of 160 TWh with 2.08 billion cubic meters of water and 13.82 million tons of greenhouse gas emission in 2025, respectively (Miller & Carriveau, 2017). In China, the wind power system consumes 0.64 liters of water for every 1 kWh of electricity generated and causes 69.9 g of CO_2 emissions (X. Li et al., 2012). Lee et al. (2017) found that the greater the risk of water resource, the greater the energy consumption intensity and greenhouse gas emission intensity of the water supply system and implementing water-saving measures can reduce energy consumption and mitigate greenhouse gas emissions. Similarly, improving energy efficiency will also help reduce water consumption and greenhouse gas emissions(Engström et al., 2017). Hickman et al. (2017) analyzed the nexus among different power generation system in Singapore and Middle East and found that solar power generation brings lower CO_2 emissions and freshwater withdrawal than other power generation methods. Zhao et al. (2022) assessed economic and environmental effects of ten ECW policy scenarios in 2050 and found that integrated policy scenarios better control ECW nexus with larger economic losses and isolated policy scenarios have stronger impact on their targeted ECW elements.

However, research on Energy-Water-Carbon nexus based on multiple industries is extremely limited. This type of research focuses on the comprehensive impact of energy, water, and CO_2 on urban economic systems. For example, Duan & Chen (2016) have calculated the energy use and CO_2 emissions related to water consumption, as well as the water consumption and CO_2 emissions related to energy consumption in a system consisting of Beijing 's energy sector, water sector, agriculture, service industry, and residential consumption. Wang et al. (2021) analyzed the critical Carbon-Water-Energy (CWE) flows across the EU27 using a multiregional input-output model, at a sector level to identify the inter-regional and-sectoral CWE flows and found that Germany, France and

Italy are the biggest beneficiaries in the CWE network of EU27.

2.3 Energy Transition in the Transportation Sector

One of the biggest obstacles to sustainable development has been the transportation sector (Mathiesen et al., 2015). The transport sector that relies on fossil fuels has contributed one-third of the EU's total final energy consumption and more than one-fifth of its greenhouse gas (GHG) emissions over the past ten years (Alises & Vassallo, 2015). The transport industry is still dominated by fossil fuels, despite current trends in the heat supply and power sectors in some countries showing significant success in reducing demand and adopting more renewable energy sources (RES). Combining the electricity and transportation sectors could increase renewable energy penetration, while battery electric vehicles (BEVs), more efficient modes of transportation, and the introduction of alternative fuels could significantly reduce the transportation sector's reliance on fossil fuels. As a result, numerous studies discuss various potential solutions for a transportation industry that is sustainable in the future. The present mainstream study on energy transition in the transportation sector may be broken down into two primary categories: one that examines the technology innovation of vehicles or related industry, and another focuses on the policy of the energy transition in the transportation sector considering various scenarios.

2.3.1 Technology Related Research

Technology innovation research has been a key focus of research in recent years, as the transportation sector seeks to transition to cleaner and more sustainable energy sources. One of the key challenges in this area is the dominance of fossil fuels, particularly oil, in the sector. Since decades ago, scholars and industries have been actively studying how to improve the fuel economy of automobiles and reduce the intensity of emissions of pollutants from their exhausts. For instance, in addition to carbon dioxide, automobile exhaust contains a significant amount of other harmful substances, including methane (CH_4), hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx). These pollutants not only severely contaminate air quality but also pose risks to human health. The three-way catalytic converter with an oxygen sensor is one of the most important inventions in automobile emission control. It was developed by Volvo Cars in the early 1970s under the leadership of environmental technology expert Stephen Wallman. Experimental results have proven that using a catalytic converter can reduce the three major pollutants (hydrocarbons HC, carbon monoxide CO, and nitrogen oxides NOx) in exhaust emissions by approximately 90%. (Engh & Wallman, 1977). Besides, Onishi et al. (1979) proposed a new combustion process for ICE called Active Thermo-Atmosphere Combustion (ATAC). Stable combustion can be achieved with lean mixtures at part-throttle operation. With ATAC the fuel consumption and exhaust emissions of two-stroke cycle spark-ignition engines are remarkably improved, and noise and vibration are reduced.

However, conventional fuel-powered vehicles, which are widely used, have various drawbacks. Statistics show that under more than 80% of road conditions, an ordinary passenger car only utilizes 40% of its power potential, which further drops to 25% in urban areas (S. Zhang et al., 2014). More importantly, these vehicles emit exhaust pollutants that seriously not only pollute the environment but also threaten human health (Luo et al., 2022). Since the 1990s, there has been an increasing global call for environmental improvement, leading to the emergence of various electric vehicles. While it is widely believed that the future belongs to electric cars, battery technology has posed challenges for their widespread adoption (Rajaeifar et al., 2022). In response, engineers have come up with a compromise solution and developed vehicles equipped with hybrid powertrains. The official launch of the world's first hybrid electric vehicle (HEV), the Toyota Prius, in 1997 marked the beginning of a new era for hybrid vehicles (A. S. O. Yu et al., 2011). The U.S. Department of Energy (DOE) evaluated of the 2007 Toyota Camry hybrid synergy drive system and programmed activities include research, development, demonstration, testing, technology validation, and technology transfer which showed that HEV is more energy efficient and environmentally friendly transportation technologies (Burress et al., 2008). Subsequently, further development from HEVs led to the emergence of PHEV. Samaras & Meisterling (2008) assessed life cycle greenhouse gas (GHG) emissions from plug-in hybrid electric vehicles (PHEVs) and finds that they reduce GHG emissions by 32% compared to conventional vehicles. With the technology developing, as a result, there is a growing need to transition to cleaner and more sustainable energy sources, such as battery electric vehicles (BEVs) and renewable energy. Several studies have examined the potential of EVs to reduce greenhouse gas emissions in the transportation sector. For example, a study by Brouwer et al. (2018) found that the adoption of EVs could significantly reduce greenhouse gas emissions in the Netherlands, particularly if the electricity used to power the EVs comes from renewable sources. However, the study also highlighted the need for significant investments in charging infrastructure and the development of more efficient batteries to make EVs a viable alternative to traditional vehicles. In addition to EVs, there has been significant research on the potential of other technologies to support the energy transition in the transportation sector. For example, hydrogen fuel cell vehicles and biofuels have been identified as potential alternatives to traditional vehicles (Acar & Dincer, 2020). However, these technologies also face significant challenges, such as the need for significant investments in infrastructure (Funke, Plötz, et al., 2019) and the development of more efficient production processes (Sun et al., 2020) and meaningful GHG emissions reductions with both PHEVs and BEVs are conditional on low-carbon electricity sources (Mou et al., 2019).

2.3.2 Policy Relate Research

Related energy transition policy research has also been a key focus of research in recent years. The development of policies and strategies to support the energy transition in the transportation sector is critical to the success of the transition (Hainsch et al., 2022). Several studies have examined the potential of different policy approaches to support the transition, such as subsidies for EVs, carbon pricing, development of other transportation forms, and regulations on vehicle emissions. For example, Ross Morrow et al. (2010) analyzed specific policy proposals for different sectors to reduce greenhouse gas emissions and oil consumption in the transportation sector in the United States under a comprehensive carbon price. Mao et al. (2012) focused on carbon dioxide emissions in the transportation sector in China and effective policy tools to reduce these emissions. Solaymani et al. (2015) examined the impact of carbon tax and its alternative, energy tax, on both the Malaysian economy and the transport sector, using a CGE (Computable General Equilibrium) framework.

In addition, Ülengin et al. (2018) assessed potential mitigation strategies and policies to reduce the climate change impact of the transportation sector and identified the most effective policies at both global and local levels. Zhang et al. (2019) found that the development of a high-speed rail system in China could significantly reduce greenhouse gas emissions and improve energy efficiency compared to traditional transportation systems. Besides, Zheng et al. (2020) provided a summary of the annual sales and market trends of PHEV in China from 2011 to 2017 at the national and regional levels. Technology related research and policy related research are two key areas of focus in this field. Further research is needed to develop new technologies and infrastructure to support the transition and to identify policies and strategies that can facilitate the transition.

2.4 Research Gap and Originality

Based on the literature review, we find that as two major carbon emission sectors, there has been sufficient research about the emission reduction in both sectors. However, in the electricity sector, most research focused on only one industry or the nexus between two environmental factors. Besides, the commonly used bottom-up or upside-down methods both have some limitations for the analysis. In the transportation sector, also most research put emphasis on carbon tax, subsidies, and considered limited scenarios, especially lack of different level of the adoption of EV. For Japan, there is currently no research that make comprehensive scenario design to analyze the impact of energy transition on both energy consumption and emission scenarios in the transportation sector. Therefore, the originality of this research are:

a) Life cycle carbon emission and water consumption of different power generation source based on Carbon-Water-Energy Nexus using a hybrid LCA model.

b) Comprehensive scenario analysis of the energy transition on both energy consumption and emission in Japan’s transportation sector.

c) Discussion of policy implications and sector coupling for future energy transition process.

Chapter 3. Materials and Methodologies

This chapter introduces the research methodology framework and several specific models involved in the research objectives, including the environmentally extended input-output model, the hybrid LCA model based on sector disaggregation, the Kaya Identity for splitting environmental impact factors, and the comprehensive energy modeling system LEAP model used for the transportation sector.

3.1 Assessment Tools for the Electricity Sector

Research on the energy-carbon-water nexus is mostly based on footprint theory, which takes a life cycle perspective to focus on the impacts on each sector of the industrial chain where the sector targeted by energy transition policies is located, and conduct a comprehensive assessment, systematically identifying the diverse impacts of policies and measures on resources and the environment. Such effects occur not only at the stages of production directly affected by policy measures, but also through the influence on changes in production activities of other industries caused by inter-industry connections, resulting in indirect effects. The life cycle hypothesis is concerned with these indirect effects.

There are two primary dominant divisions in the studies that have been done so far based on the production side and the consumption side, from the standpoint of the methodological framework for the examination of the policy implications of the energy transition and carbon neutral pathways in terms of life cycle assessment. Methods for describing the environmental implications of human activities from a production standpoint frequently concentrate on the intensity of resource usage or pollutant emissions throughout the manufacturing process. In terms of evaluation methodologies and policy development, the major measuring indicators employed are the number of resources consumed or pollutants emitted per unit of output, which provide policy direction for industrial transformation. In the planning of industrial energy conservation and emission reduction policies, for example, it is common to set targets for reducing energy consumption per unit of industrial value-added, controlling the expansion of high-energy-consuming and high-emission industries, eliminating backward production capacity, and promoting the use of low-carbon technologies. From a production standpoint, evaluation and policy guidance approaches can have a direct impact on the stages or places where environmental consequences arise. They can provide a clear description of the environmental implications of human economic and social development, as well as advocate the adoption of clean technology in manufacturing, so supporting the green transformation of the manufacturing process. However, because of the close coupling links between industries and economic exchanges between regions, structural changes caused by a single sector will be communicated to other sectors or regions via the production chain's inter-industry linkages. Specifically, the production activities of one industry necessitate the supply of raw materials from upstream industries, and the output of that industry become raw materials for downstream industries. The environmental impacts of upstream and downstream businesses are linked by this basic dependency connection. Usually, there is no absolute upstream or downstream relationship between sectors in a real economic system. Each sector's production is embedded in an infinite hierarchy of inter-industry linkages. As a result, structural changes caused by a sector's production activities will have indirect environmental and other diverse impacts on other sectors that are driven by inter-industry linkages within the economic system, in addition to direct impacts observed by the production evaluation system.

The development of footprint theory gives a model framework for representing the whole impact of human activities, including direct and indirect effects. The total environmental impact generated to meet the demand for products or services from individuals, industries, and regions is referred to as the footprint. It tracks all environmental impacts caused by products or services in the manufacturing process from the point of view of end consumption and categorizes or aggregates them based on the ultimate consumption objects defined by the boundary, which is from the consumption side perspective.

In terms of methodology, the specific implementation methods and calculation principles of LCA can be divided into two categories based on the different perspectives and approaches to product and industry relations: process analysis (PA) and environmentally extended input-output analysis (EEIOA). PA is a standard bottom-up LCA method, which considers all environmental impacts in multi-level production processes starting from the direct environmental impacts such as resource inputs and pollutant emissions of the most basic technical units in the production process. This method is represented by the methodology framework specified in ISO14040 and has clear process and specific technology targets, clear and simple data requirements, and mature technical frameworks and application examples. In the field of carbon emissions, PA has been applied to various products' carbon footprint studies, such as food (Biswas & Naude, 2016; García et al., 2016; Noya et al., 2016; Vázquez-Rowe et al., 2016; Vergé et al., 2016), water (Dias & Bernardes, 2016), buildings (Rodríguez Serrano & Porras Álvarez, 2016; Sim et al., 2016), non-metallic and metallic products (Christoforou et al., 2016; Laleicke et al., 2015; Salas et al., 2016). For example, Biswas and Naude found in their carbon footprint study of beef and chicken meatballs produced by a food factory that the largest source of carbon footprint for these foods is the raw materials used rather than the value-added process of food processing. Christoforou found that reducing the demand for transportation and increasing the use of local raw materials can effectively reduce the environmental footprint of brick production, including energy consumption and carbon emissions. In the field of water resource consumption, a series of bottom-up water footprint studies have been led by scholars such as Chapagain and Hoekstra, represented by the Water Footprint Network (WFN) (A. Chapagain et al., 2005; A. K. Chapagain & Hoekstra, 2004; Mekonnen & Hoekstra, 2011). The series of studies using the PA method adopt a standardized crop water demand model and analyze in detail the required water resources for different agricultural products under different climate conditions, especially for water consumption in agricultural products. For animal products, the water footprint of live animals is divided into three aspects: feed, drinking, and the water consumed by the services provided. The water footprint of animal products is calculated according to different stages of processing. In general, the LCA under the PA method framework includes well-defined boundaries and processes, as well as a prominent level of operational transparency. However, the artificial setting of boundaries for distinct study objects can result in considerable truncation errors, and the PA technique cannot investigate the interdependence of industries and sectors beyond the stated boundaries. Applying the PA technique to the entire economy to trace the circular linkages between all production chains is also a difficult and time-consuming task. The cascading cyclic relationships inside an economy are limitless. If the PA approach is employed to analyze from the bottom up, the quantification process will invariably be completed by truncating at a specific link, resulting in truncation mistakes. Furthermore, because to the intricacy of the accounting procedure, the PA technique is unsuitable for regional and higher-scale footprint assessments.

The EEIOA method, which corresponds to the PA method, is a top-down approach based on the input-output analysis (IOA) economic model. IOA is a model proposed by Nobel laureate Leontief in the 1930s, which describes the interrelationships and dependencies between sectors based on the flow of value between internal sectors of an economy (Leontief, 1936). By constructing input-output (IO) tables, the IOA approach specifies the input requirements across sectors in matrix form. It uncovers the intricate and quantitative linkages between social final demand and production in diverse sectors using linear algebra to develop mathematical models and represents the relationships between sectoral output using linear fixed production coefficients. The EEIOA method is an extension of IOA that incorporates the environmental indicators under study into the existing economic model. It explores the impact of changes in social final demand on the production activities of various sectors and the resulting changes in environmental impact through the existing industrial dependency relationships within the economy. This method is straightforward and uses linear algebra models to simulate the environmental impact of the complex social and economic relationships, greatly reducing the workload required to describe the inter-industry relationships within a regional economy. This type of top-down approach has been applied successfully in the fields of energy consumption or carbon emissions (Shmelev, 2010; Shui & Harriss, 2006; Weber & Matthews, 2007; Xu et al., 2021), as well as water resource consumption (X. P. Chen et al., 2023; Ridoutt et al., 2018; X. J. Wu et al., 2021; Xu et al., 2021). By utilizing input-output relationships between sectors, it is possible to clearly identify sector-based direct and indirect carbon emissions and water resource consumption that are driven by different consumer groups and import/export trade. However, the input-output tables provided by EEIOA methods have significant sectoral aggregation and homogeneity assumptions, making it difficult to target specific products and having lower resolution compared to bottom-up methods that focus on specific technological processes.

Climate policy implementation will result in differentiated impacts on carbon emissions and water resource consumption due to intra-sectoral differences within target sectors and differentiated linkages of target sectors with upstream and downstream sectors within the economy. The application of EEIOA allows for a comprehensive examination of the full impacts of low-carbon policies emerging from the interactions of all industrial chains. Traditional EEIOA models, however, struggle to identify the differentiated impact of carbon emissions and water resource consumption caused by structural differences within sectors, as well as to assess the impact of structural changes resulting from the development of emerging sectors such as the new energy sector or production adjustments within sub-sectors, due to the high degree of aggregation in sectoral classification in the EEIOA model. Combining the PA method's deep description of individual processes and technologies with the IOA method's comprehensive description of all sectors will effectively harness the benefits of the two types of models. To summarize, the PA approach and the EEIOA technique, respectively, determine the total environmental impact, i.e., footprint, of human activities from the bottom-up and top-down viewpoints. The combination of PA method's detailed description of specific processes and EEIOA method's complete description of all sectors, effectively utilizes the strengths of both models. The two methods reveal that the PA method and the EEIOA method identify the entire environmental impact, i.e. footprint, caused by human activities from two perspectives: bottom-up micro-technical processes and top-down macro-sectoral linkages, respectively. However, the truncation error of the former and the relatively low resolution of the latter limit the utility of these two methods in exploring the comprehensive impacts of human activities, especially in the new context of low-carbon measures. At this point, the hybrid analysis method based on the specific research object and combining these two methods has vast potential for application. Joshi (1999) summarized various types of models that combine LCA and IOA. Scholars such as Suh proposed integrating bottom-up LCA process analysis into top-down IOA matrix models (Suh, 2004; Suh et al., 2004). In recent years, hybrid methods have made significant progress in studying carbon emissions, water resource consumption, and material flows at multiple scales, from technology, sectors, organizations to countries. For example, Wiedmann et al. (2011) used a hybrid approach to study the life cycle emissions of wind power development in the UK, and compared the results with those calculated by the PA method, finding that the hybrid method calculated a larger life cycle emissions for wind power than the PA method. Pairotti et al. (2015) used a hybrid method to analyze the energy consumption and greenhouse gas emissions of the Mediterranean diet in the Mediterranean region and found that in Italy, the Mediterranean diet has lower levels of energy consumption and carbon emissions compared to the average Italian diet and is more environmentally friendly. Hybrid models expand the model boundaries at the micro level and improve the model resolution at the macro level.

Hybrid analysis methods can be divided into tiered hybrid analysis, IO-based hybrid analysis, and integrated hybrid analysis depending on the specific methods used (Suh & Huppes, 2005). The first type of hybrid analysis involves directly incorporating the results of PA methods into IOA models. This is the simplest and most direct, but PA and EEIOA are independent of each other in this framework. Moreover, the commodity flows considered in PA are also included in IOA, which may result in duplicate calculations. The second and third methods are relatively complex and require a high understanding and utilization of IOA. The second method involves disaggregating existing IOA models as needed and using LCA inventory data to allocate upstream requirements and downstream supplies to the newly created departments. This method is conceptually mature. The third method involves embedding the physical description of the production process based on PA into the production matrix of the original input-output table, which has higher resolution. However, existing integrated mixing methods require significant technical process parameter support, have the highest time and labor costs, and involve national data borrowing and substitution to address data missing issues. Taking into account the strengths and limitations of the three mixing methods, as well as the peculiarities of this study, the second input-output-based mixing method appears to be more appropriate and capable of meeting the needs of departmental refinement and policy simulation in this work. As a result, for the water resource impacts of low-carbon transformation in the electrical sector, this study employs a hybrid method framework based on departmental splitting to build an input-output hybrid model.

3.1.1 Hybrid LCA Model

We applied the model framework of Wan et al. (2016) and optimized sector classification as well as the disaggregation coefficient for Japan's circumstances which are listed in Table S1. The disaggregation in upstream is divided into three categories based on the different demand of each of the power generation technologies. The sectors that provide the electric sector with the fuels to generate several types of electricity are defined as fuel-related sectors which are further divided into two categories. The fuel-related_A sectors' input to electric sector all goes to bio while the fuel-related_B sectors' input goes to fossil fuels by a ratio that is based on fuel cost per unit of electricity generated by each source. Another is defined as capital-related sectors which provide investment in machinery equipment and plant construction, etc. The disaggregation of capital-related sectors is based on the overnight investment cost of each power generation technology. The remaining upstream sectors are defined as other sectors, which generally only have an indirect input to the electric sector or whose inputs to the electric sector do not vary significantly by different power generation technology, such as food manufacturing, non-metal, and metal products, and other third industries (commerce, medical service, etc.). They are disaggregated with reference to the operation and maintenance cost (O&M cost) of each technology and the share of generation capacity of each power generation technology. The downstream disaggregation is relatively easier since they can be determined by the power generation share of each technology.

The target electric sector is an aggregated sector combining gas and heat supply and thus sectoral disaggregation is needed. The method proposed by Lindner et al. (2013) is applied and a reallocated 46-sector classification can be found in Table S2. The gas and heat supply sector remains while the electric sector is divided into nine sub-sectors as shown in Table 3-1.

Table 3- 1. Disaggregation of the Original Sector

Original Sector	First Disaggregation	Final Disaggregation
Electricity, gas, and heat supply	Electricity	Coal
		Oil
		Gas
		Bio
		Nuclear
		Hydro
		Geo
		Solar
		Wind
	Gas and heat supply	Gas and heat supply

Take the disaggregation of two sectors as an example. Assume that n is the original sector (electric sector) and $a_{i,n}$ is the direct consumption coefficient from the original sector n to upstream sector i; $a_{n,j}$ is the direct consumption coefficient from sector j to the original sector n. Therefore, we have $A_{i,n}$ and $A_{i,n+1}$ which are the direct consumption coefficient from the new disaggregated sectors n and n + 1 to upstream sector i and so are $A_{n,j}$ and $A_{n+1,j}$. $a_{n,n}$ is the direct consumption coefficient within the original sector and s and 1−s are the share of the two disaggregated sector in the original sector.

Disaggregation in upstream:

$$a_{i,n} = (1 - s)\cdot A_{i,n} + s\cdot A_{i,n+1} \tag{1}$$

Disaggregation in downstream:

$$a_{n,j} = A_{n,j} + A_{n,j+1} \tag{2}$$

Disaggregation within the original sector:

$$a_{n,n} = (1 - s)\cdot(A_{n,n} + A_{n+1,n}) + s\cdot(A_{n,n+1} + A_{n+1,n+1}) \tag{3}$$

Table 3-2 depicts a basic structure of a typical EEIO table. Based on the method proposed by Hienuki et al. (2015), the direct and indirect carbon emission as well as water consumption of different energy sources can be calculated with the following equations:

$\boldsymbol{M}$ is the import coefficient vector consist of m_j,

$$m_j = \frac{\boldsymbol{IM}_j}{\boldsymbol{T}_j + \boldsymbol{Y}_j + \boldsymbol{EX}_j} \quad (j = 1, 2, \dots, n) \qquad 4)$$

where $\boldsymbol{IM}_j$, $\boldsymbol{T}_j$, $\boldsymbol{Y}_j$, $\boldsymbol{EX}_j$ are the import, intermediate demand, domestic final demand, and export of sector j, respectively. The domestic impact $\boldsymbol{X}_d$ is:

$$\boldsymbol{X}_d = \left[\boldsymbol{I} - \left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{A}\right]^{-1}\left[\left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{Y}\right], \qquad 5)$$

where $\widehat{\boldsymbol{M}}$ is the diagonal matrix of $\boldsymbol{M}$, $\boldsymbol{A}$ is the input-output coefficient vector.

