Chapter 6

Energy Transition in Japan from the Perspective of Economics and Technology

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This chapter should be cited as
Jupesta, J., U. Korwatanasakul, and K. Akimoto (2025), 'Energy Transition in Japan from the Perspective of Economics and Technology', in Zen, F., F. Kimura, and A.J. Purwanto (eds.), *Fiscal Policy to Support the Green and Just Energy Transition*. ERIA Research Project Report FY2024 No. 28, Jakarta: ERIA, pp.230-269.

Chapter 6

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1. Introduction

The Paris Agreement, which is the framework and target for reducing greenhouse gas (GHG) emissions after 2020, was decided at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCC) held in Paris in December 2015 and it came into effect on 4 November, 2016. Japan signed on 8 November, 2016 and joined the Contracting Parties on 8 December of that year. The Paris Agreement is epoch-making in that it has created a legally binding international framework for almost all countries to work on reducing GHG emissions, regardless of whether they are developed or developing countries. In November 2021, COP26, which was delayed by one year due to the Coronavirus disease (COVID-19) pandemic, was held in Glasgow, United Kingdom. The agreements reached there related to the market mechanisms regarding Article 6 of the Paris Agreement, efforts to limit the rise in global average temperature to 1.5°C and accelerating the reduction of coal-fired power generation which was not taken by any emission reduction measures. The Special Report on Global Warming of 1.5°C (SR15) of the International Panel on Climate Change (IPCC) also indicates that it is necessary to achieve net-zero emissions by around 2050 to maintain a global temperature rise below 1.5°C (IPCC, 2018). The world is seeking large reductions in emissions, including net-zero emissions.

Within this international setting, the Government of Japan has strengthened its climate change measures. It formulated a long-term growth strategy based on the Paris Agreement and in compliance with the resolution of COP21 that required each country to formulate and submit such a proposal. The Government has submitted its target to the UNFCCC. The long-term goals include (1) pursuing a level of carbon dioxide (CO_2) emissions that are well below 2°C, (2) pursuing a level of CO_2 emissions that are below 1.5°C, and (3) achieving virtually zero CO_2 emissions in the latter half of the twenty-first century. This corresponds to the Paris Agreement's long-term goals to hold the average increase in global temperature to well below 2°C above pre-industrial levels; limit increases to 1.5°C above pre-industrial levels, and achieve net-zero emissions in the second half of the twenty-first century.

According to the SR15 and the IPCC 5th Assessment Report, however, achieving the target of 2°C or 1.5°C will come at a significant financial cost. For example, according to the Assessment Report (IPCC 2014), even in the world's lowest-cost cases, the marginal CO2 abatement costs for the 2°C consistent scenarios (430–530 parts per million (ppm) equivalent in 2100) are about \$100–\$300/total CO_2 (tCO_2) [1] and \$1,000–\$3,000/tCO2 (25–75 percentile range) in 2050 and 2100, respectively. The SR15 also reports a marginal abatement cost of \$245–\$14,300/tCO_2 (median: about \$2,800/tCO_2) in 2050, for the target of 1.5°C. While the targets of 2°C or 1.5°C are technologically feasible, their economic and political feasibility is unclear, considering such high emission reduction costs. Gambhir et al. (2019) argue that the marginal CO_2 abatement costs for the 2°C consistent scenarios are about \$100–\$300/tCO_2 and \$1,000–\$3,000/tCO2 (25–75 percentile range) in 2050 and 2100, respectively, and those for the 1.5°C scenario are about \$220–\$430/tCO_2 and \$2,500–\$5,000/tCO_2 (25–75 percentile range) in 2050 and 2100, respectively, according to 240 scenarios by five different integrated assessment models. They indicate the median marginal cost in 2100 for the below 1.5°C scenarios are about three times higher than those for the 2°C scenarios (Akimoto et al., 2021).

The SR15 (IPCC, 2018) mentioned an interesting scenario for the 1.5°C target: the Low Energy Demand scenario. It assumes the demand for a decent living and rapid technological and social innovations and estimates the low final energy demands. Due to the estimated low energy demands, the marginal abatement cost for the 1.5°C target in 2050 is about \$150/tCO_2, significantly smaller than the categorised scenarios with a cost of about \$400/tCO_2 (IPCC, 2018). Van Vuuren et al. (2020) show that based on the meta-analyses of the results of integrated assessment models, the abatement costs increase exponentially and have larger uncertainties due to deep emission reductions. Thus, the existing empirical studies, with few exceptions, estimate high costs for deep emission reductions, including net-zero emissions.

Human activities, principally through GHG emissions, have unequivocally caused global warming, with the global surface temperature reaching 1.1°C above 1850–1900 levels during 2011–2020 (IPCC, 2022). Global GHG emissions have continued to increase, with unprecedented activity arising from unsustainable energy use, land use and land-use changes, lifestyle changes, and changes in patterns of consumption and production across regions, between and within countries, and amongst individuals (IPCC, 2023). COP28 in Dubai, United Arab Emirates, will focus on the Paris Agreement implementation, including the Global Stock Take targets on nationally determined contributions (NDC) in 2030, financing mitigation/adaptation, decarbonisation for clean energy, and carbon trading to accelerate the mitigation.

[1] In this report, \$ refers to US dollar.

The study for the Basic Guidelines on Climate Transition Finance was launched in 2021 to finance the Green Transition in Japan (Gov. of Japan: METI, 2023a). The study set out in this chapter analyses Japan's energy transition from an economic perspective, based on the latest green transformation policy. The case study on the carbon capture, utilisation, and storage (CCUS) of methanol production in Japan will also be elaborated upon.

2. Literature Review on the Just Energy Transition in Japan

The first section of the literature review outlines the carbon-neutral policy in Japan, including CCUS technology. The second section covers the fiscal aspect of the carbon-neutral policy.

2.1. Carbon-Neutral Policy in Japan

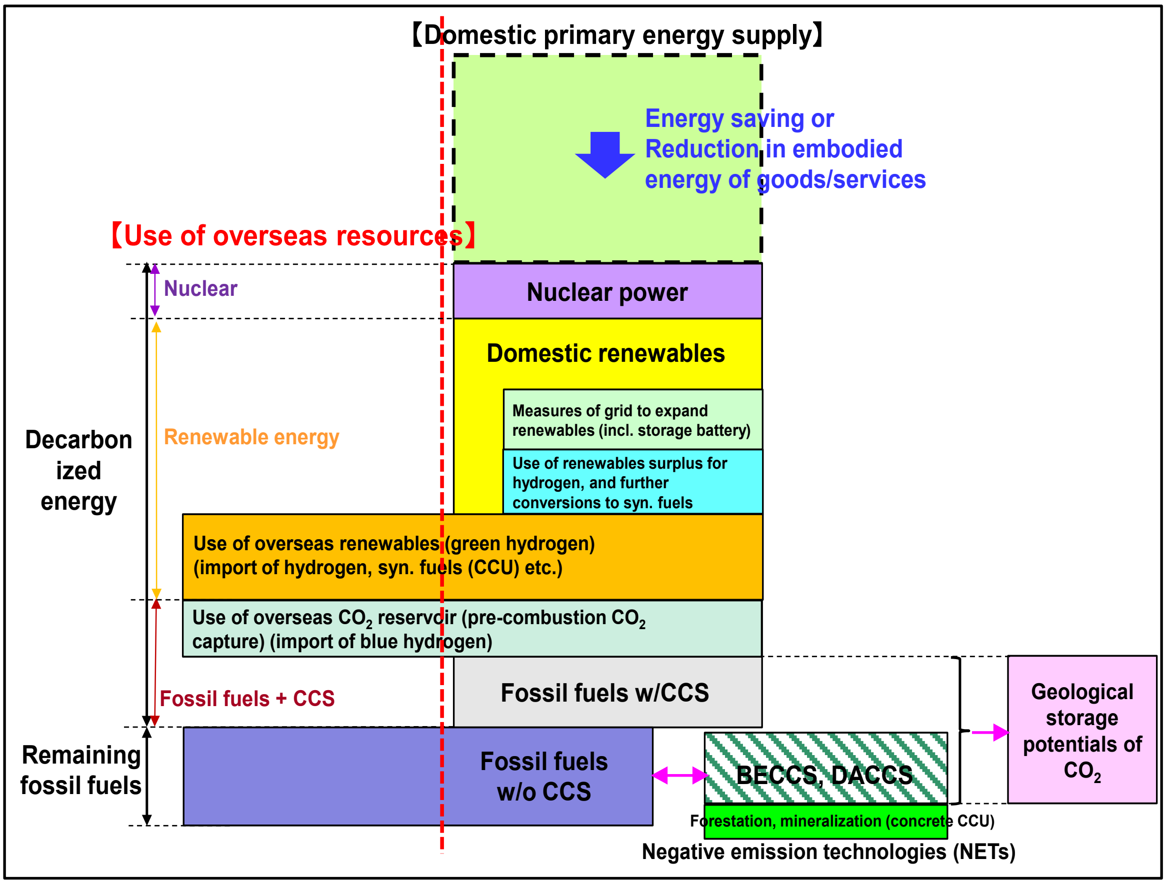
2.1.1. Green Growth Strategy

As one of the Group of Seven (G7) countries, Japan has been actively promoting decarbonisation to increase its competitiveness. Many other countries have also done this, announcing their GHG mitigation policy through carbon neutrality targets. During Yoshihide Suga's administration in 2020, Japan announced a carbon neutrality target to be reached by 2050. The Green Growth Strategy was announced in 2021 to break down the carbon neutrality target into greater detail. This was followed with a Basic Policy for Realising the Green Transformation (GX) Policy in 2022 (Gov. of Japan: METI, 2023b).

The 2021 Green Growth Strategy mentioned that carbon neutrality in 2050 would be achieved by increasing electrification in the building, industry, and transport sectors. Heat demand that cannot be electrified will rely on carbon-free fuel, hydrogen, and CO2 – carbon recycling from fossil fuels. Innovations in industrial process and technologies with negative emissions will be the next priority after electrification. The Research Institute of Innovative Technology for the Earth has been conducting scenario analysis for Japan towards carbon neutrality in 2050 (Akimoto et al., 2021). Figure 6.1 gives an overview of energy supply systems to achieve net-zero emissions, including the role of CCUS and carbon dioxide removals (CDR). The primary energy sources for carbon neutrality are renewable, nuclear, and fossil fuels, with carbon capture and storage (CCS). The CDR will be used to offset the fossil fuels without CCUS.

Since Japan is an island country, the power grid system is not connected to that of the rest of the world. Hence, pursuing other countries' hydrogen and hydrogen-based energy sources is more important. As a reference, renewable energy such as solar photovoltaic technology (solar PV), wind power, hydropower, geothermal, and biomass will contribute 50%-60% of power generation in 2050, 10% will come from hydrogen and ammonia fuel for power generation, and 30%-40% will come from nuclear power and thermal power plants with CO2 capture (Akimoto et al., 2021). It is necessary to introduce as much renewable energy as possible as a major power source and implement policy measures to drive innovation and societal implementation of all possible options: hydrogen, ammonia, and CCUS/carbon recycling, amongst others. To achieve carbon neutrality at a minimum cost, all the energy supply prices are expected to be reduced through technological innovation, cost reduction, and easing introduction restrictions.

Figure 6.1. Carbon Neutrality in Energy towards 2050 for Japan.



BECCS = bioenergy carbon capture and storage; CCS = carbon capture and storage; CCU = carbon capture and utilisation; CO_2 = carbon dioxide; DACCS = direct air carbon capture and storage; syn. = synthetic; w/o = without.
Source: Akimoto et al. (2021).

2.1.2. Green Transformation Policy

GX refers to transforming the entire economic and social system from an economy, society, and industrial structure dependent on fossil fuels to 'structures driven by clean energy' (Gov. of Japan: METI, 2023d). In 2022, the Government of Japan published the GX Policy with a detailed plan in the subsequent Basic Policy for GX Realisation (GX Basic Policy) in 2023. Its primary objective is to support a broader energy transition in Asia as both a lender and technology exporter. In short, this policy aims to drive economic growth and development by GHG mitigation. Five key initiatives are discussed to achieve ¥150 billion ($1 trillion)[2] of private and public investment for GX:

1. Growth-oriented carbon pricing (including GX Transition Bonds);
2. Integrated regulatory and assistance promotion measures;
3. New financing methods;
4. International development strategy, including the formation of the Asia Zero Emissions Community; and
5. Development of GX League (a forum for cooperation between companies, government, and academia).

GX Basic Policy outlines an ambitious plan for Japan's commitment to achieve 46% GHG emissions reduction by 2030 and carbon neutrality by 2050. It serves a dual purpose – climate change measures and economic sustainability – by ensuring the competitiveness of both industries and the nation. There are two important pillars of the GX Basic Policy: domestic renewable energy enhancement and leveraging global renewable energy, including hydrogen and fuel ammonia as energy storage. Hydrogen-based and biogenic fuels can play a role in reducing emissions. Apart from fuel usage, it is also feed stock for chemical products (e.g., methanol and ethanol). Carbon recycling (i.e., CCUS) is one of the key technologies for carbon neutrality.

2.1.3. Carbon Capture, Utilisation, and Storage

CCUS consists of two elements: CCU and CCS. CCU is the technology to utilise CO_2 to produce synthetic fuels, chemicals, cement, and agriculture products. Because CO_2 is part of fuel gas from industrial processes, capturing and recycling CO_2 is considered a circular economy. Some private actors, such as Mitsubishi Chemicals, have been on the front line of CCU. CCS can capture and store CO_2 not to be released into the atmosphere. Methods for the CO_2 capture include chemical and physical absorption and membrane separation.

