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Policy Design for Diffusing Hydrogen Economy and Its Impact on the Japanese Economy for Carbon Neutrality by 2050: Analysis Using the E3ME-FTT Model

Xu Han [1,*], Pim Vercoulen [2,3], Soocheol Lee [4,*], Aileen Lam [5], Shinya Kato [6] and Toru Morotomi [1]

[1] Graduate School of Economics, Kyoto University, Kyoto 606-8501, Japan
[2] Cambridge Econometrics, Cambridge CB1 2HT, UK
[3] Global Systems Institute, University of Exeter, Exeter EX4 4QE, UK
[4] Faculty of Economics, Meijo University, Nagoya 468-0073, Japan
[5] The World Bank, Washington, DC 20433, USA
[6] Faculty of Economics, Yamaguchi University, Yamaguchi 753-8511, Japan
[*] Correspondence: xuhan.economics@gmail.com (X.H.); soolee011@gmail.com (S.L.)

Abstract: To achieve carbon neutrality in Japan by 2050, renewable energy needs to be used as the main energy source. Based on the constraints of various renewable energies, the importance of hydrogen cannot be ignored. This study aimed to investigate the diffusion of hydrogen demand technologies in various sectors and used projections and assumptions to investigate the hydrogen supply side. By performing simulations with the E3ME-FTT model and comparing various policy scenarios with the reference scenario, the economic and environmental impacts of the policy scenarios for hydrogen diffusion were analyzed. Moreover, the impact of realizing carbon neutrality by 2050 on the Japanese economy was evaluated. Our results revealed that large-scale decarbonization via hydrogen diffusion is possible (90% decrease of CO_2 emissions in 2050 compared to the reference) without the loss of economic activity. Additionally, investments in new hydrogen-based and other low-carbon technologies in the power sector, freight road transport, and iron and steel industry can improve the gross domestic product (1.6% increase in 2050 compared to the reference), as they invoke economic activity and require additional employment (0.6% increase in 2050 compared to the reference). Most of the employment gains are related to decarbonizing the power sector and scaling up the hydrogen supply sector, while a lot of job losses can be expected in the mining and fossil fuel industries.

Keywords: hydrogen; carbon neutral; Japanese economy; E3ME-FTT model

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1. Introduction

1.1. Background

Decarbonizing energy consumption is necessary to achieve carbon neutrality in Japan by 2050. The Japanese government's 2050 energy plan calls for a complete decarbonization of the power sector, in which decarbonized electricity should be the focus, and the remainder should be hydrogen, methanation, and synthetic fuels [1].

To achieve Japan's decarbonization goals, renewable energy should be promoted as the main energy source on a large scale. Using feed-in tariffs (FITs), Japan aims to promote the utilization of renewables, such as solar, wind, and bio-based power generation [2]. However, achieving energy decarbonization for the entire economy has its challenges, including geographical constraints, the high initial costs of low-carbon alternatives, and limited decarbonization options in some sectors. The Japanese Ministry of Economics, Trade, and Industry (METI) has identified that low-carbon hydrogen has a key role to play in decarbonizing the Japanese economy and achieving its Net-Zero target [3]. The advantage of hydrogen over other decarbonization measures is its versatility. However, the disadvantage is that for many applications low-cost low-carbon alternatives already exist. Currently, the price of low-carbon hydrogen is too high to be competitive with fossil fuel prices, as it is 9, 10, and 37 times more expensive than oil, natural gas, and coal, respectively [4]. Therefore, large-scale cost reductions are required to ensure low-carbon hydrogen is competitive with other energy carriers. To that end, METI has announced targets to decrease the cost of hydrogen due to economies of scale and incremental innovation while increasing low-carbon production capacity [5], and has announced its intention to make funding available for hydrogen-related research and development (R&D), deployment, and infrastructure.

1.2. Hydrogen Roadmap towards 2050

In Japan's Roadmap to "Beyond-Zero" Carbon, the Japanese government intends to promote the use hydrogen in transportation, industry, and power generation, to achieve carbon neutrality by 2050. Additionally, the National Hydrogen Strategy [3] and Environment Innovation Strategy [6], which include hydrogen technology innovation, have been established for carbon neutrality. Hydrogen is a secondary energy source in the electricity, transportation, industrial, residential, commercial, and public services sectors. To improve the hydrogen ecosystem, hydrogen applications should be extended to ships, trains, trucks, and other transportation modes. Furthermore, industrial carbon capture and storage (CCS) is used to capture and store the carbon generated from methane and coal. However, 10–20% of carbon cannot be captured by blue hydrogen. Conversely, green hydrogen from renewable electricity via electrolysis does not generate carbon.

In 2020, Japan's primary energy consumption was mostly fulfilled by fossil fuels. Oil, coal, and natural gas had a 38%, 27%, and 24% share of the total, respectively, followed by biomass and waste, nuclear, solar and wind, hydropower, and geothermal energy at 4%, 3%, 2%, 2%, and 1% shares, respectively [6]. By 2050, the share of fossil fuels in the primary energy consumption profile is required to decrease or its subsequent emissions must be sequestered or offset. This is why the Japanese government is looking at hydrogen with interest. In 2017, Japan became the first country in the world to formulate a national hydrogen strategy [3].