The foreign indirect impact $\boldsymbol{X_f}$ is:

$$\boldsymbol{X_f} = \boldsymbol{X} - \boldsymbol{X_d} = (\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}\, \boldsymbol{Y} - \left[\boldsymbol{I} - \left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{A}\right]^{-\mathbf{1}}\left[\left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{Y}\right] \quad 6)$$

Similarly, $\boldsymbol{E}$ is the environmental impact coefficient vector consist of e_j:

$$e_j = \boldsymbol{E}_j/\boldsymbol{X}_j(j = 1, 2, \dots, n) \quad 7)$$

where $\boldsymbol{E}_j$ and $\boldsymbol{X}_j$ are the direct environmental impact and total output of sector *j*, respectively, the total environmental impact is:

$$\boldsymbol{E} = \widehat{\boldsymbol{E}}(\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}(\boldsymbol{Y} + \boldsymbol{EX} + \boldsymbol{IM}) \quad 8)$$

The domestic environmental impact is:

$$\boldsymbol{E}_d = \widehat{\boldsymbol{E}}\left[\boldsymbol{I} - \left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{A}\right]^{-1}\left[\left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{Y}\right] \quad 9)$$

the foreign indirect impact $\boldsymbol{E}_f$ is:

$$\begin{aligned}\boldsymbol{E_f} = \boldsymbol{E} - \boldsymbol{E_d} = \widehat{\boldsymbol{E}}(\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}(\boldsymbol{Y} + \boldsymbol{EX} + \boldsymbol{IM} \\ - \widehat{\boldsymbol{E}}\left[\boldsymbol{I} - \left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{A}\right]^{-1}\left[\left(\boldsymbol{I} - \widehat{\boldsymbol{M}}\right)\boldsymbol{Y}\right]\end{aligned} \quad 10)$$

Table 3- 2. Structure of Environmentally Extended Input-Output Table

	Intermediate Demand	Final Demand			Total Output
		Domestic Final Demand	Export	Import	
Intermediate Input	***T***	***Y***	***EX***	***-IM***	***X***
Value Added	***V***				
Total Input	***X***				
CO_2 Emission	***C***				
Water Consumption	***W***				

The import rate of each power generation technology in 2015, as listed in Table 3-3, is calculated by government reports. Some import components for the energy systems are processed individually in the model and thus not included in the table. Since this paper only considered the impacts brought by electricity mix change, other variables in 2030 such as total input and output and import rate are considered the same as base year.

Table 3- 3. Import Rate of Each Electricity Generation Technology

Coal	Oil	Gas	Bio	Nuclear	Hydro	Geo	Solar	Wind
99.3%	99.7%	97.5%	67.2%	100%	0%	0%	63.3%	81.1%

3.1.2 Kaya Identity

Kaya identity is a widely used method for analyzing the driving factors of carbon emissions, which was proposed by Japanese scholar Kaya (1989). The original Kaya Identity is used to analyze the total energy system as of equation (11).

$$\boldsymbol{C = P \times \frac{GDP}{P} \times \frac{TPEC}{GDP} \times \frac{C}{TPEC}} \tag{11}$$

Where ***C*** is the carbon emission, ***P*** is the population, ***GDP*** is the Gross Domestic Product, and ***TPEC*** is the total primary energy consumption.

While in this study, we focus on the electricity sector and thus some changes are made as Equation (12)

$$\boldsymbol{E_e = P \times \frac{GDP}{P} \times \frac{TEC}{GDP} \times \frac{E_e}{TEC}} \tag{12}$$

Where $\boldsymbol{E_e}$ is the life cycle environmental impacts of electric sector, and ***TEC*** is the total electricity consumption.

Define the total population is $\boldsymbol{p} = \boldsymbol{P}$; the GDP per capita is ***g = GDP/P***; the electricity intensity of ***GDP*** is ***e = TEC/GDP*** and the total environmental footprint intensity of electricity is ***f =*** $\boldsymbol{E_e}$ ***/TPEC***. The environmental impacts can be expressed as equation (13).

$$\boldsymbol{E_e = P \times g \times e \times f} \tag{13}$$

The total environmental factor change can be decomposed as equation (14)

$$\boldsymbol{\Delta E = E_t - E_0 = \Delta E_p + \Delta E_g + \Delta E_e + \Delta E_f} \tag{14}$$

Where $\boldsymbol{\Delta E_p}$, $\boldsymbol{\Delta E_g}$, $\boldsymbol{\Delta E_e}$, $\boldsymbol{\Delta E_f}$ are defined as Population Effect, Economy Effect, Electricity Intensity Effect, and Electricity Mix Effect, respectively.

Based on the LMDI (logarithmic mean division index) method proposed by Ang (2005), the impact brought by each effect can be calculated by equation (15)~(18).

$$\boldsymbol{\Delta E_p = \frac{E_t - E_0}{ln\, E_t - ln\, E_0} ln\left(\frac{p_t}{p_0}\right)} \tag{15}$$

$$\Delta E_g = \frac{E_t - E_0}{\ln E_t - \ln E_0} \ln\left(\frac{g_t}{g_0}\right) \tag{16}$$

$$\Delta E_e = \frac{E_t - E_0}{\ln E_t - \ln E_0} \ln\left(\frac{e_t}{e_0}\right) \tag{17}$$

$$\Delta E_f = \frac{E_t - E_0}{\ln E_t - \ln E_0} \ln\left(\frac{f_t}{f_0}\right) \tag{18}$$

3.2 Assessment Tools for the Transportation Sector

3.2.1 Model Selection

In recent years, there has been a greater focus on assessing long-term energy supply and demand for specific countries, regions, or industrial sectors, as well as the corresponding economic and environmental effects. For relevant investigations, the most often employed study strategy is to use various energy models. Different energy models have unique qualities and applications. Their shared advantage, however, is that they may use mathematical approaches to more clearly illustrate the intrinsic linkages between the energy system, the socioeconomic system, and the environmental system. Energy models can be used to do quantitative analysis and assessment of energy and environmental policy actions more efficiently. Since the 1970s, as new energy system challenges and socioeconomic and environmental pollution issues have emerged in various countries, regions, and industrial sectors around the world, energy models have also been developing, evolving, and improving. Energy models can be classified into three types based on the logical way of modeling: top-down models, bottom-up models, and hybrid energy models. The third category is a hybrid model that organically combines the first two.

(1) Top-Down Model

Top-Down Models (TDMs) are typically based on economic models. Multiple economic indicators related to energy can be efficiently depicted in this type of model, and the intrinsic link between energy use and production can be effectively proven. As a result, this model is more frequently employed in macroeconomic analysis and related research in energy policy planning. Nonlinear macroeconomic (MACRO) and general equilibrium (CGE) models are examples of this group. For example, W. Chen (2005) analyzed China's marginal abatement cost of carbon and potential impacts of carbon mitigation on GDP using the China MARKAL-MACRO model, an integrated energy, environment, and economy non-linear dynamic programming model. Yahoo & Othman (2017) conducted an empirical analysis of alternative carbon abatement scenarios and discusses policy implications for Malaysia using a static CGE model with environment-energy-economy interactions. J.-Y. Liu et al. (2017) used a financial CGE model to quantitatively calculate the systematic effects of China's green credit policy and compared its effectiveness with other policies such as differential electricity prices and raised production tax policies levied on energy-intensive industries.

(2) Bottom-Up Model

Bottom-Up Models (BUMs) are built on engineering and technology models to provide full descriptions and simulations of energy consumption and manufacturing methods. They are largely concerned with forecasting supply, demand, and environmental implications based on energy consumption and manufacturing methods. This model is better suited for investigating the technical aspects of energy systems. The MARKAL model, the Asia-Pacific Integrated Model (AIM) for climate change mitigation, and the Low Emissions Analysis Platform (LEAP) model (also known as Long-Range Energy Alternatives Planning System) for analyzing the impact of energy technologies from end-use energy consumption are commonly used models for mid-to long-term energy substitution planning. In terms of the MARKAL model, W. Chen et al. (2007) discussed China's primary energy consumption and carbon emissions from 1980 to 2003, and used three MARKAL family models to study China's future sustainable energy development strategies and carbon mitigation strategies. Yuan et al. (2023) focused on comparing the short-term and long-term energy-related carbon emissions and decarbonization potentials of different HVAC systems considering the UK electricity decarbonization plans by

MARKAL model and takes two recognized and widely used energy-saving and environmental protection technologies (namely the GSHP and cogeneration systems) as subjects for comparison. Lu et al. (2016) developed a national-level IN-MARKAL model using Indiana as a case study and used it to analyze the effectiveness and cost of carbon dioxide reduction policies and alternative policy options. In terms of AIM, Matsuoka et al. (1995) discussed the Asian Pacific Integrated Model (AIM), which is a large-scale model used for scenario analyses of greenhouse gas emissions and the impacts of global warming in the Asian Pacific region, comprising two main models, the AIM/emission model and the AIM/impact model, linked by global GHG cycle and climate change models. Chunark & Limmeechokchai (2015) analyzed a policy option for mitigating CO_2 emissions in Thailand's energy sectors using the AIM/Enduse model and presents two scenarios: the BAU scenario and the PEAK CO_2 scenario to conclude that to achieve ambitious CO2 reduction targets, Thailand needs transformational changes in its energy system, including the introduction of CCS technologies and efficient appliances in energy demand sectors. In terms of the LEAP model, it has been frequently utilized in examining a country's or region's energy system and its environmental implications based on socioeconomic development. Various energy policy settings are utilized to generate various energy-saving scenarios, and the model is used to examine relevant research under various scenarios. The LEAP model mainly includes functional modules such as energy demand, energy conversion, biomass resources, environmental impact prediction, cost-benefit analysis, and the TED database. On the one hand, the use of this model is concentrated in the energy demand module and the environmental impact prediction module, for example, Y. Y. Liu et al. (2011) used the LEAP model to predict and analyze the main carbon emissions from the transportation industry in Jiangxi province, China under three different scenarios from 2010 to 2030. Shabbir & Ahmad (2010) analyzed the status of emission of air pollutants and energy demands in urban transportation using the LEAP model in Rawalpindi and Islamabad. Kuldna et al. (2015) discussed the role of Strategic Environmental Assessment (SEA) in integrating environmental concerns into strategic decision-making, with a focus on knowledge exchange between researchers and policy developers in the national energy plan SEA by the LEAP model. Zou et al. (2022) proposed a LEAP model to forecast and analyze future CO_2 emissions and the time of reaching the CO_2 emissions peak in Shanxi Province, China, from 2019 to 2035 under different scenarios. One the other hand, some scholars also concentrate on using the energy conversion module and the cost-benefit analysis module of the LEAP model: McPherson & Karney (2014) used the LEAP model to quantitatively predict and analyze the power generation profile in Panama under different scenarios, including system marginal costs, global warming potential, and resource diversity composition. Ejaz et al. (2018) utilized the LEAP model to model and analyze the existing energy projects and CPEC energy projects, and proposed three different scenarios: Reference Scenario (RE), Coal Scenario (COA), and Renewable Scenario (REN), to evaluate the effectiveness of CPEC energy projects in LEAP from 2013 to 2030.

(3) Hybrid Model

The hybrid model incorporates the above two models, and this type of model simulates and simulates the entire energy system. The NEMS (National Energy Modeling System) and IIASA (International Institute for Applied System Analysis) are typical representatives among them. This type of model encompasses a wide range of technologies and fields, with comprehensive and complex functionality, requiring extremely high amounts of data and precision. Based on the descriptions of the three types of energy models above, it can be seen that:

The first type of model is more suitable for economic and macro-level research, while the second type is more suitable for the technical level. The third type of model is more complex and requires extremely high data requirements. Regarding the scenario analysis of energy transformation in the Japanese transportation sector studied in this dissertation, on the one hand, considering the close relationship between energy consumption in the transportation industry and the technologies and tools used in the industry, and on the other hand, taking into account the limited availability of energy and emission data for the Japanese transportation sector, it is more appropriate to use the second type of bottom-up model to study this issue. In the second type of bottom-up model, the AIM model is mainly used to evaluate greenhouse gas reduction policies, while the MARKAL model is mainly used to explore energy system models that meet established energy consumption and environmental emissions conditions. As for the LEAP model, the available data conditions in this study can meet the model's requirements for initial data modeling. In the LEAP software, we can tailor the model structure according to the specific research questions, and the model is applicable to a wide range of research levels and industries. It is suitable for research on transportation energy consumption and environmental issues in a particular region. Therefore, the LEAP model is used in this study for simulation and scenario analysis.

3.2.2 LEAP Model

LEAP, the Low Emissions Analysis Platform, is a software tool developed by the Stockholm Environment Institute to facilitate energy policy analysis and climate change mitigation assessment. LEAP's broad user base spans across government agencies, academics, non-governmental organizations, consulting companies, and energy utilities, with adoption in more than 190 countries worldwide. LEAP's scalability enables its use at various levels, from cities and states to national, regional, and global applications. LEAP's significance as the standard tool for integrated resource planning, greenhouse gas (GHG) mitigation assessments, and Low Emission Development Strategies (LEDS) has made it a go-to choose for developing countries. Moreover, LEAP has been chosen by many countries to report to the U.N. Framework Convention on Climate Change (UNFCCC) as part of their commitment. In fact, at least 32 countries have utilized LEAP to create energy and emissions scenarios that formed the basis for their Intended Nationally Determined Contributions on Climate Change (INDCs). Such contributions were fundamental to the Paris climate agreement, demonstrating countries' intent to decarbonize their economies and invest in climate-resilience.

The LEAP modeling tool is an integrated and scenario-based approach that enables the monitoring of energy consumption, production, and resource extraction across all sectors of an economy. This tool accounts for both energy and non-energy sector greenhouse gas (GHG) emission sources and sinks, allowing for a comprehensive understanding of emissions. Moreover, LEAP can also facilitate the analysis of local and regional air pollutants, as well as short-lived climate pollutants (SLCPs), making it a suitable choice for assessing the climate co-benefits of reducing local air pollution. According to the model's logical methodology, the LEAP model is a bottom-up energy and environment model. The model requires the input of basic data such as the activity level and energy intensity of a series of terminal energy-using devices, pollution emission variables, and so on, based on the partition of the study subject into departments and the building of the full model framework. Furthermore, numerous hypothetical scenarios can be generated, and key factors in the scenarios can be modified. This allows for the analysis and prediction of future energy demand, energy costs, applicable regulations, pollution emissions, and other findings for a certain department. It is not a model for a single sort of energy system, but rather a versatile modeling tool that can be applied to a variety of energy systems, each with its own set of data structures. The LEAP model can be used to estimate and assess energy consumption and environmental emissions at a variety of research levels, including global, national, provincial, and municipal levels, as well as individual industrial sectors. The LEAP model has been applied to many industries such as transportation, steel, electricity, cement, residential living, commercial, and logistics for energy consumption and environmental emissions study in relevant domestic and foreign research. One of the major advantages of the LEAP model is that it has relatively simple data requirements for initial inputs and some basic parameters, and its built-in Technology and Environment Database (TED) provides convenient parameter setting. In addition, the model's calculation results can be output in various chart formats, and users can set their display properties according to their needs. Operators can not only see the predicted energy consumption and environmental emissions results of different branches and departments in different scenarios in a clear and intuitive way, but also see the predicted consumption or emissions of different energy or pollutant types in different branches and departments in different scenarios. Furthermore, they can observe the proportion of each sub-branch within the same branch in the model, which is beneficial for a clear understanding of the overall structure of the model. Moreover, various function inputs built into the model can make it easier for operators to set the activity level or parameters of a future department in different scenarios.

The operator must assess the properties and data structure of the research item in the energy demand module. Based on the above characteristics and data structure, the operator divides the object into different departmental levels and clarifies the structural and proportional relationships between each department, as well as the terminal energy consumption equipment and energy consumption types at the end of each department, while taking data availability and other conditions into account. The module displays the activity level and energy intensity of each department. By multiplying the two, the energy consumption of each department may be estimated. It is possible to anticipate long-term energy consumption in various situations and vehicle types by altering the parameters and evaluating energy-saving strategies in the scenarios. This module will be utilized in this study to forecast the future energy demand of Japan's transportation industry. The specific classification of vehicles, scenario design can be found in Chapter 5.

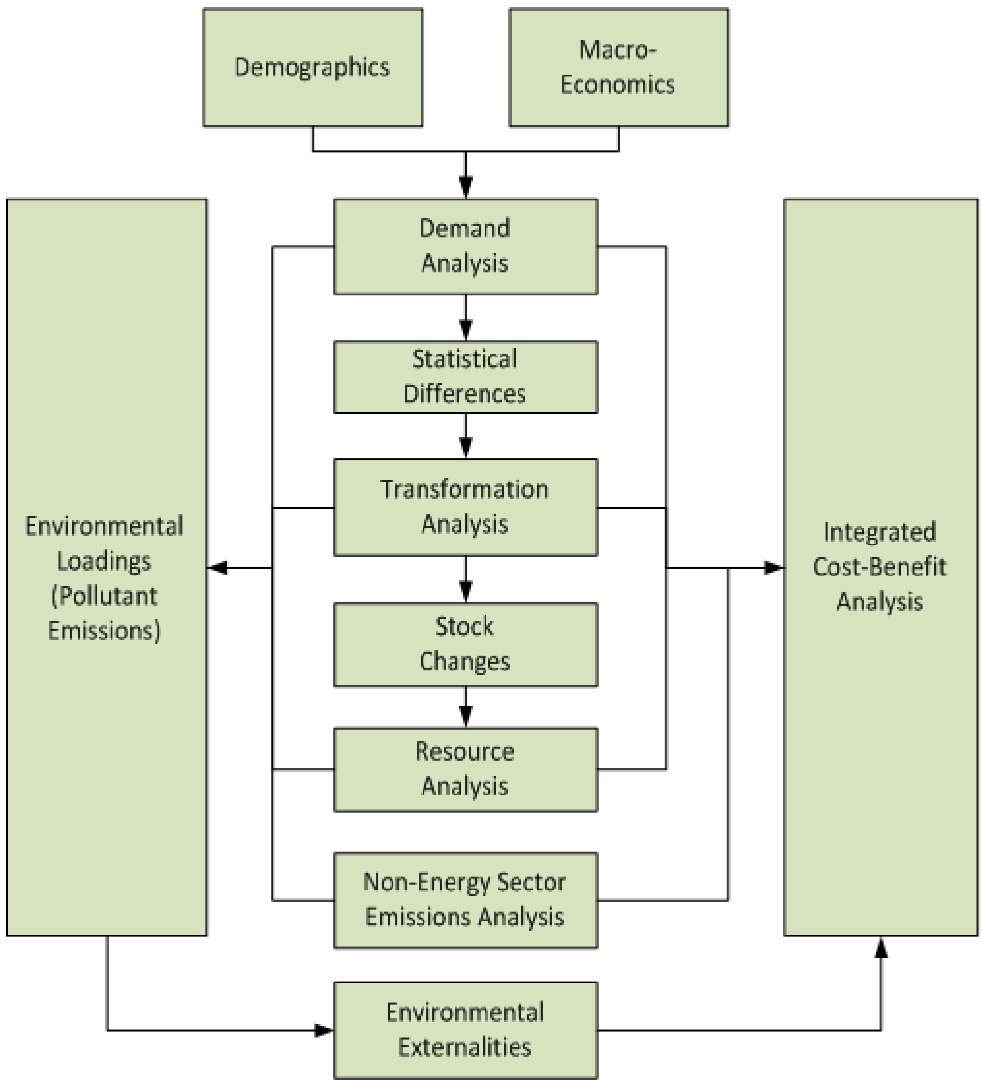


Figure 3- 1. The Structure of LEAP's Calculations

3.3 Data Availability

3.3.1 Data for Analysis in the Electricity Sector

The data used for analyzing the Energy-Carbon-Water nexus in Japan's electricity sector includes input-output data, environmental data, and scenario data.

(a) Input-Output Data

General economy is made up of various industries, each of which produces commodities and services while also engaging in frequent trade with the others. The Input-Output Tables are data that present in matrix form for a year the production and trading position among industries in a nation or region. It covers a wide range of production activities and are widely used as fundamental statistics for revealing the economic structure of our country, as well as tools for analyzing the ripple effects of the economy, and as benchmark values for other economic statistics, which is also the fundamental data for EEIOA. This research uses the official Japan input-output table of 2015 which is a 37-sector table.

Table 3- 4. Disaggregation of the original sector

Original Sector	First Disaggregation	Final Disaggregation
Electricity, gas, and heat supply	Electricity	Coal
		Oil
		Gas
		Bio
		Nuclear
		Hydro
		Geo
		Solar
		Wind
	Gas and heat supply	Gas and heat supply

The target electricity, gas, and heat supply sector is an aggregated sector combining gas and heat supply and thus sectoral disaggregation is needed. The method proposed by Lindner et al. (2013) is applied and a reallocated 46-sector classification can be found in Table S1. The gas and heat supply sector remains while the electric sector is divided into nine sub-sectors as shown in Table 3-4.

(b) Environmental Data

This research considered carbon emission and water consumption as environmental vector for the EEIOA, and thus sectoral direct carbon emission and water consumption data is necessary. In this research, the sectoral direct carbon emission data of 37 non-electric sectors were calculated by the work of the Embodied Energy and Emission Intensity Data (3EID), National Institute for Environmental Studies, Japan (Nansai, 2019; Nansai et al., 2020) which has been widely used in various studies (Hata et al., 2021; Ichisugi et al., 2019; Jiang et al., 2020; Ohno et al., 2021). The 390-fundamental-sector data were reallocated to fit our classification. The sectoral direct water consumption data of non-electric sector were calculated by the work of Ono et al. (2015). Despite the water consumption data being based on the 2005 input-output table, the result obtained from the direct water consumption intensity in 2005 with the total sectoral output in 2015 did not show a significant bias from the official total water consumption data and thus the data are considered applicable to this research. All data were pre-processed to align with the disaggregated 2015 input-output table classification. The direct carbon emissions and water consumption data of different energy sources within the electric sector were calculated with the intensity data from the report of the Central Research Institute of Electric Power Industry, Japan (Imamura, 2016), and other research data (Gao et al., 2018; Jin et al., 2019; M. Mekonnen et al., 2015), which are collected in Table S3. Note that the boundary of direct carbon emission and water consumption from the electric sector is that carbon emitted by direct combustion of fossil fuel to generate electricity (direct emission from bio is considered as net zero since it is offset by the carbon it absorbed) and the amount of water deprived from, but not returned to, the same drainage basin during the power generation process such as water used for cooling and evaporated from the dam (Ono et al., 2015).

(c) Scenario Data

Total electricity demand under NDC scenario in 2030 from different energy sources was calculated with the data proposed in Japan Sixth Strategic Energy Plan (Agency for Natural Resources and Energy, 2021). The portion of Hydrogen and Ammonia were assigned to other renewable energies since they are not considered in this research. Population, GDP, and other related data under NDC scenario were also calculated based on the reported data. Detailed scenario design is explained in Chapter 4.