In principle, Japan maximises renewable (domestic or imported) usage to reduce CO2 emissions. However, there are three key reasons for CCUS adoption:

1. Infrastructure constraints: CCUS can be easily adapted to the existing industry but adopting the new hydrogen-based renewable energy-based infrastructure, such as port or electrification infrastructure, is not simple.
2. Technology availability: The required technologies for emissions reduction vary

[2] Exchange rate in 2023: $1=¥150

depending on the industry and processes involved, and when multiple options are available, their maturity level also varies.

3. Level of funding: CCUS can be added relatively simply compared to new power generation, which requires 30–40 years of capital investment to implement renewable energy/hydrogen-based facilities.

An example of CCU is methanol production from hydrogen and CO2 conducted by Mitsubishi Chemical Group. In terms of CO2 storage, the government aims to achieve a target of 120–240 million tonnes of CO2 by 2050 by securing CO2 storage of 5 to 12 million tonnes of CO2 by 2030. The storage cost is expected to be reduced from ¥4,000/tonnes CO2 to ¥2,000/tonnes CO2 in 2030 and ¥1,000/tonnes CO2 in 2050 (MUFG, 2023). The private sector has already engaged in the CCU project and Mitsubishi Heavy Industry has a 70% share of the global market for CO2 capture facilities.

2.2. Fiscal Policy

2.2.1. The Green Innovation Fund

In 2021, the Green Growth Strategy established ¥2 trillion as the Green Innovation Fund. The New Energy and Industrial Technology Development Organisation operates the fund. To maximise the results of each project amidst intensifying competition for business leadership in the sector, the evaluation criteria for funding are:

1. potential for CO_2 reduction contribution and economic ripple effects;
2. the degree of technical difficulty and the possibility of practical application.(Policy support is based on this criterion); and
3. potential market growth and international competitiveness.

The Green Innovation Fund encourages the participation of small and medium enterprises and start-ups that support the base of the supply chain and play a role in creating new industries. This ¥2 trillion budget will encourage private investment of around ¥15 trillion in research and development (R&D) and equipment. It will also draw approximately $30.7 trillion (approximately ¥3,000 trillion) in global environmental, social, and governance (ESG) funds, and generate future income and employment for the Japanese economy.

The R&D tax expansion was also implemented due to the 2050 carbon neutrality policy. Enterprises can request tax deductions in corporate tax of up to 30% compared to 25% in the previous measure. This stimulates the desire for private companies to invest in carbon neutrality. Regarding green finance, the green bond market is expanding domestically and internationally, with annual domestic issuance exceeding ¥1 trillion in 2020. Transition finance funds GHG reduction efforts based on a long-term strategy to realise a decarbonised society. The government will promote initiatives to encourage private enterprises to actively invest in advanced equipment that contributes to low-carbon development by utilising a leasing method that is expected to encourage significant capital investment and aims to encourage investment of ¥150 billion or more.

In addition, the government will also provide risk money support to green ventures, including renewable energy businesses (e.g., offshore wind power), those that utilise low fuel consumption technology, and next-generation battery storage businesses. Government-owned banks such as the Development Bank of Japan have established the Green Investment Promotion Fund with a project scale of ¥80 billion. Japan Bank for International Cooperation also established the Post-COVID-19 Growth Facility with a project size of ¥1.5 trillion to support overseas development of quality infrastructure and other overseas business activities by Japanese companies working towards a decarbonised society.

To develop the International Financial Centre[3], the Financial Service Agency of Japan encouraged private industry to establish a certification mechanism for evaluating the eligibility of green bonds. An external organisation provides objective certification of the eligibility of green bonds. The Financial Services Agency and other independent organisations will examine the nature of ESG evaluation organisations (e.g., transparency and governance) in light of some comments that external evaluation methods for ESG are not always clear.

2.2.2. The Green Transformation Fund

The budget for the green transformation is ¥150 trillion for ten years (2023–2033) (GR, 2023) (Table 6.1). There are five targets in the energy sectors: 1) reach 38% renewable energy in power by 2030, 2) install 10 gigawatts (GW) of wind power and 118 GW of solar power by 2030, 3) increase nuclear power to 22% of by 2030, 4) lower the cost of hydrogen by ¥30 by 2030, and 5) build CCUS facilities to capture 140 million tonnes of CO_2 by 2050.

[3] Further information about this centre can be found at: https://www.fsa.go.jp/internationalfinancialcenter/

Table 6.1. Green Transformation Budget Commitment

Focus	Approx. 17 Trillion JPY (Annual)	150 Trillion JPY investment in 10 years — Examples of planned investments	Investment Cost
Decarbonisation of power supplies	5 Trillion JPY (Annual)	• Renewable energy (Implementation through FIT/FIP framework) • Hydrogen, Ammonia (Investment in infrastructure development) • Battery production (For vehicles and fixed-ground use)	2 Trillion JPY 0.3 Trillion JPY 0.6 Trillion JPY
Decarbonisation of manufacturing processes	2 Trillion JPY (Annual)	• Decarbonisation of manufacturing processes (e.g., Next-generation manufacturing process technology, carbon neutral power generation facilities) • Installation of industrial heat pumps and cogeneration facilities	1.4 Trillion JPY 0.5 Trillion JPY
End-use sector	4 Trillion JPY (Annual)	• Introduction of energy-efficient homes and buildings • Introduction of next-generation vehicles	1.8 Trillion JPY 1.8 Trillion JPY
Infrastructure development	4 Trillion JPY (Annual)	• Grid reinforcement cost (Masterplan) • Automobile infrastructure development (Charging station, Hydrogen station) • Digital society infrastructure developments (Semiconductor manufacturing facilities, data centers)	0.5 Trillion JPY 0.2 Trillion JPY 3.5 Trillion JPY
R&D	2 Trillion JPY (Annual)	• Carbon recycling (e.g., CCS, methanation, synthetic fuel, SAF) • Development of carbon-neutral manufacturing processes (e.g., hydrogen reduction steelmaking). • Nuclear (R&D on next-generation nuclear plants) • Implementation of advanced CCS projects	0.5 Trillion JPY 0.1 Trillion JPY 0.1 Trillion JPY 0.6 Trillion JPY

¥ = Japanese yen; CCS = carbon capture and storage; FIT/FIP =feed in tariff/feed in premium; R&D = research and development.
Source: GR Japan (2023).

The CCUS value chain will require ¥4 trillion between 2023 and 2033. To achieve the CCS target of 120–240 million tonnes of CO2/year, however, (approximately 10%–20% of Japan's emissions target), tens of trillions more will be required. There is a supply-side challenge with synthetic fuels, such as establishing manufacturing capacity and developing CO2 counting rules. The GX budget also indicates that funding of ¥3 trillion will be needed over the next 10 years in addition to the CCUS supply chain.

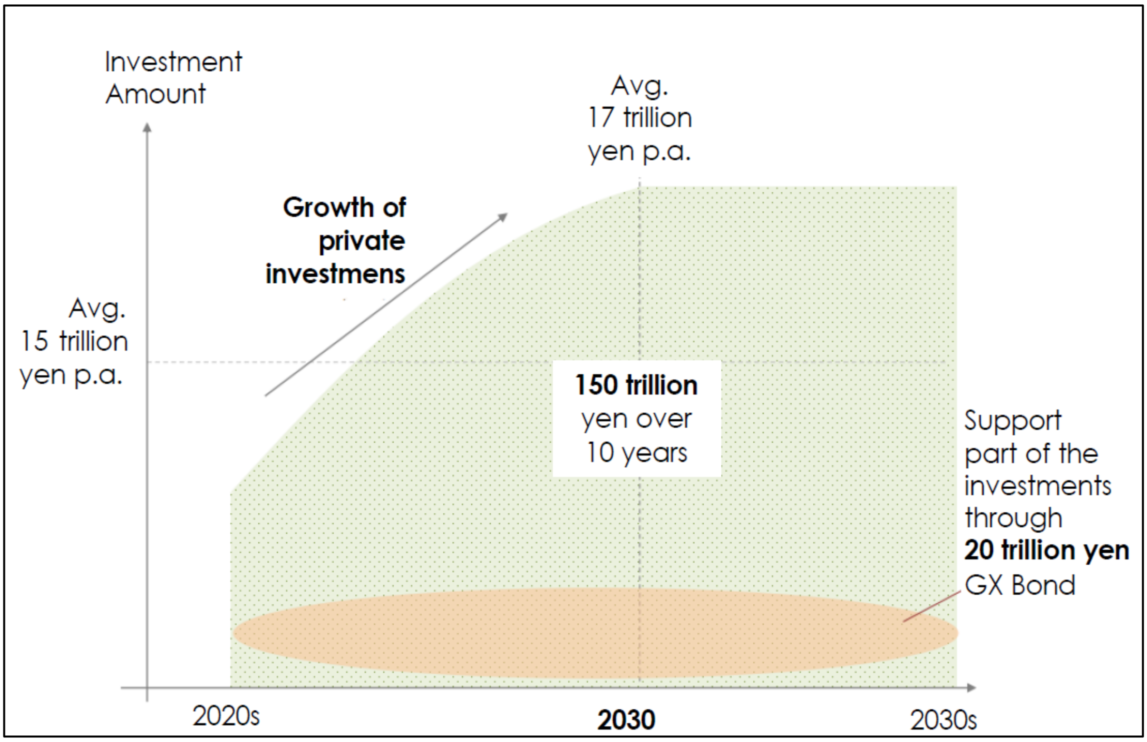
There are two aims within the Basic Policy for GX: ensuring a stable energy supply and realising and implementing the 'Pro-Growth Carbon Pricing Concept' and other initiatives. The first aim requires the expansion of renewable energy domestically and globally. The second aim relates to carbon pricing. There are four pillars to carbon pricing:

1. Upfront investment support by utilising the GX Economic Transition Bond (GX Bond): The initial investment of ¥20 trillion (about $144 billion) will be implemented to form long-term support measures and increase predictability for the private sector. Figure 6.2 shows the relationship between the GX Transition Bond and the GX Fund.
2. GX Investment incentives through carbon price to incentivise businesses to undertake GX: For example, the emissions trading scheme will be implemented in phases for high GHG emissions sectors through voluntary carbon trading

amongst the GX League. Carbon levies targeting fossil fuel importers such as power, oil, and gas companies will also be implemented. These have been introduced at an affordable rate initially. The price will be reviewed annually with a gradual increase to incentivise GX investments to reduce reliance on fossil fuels.

3. Utilisation of new financial instruments: The GX promotion organisation will consider and implement supplementary measures to address risks during the gradual social implementation of GX technologies to accelerate investment into GX. An environment will be created to promote sustainable finance, including disclosures of climate change-related information, and to strengthen efforts towards an international understanding of transition finance.
4. International strategy, Just Transitions, and GX of small and medium enterprises and others: The global market expansion will focus on green products such as steel, plastic, carbon-neutral fuel, industrial heat pumps, etc. This has also led to discussion about Japan's technological advantages, such as CDR technologies and next-generation reactors through the United States (US), Japan, and other partnerships. In Asia, Japan will focus on the Asia Zero Emissions Community as a regional platform; the Joint Crediting Mechanism to reach partnerships with 25 countries by 2025 and expand the CCS project; and the Asia Energy Transition Initiative with $10 billion for technology development and deployment, such as renewable energy, liquified natural gas, CCUS, ammonia, and hydrogen.

Figure 6.2. Green Transformation Transition Bond



¥ = Japanese yen, Avg. = average; GX = Green Transformation; p.a = per annum.
Source: GR Japan (2023).

3. Methodology

3.1. Green Economy Transition Outlook in the Group of Seven

To understand the current progress of green economy transition, this section assesses sustainable energy for all and energy and fiscal policies in Japan and its G7 peers through various indicators, namely the World Bank's Sustainable Energy for All (SE4ALL), Regulatory Indicators for Sustainable Energy (RISE), and Government Policy Indicators (GPI) of the International Monetary Fund (IMF) (Table 2). SE4ALL indicators illustrate the current energy situation, particularly renewable energy, from the demand and supply sides, whereas RISE and GPI show governments' commitments and efforts to achieve SE4ALL. Comparing the trends of the selected indicators to the benchmark countries provides insights into areas of policy that Japan should focus on and invest in more, to catch up with other G7 countries.

3.1.1. Sustainable Energy for All

In response to the SE4ALL initiative by the United Nations Secretary-General, the World Bank created a SE4ALL database with a set of country-level indicators on electricity, non-solid fuel, renewable energy, and overall energy to monitor SE4ALL's global objectives. The objectives include 1) to ensure universal access to modern energy services, 2) to double the global rate of improvement in global energy efficiency, and 3) to double the share of renewable energy in the global energy mix (World Bank, 2023a) (Table 2). Despite its usefulness, the SE4ALL database was discontinued in 2016. This study follows the proposed set of indicators and compiles SE4ALL data from the World Bank's Open Data (Energy & Mining) and the Organisation for Economic Co-operation and Development's (OECD) renewable energy data to generate up to date SE4ALL data. Some original indicators, such as energy intensity and renewable energy output, have been adjusted depending on data availability.