There are ongoing projects at the METI and NEDO (New Energy and Industrial Technology Development Organization), for example, on the international hydrogen supply chain and domestic power-to-gas. Household fuel cells have already entered the Japanese market [7] and fuel cells for business and industry use, such as MIRAI of Toyota, were launched in 2017 [8]. In addition, Japan has built a liquefied hydrogen carrier before the rest of the world. Japan is also a leader in hydrogen power generation technology [5]. However, the Renewable Energy Institute concluded that Japan is far behind the goals of its hydrogen strategy launched five years ago [9]. The uptake of stationary and mobile fuel cells has been limited and hydrogen refueling stations have seen little use.

The Basic Hydrogen Strategy published in 2017 [3] (updated in 2023 [10]) and the First Strategic Plan [11] (the 2030 Action Plan toward 2050 and the 2050 Vision toward the realization of a hydrogen society) highlight Japan's focus on the hydrogen economy in its attempt to decarbonize its economy. The 2030 Action Plan toward 2050 entails the "development of international supply chains and development of domestic technology for producing hydrogen derived from renewable energy" [11]. Moreover, the 2050 vision toward realizing a hydrogen society requires the "Realization of CO_2-free hydrogen" [11]. The Basic Hydrogen Strategy [3] provides three phases to realizing a hydrogen society:

1. Phase 1: Fast expansion of hydrogen uses. Extensive diffusion of stationary fuel cells and fuel cell electric vehicles (FCEV). Playing a leading role in the global market for hydrogen and fuel cells.
2. Phase 2: introducing hydrogen power generation/establishing a large-scale hydrogen supply system (in the late 2020s).
3. Phase 3: establishing a CO_2-free hydrogen supply system using renewable energy sources or CCS (in 2040).

The METI clarified Japan's long-term strategy for different sectors [11]. The energy sector will realize a "Hydrogen Society" and promote CCS and CCUS/carbon recycling. The industry sector will use CO_2-free hydrogen to achieve "zero-carbon steel". Additionally, the transport sector will achieve the highest level of the environmental performance of Japanese vehicles by 2050 to achieve "Well-to-Wheel Zero Emission".

The Basic Hydrogen Strategy has goals on the use (mobility, power, and fuel cells) and supply sides (fossil fuel + CCS and green hydrogen) for the hydrogen economy. To achieve these goals, targets should be set up, such as increasing the efficiency of hydrogen-fired power generation from 26% to 27%. Furthermore, the METI has set a goal to decrease the cost of electrolysis systems from 200,000 JPY/kW (1.350 USD/kW) today to 50,000 JPY/kW (340 USD/kW) by 2030 through R&D and scaling up. The goal for conversion efficiency is 4.3 kWh/Nm^3 in 2030 from 5 kWh/Nm^3 today. To achieve these goals, the Japanese government seeks to roll out hydrogen-based applications in designated regions such as highlighted in the Hydrogen Town Plan of Namie-cho in Fukushima Prefecture [11].

The government of Japan's focus on promoting the transition to a hydrogen economy has been criticized by the Renewable Energy Institute (REI). After the first formulation of the Basic Hydrogen Strategy in 2017, the REI argued that it was at odds with global hydrogen strategies and transition strategies [9]. After the revision of the Basic Hydrogen Strategy in 2023, the REI acknowledged that the strategy had caught up on some of the global trends with respect to hydrogen. However, the strategy still relied on low-priority applications (e.g., stationary fuel cells in domestic homes and private passenger fuel cell vehicles), had an overreliance on grey and blue hydrogen (produced from natural gas without and with CCS, respectively), and a delay in expanding green hydrogen production [12].

1.3. Proposed Hydrogen-Related Policies

The Japanese government provides robust funding for research, development, demonstration, and deployment, and keeps its technology options open [13]. In 2020, the funding for hydrogen research included JPY 26.4 billion (USD 179 million) for clean energy vehicles, JPY 4 billion (USD 27 million) for residential fuel cells and fuel cell innovation, JPY 5.25 billion (USD 35 million) for innovative fuel cell R&D, JPY 3 billion (USD 20 million) for hydrogen supply infrastructure R&D, JPY 12 billion (USD 81 million) for FCEV refueling stations, JPY 14.1 billion (USD 95 million) for the development of hydrogen supply chains, and JPY 1.5 billion (USD 10 million) for hydrogen production, storage, and usage technology development [13]. In the news published by the METI's Tokyo "Beyond-Zero" Week 2021 Held [14], a Green Innovation Fund of JPY 2 trillion (USD 13.5 billion) has been established to encourage companies to conduct R&D and to facilitate the deployment of carbon neutrality by 2050.

To establish a hydrogen supply chain and green hydrogen, USD 2.7 billion and USD 700 million will be invested, respectively. Japan aims to expand the hydrogen market from 2 million tons annually to 3 million tons annually by 2030, to 12 million tons annually by 2040, and 20 million tons annually by 2050. Additionally, Japan plans to decrease hydrogen costs by one third in 2030 [13].