3.3.2 Data for Analysis in the Transportation Sector

The LEAP model offers two methods for analyzing the transportation sector. The first method considers the sector as a whole and takes into account the annual passenger-kilometers and freight-tonne-kilometers (hereafter ton-kilometers) transported. Different scenarios are designed based on the proportion of different vehicle types. The second method involves subdividing the entire sector into multiple sub-sectors based on different vehicle types. Scenarios are then designed by considering the existing stock and annual additions (number of new vehicle sales) for each sub-sector, combined with the average annual distance traveled per vehicle. Considering the characteristics of the Japanese transportation sector and the availability of related statistical data, this study will employ the first analytical method. The required data includes annual passenger-kilometers and ton-kilometers, the ratio of various types of vehicles and their energy efficiency, emission factors for different types of energy sources, and scenario data that indicates the possible changes of these data in the future. We will introduce these data as of the base year (2019) one by one follow up.

(a) Annual Passenger-Kilometers and Ton-Kilometers Transported

This study uses the LEAP model to simulate and analyze the energy and emission scenarios of the transportation sector in Japan, with the most important data being the annual passenger-kilometers and ton-kilometers transported. The official data comes from The Automobile Transport Statistics Survey (MILT, 2021) conducted by the MLIT which is a statistical survey that targets automobiles engaged in transportation activities within the country, and is conducted every month as an important national statistical survey. The transportation volume and other data obtained from the Automobile Transport Statistics Survey are used to create fundamental materials for designing the scenarios and constructing the model.

(b) Classification of Vehicle Type

According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) Japan, vehicles are divided into freight vehicles and passenger vehicles based on their transport purposes. Freight vehicles are vehicles used for transporting goods, such as trucks and light vans while passenger vehicles are vehicles used for transporting passengers, such as passenger cars and buses. According to the size of the vehicle, they can be further divided into normal cars and light vehicles. For specific classification criteria, please refer to Table 3-5.

Table 3- 5. Vehicle Classification Standard

Vehicle type		Size (m)	Engine Displacement (cc)	Number of wheels
Passenger	Normal	Bigger than light	Over 660	No less than 4
	Light	Under 3.4*1.48*2.0	Under 660	No less than 3
Freight	Normal	Bigger than compact	Over 2000	No less than 4
	Compact	Under 4.7*1.7*2.0	Over 660 and under 2000	No less than 3
	Light	Under 3.4*1.48*2.0	Under 660	No less than 3

*The normal and compact passenger vehicles are all considered as normal vehicle in this research

*Specialized vehicle is not considered in this research

Besides, vehicles are also classified as commercial or private depending on their use. Commercial vehicles are those used to transport goods or passengers in response to the needs of others, and are owned by trucking companies, bus companies, limousine and taxi service providers, light vehicle transportation companies, and others. Private vehicles are those not used for commercial purposes, such as vehicles that transport goods handled by the owner of the vehicle or transport the owner (or user), their family, or employees.

Furthermore, based on the energy source, we can also divide them into internal combustion engine (ICE) vehicles including gasoline, diesel, LPG, hybrid vehicles (HV), electricity vehicles (EV), and fuel cell vehicles (FCV). The detailed classification and ratio of each type are explained in Chapter. 5.

(c) Fuel Economy

Fuel economy is a rating of how far a vehicle can travel on a specific amount of fuel. The less fuel the vehicle uses, the higher the fuel economy. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) evaluates the fuel efficiency of automobiles and publishes the "List of Fuel Economy for Cars" every year based on the "Implementation Guidelines for Evaluating and Disclosing Fuel Economy of Automobiles (MLIT Notice No. 61 of 2004)" in order to promote the spread of automobiles with high fuel efficiency. However, this survey now still only covers the ICE vehicles and a few hybrid vehicles, and thus based on this data and combined with empirical values of some typical vehicle models (especially EVs and FCVs), we constructed the data set of fuel efficiency data for each type of vehicle model required for the model construction.

(d) Emission Intensity

There are also two ways to calculate the emissions from the transportation sector in the LEAP model. The first is based on the emission factors of different vehicle types and the average travel distance, while the second is based on the emission factors of different types of energy sources. The official emission intensity published by MILT is the first type, however, the official test mode of emission intensity has changed over time. Considering the availability, accuracy, and consistency of data, the environmental loading factors of the above four pollutant given by the IPCC EFDB database in 2016 were used as the reference values of environmental emission intensity (Table 3-9).

(e) Scenario Data

Scenarios are all designed based on the Energy White Paper 2022, Survey on Fuel Economy of Motor Vehicle by MLIT, official report for specific vehicle model, commitment of car companies, and the judgement of the author.

Chapter 4. Carbon-Water-Energy Nexus of the Electricity Sector

Water systems, energy systems, and climate change are closely linked (X. Yang et al., 2018). On the one hand, the massive emissions from the energy system directly contribute to global climate change which in turn has adverse effects on the energy system (Pachauri et al., 2014; Pašičko et al., 2012). In recent years, extremely high temperatures, as well as extreme precipitation, and snow disasters have occurred more frequently because of climate change, which places higher demands on the security and stability of energy systems (A. T. D. Perera et al., 2019; Schaeffer et al., 2012). In 2008, the snow disaster in South China paralyzed power systems in more than 20 provinces (Hou et al., 2009). (Pašičko et al., 2012) found that wind power will increase with decreasing hydropower due to climate change by 2040 in Croatia. (Craig et al., 2018) reviewed climate change impacts on the planning and operation of the bulk power system in the United States due to higher power demands and declining transmission capacity. On the other hand, both water system, and energy systems play an inevitable role throughout the production and operation of each other (Hamiche et al., 2016). The energy sector is the second largest water consumer after agriculture, with the global energy sector accounting for 15% of total water consumption each year, and in some countries (e.g., the United States) its share is up to 45% (Rio Carrillo & Frei, 2009). Therefore, the energy supply is constrained by water resources, and in some areas may be affected by water scarcity (Biggs et al., 2015; Hamiche et al., 2016). With the future of energy transition and an increasing energy demand, research has shown that the water consumption of the global energy system is thought to rapidly increase (Endo et al., 2017; Kitamori et al., 2012). Mekonnen (M. Mekonnen et al., 2015) conducted a global water footprint assessment of electricity and found that biomass, hydropower, and nuclear are the top three water consumers in electricity generation and have a much higher water intensity than that of fossil fuels, while solar and wind do not demand much water. The policy scenario of IEA (IEA, 2021) suggested that the share of non-fossil energy in global electricity generation reached almost 29% in 2020 and will increase to 60% by 2030 to meet Net Zero Emissions by 2050. The total electricity generated by biomass, hydropower and nuclear sources is about the same as the sum of wind and solar. Even though the water intensity of wind and solar remains low, it cannot compensate for the exorbitant demand created by biomass and hydropower. In addition, the production, transportation, and use of water resources also requires the support of an energy system. The annual energy demand of the water system accounts for about 3% of the world's total primary energy consumption (Rothausen & Conway, 2011). Studies have shown that with the large-scale application of cutting-edge water treatment technologies, the energy consumption of global water systems will double in 25 years (Burek et al., 2016).

Furthermore, the uneven distribution of global water resources in total and geographically has brought certain constraints to the implementation of carbon emission reduction policies. Only 2.5% of total global water, excluding the storage capacity of oceans and other brackish water bodies, is freshwater among which, excluding frozen water in glaciers and ice caps and groundwater, only about 1.2% of surface water can be directly used (Gleick & Heberger, 2014). However, river water, which accounts for 0.0002% of the global water volume, is the most important water resource supporting most of the water demand for human development. In terms of geographical distribution, most of the world's water resources are distributed in the Americas, accounting for 45% of the total; followed by Asia, 28%; Europe, 15.5%; and Africa, which accounts for only 9% (Vallée et al., n.d.). According to research by the World Resource Institute (WRI) (Gassert et al., 2013), among the top 10 countries in terms of total water resources in 2013, India and Indonesia faced the highest water stress (40–80%), while the United States and China also have moderate to high water stress (20–40%). Therefore, the virtual water embedded in the global trading system, for example, the tropical fruits purchased in Japan which actually involves importing virtual water from countries mainly in the South, is widely discussed to better understand and address the issue of an uneven distribution of water. Virtual water trade accounts for 22–30% of total global water use of which 32% is scarce water (Z.-M. Chen & Chen, 2013; Lenzen et al., 2013). Lenzen et al. (2013) used an input–output model to simulate the global virtual flow and found that developed countries are importing virtual water at an increasing rate to lessen their water stress; however, this could also intensify the uneven distribution of global water resources.

4.1 Japan's Electricity Mix and the NDC Scenario

Japan, one of the top energy consumers and GHGs emitters, has announced its sixth strategic energy plan (Agency for Natural Resources and Energy, 2021) with an ambitious energy mix outlook to cut approximately 45% of energy related CO_2 emission, as well as 46% of total GHGs emission compared with 2013 (25% and 26%, respectively, as former plan) and to raise energy self-sufficiency to reach approximately 30% (25% as former plan) by 2030. Figure 4-1 explains the detailed electricity demand and mix in 2030 compared with the former plan, which is also treated as the NDC scenario of Japan in this research. With strenuous efforts in energy saving, the total electricity demand in 2030 is considered to have a 230 TWh cut, which is 20% more than the former plan. The ratio of fossil energy in the new energy mix decreases by 41% while renewables account for 36–38%. Besides, 1% hydrogen and Ammonia is projected, which is the first time it has appeared in the energy plans. Besides, the electricity loss is also expected to decrease from 85 TWh to 60–70 TWh, which suggests that the efficiency of electricity transmission and distribution will further increase. There is not yet sufficient research regarding the environmental impacts brought by the energy transition of the whole electric sector. Hienuki calculated the impacts on carbon emission, GDP, and employment of Japan's future electricity mix based on the input–output table of 2005 and found that emissions will be reduced by 8%, 16% and 16% in 2020 and 29%, 38% and 44% in 2030 for each respective scenario compared with that in 2012 (Hienuki et al., 2015a). Although the Japanese government has proposed such a strategic plan to show their determination to achieve the carbon neutral goal through continuous energy transition, the life cycle carbon emissions and water consumption, especially of different energy sources within Japan's electric sector with regard to the energy transition have not yet been well understood. It is of great importance to understand this key information through the energy transition process so that policymakers can propose and implement comprehensive and visionary plans to better adapt to the further impact from various dimensions brought by climate change.

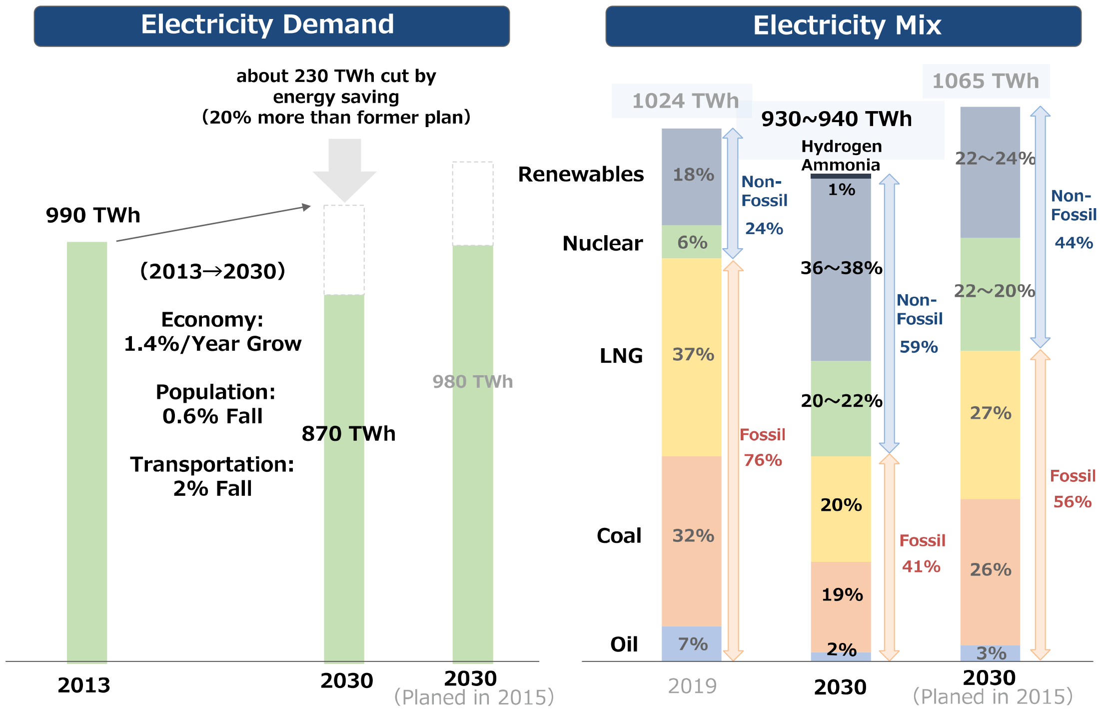


Figure 4- 1. Japan's Electricity Demand and Electricity Mix by 2030

After the Great East Japan Earthquake in 2011, nuclear power use declined drastically and the dependance on fossil fuel increased significantly. Figure 4-2 shows the detailed electricity mix change of the base year 2015 and under the NDC scenario by 2030. The total electricity in 2015 was 1037.7 TWh which ranked fifth in the world among which over 83% of electricity was generated from fossil fuel. Hydropower contributed the largest share among all renewable energies. Under the NDC scenario, total electricity generation is expected to drop to 937.8 TWh, optimistically. The overall share of fossil fuels will decrease to 41.5% percent while nuclear power shows the greatest increase to 200TWh. Solar and wind power will also become major sources in the NDC mix that show a growth by 200% and 800%, respectively, while hydropower does not show significant change. Detailed electricity mix data can be found in Table S4.

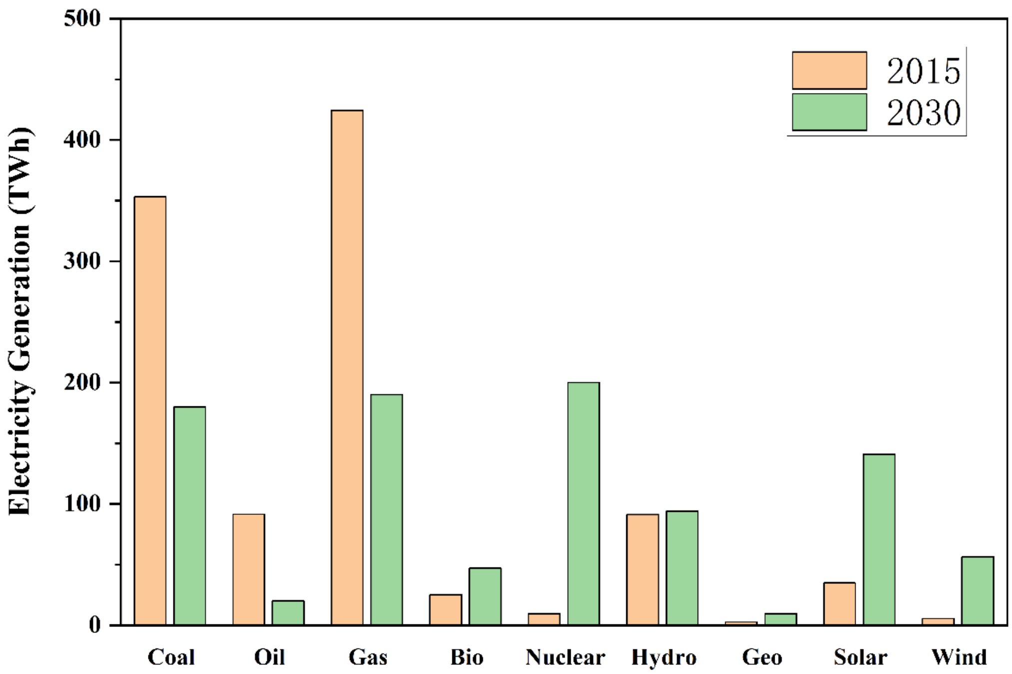


Figure 4- 2. Electricity Generation of Japan in 2015 and 2030 under the Sixth Energy Strategic Plan by the Japanese Government

4.2 Carbon Emission and Water Consumption

Figure 4-3 depicts the life cycle carbon emission and water consumption of Japan's electric sector in 2015 and 2030 by the Japanese government. In the base year, total carbon emission was about 630 Mt where fossil energy produced over 98% of all energy. Nonetheless, given that Japan has most developed technologies and equipment in the fossil power industry, the emission intensity of fossil fuel is much lower compared to that of other countries, especially developing countries. Bio emission came first after fossil fuel, producing 5.2 Mt, and all non-fossil emission was about 10.7 Mt. It is clear that the renewables did not account for enough of the capacity that nuclear power had driven after the Great East Japan Earthquake and thus the re-emergence of fossil power plants did lead to greater emissions due to the absence of nuclear power. Under the NDC scenario, the life cycle emission is expected to decline by roughly 50% to 313 Mt by 2030 among which coal power represents the highest decrease of over 170 Mt CO2 emissions, followed by gas power of 108 Mt which will become the highest emission source. Oil changes the least in fossil fuels, which is 51 Mt since the remaining capacity of oil electricity is only 2%.

Emissions from bio and nuclear will double while renewables nearly tripling, which is still no comparison with that of fossil fuel. The energy mix transition in the electric sector is expected to have a significant contribution on the emission reductions under the NDC scenario and will play a vital role in achieving the future carbon neutral goal.

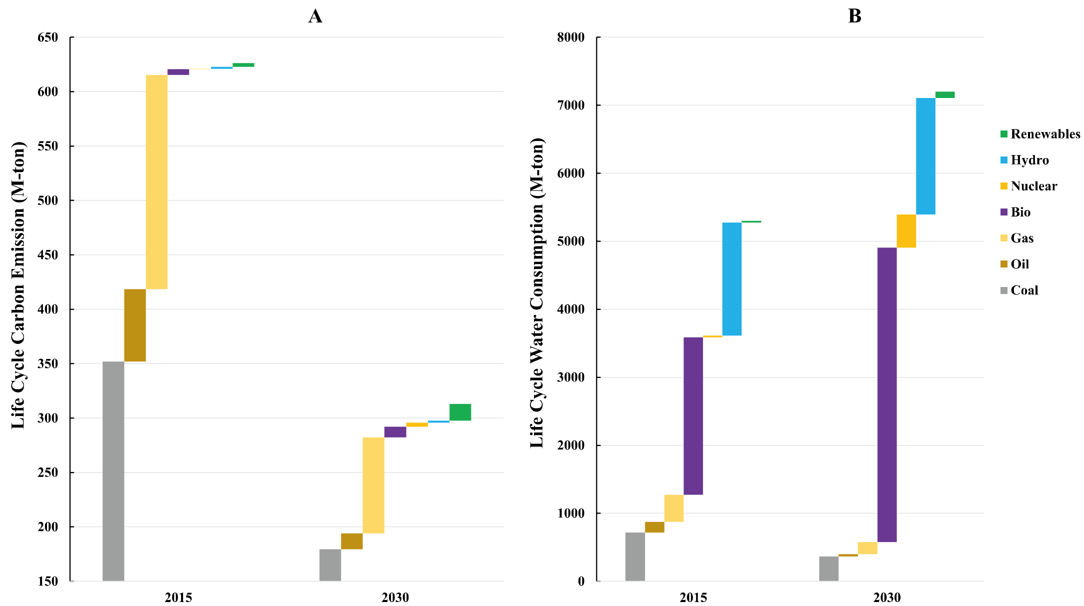


Figure 4- 3. Life Cycle Carbon Emission (A) and Water Consumption (B) of Japan's Electricity Sector in 2015 and 2030

The total life cycle water consumption of Japan's electric sector will increase by about 36% to nearly 7300 Mt under the NDC scenario in 2030. Unlike carbon emissions, bio consumes the most water and will increase by 87% to over 4300 Mt due to a large demand throughout the growth of biomass. The shift from fossil energy will save up to 700 Mt of water while with the share of nuclear and renewables continuing growing, water demand for the construction of the power plant as well as and that of the production of renewable energy generation equipment will no longer be negligible. Nuclear is expected to consume 480 Mt of water, which ranks third after bio and hydro. Within other renewables, solar becomes the largest consumer by an increase of 300% to 60 Mt followed by geo's 24 Mt. Wind power has the lowest water consumption intensity, requiring only 0.28 Mt.

We also analyzed the changes in life cycle carbon emissions and water consumption for each power generation technology separately and considered both domestic and foreign indirect footprints. The results are shown in Figure 4-4. In terms of carbon emissions throughout their lifecycle, direct emissions from fossil fuels have significantly decreased, especially coal and natural gas. Together, they are expected to reduce nearly 300 million tons of carbon dioxide emissions, becoming the main force in reducing emissions in the future power sector. Due to its relatively low proportion in power generation, oil ranks third with a reduction of about 50 million tons. In addition, as the proportion of nuclear energy, biomass energy, and other renewable energy sources increases, their indirect emissions also correspondingly increase. Biomass and nuclear energy are both around 5 million tons, and their foreign footprints are close to 50%. Hydro power and geothermal power have hardly changed much, as their lifecycle emissions are not significant. Due to the significant proportion of solar power in Japan's NDC energy scenario, its lifecycle emissions have reached around 10 million tons, of which about 40% are foreign footprints. Wind power has a foreign carbon footprint share of over 90%. However, overall, although the emissions of non-fossil fuels have increased to varying degrees, compared with the lifecycle emissions (especially direct emissions) brought by fossil fuels, they will not have a significant impact. In terms of water consumption throughout their lifecycle, the withdrawal of fossil fuels has resulted in a reduction of about 700 million tons of water consumption, with 380 million tons from coal, 210 million tons from natural gas, and 110 million tons from petroleum. This water includes both direct consumptions, mainly used for cooling during power generation, and indirect consumption during the fossil fuel extraction, transportation, and power plant construction and maintenance stages. However, even with such a significant reduction in water consumption due to the withdrawal of fossil fuels, the overall water consumption of the power generation sector in the NDC scenario still increase 36% due to the high water demand (mainly green water) during the growth process of biomass fuels. The lifecycle water consumption of biomass energy generation is expected to increase by more than 2000 million tons compared to 2015, of which over 50% comes from foreign water footprints, as Japan still heavily relies on imported biomass fuels. Although this situation is gradually being alleviated, it is difficult to further reduce the import proportion of biomass in the short term. In addition, with the further restart and expanded use of nuclear power, the indirect water consumption during the raw material mining stage and the direct water consumption for cooling during the power generation process will also increase significantly. It is expected that the water consumption caused by nuclear power in the NDC scenario will increase by more than 5,000 million tons, which is almost equal to the reduction in water consumption from coal and natural gas. It is evident that water consumption in nuclear power generation will also become an important factor in the energy transformation of the electricity sector in the future and cannot be ignored.