According to the World Bank (2023a), the definition of each indicator is as follows:

- **Access to electricity (% of rural population with access)**: Percentage of rural population with access to electricity.
- **Access to electricity (% of total population)**: Percentage of total population with access to electricity.
- **Access to electricity (% of urban population with access)**: Percentage of urban population with access to electricity.
- **Energy intensity level of primary energy (MJ/2011 $PPP)**: A ratio between energy supply and GDP measured at purchasing power parity. Energy intensity indicates how much energy is used to produce one unit of economic output. A lower ratio indicates that less energy is used to produce one output unit.

- **Renewable electricity output (GWh)**: Electric output (GWh) of power plants using renewable resources, including wind, solar PV, solar thermal, hydro, marine, geothermal, solid biofuels, renewable municipal waste, liquid biofuels, and biogas. Electricity production from hydro-pumped storage is excluded.
- **Renewable electricity share of total electricity output (%)**: Electricity generated by power plants using renewable resources as a share of total electricity output.
- **Renewable energy consumption (Terajoule)**: This indicator includes energy consumption from all renewable resources: hydro, solid biofuels, wind, solar, liquid biofuels, biogas, geothermal, marine, and waste.
- **Renewable energy share of total fine energy consumption (%)**: Share of renewable energy in total final energy consumption.
- **Total electricity output (GWh)**: Total GWh generated by all power plants.
- **Total final energy consumption** : This indicator is derived from energy balance statistics and is equivalent to total final consumption, excluding non-energy use.

Table 6.2. Selected Indicators for Analysis

Sustainable Energy for All – Sustainable Energy Situation	
Original Set of Indicators	Adjusted Indicators (Authors' Compilation)
1. Access to clean fuels and technologies for cooking (% of total population)	Unchanged
2. Access to electricity (% of rural population with access)	Unchanged
3. Access to electricity (% of total population)	Unchanged
4. Access to electricity (% of urban population with access)	Unchanged
5. Energy intensity level of primary energy (MJ per 2011 USD PPP)	Energy intensity level of primary energy (MJ per 2017 $PPP)
6. Renewable electricity output (GWh)	Total renewable energy (KTOE)
7. Renewable electricity share of total electricity output (%)	Renewable energy share of primary energy supply
8. Renewable energy consumption (TJ)	Unavailable
9. Renewable energy consumption share of TFEC	Renewable energy consumption share of TFEC

10.Total electricity output (GWh) 11.TFEC (TJ)	 Unavailable Unavailable
Regulatory indicators for sustainable energy – energy policies	
1. Electricity access 2. Clean cooking 3. Renewable energy a. Legal framework for renewable energy b. Planning for renewable energy expansion c. Incentives and regulatory support for renewable energy d. Attributes of financial and regulatory incentives e. Network connection and use f. Counterparty risk g. Carbon pricing and monitoring 4. Energy efficiency a. National energy efficiency planning b. Energy efficiency entities c. Incentives & mandates: industrial and commercial end users d. Incentives & mandates: public sector e. Incentives & mandates: energy utility programmes f. Financing mechanisms for energy efficiency g. Minimum energy efficiency performance standards h. Energy labelling systems i. Building energy codes j. Transport sector k. Carbon pricing and monitoring mechanism	
Government policy indicators – fiscal policies	
1. Fossil fuel subsidies (% of GDP) 2. Fossil fuel subsidies ($ at constant 2021 prices) 3. R&D environmental protection expenditure (% of GDP) 4. Environmental taxes (% of GDP)	

$ = US dollar; GDP = gross domestic product; GWh = gigawatt hours; KTOE = kilotonnes of oil equivalent; MJ = megajoules; PPP = purchasing power parity; R&D = research and development; TFEC = total final energy consumption; TJ = terajoule.
Source: Authors compilation.

3.1.2. Regulatory Indicators for Sustainable Energy

RISE is designed to facilitate cross-country comparisons of policy frameworks supporting universal access to clean energy as outlined in Sustainable Development Goal (SDG) 7. It analyses national legislation, policies, and strategies over 140 economies as of 31 December, 2021. It assesses their progress through 30 key indicators categorised under four pillars—electricity access, clean cooking, renewable energy, and energy efficiency. The score of each indicator and pillar ranges from 0 to 100 and can be segmented into three categories—green (67–100), indicating mature policies with room for improvement; yellow (33–67), representing developing frameworks; and red (0–33), signifying early-stage adoption (ESMAP, 2022).

3.1.3. Fiscal Policies

Governments rely on tax and expenditure policies as key instruments to combat environmental issues, particularly climate change. Environmental taxes disincentivise environmentally harmful practices while generating government revenues to invest in and subsidise economic and technological choices that positively affect the environment, e.g. public investments in eco-friendly infrastructure, subsidies to encourage renewable energy adoption, and adaptation spending for climate resilience (IMF, 2022).

As RISE documents the existence of legislation, policies, and strategies regardless of their enforcement, it is important to recognise that it may not fully capture the nuanced quality of policy content and is not an indicator of progress toward SDG 7 (World Bank, 2023a). The information regarding fiscal policies that address environmental issues such as renewable energies record actual policy implementation and the government's commitment to, and priorities for, the transition to a green economy. They thus, supplement the RISE analysis. From 2005 to 2025 the IMF created a climate change dashboard that provided international statistical data on key GPIs, including fossil fuel subsidies, environmental taxes, and government expenditure on R&D environmental protection, depending on each indicator's data availability and forecasts.

According to the IMF (2022), the definition of each indicator is as follows:

- **An environmental tax** represents a fee imposed on a specific product unit with an adverse environmental impact.
- **Government expenditure on environmental protection** illustrates each government's monetary allocation to environmental preservation activities, presented as a percentage of the country's GDP. These activities are part of a predefined range of actions outlined within the Classification of Functions of Government Framework. They encompass pollution reduction, biodiversity conservation, and waste management.

- **Fossil fuel subsidies** demonstrate the approximate worth of explicit and implicit government subsidies linked to fossil fuels (such as coal, natural gas, petroleum, and electricity). Explicit subsidies denote the under-pricing resulting from supply costs surpassing the prices paid by consumers. Implicit subsidies signify the variance between supply costs and socially optimal prices (considering the negative impacts of fossil fuel usage and the revenue loss from consumption taxes), excluding explicit subsidies. The total subsidies comprise both implicit and explicit subsidies. It is crucial to distinguish this economic concept and the estimates based on models from subsidies defined in government financial statistics.

3.2. Techno-Economic Analysis of Carbon Capture, Utilisation and Storage

The learning curve phenomenon has been commonly used for emerging hydrogen or solar PV technologies (Jupesta et al., 2022). This curve was first observed and documented in the 19th century by German psychologist Hermann Ebbinghaus. He described learning as an exponential process, meaning that the fastest learning occurs in the beginning and that exponentially more effort is required for subsequent increases in learning. Ebbinghaus was the first researcher to mathematically document the learning process in an experiment he conducted (Junginger and Louwen, 2020). The most widely used model in energy literature to forecast changes in technology costs is the 'one-factor learning curve.' This formulation is derived from empirical observations across various energy technologies that frequently indicate a log-linear relationship between the unit cost of the technology and its cumulative output (production) or installed capacity (Rubin, Davison, and Herzog, 2015). The future costs are estimated using the concept of learning-by-doing, discussed by (Ferioli, Schoots, and van der Zwaan, 2009). This can be quantitatively expressed as:

$$C_{x_t} = C_{x_0}\left(\frac{x_t}{x_0}\right)^b \quad (1)$$

Where x_0 represents carbon capture in t CO2 in year 2020 (year 1)

x_t represents carbon capture in t CO2 in year t

C_{x_0} is a unit cost of a product, process or technology in year 1

C_{x_t} is a unit cost of a product, process or technology in year t

b is a positive learning parameter.

Moreover, the fractional reduction in cost associated with a doubling of installed capacity is referred to as the learning rate and is given by:

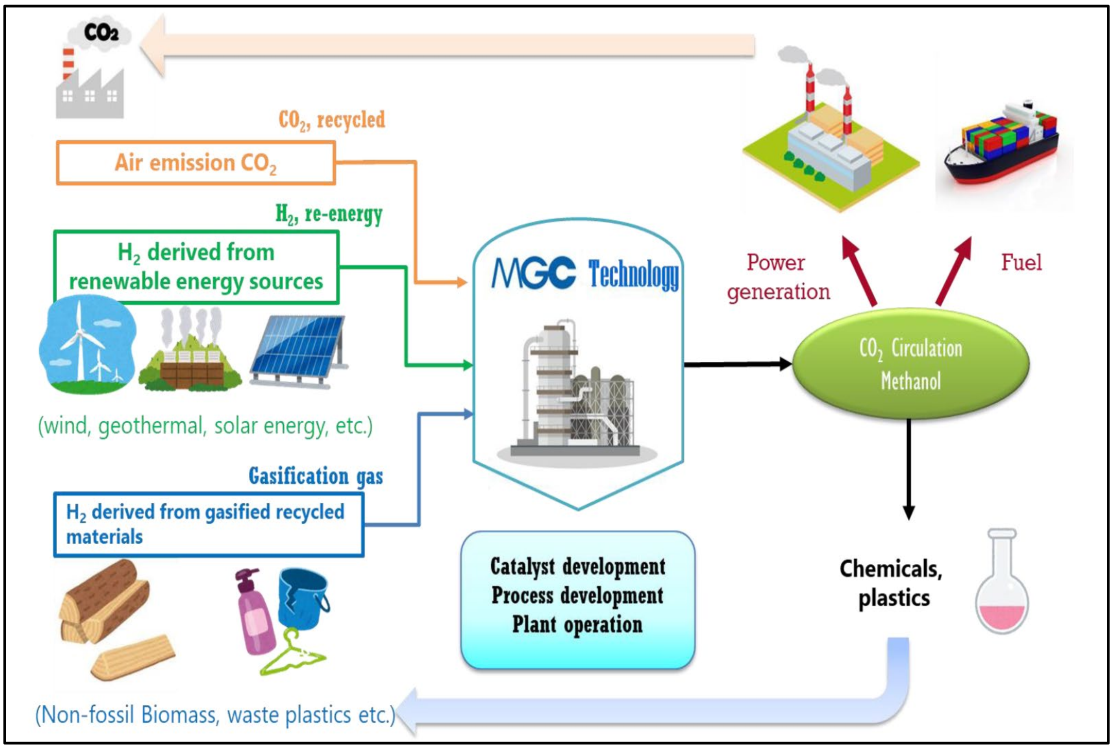
$LR = 1 - 2^b$ (2)

The case study is from the methanol production from Mitsubishi Chemical Group (2023), as depicted in Figure 6.3. For this study, there are three scenarios based on the learning rate for the methanol plant: Scenario 1 is learning rate 11.95% (50% of the LR of solar PV) (Junginger & Louwen, 2020), Scenario 2 is learning rate 23.9% (100% of the LR of solar PV), and Scenario 3 is learning rate 35.85%. (150% of the LR of solar PV).

Figure 6.3 has three elements: recycling CO_2, hydrogen from gasification gas, and hydrogen from renewable energy. All these elements will become feed stock for the methanol plant. The CO_2 source was obtained from industrial processes, including the hard-to-abate industries (chemical, iron/steel, and cement). The fuel gas from this industry has a high CO_2 concentration of 20%–30% compared with the air (440 ppm); hence, the absorption of CO_2 will need less energy compared with direct air capture. Hydrogen is obtained from renewable energy sources or water photolysis. Table 6.3 shows the input data on $CO_{2,}$ hydrogen, and methanol production costs.

To reduce the CO_2 emissions from industry, they will be recycled and reused to produce fuel such as methanol. Methanol is useful for various products, chemicals, plastics, fertilisers, and fuel. This study specialises in maritime fuel demand since this sector is a hard-to-abate industry and is getting more attention nowadays. While all supply chains need long freight maritime ships, the GHG emissions from the shipping sector will influence global trade. The techno-economic analysis is an analysis of the costs during the production process. There are four production processes of the elements for the methanol in this study: recycled CO_2, hydrogen from renewable energy, hydrogen from gasification gas, and plant operation by a mixture of all three elements.

Figure 6.3. Carbon Capture and Utilisation in Methanol Production



CO_2 = carbon dioxide; H_2 = hydrogen; MGC = Mitsubishi Gas Chemical.
Source: MGC (2023).

Table 6.3. Cost of Methanol Production

Inflow/Outflow	Mass Balance (t/t methanol)	Cost (US$/t methanol)	References
Inlet CO_2	1.46	10.88	Morimoto et al. (2022)
Inlet H_2	0.199	228.83	Galimova et al. (2023)
Inlet air to the furnace	0.813		
Outlet methanol	1	357	Statista (2023)
Outlet H_2O	0.569		
Flue gas from the furnace	0.905		
Production	Energy Balance (MWh/t methanol)	Cost ($/t methanol)	
Electricity consumption	0.169		
Heating needs	0.169		
Cooling needs	0.169		
Total energy	0.507	70.64	Global Petrol Prices, (2023)

$ = US dollar; CO2 = carbon dioxide; H2 = hydrogen; H2O = water; MWh = megawatt hours; t =tonne ‘
Source: Perez-Fortez et al. (2016).