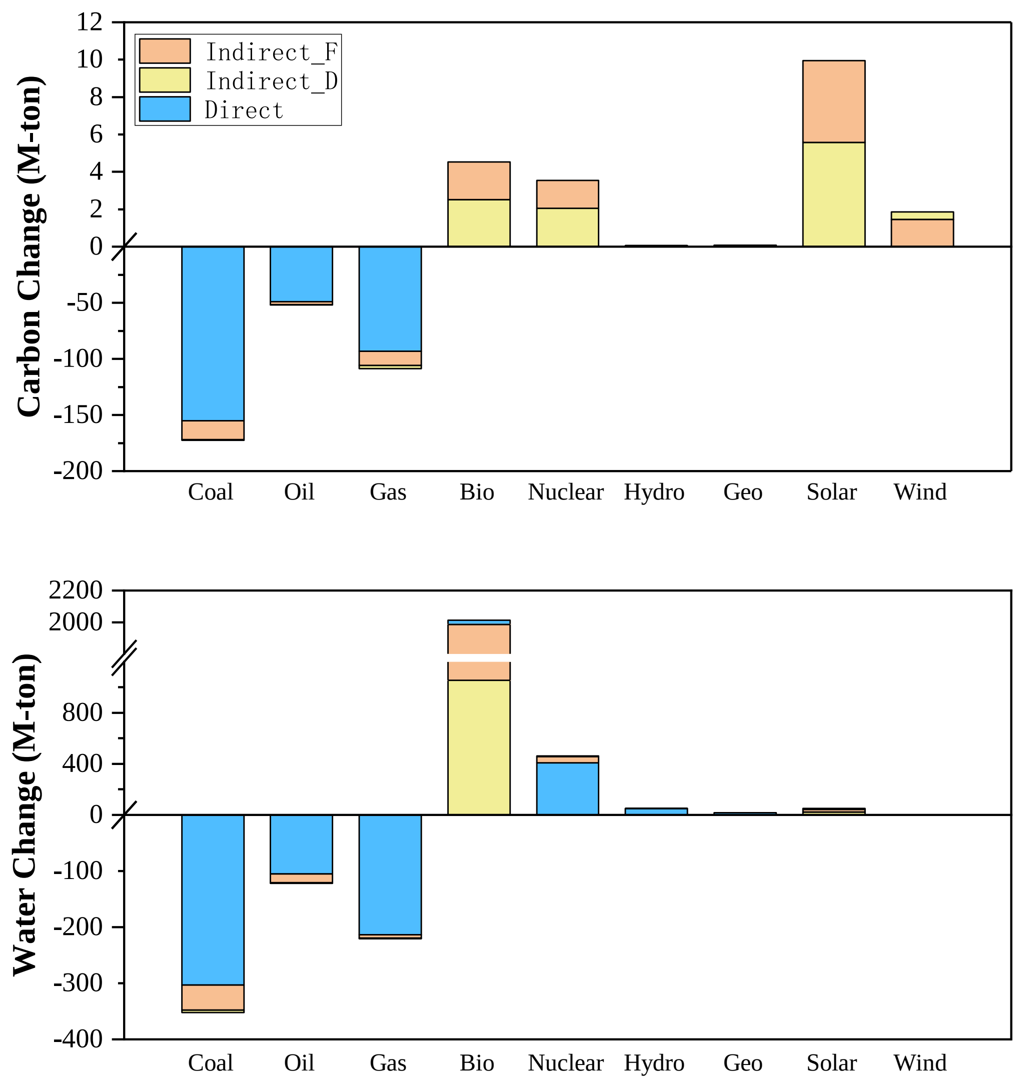


Figure 4- 4. Changes of Life Cycle Carbon Emission and Water Consumption of Nine Energy Sources in Japan's Electricity Sector

As a resource-poor island country, almost all fossil fuels are imported in Japan and thus, the extraction, processing, and transportation of fossil fuels, which consume a large amount of water and produce objective carbon emissions are all borne by the exporting countries, the detailed domestic and foreign carbon and water footprints from nine energy sources were calculated as in Figure 4-5. On the one hand, the foreign carbon footprints share of all fossil fuels will increase with the significant fall in their capacity. Most non-fossil energies have a higher foreign carbon footprint than that of fossil fuels among which wind power reaches 77%. Bio and solar power will also have over 40% of a foreign carbon footprint between 2015 and 2030. Hydro and geo power will both in-crease by about 5% and 10%, respectively. Nuclear power shows the greatest decline from 59% to 40% due to the re-emergence of nuclear power plants. On the other hand, foreign water footprint share does not show significant change in fossil fuels among which natural gas becomes the lowest because of less foreign water footprint demand during the extraction process compared with coal and oil. Bio will remain over 40% due to the self-sufficiency rate of wood stabilizing at a fairly low level. Solar power is expected to have the most significant reduction from 38% to 13% since the growing capacity will accordingly raise the water demand in operation and maintenance.

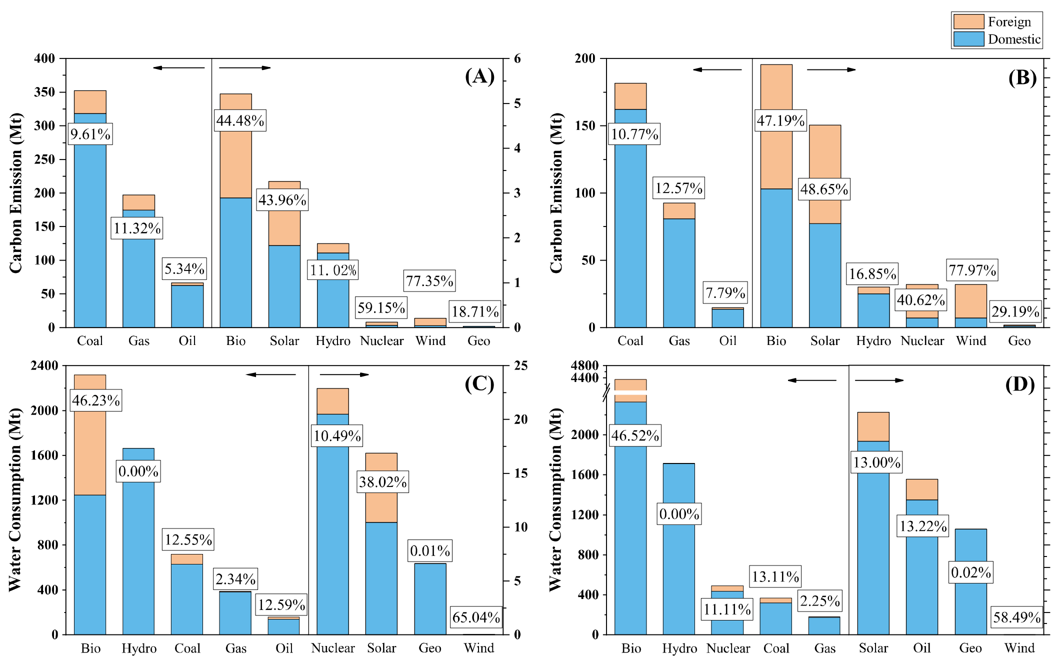


Figure 4- 5. Domestic and Foreign Carbon Footprint from Nine Energy Sources in 2015 (A) and in 2030 (B); Domestic and Foreign Water Footprint from Nine Energy Sources in 2015 (C) and in 2030 (D) (number in box represents the foreign share)

4.3 Kaya Identity Analysis

This research employed the Kaya Identity method to comprehensively assess and project the impacts of Japan's electric sector on carbon emissions and water consumption from 2015 to 2030. By utilizing this methodology, a detailed analysis was conducted to understand the anticipated changes in these environmental factors over the specified time frame. The outcomes of this investigation are presented in Table 4-1, offering valuable insights into the expected trends and providing a solid foundation for policymakers and stakeholders to make informed decisions regarding the country's energy transition. The calculations yielded promising results, indicating a substantial reduction in carbon emissions. It is estimated that there will be a total decrease of 311 million tons (Mt) of CO_2 equivalent in the electric sector's emissions. This reduction represents a significant step toward achieving Japan's emission reduction targets and aligning with international efforts to combat climate change. The findings highlight the positive impact of transitioning to cleaner and more sustainable energy sources within the electric sector. However, it is important to note that the analysis also revealed a concerning trend of increased water consumption. The research indicates that water usage in the electric sector is expected to rise by approximately 1,684 Mt during the specified period. This increase in water consumption poses challenges and necessitates careful management and sustainable practices to ensure the long-term availability and efficient use of this vital resource. Several factors influence the trends observed in emission mitigation and water conservation within the electric sector.

Table. 4- 1 Kaya Identity Analysis of Environmental Impacts Change.

Unit: Mt

Effects	Carbon Emission	Water Consumption
Population Effect	−20.996	−270.517
Economy Effect	201.562	2596.984
Electricity Intensity Effect	−251.947	−3246.155
Electricity Mix Effect	−240.408	2603.824
Total Change	−311.789	1684.135

One of the primary drivers is the population decline. As the population decreases, there is a slight positive impact on emission reduction and water conservation due to the reduced overall electricity demand. This demographic change presents an opportunity to achieve greater efficiency and optimize resource allocation in the electric sector. On the other hand, the continuous economic development of the country has a significant influence on both emission levels and water consumption. As Japan's economy grows, the increased demand for energy contributes to a rise in carbon emissions and water usage. Balancing economic growth with sustainable practices becomes imperative to ensure that the benefits of development are not offset by detrimental environmental consequences. This calls for the implementation of robust policies that prioritize both economic prosperity and environmental preservation. Among the driving factors considered, the electricity intensity effect emerges as a key determinant in the outcomes of emission reduction and water consumption. Technological advancements and improvements in the industrial structure play a pivotal role in optimizing energy efficiency and reducing carbon emissions. Investments in research and development, coupled with the adoption of innovative technologies, can significantly contribute to achieving emission reduction targets while minimizing water consumption. Additionally, the electricity mix effect exerts a notable influence on the observed trends. Shifting away from fossil fuel-based energy sources toward renewable and low-carbon alternatives is crucial for mitigating carbon emissions. However, it is important to acknowledge that this transition can have unintended consequences on water consumption. The findings align with those obtained in Section 3.2, which indicated that certain non-fossil energy sources exhibit higher life cycle water consumption intensity compared to their fossil fuel counterparts. Therefore, a comprehensive approach is required to strike a balance between emission reduction goals and water conservation efforts. In summary, this research offers a comprehensive assessment of the impacts of Japan's electric sector on carbon emissions and water consumption. The projected decrease in carbon emissions represents a significant achievement and underscores the country's commitment to mitigating climate change. However, the observed increase in water consumption poses challenges that necessitate careful management and sustainable practices. The findings emphasize the need for a holistic approach to energy planning, one that considers the interconnectedness of various factors and strives for a harmonious balance between emission reduction, water conservation, and economic development. By adopting a sustainable and forward-thinking approach, Japan can pave the way for a cleaner, more resilient, and environmentally responsible energy future.

Chapter 5. Energy Transition in the Transportation Sector

The battery electric vehicle (BEV) market is now steadily gaining ground in the automobile industry and is fueled by renewable energy sources including electricity and hydrogen. This covers fuel cell vehicles (FCVs), electric cars (EVs), and plug-in hybrid electric vehicles (PHEVs). Within the automobile sector, it has grown in importance. The EV industry now has entered a phase of rapid expansion with the onset of a new round of industrial revolution and technological developments, providing new momentum to global economic growth and improving the ecological environment on a global scale. In addition to easing energy crises, the EV industry also encourages technological advancement in the automobile sector, supports industrial reorganization, and promotes sustainable growth. It contributes significantly to the economy and society of not only regional but also global sustainable development. According to the Paris Agreement, in order to meet the temperature control targets of 2°C and 1.5°C, the world must achieve a balance between anthropogenic emissions sources and carbon sinks in the second half of the twenty-first century (United Nations Framework Convention on Climate Change (UNFCCC), 2015). To that aim, several countries' nationally determined contributions (NDCs) have specified greenhouse gas emission reduction objectives for 2030, with some countries setting carbon neutrality targets. Limiting global warming and attaining carbon neutrality has become a shared aim for humanity, and a rapid and comprehensive low-carbon transformation of the energy system is critical to accomplishing this objective.

As one of the end-use sectors, the transportation sector plays a critical role in the energy system. According to data from the International Energy Agency, global carbon dioxide emissions reached 33 billion tons in 2022, with the transportation sector accounting for 8.2 billion tons, or 24.8% of the total emissions (IEA, 2020). The carbon emissions from the transportation sector in most developed countries are proportionally higher than those in developing countries, indicating that the share of energy consumption and carbon emissions from the transportation sector may continue to grow in developing countries as they evolve into developed countries in the future (Kyle & Kim, 2011). However, reducing carbon emissions from the transportation sector is relatively challenging, and the pace of carbon reduction may lag behind other sectors by more than 10 years (Pietzcker et al., 2014; Yin et al., 2015). The transportation sector is a significant contributor to global carbon emissions, and it is crucial to find effective strategies to reduce its carbon footprint. A variety of measures have been proposed to tackle this challenge, such as promoting the use of low-carbon fuels, increasing energy efficiency in transportation, and developing advanced vehicle technologies. In addition, the deployment of innovative policies and business models that can encourage sustainable transportation practices may also contribute to reducing carbon emissions from the transportation sector. Despite the complexity of reducing carbon emissions from the transportation sector, it is crucial to continue investing in research and development to develop effective strategies for decarbonizing the transportation sector. The transportation sector's role in energy consumption and carbon emissions makes it a vital area for achieving global sustainability goals, such as those outlined in the Paris Agreement. Achieving these goals will require a comprehensive and collaborative effort from governments, industry stakeholders, and the whole society.

As the third largest economy in the world, Japan has a population of over 120 million people. According to MILT's statistics, Japan's national vehicle fleet has reached over 82 million as of the end of February 2023. However, as a long-standing automotive powerhouse, Japan has shown less enthusiasm in transitioning towards EVs, resulting in a very low penetration rate of EVs. According to data provided by the Japan Next Generation Vehicle Promotion Center, as of 2021, the total number of BEVs in Japan was just over 150,000, while PHEVs accounted for over 170,000. The number of FCVs, which the Japanese government and relevant industries place great importance on, was only around 7,000. Overall, the penetration rate of electric vehicles in Japan stands at a mere 0.4% (Next Generation Vehicle Promotion Center, 2022). Although Japanese automakers have a substantial technological reserve in HEVs and the number of HEVs currently surpasses 13 million, however, the global electric vehicle industry is gradually transitioning towards EVs and PHEVs, with China, the world's largest market for electric vehicles, particularly surpassing HEVs in terms of PHEV adoption. The energy transition in the transportation sector is essential for achieving carbon neutrality goals, and the Japanese government is currently taking measures such as subsidies and improving infrastructure to further promote the widespread adoption of EVs in Japan. However, the extent to which this transition goal can contribute and the impact it will have on the existing energy supply-demand relationship remain to be analyzed.

Note that in this research, the boundary of the term “transportation sector” of Japan refers specifically to the automotive sector, unless otherwise specified. It does not include railways, aviation, maritime transportation, or other modes of transportation.

5.1 Scenario Design

The energy consumption and pollutant emissions of the transportation sector in a certain region are influenced by multiple variables. The first and fundamental determining factors are the passenger-kilometers traveled by passenger vehicles annually and the ton-kilometers of goods transported by freight vehicles annually. Additionally, the corresponding proportions of different vehicle types in the area, energy efficiency, and emission coefficients also impact the simulation results. Therefore, this study will construct different development scenarios based on the aforementioned influencing factors. The study establishes a total of six scenarios, as shown in Figure 5-1. First and foremost, the foundation of everything is the business as usual (BAU). Building upon the BAU, we further design three branches: the Fuel Efficient Scenario (FES) that brings energy efficiency improvements through technological advancements, the Emission Restriction Scenario (ERS) that involves stricter emission regulations, and the EV Promotion Scenario (EPS) that aims to increase the adoption of electric vehicles through policy guidance and market competition. Additionally, considering factors such as industrial upgrading delays, infrastructure construction progress, and fiscal burden, we have two sub-scenarios under EPS: the Active Promotion Scenario (APS), which signifies a more proactive government approach and more aggressive policies to support the widespread use of electric vehicles, and the Limited Effort Scenario (LES), which represents partial compromises made by the government in electric vehicle adoption due to various factors, resulting in significantly lower electric vehicle market share compared to APS. Besides, by utilizing the unique scenario merging feature of the LEAP model, an Optimal Development Scenario (ODS) will be generated, incorporating all the scenarios' designs to calculate the optimal development path for optimizing the overall energy consumption and pollutant emissions of the transportation sector. The following section will provide a detailed introduction to

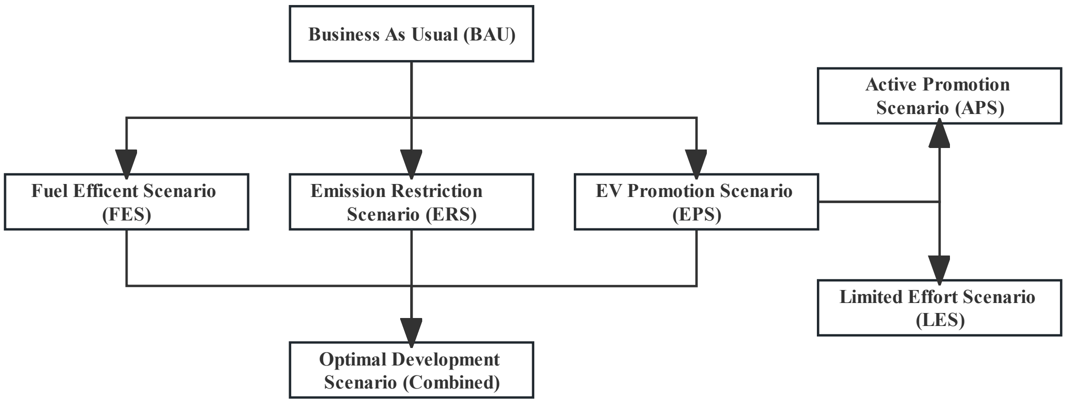


Figure 5- 1. Structure of the Scenario Design

each scenario's design rationale and corresponding quantified data.

5.1.1 Business As Usual (BAU)

The BAU scenario, which stands for Business As Usual scenario, is the most commonly used baseline scenario in scenario modeling and analysis research. It can be understood as a scenario where things continue to develop as they currently are, without any additional policy intervention. Based on this understanding, the BAU scenario has two key points. First, the primary role of the BAU scenario is to forecast future economic and social development, following the principle of not altering the original trajectory of economic and social development. Second, in terms of policies, apart from the existing policies, the BAU scenario can assume the absence of additional binding policies. In general, the BAU scenario refers to the economic and social path that evolves along the existing trajectory and trends, starting from a certain point in time, without the implementation of any specific policy measures. In this study, considering multiple scenarios for the future energy transition in the transportation sector, it is necessary to first construct a baseline scenario that all individual sub-scenarios adhere to, which is the BAU scenario. Considering the significant impact of the COVID-19 pandemic on the global economy and various aspects of society, including Japan, and the stay-at-home policies that have resulted in a significant decrease in transportation sector data, this study designates 2019 as the base year and 2021 as the starting year for policy implementation to ensure consistency in analysis and the interpretability of results. The BAU scenario primarily consists of three main parameters, namely passenger-kilometers and ton-kilometers transported per year, the proportion of transportation by different vehicle types, and the corresponding emission factors. The following will introduce each of these parameters in detail.

Firstly, the annual passenger-kilometers and ton-kilometers transported, which serve as the foundation for modeling and calculations are based on the "Automobile Transportation Statistics Survey" as mentioned in Section 3.3.2. However, in October 2010, the survey method and tabulation method of transportation survey for some vehicle types were changed for the purpose of further improving the reliability of the statistical data. As a result, the time-series continuity between the published statistical values and those before September 2010 was not ensured. Therefore, a connection coefficient was set by MLIT to ensure the continuity of the figures as shown in table 5-1.

Table 5- 1. Connection Coefficient for Each Vehicle Type

Vehicle Type			Connection Coefficient
Fright Vehicle	Commercial	Normal	0.653
		Compact	0.714
		Light	0.660
	Private	Normal	0.749
		Compact	0.654
Passenger Vehicle	Commercial	Normal	0.803

* Data Source: e-Stat

https://www.estat.go.jp/statsearch/files?page=1&layout=dataset&toukei=00600330&tstat=000001078

083&cycle=8&year=20121&month=0

Based on the connection coefficient above we adjust the historical data of annual passenger-km and ton-km transported in Japan and the trends from 1995 to 2019 are shown in Figure 5-2. Detailed data can be found in Table S5. Since the BAU scenario does not take into account other policy interventions, we need to extrapolate the annual passenger-kilometers and ton-kilometers transported data from the base year 2019 to 2050 based on actual historical data as inputs for the model. After reviewing numerous government reports, white papers, think tank predictions, and other sources, we have established the projected figures for passenger-kilometers and ton-kilometers in Japan's transportation

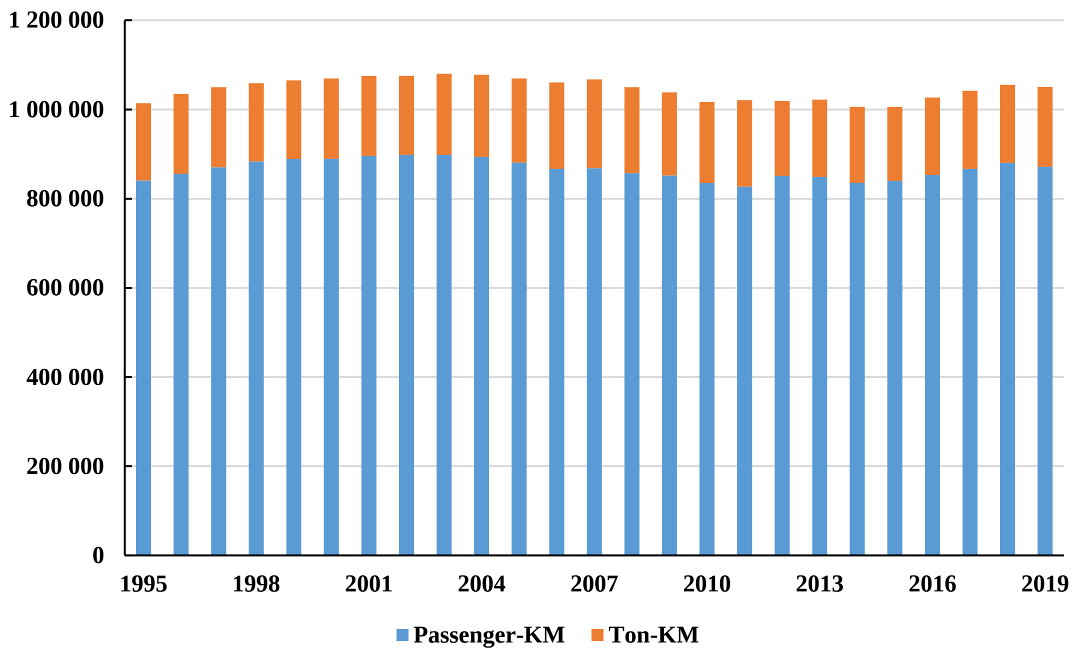


Figure 5- 2. Trends of Annual Passenger-KM and Ton-KM Transported in Japan

sector for the year under the Business as Usual (BAU) scenario, as shown in Table 5-2.

Table 5- 2 Projection of Annual Passenger-KM and Ton-KM Transported

Unit: Million

	2020	2030	2040	2050

Passenger-KM	888600	879600	861650	833400
Ton-KM	175000	165000	155000	148000

Secondly, the proportion of transportation by different vehicle types is also considered. Since the vehicle transportation data collected by MLIT does not include specific data on different types of ICE vehicles, we have opted to use the ratio of existing stock for each vehicle type instead. For specific classifications and corresponding proportions of each vehicle type, please refer to Figure 5-3. As of 2021, the total number of EVs in Japan is approximately 330,000. Among them, normal BEVs account for around 138,000, light EVs account for approximately 21,000, PHEV account for around 174,000, while FCV make up less than 7,000, representing about 0.3% of the total passenger vehicle inventory. Additionally, the total number of normal and light HEV is approximately 13 million, accounting for about 27% of the total passenger vehicle inventory. It is important to note that due to the Japanese government's policy to phase out LPG taxis, which started in 2017, and the official discontinuation of LPG taxis in 2019, even under the BAU scenario, we assume that the proportion of LPG taxis will gradually decrease over the years.