4. Results and Discussions

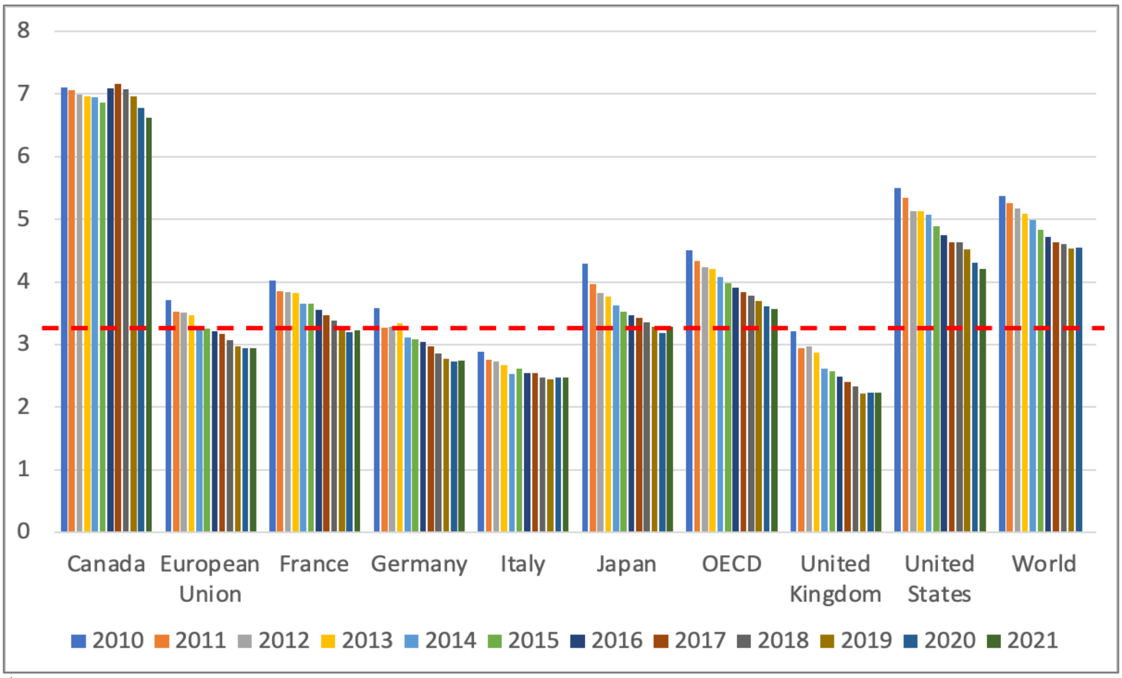
4.1. Economic Analysis of the Group of Seven Countries

4.1.1. Sustainable Energy for All

Access to modern energy services is not an issue for the G7. The G7 economies provide universal access to electricity (100% of the population), clean fuels, and cooking technologies in urban and rural areas. The world average for this provision is 51% in rural areas and 87% in urban areas (World Bank, 2023a).

For the past decade, the decline in the energy intensity level of primary energy has been observable amongst the G7 (Figure 6.4). However, Japan has been ranked as the third- or fourth-largest country amongst the G7 that utilises more energy to produce a unit of economic output, i.e., a higher energy intensity level. As energy intensity level is the ratio between energy supply and GDP measured at purchasing power parity, Japan's relatively high energy intensity level possibly indicates 1) the country's lower energy efficiency technologies for consumption and production, 2) lower commitment to promoting energy-saving behaviours, technologies, and systems, e.g. energy, transport, industry, food, and land use (UN DESA and UNFCCC, 2022), or 3) more energy consumption for non-economic activities that do not contribute to GDP.

Figure 6.4. The Energy Intensity Level of Primary Energy
(Megajoules per Gross Domestic Product (Measured at 2017 $ Purchasing Power Parity))

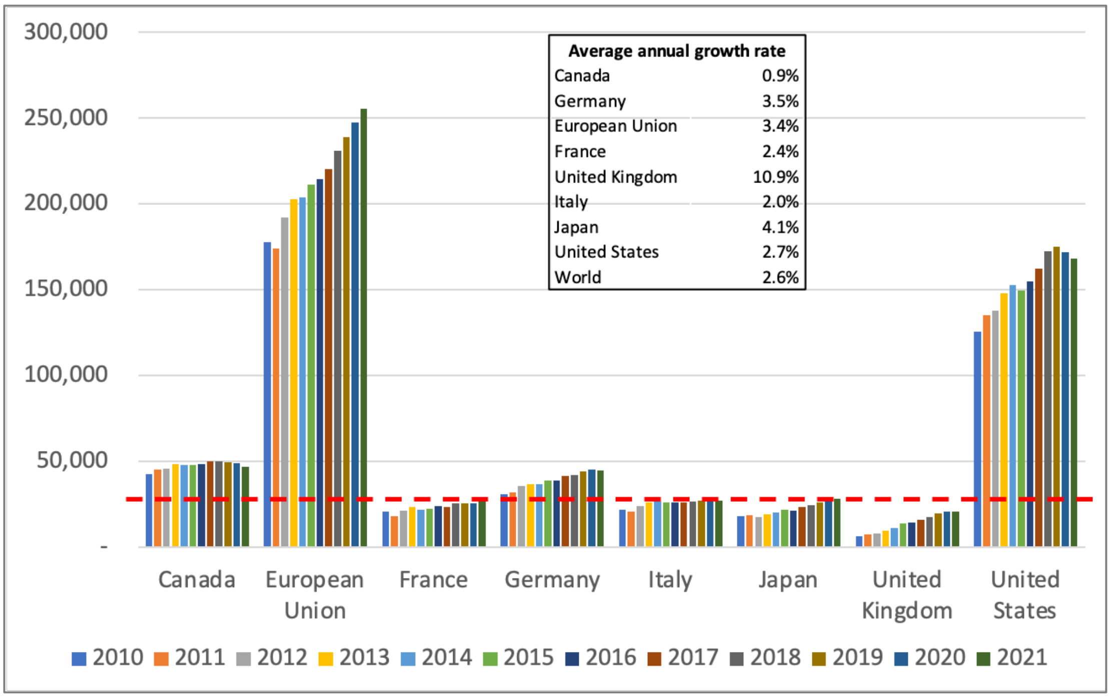


$ = US dollar; GDP = gross domestic product; MJ = megajoule; OECD = Organisation for Economic Co-operation and Development; PPP = purchasing power parity.
Source: Author's calculations, based on World Bank (2023b).

In terms of the production and consumption of renewable energy, Japan performs the worst amongst the G7. This leads to questions over its commitment to sustainable energy for all and its ability to meet the SDG targets, particularly SDG 7.2: 'By 2030, increase substantially the share of renewable energy in the global energy mix.' In response to SDG 7.2, Japan's Sixth Strategic Energy Plan states that 36%–38% of the country's power generation mix should come from renewable energy by 2030 (Gov. of Japan: METI, 2021).

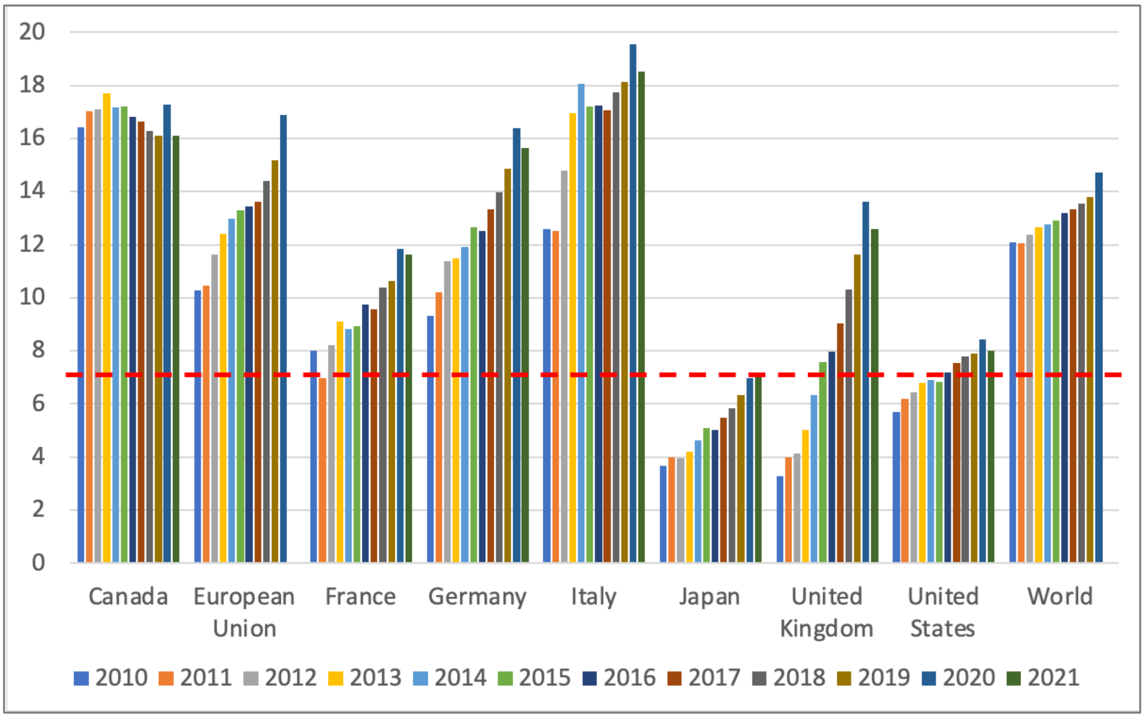
Despite the high growth of Japan's renewable energy supply, the shares of renewable energy in total energy supply and consumption are the lowest amongst the G7. Japan's renewable energy supply grows 4.1% annually, from 18,368 kilotonnes of oil equivalent in 2010 to 28,457 kilotonnes of oil equivalent in 2021. The growth is faster than in most G7 countries, behind only the United Kingdom (10.9%) (Figure 6.5). Even though Japan's renewable energy supply has been lower than that of France and Italy for the last decade, it outweighed the supplies of both countries in 2021. The rising shares of renewable energy production and consumption have also been observable during the same period due to the growth in renewable energy supply (Figures 6.4 and 6.5). Nevertheless, the share of renewable energy in the Japanese energy mix is less than 10% in production and consumption, lower than the rest of the G7. While Figure 6.5 shows the increase in renewable energy supply with high growth, the increase cannot catch up with the faster growth of energy demand illustrated by the small shares of the national energy mix in Figures 6.6 and 6.7.

Figure 6.5. Renewable Energy Supply
(Kilotonnes of oil equivalent)



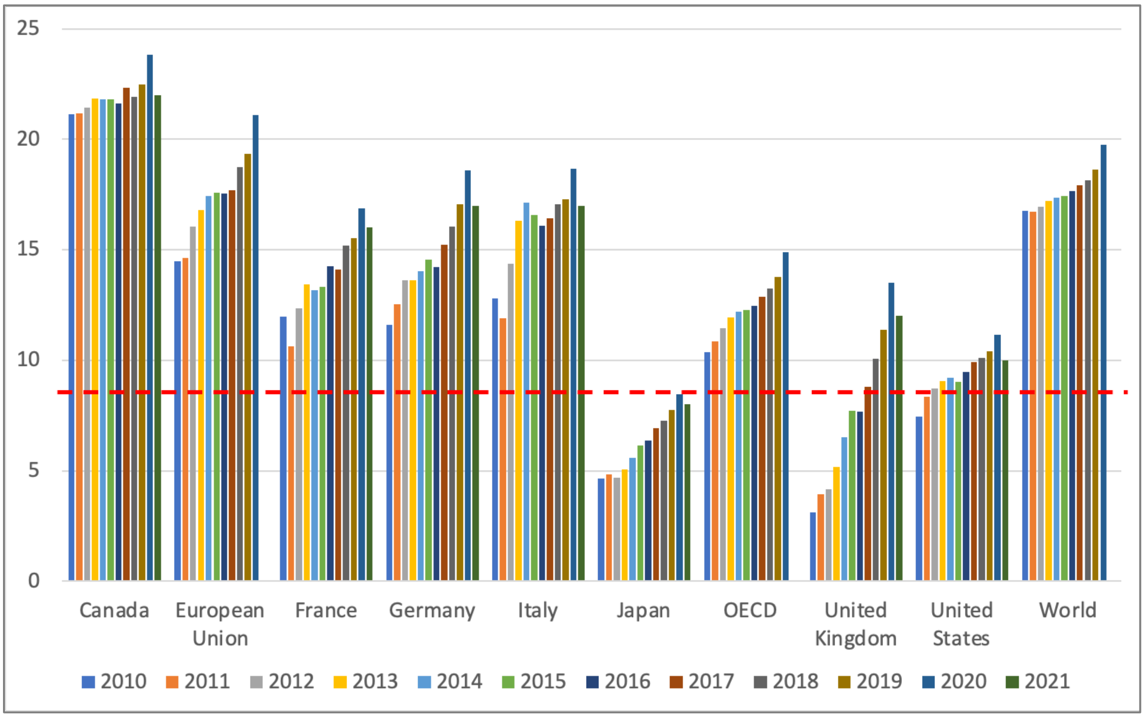
Source: Author's calculations, based on OECD (2023).

Figure 6.6. Renewable Energy Supply
(% of primary energy supply)



Source: Author's calculations, based on OECD (2023).