Table 5- 3. Proportion of Vehicle Type in Japan under the BAU Scenario

			ICE			HEV		EV	FEV	ICE	HEV	EV	FEV
			Gasoline	Diesel	LPG	Gasoline	Diesel	Electricity	Hydrogen				
Passenger (871531 million passenser• km)	Private (92.48%)	Nromal (66.67%)	94.80%	5.20%	0.00%	100.00%	0.00%	0.30%	0.00%	72.70%	27.00%	0.30%	0.00%
		Light (33.33%)	100.00%	0.00%	0.00%	100.00%	0.00%	0.02%	0.00%	91.98%	8.00%	0.02%	0.00%
	Commercial (7.52%)	Bus (91.63%)	0.00%	100.00%	0.00%	0.00%	100.00%	0.04%	0.02%	99.34%	0.60%	0.04%	0.02%
		Taxi (8.37%)	23.00%	0.00%	77.00%	100.00%	0.00%	0.02%	0.00%	89.18%	10.80%	0.02%	0.00%
Freight (178697 million ton• km)	Private (13.7%)	Nromal (81.5%)	7.00%	93.00%	0.00%	10.00%	90.00%	0.00%	0.00%	99.60%	0.40%	0.00%	0.00%
		Compact (12.5%)	53.90%	46.10%	0.00%	50.00%	50.00%	0.00%	0.00%	99.80%	0.20%	0.00%	0.00%
		Light (7%)	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	99.80%	0.20%	0.00%	0.00%
	Commercial (86.3%)	Normal (99.5%)	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	99.30%	0.70%	0.00%	0.00%
		Compact (0.3%)	30.70%	69.30%	0.00%	30.00%	70.00%	0.00%	0.00%	99.30%	0.70%	0.00%	0.00%
		Light (0.2%)	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	99.80%	0.20%	0.00%	0.00%

Thirdly, fuel economy is also an important factor. Vehicle fuel economy refers to the ability of a vehicle to save fuel consumption during its use, which is a key indicator of vehicle performance. The better the fuel economy, the less fuel a vehicle consumes to complete a unit of transportation work under certain conditions. As explained in section 3.3.2, this study utilized official data from MLIT and also referred to the fuel economy of specific vehicle models such as HEVs, EVs, and FCVs available in the market to construct the necessary dataset for our research model. The specific details can be found in Table 5-4.

Table 5- 4. Average Fuel Economy by Vehicle Type in Japan under BAU Scenario

			ICE			HEV		EV	FEV
			Gasoline	Diesel	LPG	Gasoline	Diesel	Electricity	Hydrogen
Commercial	Freight	Nromal	-	0.078	-	-	0.065	0.2	0.25
		Compact	0.55	0.5	-	0.48	0.42	0.6	-
		Light	1.85	-	-	1.5	-	0.8	-
	Passenger	Bus	-	0.023	-	-	0.02	0.045	0.05
		Taxi	0.16	-	0.28	0.14	-	0.1	0.12
Private	Freight	Nromal	0.132	0.198	-	0.11	0.15	1	1.25
		Compact	1.36	1.5	-	1.15	1.2	2	-
		Light	3.1	-	-	2.81	-	2.5	-
	Passenger	Normal	0.06	0.065	-	0.04	-	0.1	0.12
		Light	0.048	-	-	0.042	-	0.08	-

*kWh/passenger (ton)-km for EV and FCV

*L/passenger (ton)-km for ICE and HEV

Lastly, emission standards. Japan also has official emission standards for various types of vehicles, with the measurement standard being the weight of pollutants emitted per kilometer. However, the official test mode of emission intensity has changed over time and cannot cover the types we considered in this research. Therefore, considering the availability, accuracy, and consistency of data, we applied another form of emission standard to calculate the direct emission by vehicles, that is, the environmental loading factors of different fuel types. We can calculate the accordingly emission by how much fuel consumed rather than the distances traveled. The environmental loading factors of the four

Table 5- 5. Emission Intensity by Fuel Type

pollutants analyzed in this research are given by the IPCC EFDB database in 2016 as the reference values of environmental emission intensity (Table. 5-5).

	CO_2	CO	CH4	N_2O
Gasoline	69.3	1.225	0.025	0.008
Diesel	74.1	0.171	0.004	0.004
LPG	63.1	0.11	0.062	0.001

* Source: IPCC EFDB

Unit: kg/GJ

No direct emission from EV and FCV

Furthermore, note that since we do not consider the influence of other external factors under the BAU scenario, apart from the annual passenger-kilometers and ton-kilometers transported, the aforementioned parameters, including the proportion of vehicle types, fuel economy, and emission standards for different fuels, will remain unchanged over time in the BAU scenario.

5.1.2 Fuel Efficient Scenario (FES)

In the context of global concerns surrounding climate change, the transportation sector's escalating carbon emissions pose a formidable barrier to the attainment of targets set forth in the Paris Agreement. Despite the impracticality of completely eliminating internal combustion engine (ICE) vehicles within a short timeframe, due to multifaceted considerations such as infrastructure limitations, consumer preferences, and economic considerations, nations worldwide are diligently focusing their efforts on pursuing technological advancements and industrial upgrades to enhance energy efficiency. For example, The U.S. Department of Transportation’s National Highway Traffic Safety Administration announced new, landmark fuel economy standards in 2022 which will make vehicle miles per gallon more efficient, save consumers money at the pump, and reduce transportation emissions. The Corporate Average Fuel Economy (CAFE) standards mandate an industry-wide fleet average of approximately 49 miles per gallon (mpg) for passenger cars and light trucks by the model year 2026, representing the most stringent cost-saving and fuel efficiency requirements implemented thus far. These revised standards stipulate an annual fuel efficiency improvement rate of 8% for model years 2024-2025, followed by a higher rate of 10% for model year 2026. Consequently, these measures are projected to yield a substantial increase of nearly 10 mpg in the estimated fleetwide average for the model year 2026, in comparison to the baseline of the model year 2021 (Department of Transportation, U.S., 2022). In an endeavor to align with the transition towards zero-emissions, Japan has announced a stringent mandate that will necessitate automakers to enhance fleetwide fuel efficiency by over 30% by fiscal year 2030. This ambitious target, unveiled in 2019, entails achieving an average fuel economy of 25.4 kilometers per liter of gasoline across total vehicle sales for each respective company. This represents a significant increase of 32% from the fiscal year 2016 performance. Notably, Japan had already implemented a requirement for a 24% improvement by fiscal year 2020 in comparison to the performance recorded 11 years prior. These regulations will be subject to revision by March. After referring to the fuel economy improvement plans proposed by MLIT and the planning reports of multiple automotive companies, we have established the fuel economy improvement efficiency for different vehicle types in the Japanese transportation sector at the 2035 and 2050 milestones, as shown in the table. We assume a linear progression between these milestones. Detailed fuel economy of different vehicle type by 2035 and 2050 are listed in table S6 and table S7.

5.1.3 Emission Restriction Scenario (ERS)

As mentioned in the previous section, in order to mitigate the direct pollutant emissions from the transportation sector, particularly from conventional ICE vehicles, alternative approaches are required in the absence of widespread adoption of electric vehicles in the short term. In addition to enhancing fuel economy, another crucial method to address this issue is to reduce emission intensity. This involves implementing measures and technologies that minimize the number of pollutants emitted per unit of fuel consumed, thereby reducing the environmental impact associated with transportation activities. Such efforts contribute to the overall reduction of greenhouse gas emissions and help pave the way towards a more sustainable and environmentally friendly transportation system. Many countries and organizations have already set corresponding targets for reducing emission intensity. For instance, passenger cars and light commercial vehicles (vans) collectively contribute approximately 12% and 2.5% of the total CO_2 emissions in the European Union (EU), the primary greenhouse gas responsible for climate change. Effective from 1st January 2020, Regulation (EU) 2019/631 established CO_2 emission performance standards for new passenger cars and vans. The Regulation sets fleet-wide CO2 emission targets for

Table 5- 6. Improvement of Fuel Economy by 2035 and 2050

Type			2035	2050
Commercial	Freight	ICE	15%	25%
		HEV		
		EV/FCV	10%	20%
	Passenger	ICE	20%	25%
		HEV	15%	30%
		EV/FCV	10%	20%
Private	Freight	ICE	15%	25%
		HEV		
		EV/FCV	10%	20%
	Passenger	ICE	25%	25%
		HEV	15%	30%
		EV/FCV	10%	20%

the EU, applicable from 2020, 2025, and 2030. It also includes provisions to incentivize the adoption of zero- and low-emission vehicles (European Commission, 2021).

In Japan, the regulation of automobile emissions started in 1966. More recently, for gasoline vehicles, regulations were implemented in 2000, 2001, and 2002 (New Short-term Regulation), which involved enhancing the emission standards for CO, HC, and NOx, as well as mandating the installation of On-Board Diagnostics (OBD) systems. For diesel vehicles, regulations were implemented in 2002, 2003, and 2004 (New Short-term Regulation), focusing on strengthening regulations for NOx, PM, and other emissions. In 2005, both gasoline and diesel vehicles underwent a revision of the emission test methods, leading to the implementation of the 2005 regulation (New Long-term Regulation). Subsequently, in 2008, the 2010 regulation (Post-New Long-term Regulation) was implemented. Furthermore, in 2015, there was a reinforcement of the emission standards for heavy diesel vehicles and motorcycles, aiming to achieve further reduction of automobile emissions. Although Japan has set a target to ban the sale of pure internal combustion engine vehicles starting from 2035, this prohibition does not encompass non-plug-in hybrid electric vehicles (HEVs). Consequently, direct pollutant emissions from internal combustion vehicles will persist for a considerable period of time. Furthermore, Japan has not updated its emission standards for passenger cars since 2010 and has not issued any statements regarding new regulations. Taking into account the policies implemented by other countries worldwide and considering the specific circumstances in Japan, we have formulated the following targets for reducing emission intensity where the emission intensity reduction is considered as a 15% and 25% reduction in CO_2 and a 10% and 20% in other gases by 2035 and 2050, respectively (Table. 5-7).

Table 5- 7. Emission Intensity under ERS Scenario

Year	Fuel	CO_2	CO	CH_4	N_2O
2035	Gasoline	58.9050	1.1025	0.0225	0.0072
	Diesel	62.9580	0.1539	0.0036	0.0036

2050	Gasoline	51.9750	0.9800	0.0200	0.0064
	Diesel	55.5750	0.1368	0.0032	0.0032

Unit: kg/GJ

5.1.4 EV Promotion Scenario (EPS)

Japan, renowned for its automotive industry and technological advancements, has faced delays in transitioning to electric vehicles (EVs). Despite being an early innovator in hybrid vehicles, Japan has encountered challenges in embracing a fully electric future. Translation: In 2021, Japan's sales of EVs and PHEVs were only 50,000 units, accounting for approximately 1.1% of total car sales. In the same year, China's sales of new energy vehicles accounted for 13.4% of the market, while the United States accounted for 4.3%. To achieve the 2050 carbon neutrality goal, the energy transition in the transportation sector, especially the switch to electric vehicles, will be crucial. Currently, the Japanese government provides a subsidy of 850,000 yen (6000 USD as of May 2023) for EVs. However, due to the lack of competitive advantages in terms of performance and price compared to traditional fuel-powered vehicles offered by Japanese automakers, the widespread adoption of EVs in Japan remains challenging.

Considering the actual situation in Japan, we have further designed two sub-scenarios. The first one is the Active Promotion Scenario (APS), which represents the Japanese government and related industries accelerating the process of transitioning to EVs and proposing more aggressive policies while rapidly improving the corresponding infrastructure. The market share of EVs in Japan will see a significant increase in the short term. Under this scenario, the EV penetration rate for passenger cars is projected to reach

15% by 2030 and 35% by 2050. As for commercial trucks, the EV share is expected to reach around 30% by 2050 (Table 5-8).

The second one is the Limited Effort Scenario (LES), where the Japanese government will continue to promote the sales and adoption of EVs in Japan. However, due to an

Table 5- 8. Proportion of transportation by vehicle type under APS

			base year				2035				2050			
			ICE	HEV	EV	FCV	ICE	HEV	EV	FCV	ICE	HEV	EV	FCV
Passenger	Private	Nromal	72.70%	27.00%	0.30%	0.00%	49.00%	35.00%	15.00%	1.00%	10.00%	50.00%	35.00%	5.00%
		Light	91.98%	8.00%	0.02%	0.00%	55.00%	30.00%	15.00%	0.00%	20.00%	45.00%	35.00%	0.00%
	Commercial	Bus	99.34%	0.60%	0.04%	0.02%	65.00%	20.00%	10.00%	5.00%	35.00%	35.00%	20.00%	10.00%
		Taxi	89.18%	10.80%	0.02%	0.00%	45.00%	35.00%	15.00%	5.00%	10.00%	50.00%	30.00%	10.00%
Freight	Private	Nromal	99.60%	0.40%	0.00%	0.00%	60.00%	25.00%	10.00%	5.00%	30.00%	40.00%	20.00%	10.00%
		Compact	99.80%	0.20%	0.00%	0.00%	60.00%	25.00%	15.00%	0.00%	35.00%	40.00%	25.00%	0.00%
		Light	99.80%	0.20%	0.00%	0.00%	55.00%	25.00%	20.00%	0.00%	30.00%	40.00%	30.00%	0.00%
	Commercial	Normal	99.30%	0.70%	0.00%	0.00%	55.00%	25.00%	15.00%	5.00%	25.00%	40.00%	25.00%	10.00%
		Compact	99.30%	0.70%	0.00%	0.00%	55.00%	25.00%	20.00%	0.00%	30.00%	40.00%	30.00%	0.00%
		Light	99.80%	0.20%	0.00%	0.00%	50.00%	25.00%	25.00%	0.00%	25.00%	40.00%	35.00%	0.00%

immature industry chain and low social acceptance, the penetration of EVs will only increase slightly, still leaving a significant gap compared to China and the European Union, where EV adoption is progressing at a faster pace. As ICE vehicles being phased out, the mainstay of the private passenger vehicles will shift to HEV and the freight vehicle remain ICE vehicles in major. Under this scenario, the EV penetration rate for passenger cars is only 5% by 2030 and remains at 10% by 2050. Due to the exemption of ICE freight vehicles from the sales ban, the electrification process of trucks will be much slower compared to passenger cars, particularly in terms of hybrid electric vehicle (HEV) adoption. For specific proportions of each vehicle type, please refer to Table 5-9.

Table 5- 9. Ratio of Transportation by Vehicle Type under LES

			base year				2035				2050			
			ICE	HEV	EV	FCV	ICE	HEV	EV	FCV	ICE	HEV	EV	FCV
Passenger	**Private**	**Nromal**	72.70%	27.00%	0.30%	0.00%	60.00%	35.00%	5.00%	0.00%	40.00%	50.00%	10.00%	0.00%
		Light	91.98%	8.00%	0.02%	0.00%	80.00%	15.00%	5.00%	0.00%	65.00%	25.00%	10.00%	0.00%
	Commercial	**Bus**	99.34%	0.60%	0.04%	0.02%	86.00%	10.00%	3.00%	1.00%	69.00%	20.00%	8.00%	3.00%
		Taxi	89.18%	10.80%	0.02%	0.00%	75.00%	20.00%	5.00%	0.00%	55.00%	35.00%	10.00%	0.00%
Freight	**Private**	**Nromal**	99.60%	0.40%	0.00%	0.00%	87.00%	10.00%	3.00%	0.00%	70.00%	20.00%	8.00%	2.00%
		Compact	99.80%	0.20%	0.00%	0.00%	80.00%	15.00%	5.00%	0.00%	65.00%	25.00%	10.00%	0.00%
		Light	99.80%	0.20%	0.00%	0.00%	80.00%	15.00%	5.00%	0.00%	65.00%	25.00%	10.00%	0.00%
	Commercial	**Normal**	99.30%	0.70%	0.00%	0.00%	87.00%	10.00%	3.00%	0.00%	70.00%	20.00%	8.00%	2.00%
		Compact	99.30%	0.70%	0.00%	0.00%	87.00%	10.00%	3.00%	0.00%	72.00%	20.00%	8.00%	0.00%
		Light	99.80%	0.20%	0.00%	0.00%	80.00%	15.00%	5.00%	0.00%	65.00%	25.00%	10.00%	0.00%

5.1.5 Optimal Development Scenario (Combined)

The Optimal Development Scenario (Combined) is a unique analytical tool provided by the LEAP model, which comprehensively incorporates the influencing factors from all the designed scenarios. It represents a more ideal scenario. In this scenario, the annual passenger-kilometer and ton-kilometer transported remain the same as in the BAU scenario. Fuel economy is consistent with the FES, and emission standards align with the ERS. The transport mode shares for each vehicle type are the same as in the APS. This scenario aims to consider the corresponding energy consumption and pollutant emission reductions in the transportation sector under the combined effect of various policy measures. It can provide policymakers with more in-depth insights for decision-making.

5.2 Energy Consumption

In all examined scenarios, transportation sector of Japan demonstrates a consistent declining trend in total energy consumption (Figure 5-3). Notably, BAU scenario exhibits the slowest decline, while the Combined scenario showcases the most rapid reduction. For the purpose of this summary, the ERS scenario is not taken into account as its parameters do not directly pertain to energy considerations. The base year records a total energy consumption of 2,441 million GJ within the transportation sector. As the policies designed in 2021 are progressively implemented, the disparities in energy consumption patterns become increasingly apparent. Within the BAU scenario, the total energy consumption is projected to diminish to 2,207 million GJ by the year 2050, with an annual reduction rate of 1.1 million GJ per year. Analyzing the three sub-scenarios considered, the LES displays the highest total energy consumption, trailed by the FES, while the APS exhibits the lowest consumption. Projections indicate that by the year 2050, the total energy consumption within these sub-scenarios will amount to approximately 1,890 million GJ for LES, 1,770 million GJ for FES, and 1,389 million GJ for APS. In the comprehensive Combined scenario, which incorporates a synthesis of all sub-scenario policies, the total energy consumption in the transportation sector reaches a notably minimal level, amounting to a mere 1068 million GJ. This achievement reflects a substantial reduction of 56% when compared to the baseline BAU scenario. Such a pronounced decrease underscores the considerable effectiveness of a multifaceted policy integration approach in curtailing the overall energy requirements within the transportation sector.

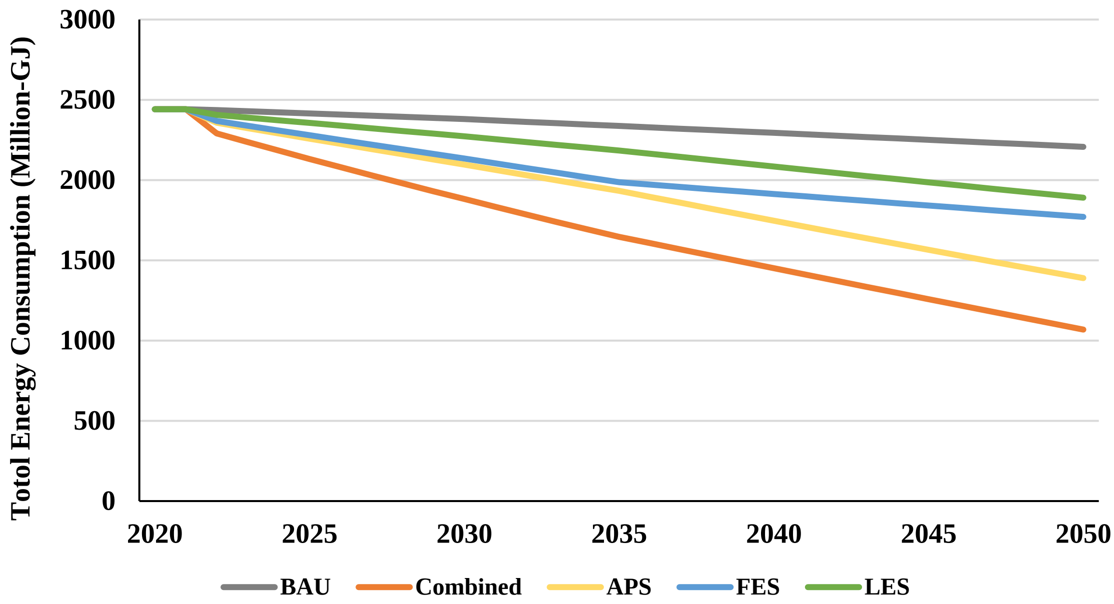


Figure 5- 3. Total Energy Consumption of Japan's Transportation Sector under Different Scenarios

5.2.1 Gasoline and Diesel

Additionally, we have also calculated the energy consumption of the transportation sector across various types of energy in different scenarios. We have selected gasoline, diesel, electricity, and hydrogen as the primary subjects of analysis and the results are shown in Figure. 5-4. In the baseline year, the consumption of gasoline in the transportation sector of Japan was 49.4 billion liters. Under BAU scenario, this consumption exhibited a slight decrease over the years due to declining annual transportation volumes, reaching 49.2 billion liters in 2030 and further declining to 46.6 billion liters by 2050, which is only a 5.6% reduction compared with the baseline year. However, under the FES, the reduction in gasoline consumption was more significant. It is projected to decrease to 44.2 billion liters by 2030, 40.5 billion liters by 2040, and further decline to 38.3 billion liters by 2050. Significant variations in gasoline consumption were observed between two sub-scenarios under the EPS. The disparity arose from the varying degrees of EV adoption. Surprisingly, under the LES sub-scenario, the consumption for gasoline in the transportation sector even surpassed that of the FES scenario. It amounted to 46.9 billion liters in 2030, 43.2 billion liters in 2040, and decreased to 39.0 billion liters by 2050. In contrast, the more aggressive APS sub-scenario witnessed a substantial reduction in gasoline consumption. It is anticipated to reach 42.8 billion liters by 2030, 34.7 billion liters by 2040, and further decline to 25.5 billion liters by 2050. The reduction in gasoline consumption under the APS scenario relative to BAU amounted to an impressive 45%, whereas under LES, the reduction was a modest 16%. Under the comprehensive Combined scenario that integrates various sub-scenarios, the consumption for gasoline experienced further decline. It is projected to reach 38.4 billion liters in 2030, 29.8 billion liters in 2040, and a mere 19.7 billion liters by 2050. This signifies a substantial decrease in gasoline consumption, with a reduction of 57% compared to BAU, and a remarkable decrease of over 60% compared to the baseline year.