Figure 6.7. Renewable Energy Consumption
(% of total final energy consumption)



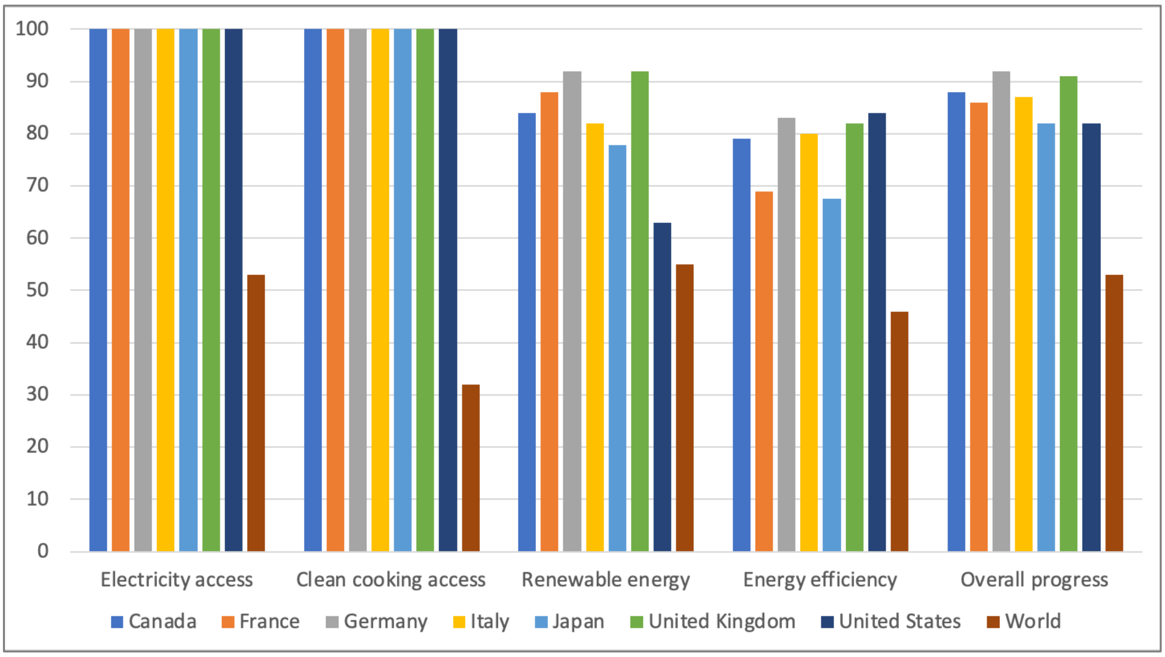
Source: Author's calculations, based on World Bank (2023b).

4.1.2. Regulatory Indicators for Sustainable Energy

Japan's overall progress on sustainable energy regulation lags behind the rest of the G7. Its overall score is 82, the same as the US (Figure 6.6). Consistent with the SE4ALL indicators, Japan and the other G7 economies' scores relating to regulations regarding access to modern energy services, i.e., electricity and clean cooking, reach the maximum score, ensuring universal access to the services. In contrast, the global average for these scores is 53 for electricity access and 32 for clean cooking (Figure 6.8).

In terms of renewable energy policy and regulation, Japan (78) scores 4, which is 14 points lower than the other G7 members, except the US (63), making it the second-worst performing country amongst the G7 (Table 6.4). Japan's lower than average score for renewable energy is primarily due to low scores achieved on Indicator 5: Network Connection and Pricing (57). This is particularly noticeable in the areas of connection, where, for example, there is no grid code that specifies connection procedures, and cost allocation and there is a lack of real-time dispatch operation.

Figure 6.8. Progress on Sustainable Energy Regulation by Pillar



Source: Authors calculations, based on ESMAP (2022).

Table 6.4. Renewable Energy Policy and Regulation Pillar

Country	Indicator 1: Legal framework for renewable energy	Indicator 2: Planning for renewable energy expansion	Indicator 3: Incentives and regulatory support for renewable energy	Indicator 4: Attributes of financial and regulatory incentives	Indicator 5: Network connection and pricing	Indicator 6: Counterparty risk	indicator 7: Carbon pricing and monitoring mechanism
Canada	80	79	89	82	81	75	100
France	100	92	74	100	66	82	100
Germany	100	96	94	82	87	85	100
Italy	80	96	85	55	94	67	100
Japan	80	75	79	82	57	77	100
United Kingdom	80	100	94	100	94	75	100
United States	56	59	56	31	77	63	100

Source: Authors, based on ESMAP (2022).

Similarly, Japan's average score for energy efficiency (68) trails behind the G7's average score by ten points, sitting at the bottom of the league table (Figure 6.6). Relatively low scores on incentives and mandates (Indicators 4 and 5), financing mechanisms (Indicator 6), and building energy codes (Indicator 9) contribute to Japan's weak performance in this pillar (Table 6.4). Japan's incentive and mandate regulations regarding energy utility programmes and the public sector are at an early stage. Several mechanisms and measures are missing, such as regulations for transmission and distribution networks, demand-side management and demand-response, cost recovery, and utility consumer pricing and information. Like the other G7 economies, insufficient financing mechanisms for energy efficiency are evident in Japan. The country has not adopted on-bill financing and repayment; green or energy efficiency bonds; credit lines and revolving funds for energy efficiency activities; and partial risk guarantees in residential, commercial, and industrial sectors.

In contrast to the other G7 countries, Japan's residential sector adopts more mechanisms that are less available to the commercial and industrial sectors, such as discounted green mortgages. In addition, building energy codes is another area in which Japan does not perform well (Table 6.5). The building energy standards are not regularly updated, and building energy information is not disclosed in the residential and commercial sectors.

Table 6.5. Energy Efficiency Policy and Regulation Pillar

Country	Indicator 1: National energy efficiency planning	Indicator 2: Energy efficiency entities	Indicator 3: Incentives & mandates: industrial and commercial end users	Indicator 4: Incentives & mandates: public sector	Indicator 5: Incentives & mandates: energy utility programs	Indicator 6: Financing mechanisms for energy efficiency	Indicator 7: Minimum energy efficiency performance standards	Indicator 8: Energy labeling systems	Indicator 9: Building energy codes	Indicator 10: Transport sector	indicator 11: Carbon pricing and monitoring mechanism
Canada	100	75	67	100	35	52	90	92	75	83	100
France	93	92	75	75	39	25	83	50	81	50	100
Germany	89	100	100	63	30	60	92	100	77	100	100
Italy	82	100	63	100	73	43	90	50	79	100	100
Japan	78	67	75	38	31	35	92	96	58	83	100
United Kingdom	89	100	100	88	72	43	78	88	84	67	100
United States	78	87	100	80	51	58	88	87	90	100	100

Source: Authors, based on ESMAP, (2022).

Figure 6.9 shows a positive relationship between renewable utilisation and the G7 economies' scores on the renewable energy regulation pillar. On average, the renewable energy share of the primary energy supply and the renewable energy consumption share of total fine energy consumption tend to rise with the progress in renewable energy regulation. It is possible that regulatory efforts to plan for renewable energy expansion in Canada, Germany, and Italy provide incentives and regulatory support for renewable energy. The efforts, in turn, develop better network connections and pricing mechanisms, positively affecting renewable utilisation (Table 4). However, Japan and the US perform poorly in these areas, resulting in the lowest renewable energy shares in production and consumption.

Figure 6.9. Correlation between Renewable Utilisation and Progress on Renewable Energy Regulation amongst the Group of Seven Economies, 2021

a. Renewable Energy Share of Primary Energy Supply

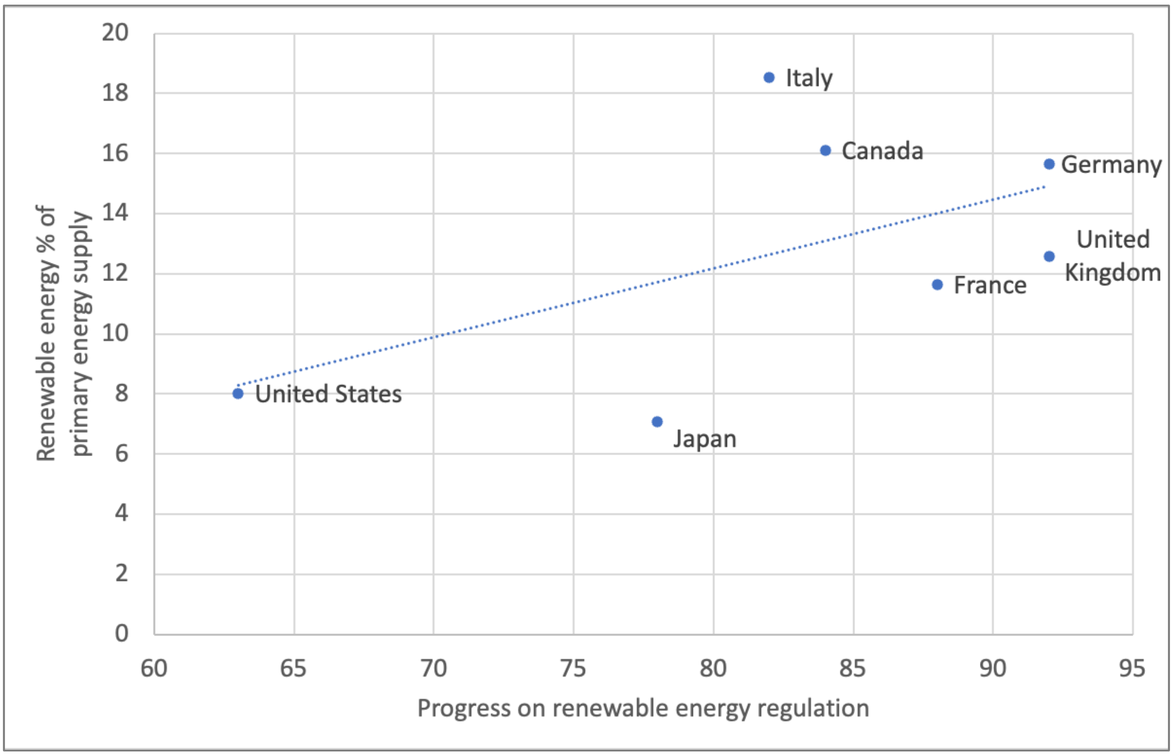
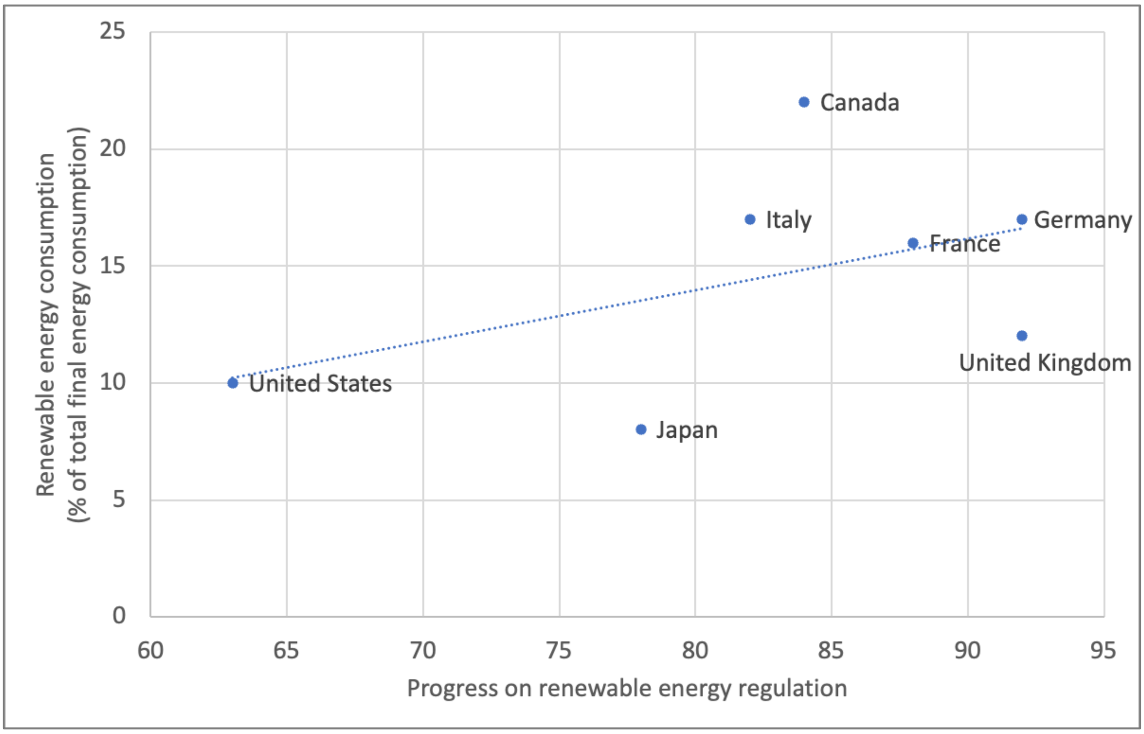


Figure 6.9. *Continued*

b. Renewable Energy Consumption

(% of total final energy consumption)



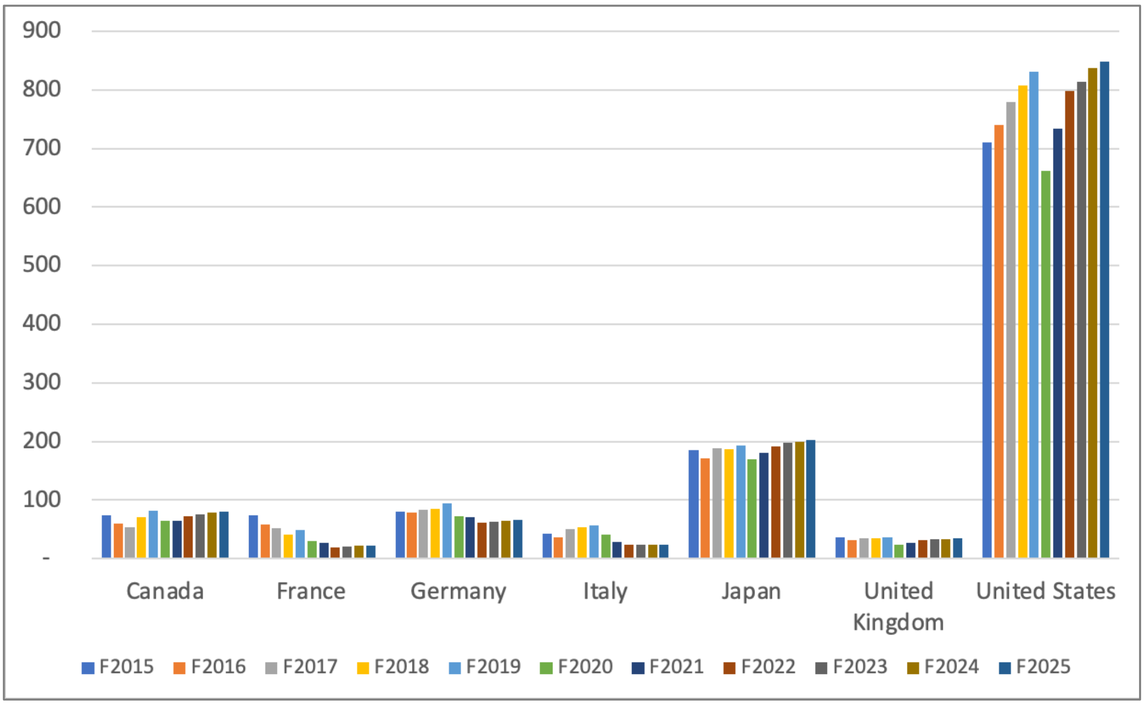
Source: Authors calculations, based on OECD, (2023) and ESMAP, (2022).

4.1.3. Fiscal Policies

Figures 6.10 and 6.11 show the estimated value of explicit and implicit government subsidies related to fossil fuels, including coal; natural gas; petroleum; and electricity; and their share of GDP. There was a sharp drop in the subsidies due to the COVID-19 pandemic amongst G7 economies. However, the subsidies constantly grow after 2021 in most countries, especially Canada, Japan, and the US, representing the top three within the G7. Figure 6.11 illustrates a similar trend, showing the rising subsidies one or two years after the COVID-19 pandemic, accounting for approximately 3.5% of GDP in Canada, Japan, and the US, the highest share amongst the G7.

Subsidies aim to ensure that all consumers have access to, or can afford, a particular product or service, in this case, fossil fuel, through market distortions, resulting in inefficient resource allocation and fiscal burdens. Greater fiscal burdens may force the government to raise taxes, increase borrowing (to continue subsidising fossil fuels), or cut spending (on renewable energy-related policies). Literature reveals that fossil fuel subsidies cause fossil fuel overconsumption with environmental externalities (Burniaux and Chateau, 2014; Schwanitz et al., 2014) and hinder the development of low-carbon technological substitutes, e.g. renewable energy and the overall green economy transition (Bridle and Kitson, 2014; Merrill et al., 2015; Schmidt, Born, and Schneider, 2012). Figure 6.14a indicates a negative relationship between renewable utilisation and fossil fuel subsidies amongst the G7, supporting the existing literature.

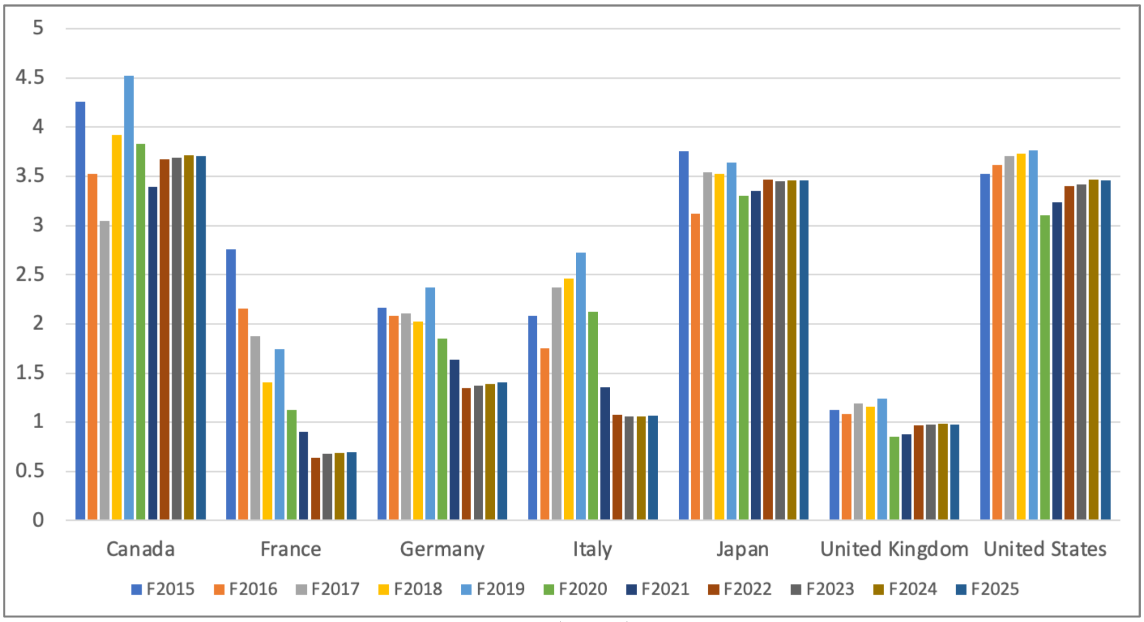
Figure 6.10. Fossil Fuel Subsidies
($ billion at constant 2021 prices)



$ = US dollars.
Source: Author's calculations, based on IMF, (2022).

Figure 6.11. Fossil Fuel Subsidies

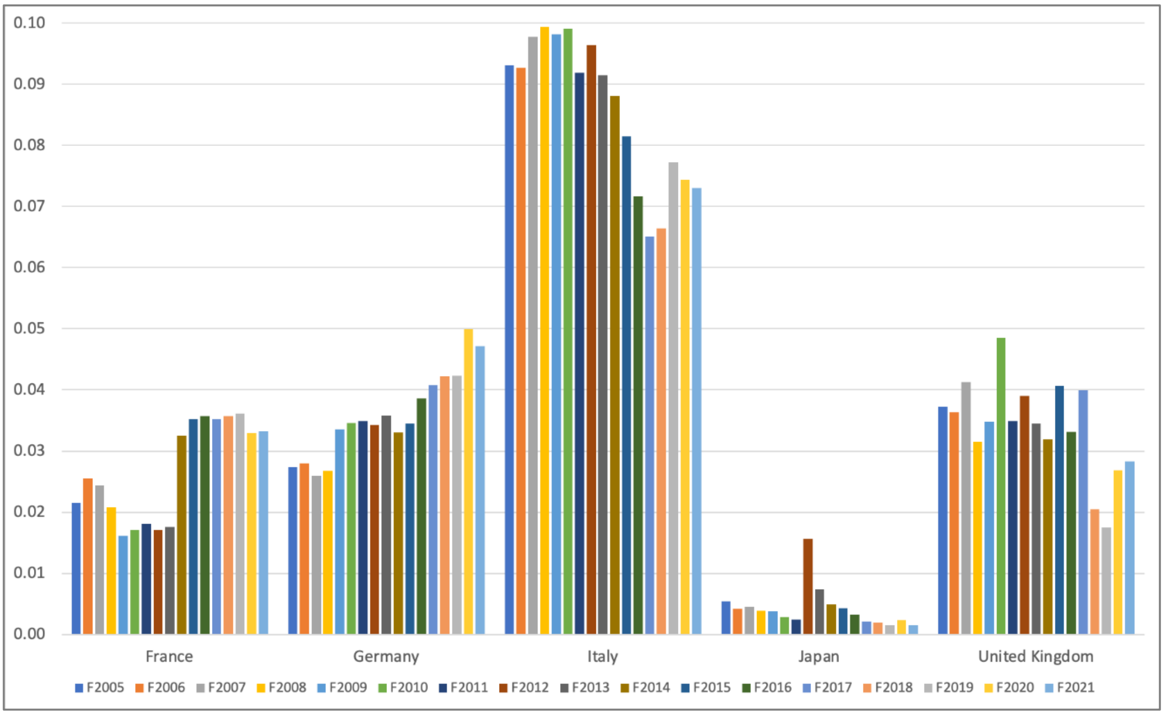
(Percentage of gross domestic product)



Source: Author's calculations, based on IMF, (2022).

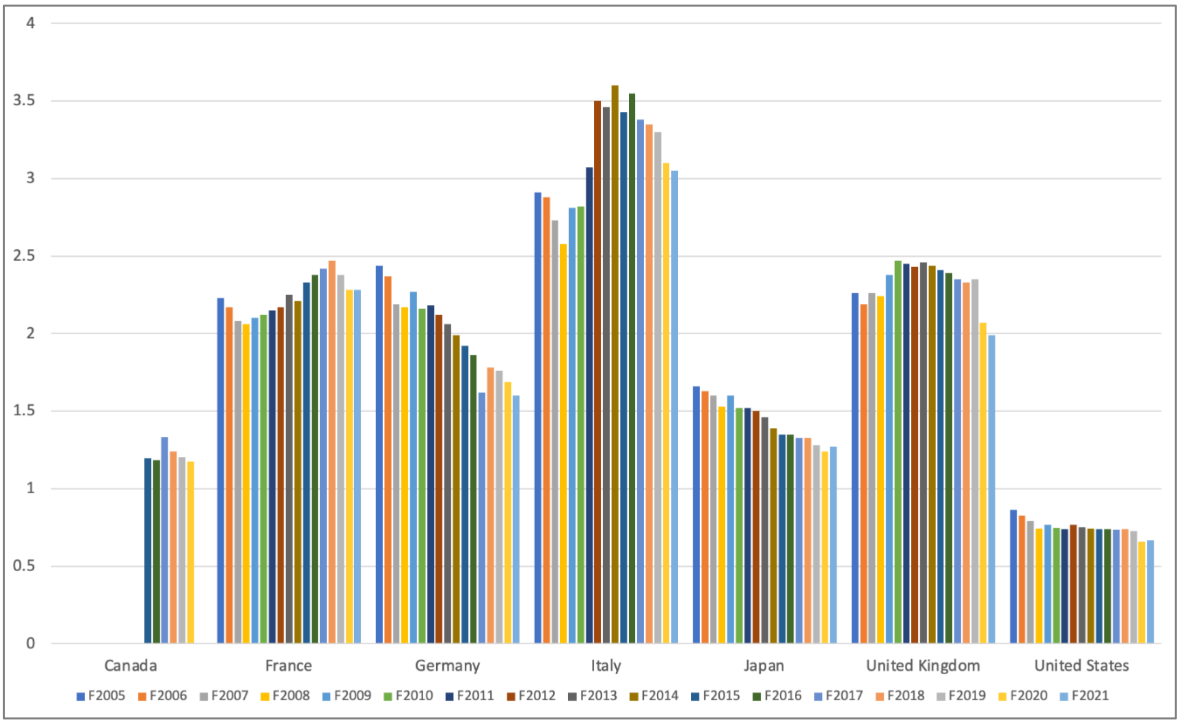
Japan performs poorly in government expenditure on R&D for environmental protection and environmental taxes. Amongst the G7, it ranks the worst in R&D for environmental protection spending (Figure 6.12) while being third from the bottom regarding environmental taxes (Figure 6.13). The two indicators are important as they point to the government's commitment and financial resources to develop measures to engage with environmental issues, including renewable energy technologies. Countries with low government expenditure on R&D for environmental protection share of GDP and environmental tax share of GDP, i.e. Japan and the US, tend to have low renewable energy share of primary energy supply (Figures 6.14b and 6.14c), signalling a slower transition towards a green economy.

Figure 6.12. Government Expenditure on Research and Development Environmental Protection
(Percentage of gross domestic product)



Source: Author's caculations, based on IMF, (2022).

Figure 6.13. Environmental Taxes
(percentage of gross domestic product)

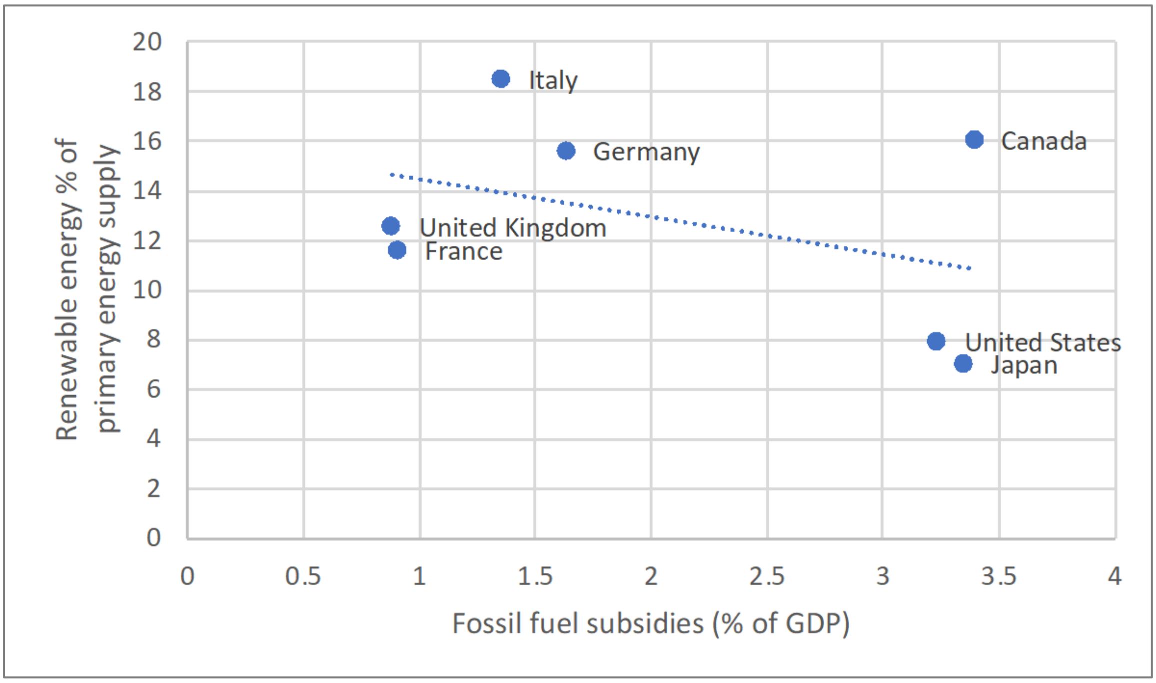


Source: Author's calcuations, based on IMF (2022).