Another widely used fuel is diesel. Unlike gasoline which is predominantly utilized in private passenger vehicles, diesel finds extensive use in trucks and buses. Actually, diesel has a higher energy density, meaning it contains more potential energy per unit volume compared to gasoline. This higher energy density enables diesel engines to achieve better fuel efficiency, resulting in improved mileage and reduced fuel consumption. Diesel engines are also known for their robustness and durability. The design of diesel engines allows for higher compression ratios, leading to better thermal efficiency and torque output. These characteristics make diesel engines well-suited for heavy-duty applications, such as in trucks, buses, and industrial machinery. Moreover, diesel fuel exhibits a higher flash point and lower volatility compared to gasoline. This property enhances safety during storage and transportation, reducing the risk of fuel evaporation and flammability. Simulation results indicate that, overall, diesel consumption exhibits similar trends to gasoline across different scenarios. Under the BAU scenario, diesel consumption is

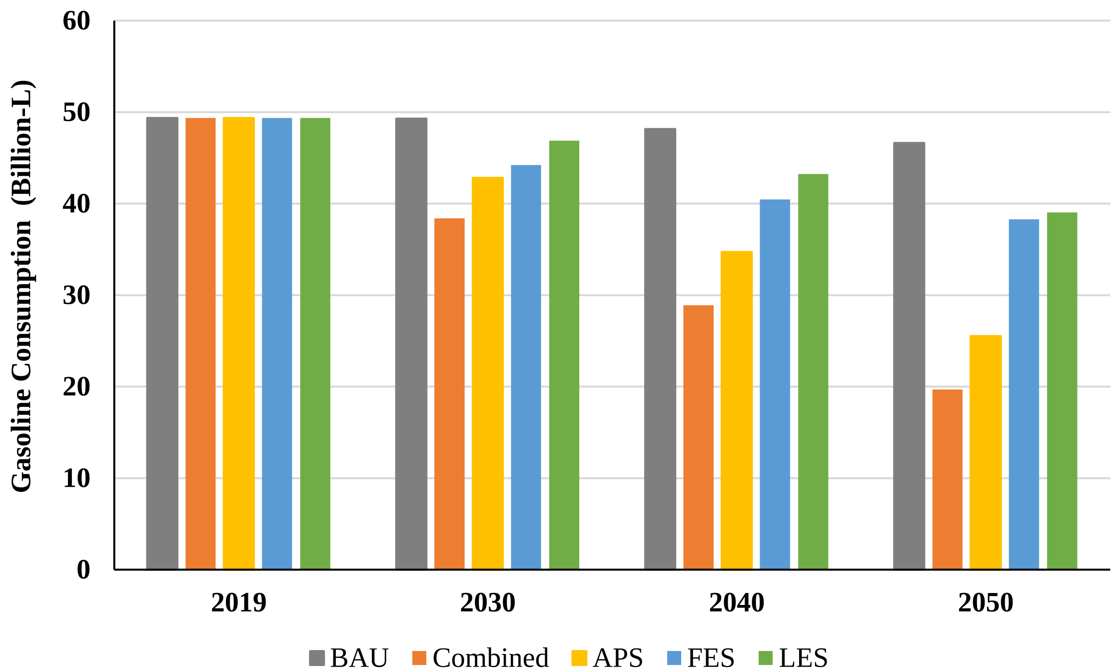


Figure 5- 4. Gasoline Consumption under Different Scenarios

projected to decrease from 23.3 billion tons in the baseline year to 19.7 billion tons by 2050, representing a reduction of 15%. This reduction is significantly higher compared to the 5% decrease observed in gasoline consumption. Under the FES, the reduction in diesel consumption remains higher than that of the LES. It is estimated to decrease to 19.5 billion tons in 2030 and further decline to 14.9 billion tons by 2050, representing a reduction of 24% compared to BAU. Under the two sub-scenarios of the EPS, the disparity in diesel consumption between LES and APS is not as significant as that observed in gasoline consumption. This is primarily due to the larger, long-haul mileage requirements of heavy trucks and buses that predominantly rely on diesel. Considering the current technological limitations of power batteries, the electrification of heavy vehicles is expected to progress at a slower pace compared to private passenger vehicles. Under LES in 2050, diesel consumption is projected to be approximately 16.3 billion tons, while under APS, it is estimated to be only 11.2 billion tons. These reductions represent 17% and 43% respective decreases compared to BAU. Under the idealized Combined scenario, the introduction of hybrid diesel engines leads to significant improvements in fuel economy for HEV. Combined with the increased share of HEV and EVs under APS, diesel consumption is estimated to decrease to 8.46 billion tons by 2050, representing a substantial reduction of 57%.

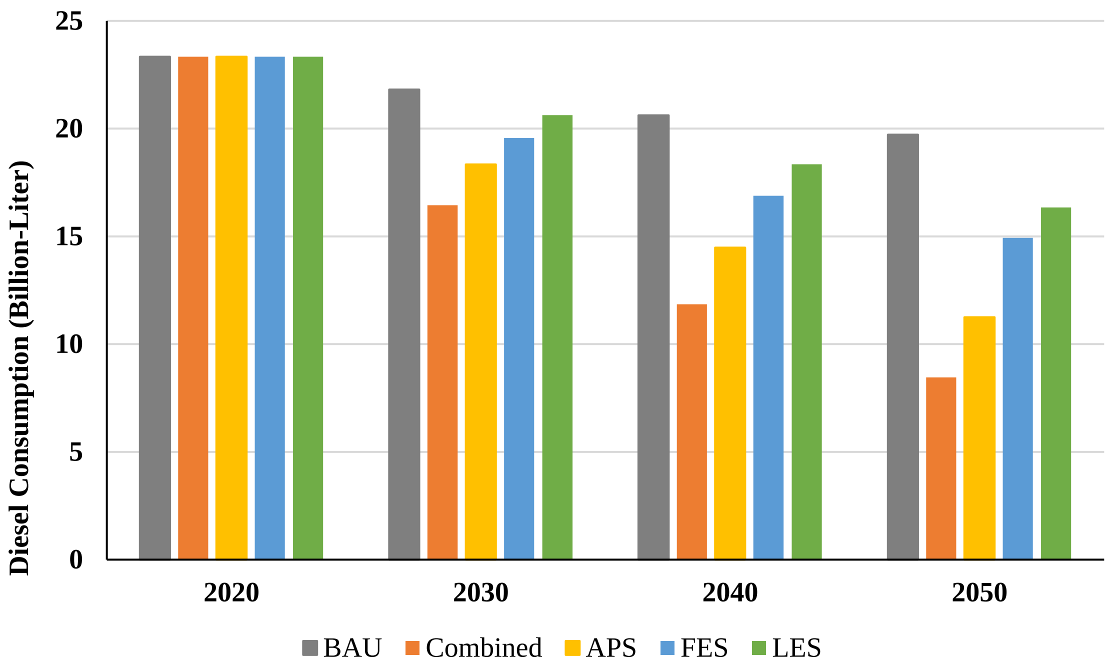


Figure 5- 5. Diesel Consumption under Different Scenarios

These findings highlight the potential for reducing fuel consumption through a combination of technological advancements, policy interventions, and the adoption of hybridization strategies in the transportation sector. Under the BAU scenario, the slight decrease in both gasoline and diesel consumption can be attributed to declining transportation volumes. However, the FES demonstrates a more pronounced decline in fuel consumption, showcasing the effectiveness of a comprehensive policy approach. This reduction is driven by measures such as improved fuel efficiency, alternative fuel options, and modal shift strategies. Interestingly, the EPS reveals contrasting trends between the two sub-scenarios, LES and APS. The LES sub-scenario, characterized by limited EV adoption, surprisingly exhibits higher fuel consumption compared to the FES scenario. This highlights the significance of EV penetration as a key determinant in reducing fuel consumption. In contrast, the APS sub-scenario, which adopts more aggressive measures including extensive EV adoption and advanced power systems, demonstrates a substantial reduction in fuel consumption. The comprehensive Combined scenario further magnifies the reduction in fuel consumption, indicating the synergistic effects of integrating multiple policies. This scenario showcases the most substantial decline in fuel consumption, with an impressive reduction of a remarkable decrease of about 60% in both gasoline and diesel consumption compared to the baseline year. This highlights the importance of a comprehensive and holistic approach in achieving significant energy savings and promoting sustainable transportation and achieving significant reductions in fuel consumption would contribute to the overall goal of achieving a more sustainable and energy-efficient transportation system.

5.2.2 Electricity and Hydrogen

In the future, the widespread adoption of EVs will result in the connection of numerous EV batteries to the power grid, and there is an expectation for cooperation with the stable power supply system. It is difficult to accurately anticipate the extent of future EV adoption at present, but it is anticipated that electricity demand will increase in line with the level of EV penetration. The integration of a large number of EV batteries into the power system has the potential to impact the overall electricity supply-demand dynamics. As EVs become more prevalent, the demand for electricity will likely experience a substantial increase. This necessitates careful planning and coordination between the power grid and the EV charging infrastructure to effectively manage the additional load. It is worth noting that the increase in electricity demand is not solely attributed to EVs. Other factors, such as the electrification of other sectors like heating and industrial processes, should also be taken into account. Proper assessment of the overall electricity demand growth potential is crucial for long-term planning and investment in power generation and distribution infrastructure. Therefore, it is of significant importance to anticipate in advance the electricity demand under different levels of electric vehicle (EV) adoption, as it pertains to the future construction of grid infrastructure and the generation of power to maintain balance. Accurately estimating the electricity demand associated with widespread EV adoption is crucial for ensuring the reliability and stability of the power grid. Furthermore, the integration of EVs with the power grid presents opportunities for the development of innovative solutions. Vehicle-to-Grid (V2G) technology allows EVs to serve as mobile energy storage units, enabling bidirectional power flow between the grid and the vehicles. This concept holds potential for grid stabilization, peak load management, and even revenue generation for EV owners. However, the technical and regulatory challenges associated with V2G implementation need to be carefully addressed.

Besides, Japan has long been a global leader in the development and deployment of hydrogen technologies, including fuel cells, and sees FCVs as a viable alternative to conventional internal combustion engine vehicles. One of the key motivations behind Japan's emphasis on FCVs is the country's limited domestic fossil fuel resources. As a result, Japan has sought to diversify its energy sources and reduce its dependence on imported fossil fuels. Hydrogen, as a clean and versatile energy carrier, presents an attractive solution for Japan's energy security concerns. The Japanese government has implemented supportive policies and provided financial incentives to encourage the adoption of FCVs. These measures include subsidies for vehicle purchases, tax benefits, and the establishment of hydrogen refueling infrastructure. Japan aims to create an ecosystem that facilitates the widespread use of FCVs and promotes collaboration among stakeholders, including automakers, energy companies, and research institutions. However, the adoption of hydrogen fuel cell vehicles in Japan faces several challenges. One of the primary concerns is the high cost of producing and distributing hydrogen, as well as the limited availability of refueling infrastructure, particularly outside urban areas. The development of a robust hydrogen supply chain and the expansion of refueling infrastructure are crucial for overcoming these challenges and ensuring the practicality of FCVs on a larger scale.

Under this background, this study analyzes the mid-long-term electricity consumption in Japan's transportation sector under two different scenarios of EV adoption (LES and APS) and an integrated policy scenario (Combined scenario). The results are presented in the figure 5-6. Firstly, considering electricity consumption, Japan's total electricity demand for the year 2019 was 877 TWh, whereas the consumption attributable to EVs at that time was relatively low due to their limited adoption, amounting to only 166 GWh. Under the Low Electric Scenario (LES), the overall electricity consumption by the transportation sector reaches 4.4 TWh by 2030, 8.3 TWh by 2040, and 12.2 TWh by 2050. It is observed that the overall electricity demand increase resulting from the transition of the transportation sector to EVs is not particularly significant under the low EV adoption scenario. However, under the more aggressive Advanced Policy Scenario (APS), the electricity demand in the transportation sector reaches 13.5 TWh by 2030, 25.7 TWh by 2040, and 38 TWh by 2050, showing a considerably faster growth compared to the LES. Reference can be made to Japan's Nationally Determined Contribution (NDC) scenario, which estimates the total electricity demand in Japan to be 864 TWh by 2030, and the projection by Central Research Institute of Electricity Power Industry suggests that the total electricity demand in Japan will reach 1,110 TWh by 2050. Thus, even under the more aggressive APS, the growth in electricity demand caused by the transportation sector in 2030 accounts for only 1.5% of the total electricity demand and reaches a modest 3% by 2050, implying that it will not impose a significant burden on the power system. Moreover, it should be noted that the majority of EV charging occurs during nighttime, which aligns with the ongoing research on Vehicle-to-Grid (V2G) integration, potentially making EVs a crucial participant in balancing the future power grid. Furthermore, in the Combined Scenario, the combination of multiple policies ensures substantial benefits while keeping electricity demand within a reasonable growth range. By 2030, the demand is projected to be 12.5 TWh, which is similar to the APS, but by 2050, it decreases to 30.3 TWh, representing a 20% reduction compared to the APS scenario.

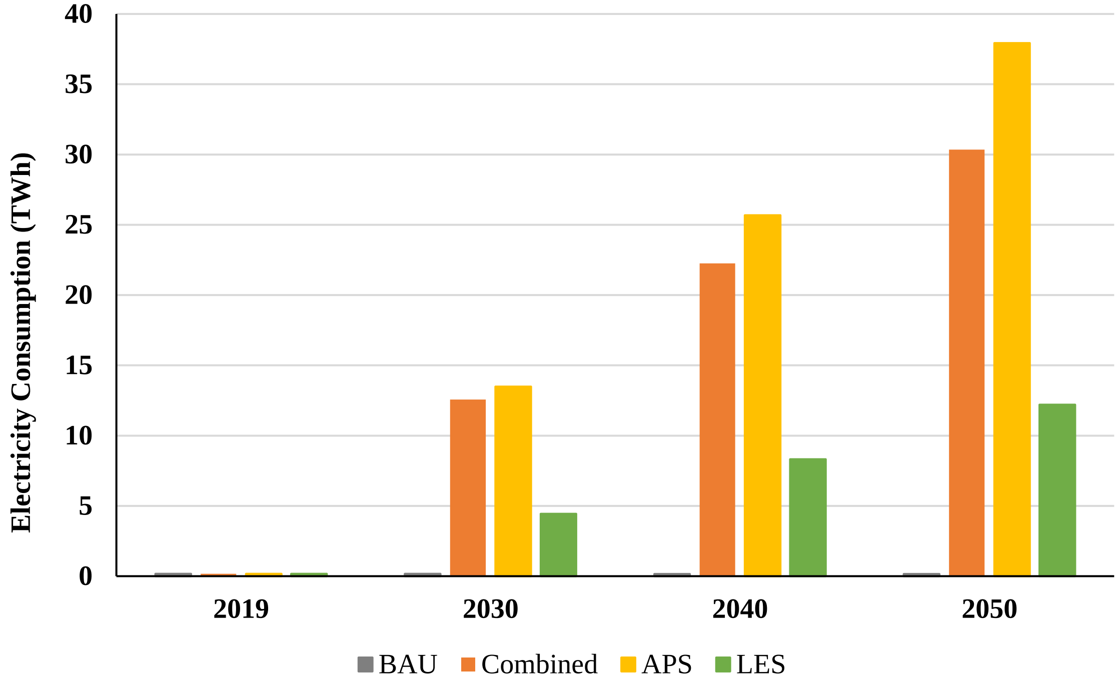


Figure 5- 6. Electricity Consumption under Different Scenarios

Regarding hydrogen energy, the development of hydrogen fuel cell vehicles is still in its early stages, primarily due to limitations in refueling infrastructure and cost factors. Currently, the majority of fuel cell vehicles are deployed in fixed-route vehicles such as buses and trucks, with relatively limited applications in private passenger cars. However, it is undeniable that hydrogen energy remains one of the cleanest and most efficient power sources available. Therefore, this study also considers the potential future application of hydrogen energy in the transportation sector and calculates the corresponding demand, as shown in Figures 5-7. The hydrogen energy consumption output by the LEAP model is measured in joules and, for the sake of analysis, we have converted it to metric tons using a reference hydrogen energy density of 120 MJ/kg. Under the LES, the adoption of FCVs in the transportation sector remains relatively conservative, with FCVs primarily introduced in some buses and freight trucks. By the year 2030, the projected hydrogen energy consumption in the transportation sector is estimated to reach 20,000 tons, while in 2040 it is expected to be 36,700 tons, and by 2050, it is projected to reach 52,500 tons. The overall growth rate is relatively slow. However, under the APS, we have considered more proactive policy incentives, leading to a higher proportion of FCV adoption in private vehicles. Consequently, the consumption of hydrogen energy is significantly increased compared to the LES. Specifically, by 2030, it is estimated to reach 77,200 tons, by 2040 it is projected to be 161,000 tons, and by 2050 it is expected to reach 259,500 tons, which is nearly five times the consumption under the LES. Under the Combined Scenario, thanks to the comprehensive effects of various policies, the total consumption of hydrogen energy is slightly lower compared to the APS. By 2030, it is projected to be 71,900 metric tons, and by 2050, it is estimated to reach 207,600 metric tons, representing a decrease of 20%.

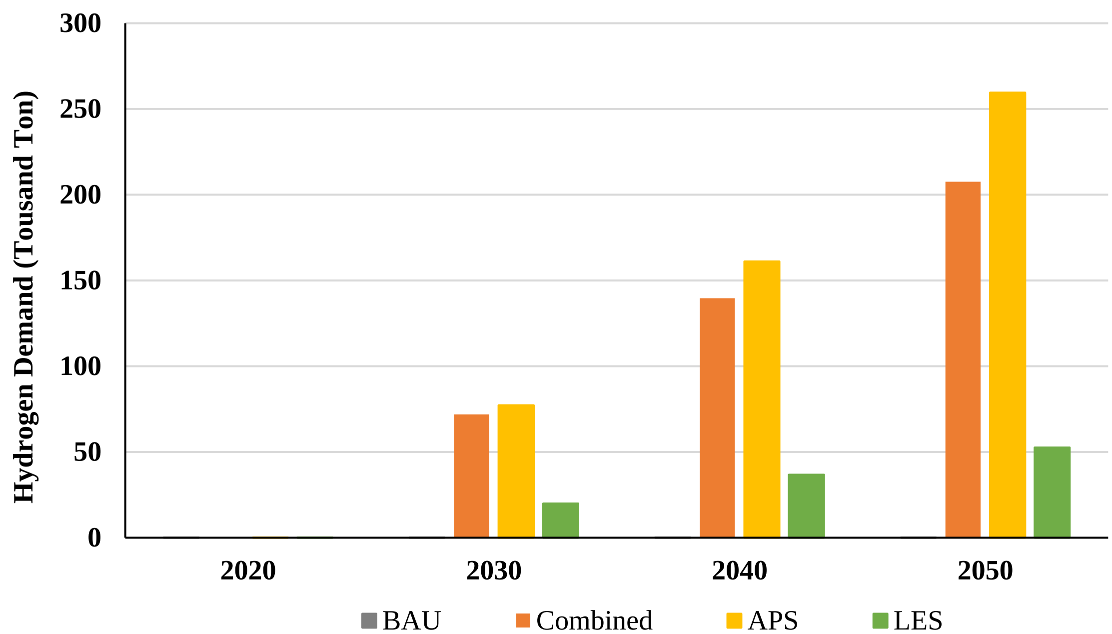


Figure 5- 7. Hydrogen Fuel Consumption under Different Scenarios

According to data and information from the "Issues and Directions for Future Hydrogen Policy" report published by the Ministry of Economy, Trade, and Industry (METI) in 2021, Japanese companies are leading globally in the development of combustion turbine technology, which controls the combustion of flammable hydrogen gas in turbines. The potential domestic demand for hydrogen fuel is estimated to be between 5 and 10 million metric tons per year. In response to the growing demand for hydrogen energy, Japan plans to establish an international hydrogen supply chain and import a large amount of hydrogen from overseas. Additionally, Japan aims to further reduce the cost of electrolysis equipment, integrate it into the power system, and invest in innovative hydrogen production technologies. By expanding the adoption of hydrogen, Japan expects to lower the cost of hydrogen power generation to below that of natural gas (with hydrogen costs estimated to be below 20 Japanese yen per cubic meter). The ultimate goal is to achieve a competitive level by 2050, with plans to introduce a maximum of 3 million tons of hydrogen by 2030, and a target of approximately 20 million tons by 2050. The planned production for hydrogen energy associated with this target encompasses various applications, including hydrogen power generation. However, even under the more ambitious APS, the projected hydrogen fuel consumption in the transportation sector is estimated to be only approximately 77,000 tons by 2030 and 260,000 tons by 2050. The planned targets of 3 million metric tons and 20 million metric tons are fully capable of meeting the transportation sector's demand for hydrogen fuel, considering these figures.

5.2 Pollutant Emission

This research considered four types of pollutants mainly emitted in the transportation sector including CO_2, Carbon Monoxide (CO), Methane (CH_4), and Nitrous Oxide (N_2O). CO_2 is a major greenhouse gas responsible for climate change. It is primarily emitted from the combustion of fossil fuels in vehicles. High levels of CO_2 in the atmosphere contribute to the greenhouse effect, trapping heat and leading to global warming. Increased global temperatures have detrimental effects on ecosystems, weather patterns, sea levels, and human health. CO is a toxic gas produced by incomplete combustion of fossil fuels. It is a colorless and odorless gas that binds to hemoglobin in the blood, reducing its ability to transport oxygen to body tissues. Exposure to high levels of CO can lead to headaches, dizziness, nausea, and even death. CO emissions from vehicle exhaust pose a significant threat to air quality and public health, particularly in congested urban areas. CH_4 is another potent greenhouse gas emitted from vehicle exhaust. It is produced during the combustion of fossil fuels and is also released from natural gas leakage in the transportation and production processes. Methane has a much higher global warming potential compared to carbon dioxide over a 20-year period. Its accumulation in the atmosphere contributes to climate change and exacerbates the greenhouse effect. N_2O is a greenhouse gas released from vehicle exhaust and other combustion processes. It is produced through the oxidation of nitrogen compounds present in fuel and air at high temperatures. Nitrous oxide has a long atmospheric lifetime and is responsible for both climate change and stratospheric ozone depletion. It contributes to the formation of smog and has adverse effects on air quality and human health.

Figure 5-8 shows the model results of direct emission from all fossil fuels. We focus on analyzing the changes in pollutant emissions in various scenarios, with CO_2 as a representative. The CO_2 emission in base year was 172.7 million tons. Under different scenarios, the total CO_2 emissions from Japan's transportation sector exhibit varying trends, reflecting the impact of different policy approaches. Under the BAU scenario, where no significant external policy interventions occur, emissions are projected to remain relatively high at 168 million tons by 2030 and 156 million tons by 2050. The ERS enforces stricter emission standards for motor vehicles, aiming to limit their emission intensity. This approach is projected to yield emissions of approximately 157 million ton by 2030 and 125 million tons by 2050, which is a 20% reduction compared to the emission under BAU by 2050. Furthermore, the FES emphasizes advancements in technology and industrial upgrades to enhance the fuel economy of conventional vehicles. As a result, emissions are estimated to reach 150 million tons by 2030 and 124 million tons by 2050, which shows a similar reduction rate with ERS. The technological innovation and industrial upgrading of ICE vehicles have brought about carbon dioxide emission reduction benefits equivalent to the low-emission intensity benefits brought about by more stringent emission standards. Under the two sub-scenarios of EPS, LES represents a more conservative policy approach, with only a modest increase in electric vehicle adoption. This scenario contributes even less to emission reductions compare with ERS and FES, with estimated emissions of around 159 million tons by 2030 and 130 million tons by 2050, only a 16% reduction compare with BAU. In contrast, under the APS, the Japanese government proactively promotes the adoption of electric vehicles. As a result, emissions are expected to decrease to 144 million tons by 2030 and 86 million tons by 2050, a significant 45% reduction compared with BAU. This scenario leverages the increasing popularity of electric vehicles as a key driver of emission reductions. Furthermore, when multiple policies are combined in the Combined scenario, a more comprehensive and integrated approach leads to a notable decrease in emissions, with an estimated total of 67% reduction by 2050, only 52 million tons of CO_2 emission. This scenario encompasses a range of measures aimed at reducing carbon emissions from the transportation sector and highlight the potential for significant emission reductions in Japan's transportation sector through various policy interventions. As for individual scenarios, The APS demonstrates the most substantial reductions, driven by the active promotion of electric vehicles. Even in more conservative scenarios like LES, noteworthy emission reductions can still be achieved. Besides, ERS that enforcement of stricter emission standards and initiatives focusing on fuel efficiency like FES show obvious changes of up to 20% reduction by 2050 as well.