Figure 6.14. Correlation between Renewable Utilisation and Fiscal Policies amongst the Group of Seven Economies, 2021

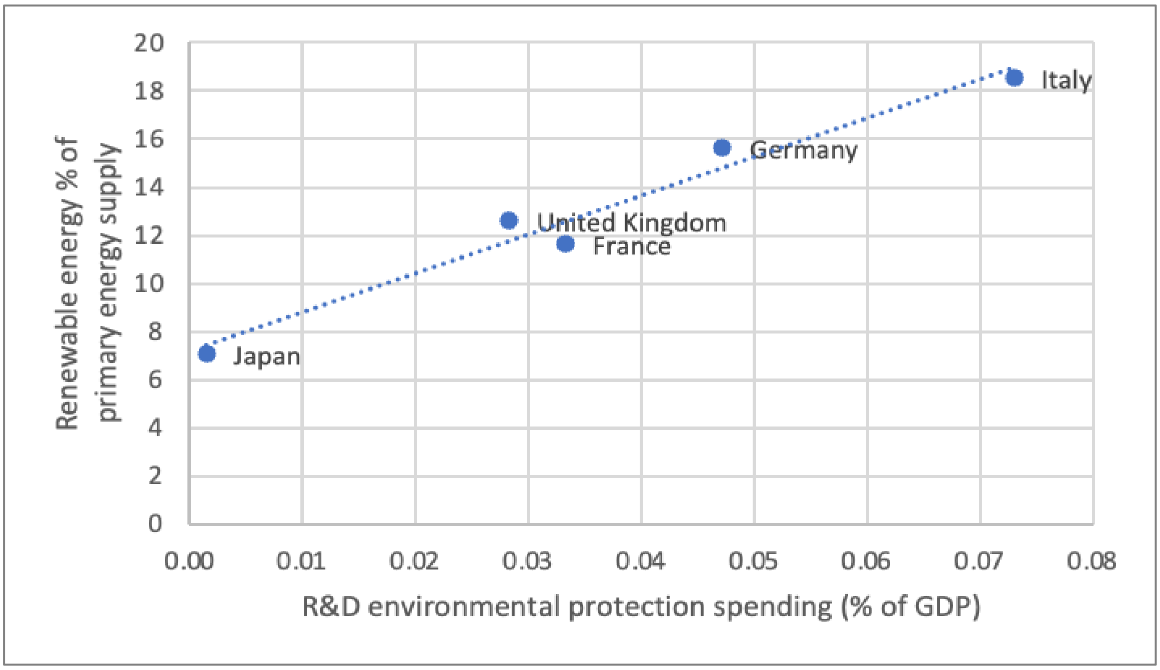
a. Fossil Fuel Subsidies

(percentage of gross domestic product)

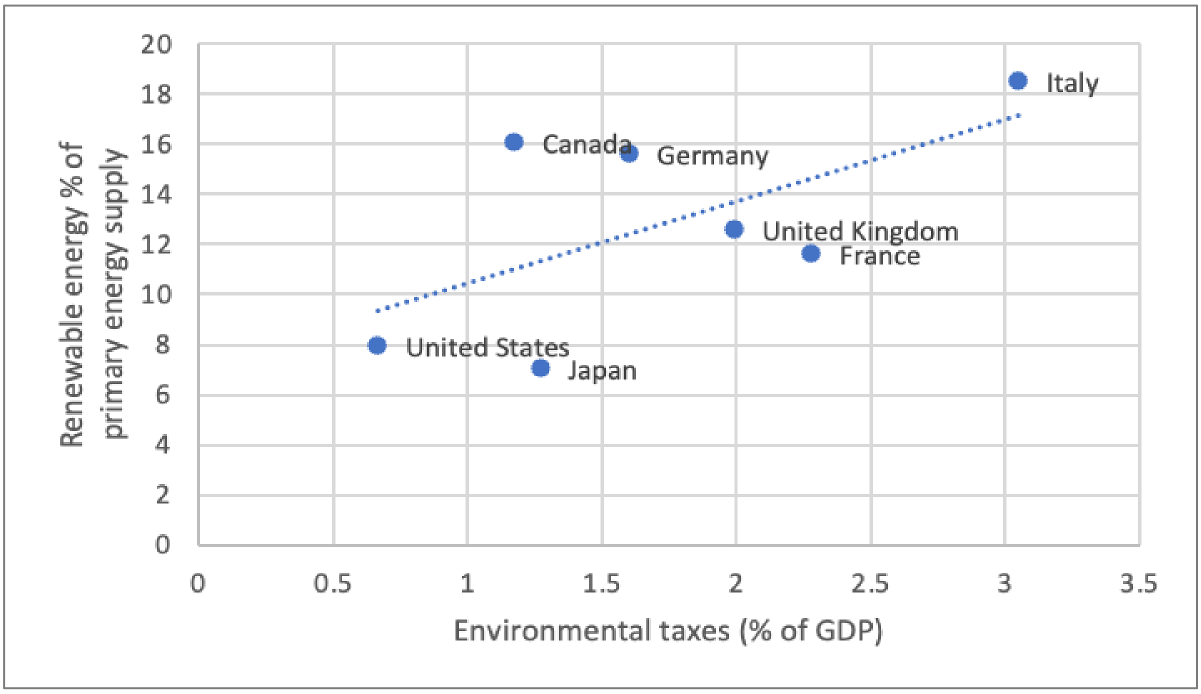


b. Government Expenditure on Research and Development Environmental Protection

(percentage of gross domestic product)



c. Environmental Taxes
(percentage of gross domestic product)



Source: Author's calculations, based on IMF, (2022) and OECD, (2023).

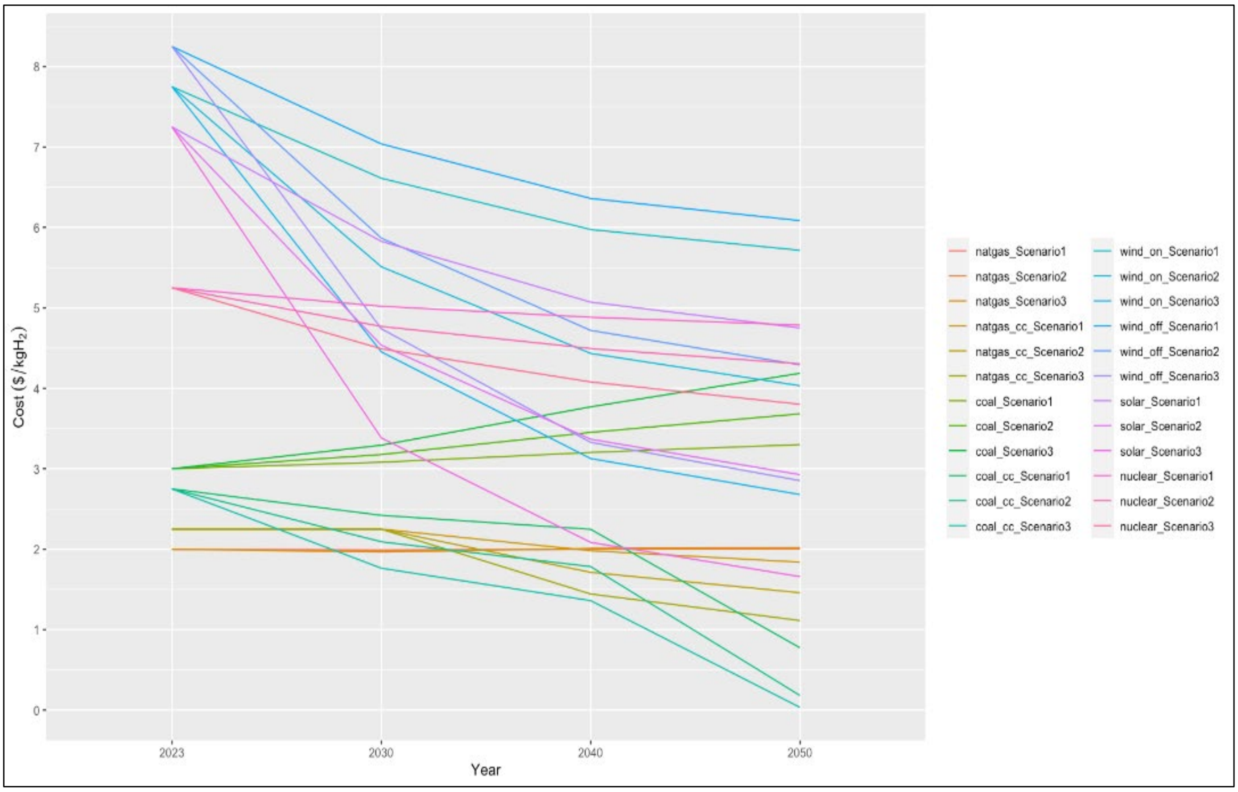
4.2. Carbon Capture, Utilisation, and Storage Case Study in Methanol Production in Japan

While the methanol was obtained from hydrogen and CO2, the focus of the study is the hydrogen cost since the CO2 cost almost free; it isobtained from the flue gas from the power plant/industries as mentioned in 3.2. It also discussed on the electrolyser technology cost which is critical for the hydrogen production. The transport cost for the hydrogen will be outlined as well assumed the hydrogen partly imported from abroad.

4.2.1. The Hydrogen Production Cost

The cost of hydrogen production has declined from 2023 to 2050 thanks to the learning curve, as shown in Figure 15. Due to technological learning/R&D, hydrogen production costs have declined from various energy sources (natural gas only and with CCS, coal only and CCS, wind onshore and offshore, solar PV, and nuclear). The lowest cost of hydrogen production will be from coal with CCS $0.03/kilogramme of hydrogen (kg H2) followed by natural gas with CCS $1.18/kg H2 and solar PV $1.66/kg H2. This all comes from Scenario 3 with a learning rate of 35.9%; 150% of the current learning rate of solar PV. In the case of Scenario 2, whereas the learning rate is similar to the current learning rate of solar PV at 23.9%, the lowest cost for hydrogen production will be from coal: $0.18/kg H2, natural gas with CCS $1.46 US/kg H2; and solar PV $2.93 US/kg H2. In the case of Scenario 1, with a learning rate of 11.59%, 50% of the current learning rate of solar PV, only coal with CCS could reach the cost of hydrogen production below $1/kg H2 ($0.77/kg H2). The Ministry of Economy, Trade, and Industry (METI) of the Government of Japan aims to achieve a hydrogen cost of ¥222/kg H2 (Gov. of Japan: METI, 2023c: 15) or $1.59/kg H2 with an exchange rate of ¥140/$ (World Currency Shop, 2023). Hence, only coal with CCS and natural gas with CCS is eligible to deliver the target of METI hydrogen cost ¥222 in 2050 in Scenarios 2 and 3 and only coal with CCS meets the target for Scenario 1. While domestically produced and internationally imported renewable energy such as solar PV can deliver the cost target for hydrogen production in Japan, hydrogen production from carbon-neutral fuels such as coal and natural gas with CCS is still the best available option and the one that seems most feasible from Southeast Asia producer countries such as Indonesia (coal), Malaysia, and Brunei Darussalam (natural gas).