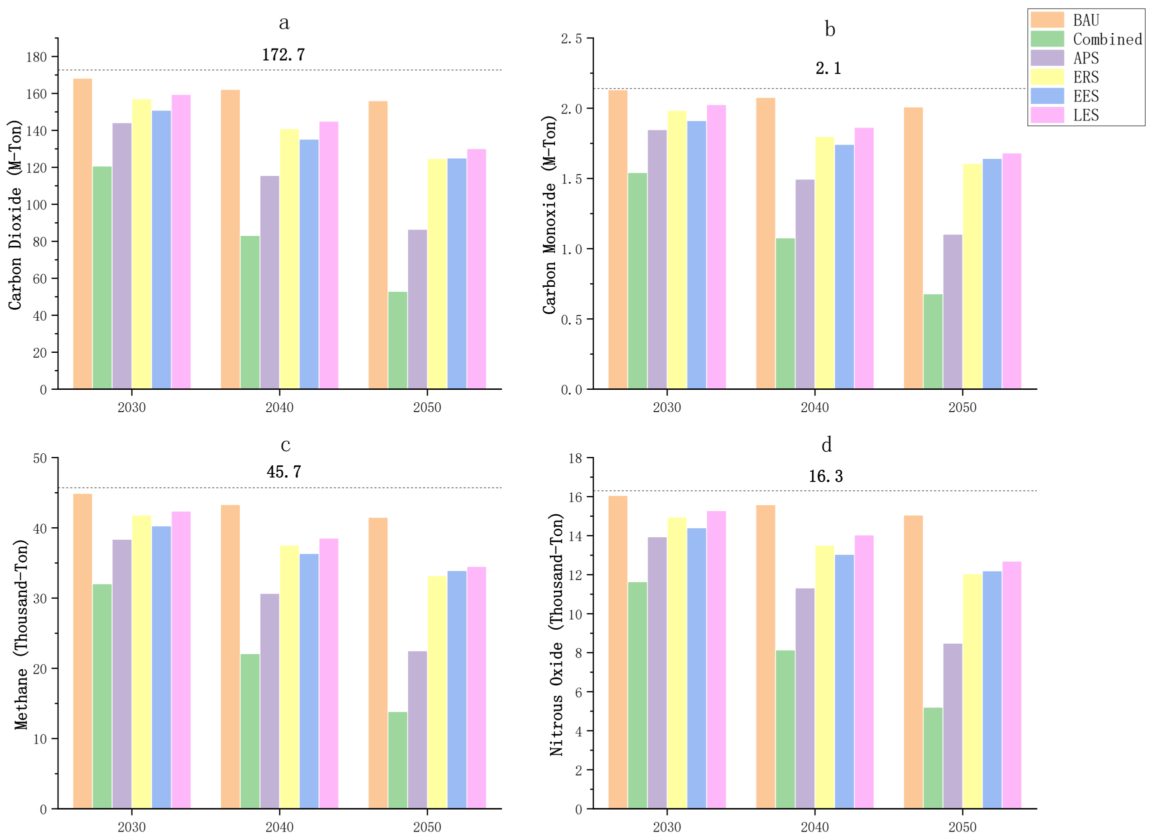


Figure 5- 8. Total Emissions of Four Pollutants: CO_2 (a), CO (b), Methane (c), N_2O (d)

* The dotted line represents the actual emission data in base year

Under various situations, the emissions of the other three contaminants likewise exhibited comparable tendencies. The emission of CO in the base year was 21 million tons. The ERS and FES scenarios predict a decline to roughly 16 million tons by 2050. The LES was approximately 17 million tons under the two EPS sub-scenarios, and the APS was further decreased by 35% to 11 million tons. By 2050, CO emissions are anticipated to drop to 6.8 million tons under the Combined Policy scenario, a 66% decrease from the 20 million tons under the BAU scenario. In the base year, there were 45,700 tons and 16,300 tons, respectively, of emissions of CH_4 and N_2O. By 2050, the total amount of CH_4 emissions for each scenario was 34,500 tons for LES, 33,900 tons for FES, 33,200 tons for ERS, 22,500 tons for APS, and 13,800 tons for the combined scenario, representing respective reductions of 16.8%, 18.2%, 20.1%, 45.8%, and 66.7% from BAU. The N_2O emissions for each scenario were 12,700 tons for LES, 12,200 tons for FES, 12,000 tons for ERS, 8,500 tons for APS, and 5,200 tons for the combined scenario, respectively. These emissions decreased by 15.7%, 19.0%, 20.0%, 43.6%, and 65.4% from BAU.

Chapter 6. Conclusion and Discussion

6.1 Conclusion

In conclusion, this dissertation aimed to address two fundamental research questions related to Japan's energy transition towards achieving its carbon neutral goal. The research questions were as follows:

a) What scenario has Japan designed or could design for the future energy transition in the top emission sectors to achieve the carbon neutral goal?
b) What are the impacts on both the energy system and carbon emissions that will be made under these scenarios?

To achieve these objectives, the study designed several energy transition scenarios for the electricity and transportation sectors in Japan based on current policies and determinations. It then analyzed the impact of these scenarios on both the energy system and the natural environment. The ultimate goal was to draw policy implications and provide references based on the research findings. Throughout the dissertation, a comprehensive literature review was conducted to understand the historical evolution of energy transition and sustainable development. The review also explored the sectoral energy transition process, specifically focusing on the Carbon-Water-Energy nexus within the electricity sector and the energy transition within the transportation sector to establish the research gaps and highlight the originality of this study. The research employed appropriate materials and methodologies to achieve its objectives. The theoretical framework, data sources, and methodologies used in the study were described in detail. The hybrid LCA model with sector disaggregation based on environmentally-extended input-output analysis (EEIOA) approach and Kaya Identity was employed for the analysis of the electricity sector, while the system dynamics approach with comprehensive scenario design was utilized for the transportation sector analysis.

The results and analysis presented in Chapter 4 highlighted the electricity mix in the base year (2015) and under the NDC scenarios (2030). In the base year of 2015, Japan experienced a significant decline in nuclear power utilization following the Great East Japan Earthquake, leading to a substantial increase in dependence on fossil fuels. However, under the NDC scenario projected for 2030, there is an optimistic expectation of a drop in total electricity generation to 937.8 TWh. Fossil fuels are projected to account for 41.5% of the electricity mix, with nuclear power experiencing the greatest increase to 200 TWh. Solar and wind power are expected to become major sources, growing by 200% and 800%, respectively. These findings highlight the determination of transition towards renewable energy sources in Japan's electricity sector.

Furthermore, the study calculated the life cycle carbon emissions and water consumption associated with different electricity generation technologies. The analysis of life cycle carbon emissions in the electric sector reveals that in 2015, fossil fuel-based energy accounted for over 98% of total carbon emissions, with bio energy being the largest non-fossil emitter. The absence of nuclear power led to a re-emergence of fossil power plants, resulting in greater emissions. However, under the NDC scenario, life cycle emissions are projected to decline by approximately 50% to 313 Mt by 2030. This reduction is primarily attributed to a significant decrease in coal power emissions. The emissions from bio and nuclear energy sources are expected to double, while renewables are projected to nearly triple. These findings emphasize the importance of the energy mix transition in achieving emission reductions and working towards Japan's carbon neutral goal. However, the total life cycle water consumption is anticipated to increase by about 36% to nearly 7300 Mt by 2030 under the NDC scenario. Bio energy was found to be the largest water consumer, expected to increase by 87% due to the growing demand for biomass. The transition away from fossil fuels is projected to save up to 700 Mt of water.

However, the increasing share of nuclear and renewable energy sources will lead to a significant water demand for power plant construction and renewable energy generation equipment production. Solar power is expected to have the largest increase in water consumption, followed by geo power, while wind power has the lowest water consumption intensity. Furthermore, the analysis of carbon and water footprints revealed the impact of Japan's reliance on imported fossil fuels. The foreign carbon footprint share is expected to increase for most fossil fuels, with wind power reaching 77%. Bio and solar power will also have significant foreign carbon footprints. In terms of water footprints, natural gas will have the lowest foreign water footprint due to less demand during the extraction process compared to coal and oil. Solar power is projected to have the most substantial reduction in foreign water footprint, primarily due to increased water demand during operation and maintenance.

The chapter also identified the driving factors influencing CO_2 emissions and water consumption. It is projected that by 2030, there will be a total reduction of 311 Mt in emissions while water consumption is expected to increase by 1684 Mt. The population decline has a slight positive impact on emission mitigation and water saving, while economic development contributes to the growth of both environmental factors. The most significant driver of emissions reduction is the electricity intensity effect, indicating that technological advancements and changes in the industry structure play a crucial role in the energy transition process. The shift away from fossil fuels also contributes to carbon emission mitigation but intensifies water consumption, as observed in the higher water consumption intensity of some non-fossil energy sources. At last, a discussion of their implications for policymakers and stakeholders was proposed. The Japanese government has set ambitious targets for transitioning the electricity sector towards a more sustainable and low-carbon future. However, achieving these targets will require significant policy changes and strategic actions. Based on the analysis conducted in this chapter, several key policy implications were recommended to policymakers to facilitate the shift towards a greener electricity mix and meet emission reduction goals by 2030.

The results and analysis presented in Chapter 5 highlighted the energy consumption of different energy sources and related emissions under various scenarios. The energy consumption in Japan's transportation sector is projected to decline in all examined scenarios. The consumption of gasoline in the transportation sector shows a slight decrease in the BAU scenario. However, under the FES, the reduction in gasoline consumption is more significant. In the LES sub-scenario, gasoline consumption surpasses that of the FES scenario, while the more aggressive APS sub-scenario witnesses a substantial reduction in gasoline consumption. Under the Combined scenario, gasoline consumption is projected to decrease to 19.7 billion liters by 2050, representing a substantial decrease of 57% compared to BAU and over 60% compared to the baseline year. Diesel consumption exhibits similar trends to gasoline consumption across different scenarios. Under the BAU scenario, diesel consumption is projected to decrease from 23.3 billion tons in the baseline year to 19.7 billion tons by 2050, representing a reduction of 15%. Under the FES, the reduction in diesel consumption remains higher than that of the LES. In the LES sub-scenario, diesel consumption is projected to be approximately 16.3 billion tons by 2050, while under the APS, it is estimated to be only 11.2 billion tons. The idealized Combined scenario leads to a substantial reduction in diesel consumption, estimated to be 8.46 billion tons by 2050, representing a reduction of 57%. The adoption of EV in the transportation sector is expected to increase electricity demand. Under the LES, the overall electricity consumption by the transportation sector is projected to reach 12.2 TWh by 2050. Under the more aggressive APS, the electricity demand in the transportation sector reaches 38 TWh by 2050. However, even under the APS, the growth in electricity demand caused by the transportation sector in 2030 accounts for only 1.5% of the total electricity demand and reaches a modest 3% by 2050. Hydrogen energy consumption in the transportation sector is also considered. Under the LES, the adoption of FCV remains relatively conservative, with projected hydrogen energy consumption of 52,500 tons by 2050. Under the APS, the consumption is significantly increased, reaching 259,500 tons by 2050. The Combined Scenario shows slightly lower consumption, projected to be 207,600 metric tons by 2050.

Besides, the transportation sector in Japan contributes to significant emissions and four types of pollutants, including CO_2, carbon monoxide (CO), methane (CH_4), and nitrous oxide (N_2O) were analyzed. These emissions have detrimental effects on climate change, air quality, and human health. The research examined various scenarios to assess the impact of different policy approaches on pollutant emissions. Under the BAU scenario, where no significant policy interventions occur, CO_2 emissions are projected to remain high. However, under ERS) and FES, emissions are expected to decrease by 20% compared to BAU by 2050. The adoption of EPS shows varying results, with the more conservative LES scenario leading to a 16% reduction in emissions, while the more proactive APS scenario achieves a significant 45% reduction by 2050. When multiple policies are combined in the comprehensive Combined scenario, a notable decrease of 67% in CO_2 emissions is projected by 2050, highlighting the potential for significant emission reductions in Japan's transportation sector. The APS scenario, driven by the promotion of electric vehicles, demonstrates the most substantial reductions. However, even in more conservative scenarios like LES, noteworthy emission reductions can still be achieved. Additionally, the enforcement of emission standard (ERS) and initiatives focusing on fuel efficiency (FES) also show significant emission reduction benefits. Similar trends are observed for the emissions of other pollutants such as CO, CH_4, and N_2O. The implementation of different policies leads to reductions in these emissions, with the Combined scenario showcasing the most substantial decreases. By 2050, under the Combined scenario, CO emissions are expected to decrease by 66%, CH_4 emissions by 66.7%, and N_2O emissions by 65.4% compared to BAU.

In conclusion, this research comprehensively analyzed the impact of energy transition in Japan's top 2 emission sectors and obtained meaningful results that emphasize the importance of transitioning towards renewable energy sources in Japan's electricity sector while focusing on the water management simultaneously to achieve emission reductions and work towards the carbon neutral goal and highlights the potential for significant emission reductions in Japan's transportation sector through the implementation of various policy interventions. The adoption of electric vehicles, stricter emission standards, advancements in fuel efficiency, and a comprehensive approach combining multiple policies all contribute to the reduction of CO_2 and other pollutant emissions. These findings emphasize the importance of targeted policies and technological advancements in achieving sustainable and environmentally friendly society and can be used as solid references for policymakers.

6.2 Discussion

6.2.1 Energy Transition in the Electricity Sector

The results of this research showed that the shift away from fossil energy can greatly reduce total carbon emissions while leading to a considerable growth in total water consumption since the electricity mix effect mitigates emissions but also intensifies water consumption. The electricity intensity effect has the most significant impact on cutting carbon emissions and water consumption in the electric sector, which is one of the results of the ambition for continuous energy saving in the Sixth Strategic Energy Plan. Other research has also confirmed that improved energy intensity can contribute to considerable carbon emission reduction (Tavakoli, 2018; M. Zhang et al., 2009) and "In Japan, the energy efficiency of the energy conversion is assumed to be improved relatively well" (Kawase et al., 2006). The development of technologies and continuous efforts in energy saving can provide a substantial contribution to sustainable development. With most focus having been placed on carbon emissions; the water consumption of the whole energy system can also no longer be neglected. This research calculated a water demand increase of 36% in the electricity sector and the total water consumption intensity. Japan imports from various countries in the Middle East, including Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, Iran, Iraq, and Oman, with their combined total accounting for approximately 88% of the overall imports. In particular, the highest proportion of imports comes from Saudi Arabia and the United Arab Emirates, representing shares of 38.2% and 25.4%, respectively. In contrast, the United States had a Middle East dependency rate of 19.0% in 2018, and the European OECD countries had a rate of 21.6%. Therefore, Japan's dependency on the Middle East is relatively high compared to other countries (Ministry of the Environment, Government of Japan, 2023). Although Japan is an island country with rich water resources, the water footprint of its international resources trade does intensify the unequal distribution of water resources, especially given that some of the oil-rich Middle Eastern countries are also among the world's most water-scarce countries which have excessively high water stress (Procházka et al., 2018).

Besides, biomass power also requires a great deal of firewood and wood waste from construction which largely depend on imports. According to the Ministry of Agriculture, Forestry and Fisheries (MAFF), the import rate of wood pellets increased drastically from 42.3% in 2012 to 91.6% in 2019 and the top two importing countries are Vietnam and Canada that together constitute over 83% of total imports. The massive water demand during the growth of wood has also resulted in the emerging water crisis among these wood export countries to some extent. Forests do not require watering, however, the growth of wood would consume a massive water through evapotranspiration which is a major green water flux (used by vegetation), while river discharge and groundwater are typical blue water fluxes (used by human). Tree growth can consume more water than other shorter vegetation (Schwärzel et al., 2020; Xiao et al., 2019). According to the mass balance principle, if more water is used by trees (such as demand of biomass in this research), less water will flow into rivers and lakes or recharge the groundwater so that people can directly use water. Although the impacts of the low-carbon transition of the electric sector on water consumption is not as significant on the whole economy as it is for carbon emissions, with the share of electricity in the energy system continuing to increase and renewable energy technologies being promoted, the potential for elevating water consumption in the future cannot be ignored.

Furthermore, after the Fukushima nuclear disaster, the public trust and acceptance of nuclear energy also exacerbated the difficulty in restarting nuclear power plants. On August 11, 2015, the Sendai nuclear power plant in Kyushu resumed after the Atomic Energy Commission's compliance review, which was the first nuclear power plant to be restarted, ending Japan's nearly two-year "zero nuclear power" period. As anti-nuclear voices and forces grow stronger in Japan, nuclear restarts will also face additional legal risks. Due to different meteorological conditions and topography, the cost of renewable energy in Japan is much higher than the world average and the uncertainty of renewable power makes it hard to totally replace the traditional power generation technologies. However, research has illustrated the potential of renewable energies in Japan and 100% renewables could be possible (Asuka & Jin, 2022; Sakaguchi & Tabata, 2015). The uncertainty of renewable energy may be greatly alleviated by the development of electricity storage technology, whose levelized cost has decreased and makes it possible to proliferates from 2030 (Ralon et al., 2017; Schmidt et al., 2019). Moreover, other forms such as pumped-storage power station can also act as an adjuster to make full use of the power (Kong et al., 2017; J. Li et al., 2019). Besides, Japan has planned a 1% share of Hydrogen and Ammonia in the NDC electricity mix. Even though there are still limitations on Ammonia as a Hydrogen carrier for transportation and storage such as evaporation and loss of energy content (Chatterjee et al., 2021), researchers are still working on the optimization of this technology to prepare it for the market (Kojima, 2015; Salmon et al., 2021). As one of the most active countries to promote hydrogen-powered vehicles, Japan is exploring the possibility of renewable energy sources in multi-energy systems. Nonetheless, if the Japanese government becomes overdependent on nuclear power, the possible return of fossil energy will be ever-present if nuclear power and renewable energy cannot meet the expected capacity in the near future, which could make it counterproductive.

Existing studies have suggested that the actions from 2020 to 2030 are somewhat inadequate for achieving long-term temperature control goals. More aggressive emissions reduction actions and ambitions are significantly important to successfully achieve the Paris Agreement goal (Rogelj et al., 2016; Schleussner et al., 2016). Energy transition is surely an indispensable and important measure to face the challenge of climate change, however, current efforts in dealing with climate change do not show a satisfactory result and an optimistic future. Therefore, the low-carbon transition of the electric sector including the promotion of renewable energy in the future still has a large scope for development, which will also pose greater challenges to the future global water demand in energy systems and regional water stress.

6.2.2 Energy Transition in the Transportation Sector

Japan has been slow to transition its transportation sector to more sustainable energy sources compared to other developed nations. The shift to EVs in particular has been sluggish due to several factors. One of the primary obstacles to EV adoption in Japan is the inadequate charging infrastructure (Funke, Sprei, et al., 2019). To facilitate widespread EV use, an extensive network of charging stations is necessary to ensure convenient and accessible charging options for EV owners. However, the development of charging infrastructure has been relatively slow in Japan compared to other countries and in Japan, a significant portion of the population resides in rental housing for extended periods., which means the access to private charging stand is almost impossible. Insufficient charging stations can lead to "range anxiety" among potential EV buyers and deter them from transitioning to electric vehicles. Besides, as the world leading country in hydrogen FCV, under the influence of government policies, industries, and markets, consumer preferences for hydrogen fuel cell vehicles in Japan (U. Khan et al., 2020). Government incentive measures, such as free public parking and free public transportation, have had a significant impact on the preference for hydrogen fuel cell vehicles. In terms of social demographics, education and apartment parking have exerted a notable influence on the adoption of hydrogen fuel cell vehicles. However, there are still four major obstacles on the road to promoting FCVs: supply-side, infrastructure readiness, demand-side, and institutional design. To accelerate the development and adoption of FCVs in Japan, the government and industry need to continue increasing investments and implementing more attractive measures, especially in infrastructure development. (Trencher et al., 2020)

Based on the findings of the scenario analysis, a comprehensive enhancement of fuel economy in ICV vehicles and the introduction of more stringent automotive emission standards can significantly contribute to the reduction of pollutant emissions in Japan's transportation sector. These measures hold the potential to achieve even greater emission reductions compared to the conservative scenario of widespread electric vehicle (EV) adoption. The unique national circumstances and industrial chain structure in Japan have presented certain barriers to the mass adoption and promotion of EVs. Despite the ban on pure ICVs sales by 2035, it is anticipated that HEVs will continue to dominate the market. This scenario underscores the need for substantial investments in technology to improve the thermal efficiency of internal combustion engines in HEVs. By maximizing the energy conversion efficiency of ICVs, the overall carbon intensity and pollutant emissions can be effectively reduced. Moreover, the Combined scenario, which encompasses a holistic approach to policymaking, demonstrates promising results in terms of energy consumption and pollutant emissions reduction. This comprehensive approach entails integrating various policy measures across multiple dimensions, such as vehicle technology advancements, fuel quality improvements, infrastructure development, and transportation demand management. The Combined scenario recognizes that a singular focus on EV adoption may not be sufficient to address the challenges posed by the existing stock of traditional ICVs and the limited feasibility of short-term electrification for heavy-duty vehicles. Considering the significant proportion of traditional ICVs still in circulation globally, it is essential to recognize the complexity of the transportation sector and the various factors that influence its energy transition. While promoting the sales of new EVs is an undeniable trend, it is crucial to acknowledge the diverse range of vehicles and the specific needs they serve, particularly in the case of heavy-duty vehicles such as large buses and trucks. Achieving their complete electrification within a short timeframe presents considerable challenges, including battery capacity limitations, charging infrastructure requirements, and operational considerations. Therefore, in future policy scenarios, the development and application of comprehensive, multi-faceted, and multi-level policies are pivotal in driving the energy transition in the transportation sector. This entails a synergistic approach that combines advancements in vehicle technology, the optimization of internal combustion engine efficiency, the adoption of alternative fuels, the deployment of appropriate charging infrastructure, and the implementation of demand-side management strategies. By considering the entire spectrum of stakeholders, including vehicle manufacturers, energy providers, policymakers, and consumers, a well-coordinated and integrated policy framework can effectively accelerate the transformation of the transportation sector toward a more sustainable and low-emission future.

6.2.3 Sector Coupling

As climate change becomes increasingly severe, the importance of low-carbon transition is becoming more prominent. According to the International Energy Agency (IEA, 2023), the power sector and the transportation industry are the top two carbon-emitting sectors globally, accounting for 42% and 25% of carbon emissions, respectively, and are the main contributors to global climate change. In the case of Japan, the carbon emissions from the transportation sector surpassed those from the industrial sector last year and became the second-largest emitter after the power sector. In 2019, carbon emissions from the transportation sector accounted for approximately 18.6% of Japan's total carbon emissions, with road transportation alone contributing to over 86% of the country's transportation-related carbon emissions. Even though EVs themselves do not have direct emissions, the additional electricity demand they require still carries a significant carbon footprint. However, Japan's current power generation structure is still heavily reliant on thermal power generation. According to data from The Electric Power Council for a Low Carbon Society (ELCS, 2020) in Japan, the average emission coefficient of the electricity sector in 2019 was 0.444 kg-CO_2/kWh. Assuming an average energy consumption of 15 kWh/100 km for private passenger EVs, the actual carbon footprint reaches 6.66 kg-CO_2/100 km. In comparison, according to data from the National Institute for Land and Infrastructure Management (NILIM, 2014) in Japan, under the current fuel efficiency and emission standards, the average emission coefficient for private passenger ICE vehicles is approximately 10~12 kg-CO_2/100 km, while HEVs require only 8~10 kg-CO_2/100 km. Considering the lifecycle carbon emissions, it can be seen that if the power sector cannot reduce its reliance on fossil fuels and increase the share of renewable energy generation, the substantial emission reduction effect that EVs can bring may not be significant. Therefore, the energy transformation of the power sector is indispensable to achieve substantial emission reductions through the widespread adoption of new energy vehicles. The coupling of these two major carbon-emitting sectors, known as sector coupling, becomes particularly important.

The biggest challenges in the current widespread adoption of EVs are still "limited range" and "long charging time". Firstly, the range of EVs still lags behind that of traditional ICE vehicles, which remains a major concern for many consumers and a significant barrier to purchasing EVs. Especially in winter, the energy storage and conversion efficiency of batteries are significantly reduced in low-temperature environments and the driving range will significantly decline (Armenta-Déu & Giorgi, 2023). Additionally, the long charging time of EVs is also a point of criticism. Data shows that in China, in 2021, the average theoretical charging rate of popular models with fast charging support was approximately 1C, which means it takes around 30 minutes to charge the battery from 30% to 80% capacity, providing a range of about 219 km (according to the NEDC standard). However, in practice, most pure electric vehicles require 40-50 minutes to achieve the same battery capacity and have a driving range of approximately 150-200 km. If we consider the time spent entering and exiting charging stations (around 10 minutes), an hour of charging time for a pure electric vehicle can only provide a little over an hour of highway driving.

In fact, EVs serve as a catalyst for driving the energy transition in both the power and transportation sectors. It is well-known that a major challenge of renewable energy generation is its low stability and susceptibility to weather conditions. Additionally, the widespread development of renewable energy generation to maintain grid balance necessitates large-scale energy storage systems. However, the current technology for such storage systems is associated with high land requirements and economic costs. The core component of electric vehicles is the battery, and the current methods of energy replenishment primarily involve charging and battery swapping. As long as unified standards can be established to enable the electric vehicle batteries to connect to the grid and undergo dynamic adjustments from smart grids during energy replenishment, they can function as mobile energy storage devices. This is known as Vehicle-to-Grid (V2G) technology which serves as a means to utilize new energy vehicles as energy storage devices, allowing their battery energy to be fed back into the power grid. This process provides support for grid dispatch and energy management, achieving sector coupling between the power and transportation sectors. By doing so, it improves the stability of renewable energy generation and mitigates the challenges of slow EV charging and limited range (Dik et al., 2022).

V2G, as one of the crucial means to couple the power and transportation sectors, can simultaneously address multiple pain points in the energy transition of these two sectors. This necessitates multi-party cooperation among the government, technology sector, and industry to facilitate this process. Firstly, from a government policy perspective, the establishment of unified V2G technology standards and regulations is crucial to ensure consistency and interoperability across regions and manufacturers. This involves creating a bidirectional energy flow channel, enabled by V2G technology, allowing EV batteries to feed stored energy back into the grid. It requires the installation of bidirectional charging and discharging equipment in EVs, charging facilities, and battery swapping stations, enabling seamless energy transfer between the grid and vehicles. Moreover, expediting the development of charging and swapping infrastructure, along with implementing incentives and economic mechanisms, will facilitate the convenience and attractiveness of V2G operations for EV owners and charging station operators, thereby encouraging their active participation in the energy feedback process. On the technological front, increased research and development investment in battery technology is essential. This investment should focus on enhancing battery energy density, extending the range of EVs, and reducing battery costs. Simultaneously, advancements in grid technology are required to support the high-voltage and large-current demands of fast-charging EVs, while also meeting the more complex requirements imposed by V2G technology for intelligent grid management and dispatch. These technological advancements will be key in improving the performance and efficiency of V2G systems. Furthermore, industrial development plays a pivotal role in driving the V2G transition. New energy vehicle manufacturers should be encouraged to invest in the research, development, and production of V2G technology, leading to the introduction of EV models equipped with V2G capabilities and expanding the market size. Collaboration and coordination across the entire industry chain, including automobile companies, charging equipment manufacturers, and grid operators, are crucial to drive the commercialization of V2G technology. Establishing promotion and demonstration projects for V2G technology will provide empirical data and experiences, accelerating market acceptance and wider adoption.

By integrating these approaches, governments can create an enabling environment for V2G technology deployment. This will not only address concerns related to EVs, such as limited driving range and long charging times but also enhance the stability of renewable energy generation by utilizing EVs as mobile energy storage devices. Ultimately, the integration of EVs into the grid through V2G technology holds significant potential in realizing the full benefits of the energy transition and achieving a sustainable and decarbonized society.

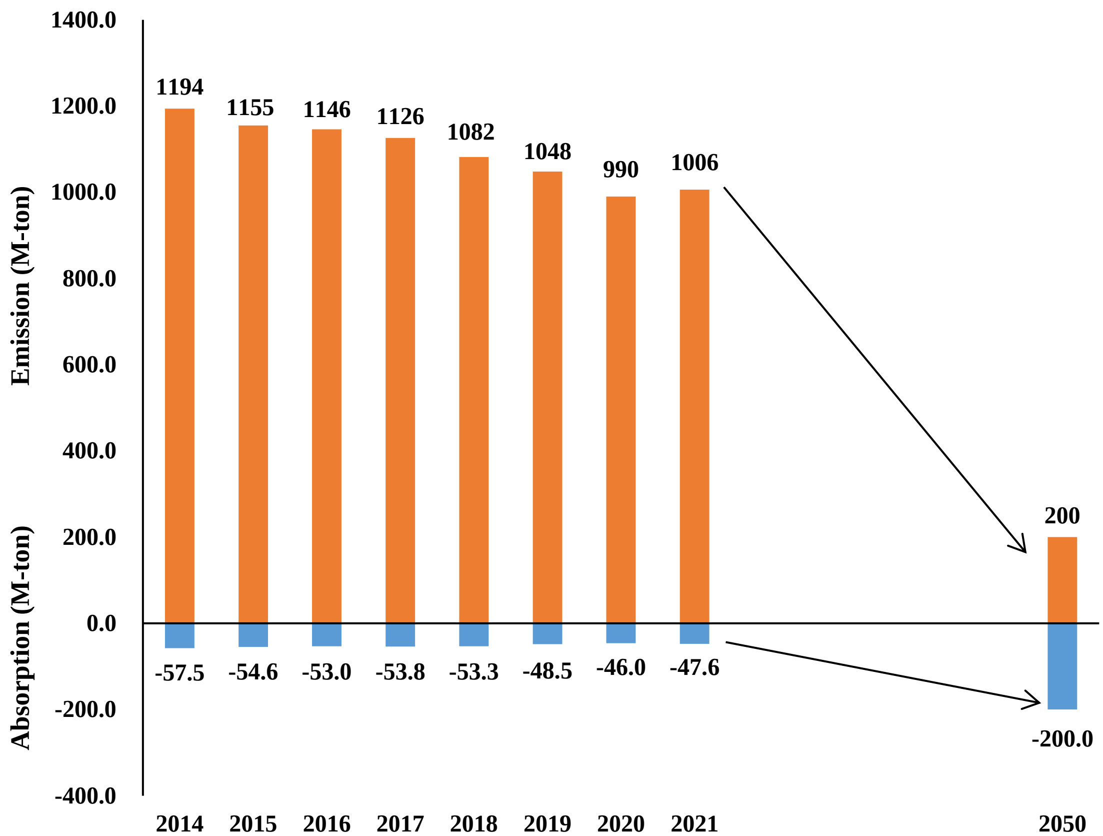
6.2.4 Carbon Neutral Scenario

Japan has made the commitment to achieve carbon neutral by 2050 which suggests the total carbon emission can be offset by the carbon absorption. We can make the analysis from both the absorption side and the emission side. From the emission side, Japan's total emission will be reduced by 46% compared with that of 2013, which is expected to be around 800 million tons under the NDC scenario. Furthermore, with continuous efforts in energy saving and energy transition, the government has projected a 80% GHGs reduction by 2050 (Ministry of the Environment, Government of Japan, 2023), which suggests the total emission to be reduced to a level of 200 million tons. To achieve this goal, decarbonized power generation systems are crucial for the electricity sector. By 2050, renewable energy will serve as the main source of electricity generation. To ensure the stability of power supply, the share of renewable energy in total power generation is projected to reach 60% to 80%, depending on the development of energy storage technologies. With the support of Carbon Capture, Usage, and Storage (CCUS) and Carbon Recycling technologies, the carbon emission intensity of fossil fuel power generation will significantly decrease. Nuclear power generation, continuously improving its safety measures and gaining further public support and acceptance, is expected to account for 10% to 30% of total electricity generation together with fossil fuel power, primarily serving as a means to balance the fluctuation of renewable energy generation in the grid. The further development of hydrogen energy and ammonia energy as complementary green energy sources is expected to represent approximately 10% of total power generation. As a result, the overall carbon emissions from the electricity sector will be reduced to around 100 million tons. For the transportation sector, according to data from the IEA, Transport emissions grew at an annual average rate of nearly 1.7% from 1990 to 2021, faster than any other end-use sector. To get on track with the Net Zero Emissions by 2050 Scenario, CO_2 emissions from the sector must fall by about 3% per year to 2030 (IEA, 2022), which all suggest that currently the global energy transition in the transportation sector is not on track. Our simulation results showed that total CO_2 emission of Japan's transportation sector is expected to be reduced by 67% to 52 million tons under the Combined scenario by 2050. However, in order to achieve the target of an 80% reduction in carbon emissions by 2050 and achieve carbon neutrality, the Japanese government needs to implement stricter emission standards and strongly promote further adoption of EV and PHEV. Despite having better fuel efficiency compared to traditional internal combustion vehicles, HEVs still generate significant emissions of direct carbon dioxide and other greenhouse gases and harmful pollutants. Therefore, increasing the promotion of EVs and PHEVs becomes an indispensable means to achieve the carbon neutrality goal. Referring to the model results in Chapter 5, we estimate that to achieve the carbon neutrality target by 2050, Japan's transportation sector should reduce its overall carbon emissions to around 30 million tons. This requires an EV market share of over 60% in the passenger vehicle segment, and EVs and FCVs accounting for 40% to 50% of large freight vehicles and buses.

From the absorption side, according to data by the Ministry of the Environment, in 2021, Japan's absorption capacity of CO_2 reached 47.6 million tons, marking an increase for the first time in four years. However, compared to the 57.5 million tons in 2014, the absorption capacity has still decreased by 17%. Besides, Japan has over 1000 million tons of CO_2 emission in 2021 and in comparison, an absorption level of around 50 million tons appears insignificant. This has raised significant doubts about Japan's ability to achieve its carbon neutral goals. Due to limitations in the total amount of land and utilization methods, it is difficult to significantly increase the absorption capacity of forests. Therefore, it is crucial to vigorously develop Carbon Capture, Usage, and Storage (CCUS) and Direct Air Capture (DAC) as alternatives. Under the carbon neutral scenario, Japan still have a carbon absorption deficit of approximately 150 million tons by 2050. With a 20% share of fossil power generation and 100% coverage of CCUS technology, the direct carbon emissions absorption in the power sector can reach approximately 100 million tons, accounting for around 50% of the total absorption. Beside, BECCS is an approach that could be used to achieve net negative emission. For biomass power, when growing, the biomass will capture CO_2 from the atmosphere. If the released CO_2 is captured when the biomass is burned, there will be a net negative emission. The rest 50 million tons absorption capacity will be covered by DAC. The good thing with DAC is that we don't have to link the capture process to the emission source, which means that we for example can place the capture units where you have the storage opportunities. However, a challenge with DAC is that it is much more costly to capture CO_2 from the atmosphere.

In summary, we project that by 2050, in a carbon neutrality scenario, Japan's total carbon emissions will need to be reduced to 200-250 million tons. Approximately 20% of emissions will be absorbed by forests, land, and other natural processes, while around 50% will be captured through CCUS technology during power generation. Another 30% will be directly absorbed from the atmosphere using DAC technology. The absorbed CO_2 will primarily be stored underground, in the oceans, or transported for overseas storage. Additionally, a portion of the CO_2 will be utilized in the production of hydrogen, ammonia, and other materials.

Figure. 6- 1 Changes in CO_2 Balance in Japan



Source: Ministry of the Environment, MLIT Japan

https://www.env.go.jp/content/000129138.pdf

6.2.5 Policy Implications

This study provides a comprehensive analysis of the energy demand and environmental impact of two major carbon-emitting sectors in Japan, namely the electricity sector and the transportation sector, under future energy transition scenarios, which can offer valuable insights to policymakers in planning carbon neutral pathways.

Regarding the electricity sector, to achieve the goal of carbon neutral by 2050, it is imperative to prioritize renewable energy as the primary source of electricity generation. The analysis results of this study indicate that phasing out fossil fuels can significantly reduce the lifecycle carbon emissions of the power sector. However, it would lead to a substantial increase in lifecycle water consumption, particularly for biomass and nuclear power generation. Concerning biomass power generation, Japan currently relies heavily on general wood materials, which result in significant water consumption during the growth process. Vietnam and Canada, as Japan's major sources of wood imports, have been experiencing increasing water scarcity in recent years. Therefore, in terms of global water resource planning and utilization, Japan should consider enhancing its domestic self-sufficiency in wood biomass production and increasing the utilization of alternative liquid biofuels such as methane. As for nuclear power, it accounted for a significant proportion, reaching 28.6%, before the 2011 Great East Japan Earthquake. However, following the disaster, several nuclear power plants were shut down. With the recent restart of some nuclear power plants, the Japanese government has planned for 20% of nuclear power generation in the latest NDC scenario. Nevertheless, considering the continuous decline in the cost of renewable energy in recent years, the higher investment and water consumption associated with nuclear power no longer provide significant advantages. Furthermore, public concerns about its safety have increased. Therefore, we recommend that the Japanese government consider nuclear power as a backup stabilizing energy source in the long term to support renewable energy generation. Similarly, due to the instability of renewable energy generation and the high cost of energy storage technologies, we anticipate that even in a carbon-neutral scenario, fossil fuel generation will still account for approximately 10%-20% of Japan's power structure. Hence, it is crucial to further research and develop CCUS technologies and reduce their costs so that the fossil fuel electricity generation can achieve carbon neutral by itself.

Regarding the transportation sector, Japan has been slow in the energy transition of the transportation sector, and the market share of EVs in new car sales is much lower compared to other developed countries. As mentioned earlier, achieving Japan's proposed goal of carbon neutral by 2050 would require an essential energy transition in the transportation sector, which currently ranks second in terms of carbon emissions. The Japanese government must implement more ambitious policies to promote the sales and widespread adoption of EVs. The results obtained from this study can provide important reference points for the Japanese government in formulating future targets for the widespread adoption of EVs and emission standards for pollutants. Additionally, this study has identified the emission reduction potential under independent policies such as improving fuel efficiency and implementing stricter emission standards, as well as the potential under various combined policy scenarios. The synergistic effect of multiple policies can achieve more effective results than a single policy, which further underscores the necessity of implementing a combination of policies in the transportation sector. Building upon these findings, it is recommended to develop more comprehensive policy standards and implementation plans, which will contribute to the planning and implementation of the 2050 carbon neutrality pathway.

6.3 Limitation

Due to data limitation, we cannot construct a multi-region Input–Output (MRIO) model to assess the flow with other countries and thus the export part is included in the domestic sector, and it was not within the remit of this research to assess domestic exports. Besides, the formulation and implementation of policies are closely related to government fiscal budgets and the socio-economic environment. This article, however, only analyzes the environmental aspects of the corresponding policies and does not delve into the detailed accounting of the financial budgets required for these policies. It is hoped that future research can enhance the content in this aspect.

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Appendix

Table S 1. Coefficient of sectoral disaggregation in the upstream (%).

Sources	Fuel-related_A	Fuel-related_B	Capital-related	Other
Coal	0	32.5	24.2	22.2
Oil	0	15.2	7.6	4.2
Gas	0	49.2	22.8	14.3
Bio	100	0.0	2.7	11.2
Nuclear	0	3.1	14.1	20.8
Hydro	0	0.0	24.8	21.2
Geo	0	0.0	1.1	1.4
Solar	0	0.0	1.9	3.9
Wind	0	0.0	0.8	0.8

Table S 2. Disaggregated 46-sector classification.

Code	Industry Name	Property	日本語分類名
01	Agriculture, forestry and fishery	Fuel-Related_A	農林漁業
02	Mining	Fuel-Related_B	鉱業
03	Beverages and Foods	Other	飲食料品
04	Textile products	Other	繊維製品
05	Pulp, paper and wooden products	Fuel-Related_A	パルプ・紙・木製品
06	Chemical products	Other	化学製品
07	Petroleum and coal products	Fuel-Related_B	石油・石炭製品
08	Plastic products and rubber products	Other	プラスチック・ゴム製品
09	Ceramic, stone and clay products	Other	窯業・土石製品
10	Iron and steel	Other	鉄鋼
11	Non-ferrous metals	Other	非鉄金属
12	Metal products	Other	金属製品
13	General-purpose machinery	Capital-Related	はん用機械
14	Production machinery	Capital-Related	生産用機械
15	Business oriented machinery	Capital-Related	業務用機械

16	Electronic components	Capital-Related	電子部品
17	Electrical machinery	Capital-Related	電気機械
18	Information and communication electronics equipment	Other	情報通信機器
19	Transportation equipment	Capital-Related	輸送機械
20	Miscellaneous manufacturing products	Other	その他の製造工業製品
21	Construction	Capital-Related	建設
22	Gas, heat	Other	ガス・熱供給
23	Water supply	Capital-Related	水道
24	Waste management service	Capital-Related	廃棄物処理
25	Commerce	Other	商業
26	Finance and insurance	Other	金融・保険
27	Real estate	Other	不動産
28	Transport and postal services	Other	運輸・郵便
29	Information and communications	Other	情報通信
30	Public administration	Other	公務
31	Education and research	Other	教育・研究
32	Medical, health care and welfare	Other	医療・福祉
33	Membership-based associations, n.e.c.	Other	他に分類されない会員制団体
34	Business services	Other	対事業所サービス
35	Personal services	Other	対個人サービス
36	Office supplies	Other	事務用品
37	Activities not elsewhere classified	Other	分類不明
38	Coal	Sub-Sector	石炭発電
39	Oil	Sub-Sector	石油発電
40	Gas	Sub-Sector	天然ガス発電
41	Bio	Sub-Sector	バイオマス発電
42	Nuclear	Sub-Sector	原子力発電
43	Hydro	Sub-Sector	水力発電
44	Geo	Sub-Sector	地熱発電
45	Solar	Sub-Sector	太陽光発電

46	Wind	Sub-Sector	風力発電

Table S 3. Direct carbon emission and water consumption intensity of Japan's electric sector used in this research.

Unit: ton/GWh

Sources	Carbon Emission Intensity	Water Consumption Intensity
Coal	896	1752
Oil	685	1472
Gas	398	913
Bio	0	1284
Nuclear	0	2148
Hydro	0	18215
Geo	0	2541
Solar	0	85
Wind	0	0.6

Table S 4. Electricity mixes of Japan in 2015 and 2030.

Unit: TWh

	Coal	Oil	Gas	Bio	Nuclear	Hydro	Geo	Solar	Wind	Total
2015	353.2	91.5	424.3	25.2	9.4	91.3	2.6	34.8	5.6	1037.7
2030	180.0	20.0	190.0	47.0	200.0	94.0	9.4	141.0	56.4	937.8
Difference	-173.2	-71.5	-234.3	21.8	190.6	2.7	6.8	106.2	50.8	-99.9
Ratio (%)	-49.0	-78.1	-55.2	86.9	2019.3	3.0	262.2	305.1	910.8	-9.6

Table S 5. Annual Passenger-KM and Ton-KM transported in Japan.

Year	Passenger-KM	Ton-KM (adjusted)
1995	840 813	173092.245
1996	855 993	178864.526
1997	870 413	179193.861
1998	883 712	174948.187
1999	888 478	176835.377
2000	889 446	180123.964
2001	895 751	179089.835
2002	898 449	176979.993
2003	897 715	182045.062
2004	893 544	184125.809
2005	881 000	188337.025
2006	867 221	193468.972
2007	868 218	199141.274
2008	856 915	192963.803
2009	852 125	186246.091
2010	834 791	181964.7
2011	827 071	193572
2012	851 238	167815
2013	848 687	173528
2014	835 428	170231
2015	839 441	166284
2016	852 789	174028
2017	866 693	175143
2018	879 806	175184
2019	871 531	178697

Table S 7. Fuel economy of different vehicle types by 2035.

			ICE			HEV		EV	FEV
			Gasoline	Diesel	LPG	Gasoline	Diesel	Electricity	Hydrogen
Commercial	Freight	Nromal	-	0.0663	-	-	0.05525	0.18	0.225
		Compact	0.4675	0.425	-	0.408	0.357	0.54	-
		Light	1.5725	-	-	1.275	-	0.72	-
	Passenger	**Bus**	-	0.01955	-	-	0.017	0.0405	0.045
		Taxi	0.136	-	0.238	0.119	-	0.09	0.108
Private	Freight	Nromal	0.1122	0.1683	-	0.0935	0.1275	0.9	1.125
		Compact	1.156	1.275	-	0.9775	1.02	1.8	-
		Light	2.635	-	-	2.3885	-	2.25	-
	Passenger	**Normal**	0.045	0.04875	-	0.034	-	0.09	0.108
		Light	0.036	-	-	0.0357	-	0.072	-

Table S 6. Fuel economy of different vehicle types by 2050.

			ICE			HEV		EV	FEV
			Gasoline	Diesel	LPG	Gasoline	Diesel	Electricity	Hydrogen
Commercial	Freight	Nromal	-	0.0585	-	-	0.04875	0.16	0.2
		Compact	0.4125	0.375	-	0.36	0.315	0.48	-
		Light	1.3875	-	-	1.125	-	0.64	-
	Passenger	**Bus**	-	0.01725	-	-	0.015	0.036	0.04
		Taxi	0.136	-	0.238	0.105	-	0.08	0.096
Private	Freight	Nromal	0.099	0.1485	-	0.0825	0.1125	0.8	1
		Compact	1.02	1.125	-	0.8625	0.9	1.6	-
		Light	2.325	-	-	2.1075	-	2	-
	Passenger	**Normal**	0.051	0.05525	-	0.03	-	0.08	0.096
		Light	0.0408	-	-	0.0315	-	0.064	-