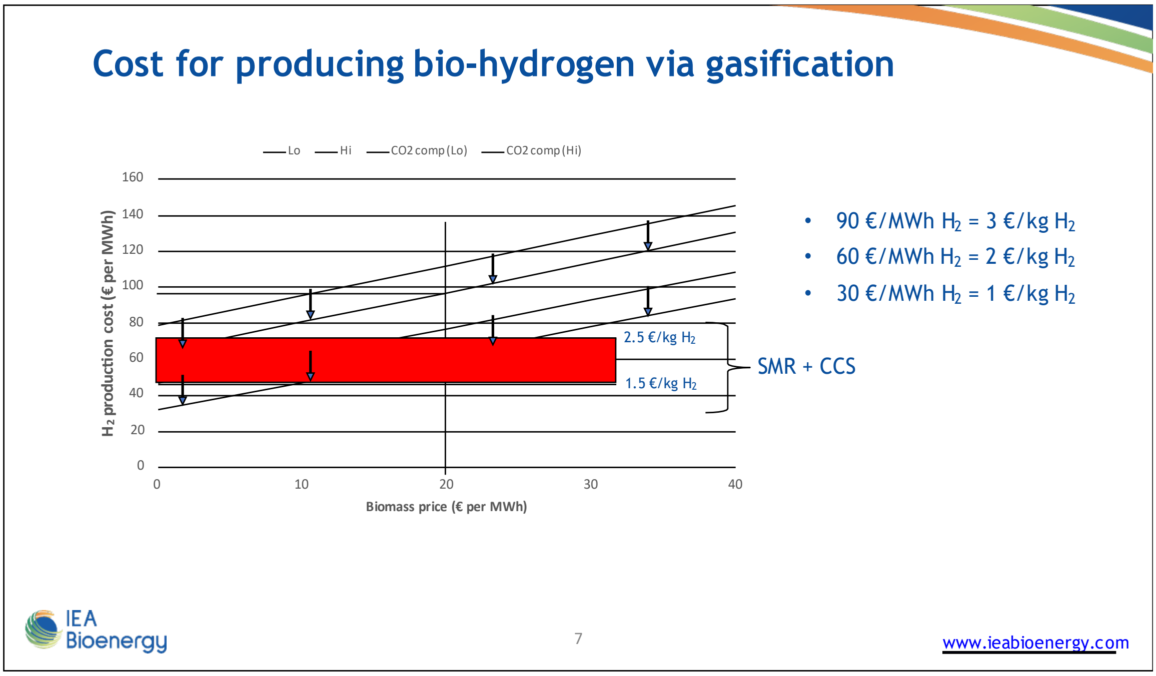
Figure 6.15. Cost of Hydrogen Production



$ = US dollar; kgH2 = kilogramme of hydrogen; natgas = natural gas.
Source: Authors calculations based on cost data in 2023 from IEA (2023a) and energy supply data from IEA (2023b).

While the hydrogen from Figure 6.15 doesn't consider biomass, to add the biomass, we elaborate on the study from International Energy Agency Bioenergy (Lundgren, 2023) on the biomass-based hydrogen production cost. That study showed that biomass could be carbon emissions negative/carbon removal since biomass absorbs CO_2 from the atmosphere during its lifetime. For every tonne of biomass gasified, 0.15 tonnes of hydrogen can be produced together with 1.5 tonnes of CO_2. While the cost of producing biomass-based hydrogen through gasification/steam methane reforming is €1–€2/kg H_2, adding CCS will cost €0.5/kg H2 as depicted in Figure 6.16. With the exchange rate of €1 = ¥155 (World Currency Shop, 2023), the cost for hydrogen production with a biomass price of €20/MWh still exceeds the METI target cost in 2050: ¥232–¥387.5/kg H_2 However, since biomass has other co-benefits in terms of carbon-negative emissions, there is a possibility of lowering the cost from the carbon market as CDR, which is under discussion at COP28 in Dubai, United Arab Emirates Arab (UNFCCC, 2023).

Figure 6.16. Biohydrogen from Gasification

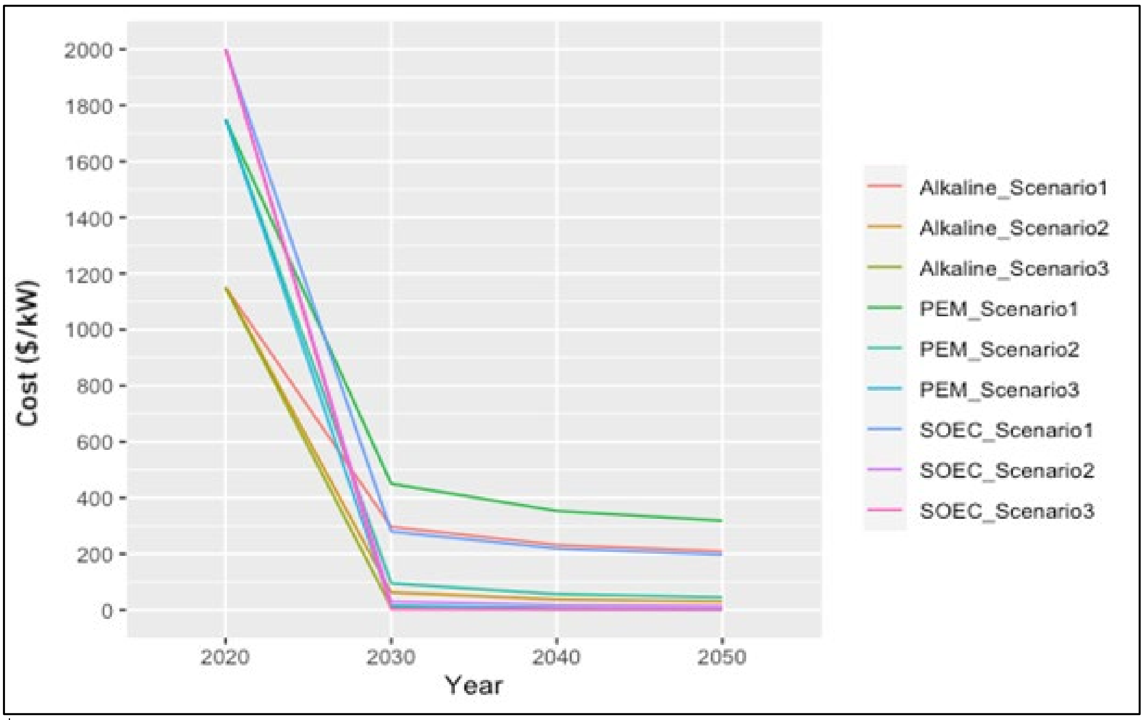


€= euro; CCS = carbon capture and storage; H2 = hydrogen; kg = kilogram; MWh = megawatt hour; SMR =.steam methane reforming.
Source: Lundgren, (2023).

4.2.2. The Electrolysis Cost

The highest component cost when producing green hydrogen from renewable energy sources (solar PV, offshore and onshore wind, geothermal, biomass) is the electrolysis cost, followed by the electricity cost relative to the location where it is produced (Galimova et al., 2023). Electrolyser technology, which can use electricity to split water into hydrogen and oxygen, is critical for producing low-emission hydrogen from renewable or nuclear electricity. This technology has grown rapidly in the past few years (IEA, 2023a). Amongst all three existing technologies, the solid oxide electrolyser cell delivers the lowest cost ($0.62/kilowatts (kW) in 2050) followed by alkaline technology ($3.02/kW) and polymer electrolyte membrane technology ($4.58/kW) in Scenario 3. In Scenario 2, the electrolyser costs in 2050 will be $13.95/kW, $29.72/kW and $45.14/kW, respectively. In Scenario 1 the electrolyser costs will be $197.76/kW, $209.35/kW and $318.32/kW (Figure 6.17 and Table 6.6).

Figure 6.17. The Technological Learning from Electrolysis Technology



$ = US dollar; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolyser cell.
Source: Author's calculations, based on cost data from IEA (2020).

Table 6.6. The Technological Learning from Electrolyser Technology

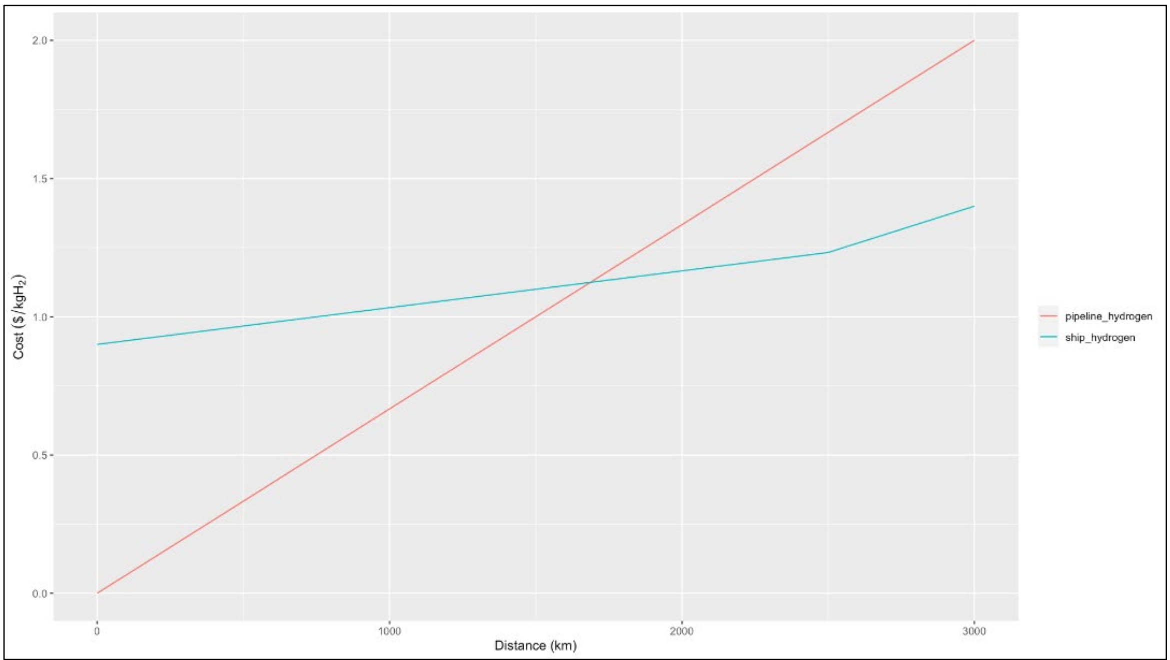
	Cost (USD/kW)	2020	2030	2040	2050
Alkaline	Scenario 1	1150	296	232	209
	Scenario 2	1150	63	37	29
	Scenario 3	1150	10	4	3
PEM	Scenario 1	1750	450	353	318
	Scenario 2	1750	95	56	45
	Scenario 3	1750	15	7	5
SOEC	Scenario 1	2000	280	219	198
	Scenario 2	2000	29	17	14
	Scenario 3	2000	2	1	1

$ = US dollar; kW = kilowatt; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolyser cell.
Source: Authors calculations based on electrolyser technology cost data from IEA (2020).

4.2.3. Transport Cost

While hydrogen production in Japan is not sufficient to fulfil the targeted demand, there is a possibility that additional costs, such as transportation, would be incurred due to imported hydrogen from overseas. Figure 6.18. shows the cost of storage and long-distance transportation of hydrogen by ship and pipeline. For every kilometre in transport distance, the hydrogen transported by pipeline tends to have a higher cost than hydrogen transported by ship. The shipping cost will be from $0.90, $1.00, $1.10, $1.10, $1.20, and $1.40 /kg H2 for 500km, 1,000km, 1,500km, 2,000km, 2,500km, and 3,000 km respectively, while the transport cost through a pipeline is $0.30, $0.70, $1.00, $1.30, $1.70, and $2.00 for the same distances. Pipeline costs will be lower than shipping costs for distances up to 1,700 km. After that, shipping costs are the less expensive option. The maritime shipping industry is one of the most conservative industries with small margins and it is hard to decarbonise (IMO, 2023). By implementing net-zero GHG emissions in the shipping industry, the cost will decline further in the long run.

Figure 6.18. Costs of Storage and Long-Distance Hydrogen Transport



$ = US dollar; kgH_2 = kilogramme of hydrogen; km = kilometre;
Source: Author's calculations, based on the transport cost data from IEA (2019).

5. Conclusion and Outlook

It is possible that Japan's relatively high energy intensity level implies lower energy efficiency technologies for consumption and production; lower commitment to promoting energy-saving behaviours, technologies, and systems; and more energy consumption for non-economic activities. Despite Japan's high renewable energy supply growth, the increase cannot match the faster growth of energy demand illustrated by the small shares of the national energy mix. The newly enacted GX Policy in December 2022 will enhance Japan's commitment to sustainable energy for all and its ability to meet the SDG targets. Regarding sustainable energy regulation, Japan must improve its renewable energy, i.e., network connection, pricing, connection and cost allocation; renewable grid integration; energy efficiency (incentives and mandates); financing mechanisms; and building energy codes. Japan has already committed to raising its government budget towards the transition to a green economy and sustainable development while prompting a just transition through a reduction in fossil fuel subsidies; improvement in spending on R&D environmental protection, particularly those promoting renewable energy; and enhancement of environmental taxes.

CCUS is one of the key policies in GX that combines CO2 from industry with hydrogen. Achieving clean hydrogen is important through fossil fuel with CCS or renewable energy sources. This study highlights the significant advances in hydrogen production technology and the economic feasibility of several methods in the run-up to 2050. The learning curve has significantly reduced the cost of hydrogen production, with coal combined with CCS emerging as the most cost-effective option at $0.03/kg H2, followed by natural gas with CCS at $1.18/kg H2, and solar PV at $1.66/kg H2 under Scenario 3. METI's target hydrogen cost of ¥222/kg H2 ($1.59/kg H2) is achievable mainly through coal and natural gas with CCS, showing the crucial role these technologies will play in Japan's energy strategy. The electrolyser technologies that are critical for low-emission hydrogen production from renewable or nuclear electricity show promising cost reductions, particularly the solid oxide electrolyser cell that is projected at $0.62/kW by 2050 in Scenario 3.

A study of transportation costs shows that while pipeline transport is initially cheaper, shipping becomes more cost-effective for distances beyond 1,700 km. The transition to net-zero GHG emissions in the shipping industry is likely to further decrease these costs. Japan's green transformation, supported by the newly enacted GX policy, promises significant economic benefits. By fostering partnerships with Southeast Asian countries for hydrogen production, Japan can secure a sustainable and economically viable energy future. Robust capacity-building, including the development of digital skills, will be essential to reach these goals.

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