Furthermore, the subsidy's upper limits for promoting the introduction of clean energy vehicles such as EVs, light EVs, plug-in hybrid electric vehicles (PHEVs), and FCEVs are JPY 650,000 (USD 4400), JPY 450,000 (USD 3000), JPY 450,000 (USD 3000), and JPY 2.3 million (USD 15,500), respectively [3].

The Japanese government will develop 1000 hydrogen refueling stations for FCEV [15]. From Japan's Roadmap to "Beyond-Zero" Carbon [16], Japan must overcome several challenges to become a full-fledged hydrogen energy source. For example, Japan should broaden its hydrogen applications to ships, trains, and trucks and build a ubiquitous hydrogen ecosystem. Furthermore, hydrogen will become more affordable in Japan by establishing a global supply chain, building on-site storage facilities, and validating hydrogen production setups. Moreover, strengthening R&D is vital, including the strategic development of human resources. The New Energy and Industrial Technology Development Organization is searching for 500 researchers to oversee the Zero Emissions Creator 500 program [16].

Japan seeks secure access to hydrogen; therefore, various hydrogen sources have been tested. Hydrogen supply chains are currently based on fossil fuels [13]. Moreover, Japan plans to establish a manufacturing technology base by 2030 to produce hydrogen from renewable domestic sources [13]. However, the METI [11] states that it is necessary to "supply at low-cost (the price equivalent to natural gas) and low-carbon hydrogen for production, transportation, and storage to expand industrial use".

1.4. Modelling the Promotion of the Hydrogen Economy in Japan

Various studies have investigated how the hydrogen economy could develop in Japan. The multi-sectoral open-source Global Energy System Model (GENeSYS-MOD) and power system dispatch model are applied in Burandt [17] to analyze the necessity of importing hydrogen for Net-Zero emission in Japan. According to the analysis, Net-Zero emissions in 2050 can be achieved via a transition to hydrogen-based industry and transport. Importing hydrogen will also help develop the energy system. Consequently, the policy of focusing on green or blue hydrogen for global hydrogen markets is suggested.

A global and long-term intertemporal optimization energy model (GRAPE) is used in Ishimoto et al. [18] to analyze global hydrogen demand. They found that a large number of fossil fuels are substituted by other low-emission energies. Among them, the demand of global hydrogen will be 2.4 trillion Nm3 by 2050, and it will be mainly used by the transportation sector. On top this, hydrogen power plants will also be launched in Japan.

There are more studies, such as the AIST MARKAL model is used in Ozawa et al. [19] to analyze the role of hydrogen in the future energy systems of Japan for realizing environmentally sustainable economies. To achieve the 80% emission reduction target in 2050, the electricity sector must achieve almost zero emissions, and hydrogen power generation is crucial. Moreover, developing other low carbon technologies is required for establishing the hydrogen economy.

The energy system transition is the key to achieving an 80% reduction of emissions by 2050. The six energy–economic and integrated assessment models are applied for analyzing decarbonization in the energy system in the research of Sugiyama et al. [20]. The simulation result shows that marginal costs of emission reduction in Japan are high. Additionally, since the industry sector has a large final energy share, it is the most difficult sector in which to achieve emission reduction. Along with this result, importing of hydrogen and other carbon-free energy is a good choice for Japan.

Most economic models or integrated assessment models, like the ones mentioned above, build on the Neoclassical school of thought. Mercure et al. provide a detailed overview of various types of macro-economic models [21]. In brief, macro-economic models that build upon Neoclassical theory usually show the following features: central to the models lie a production function that is optimized; in accordance with Say's Law, prices adjust to clear the market; the supply of money builds on the loanable funds theory; agents behave rationally; economies operate at equilibrium, at least in the long-term; and involuntary unemployment does not exist, among others. These features have implications on climate change policy. If economies operate at equilibrium and at full capacity, then any change will lead to a negative impact initially. Due to the optimizing nature of such models, they tend to shed light on how the economy ought to develop given the assumptions.

In E3ME-FTT, the flow of logic and assumptions are different. The model follows post-Keynesian school of thought and builds upon effective demand. Economic relationships are built on timeseries data. Prices and wages can be sticky, involuntary unemployment can exist, money can be created without leading to full-crowding out [22], and economies per se do not operate at equilibrium. Therefore, policies can be used to unlock underutilized capital or employment and may lead to positive economic outcomes. E3ME-FTT is better suited for investigating economic impacts due to policies focused on promoting decarbonization and the hydrogen economy, because it considers the likely outcome, and it does not rely on restrictive assumptions.

In this study, we design a policy scenario in line with policies proposed by METI, and we evaluate its impacts on GDP, employment, technological diffusion, and emissions using the Energy-Economy-Environment Macro-econometric (E3ME)-Future Technology Transformations (FTT) model. The suite of FTT models allows us to investigate the diffusion of hydrogen-demanding technologies under the influence of the policy settings, and it covers power generation (FTT:PG), passenger road transport (FTT:PRT), freight road transport (FTT:FTR), residential heating (FTT:Heat), and the iron and steel (FTT:Steel) sectors. Hydrogen supply is represented through a set of projections and informed assumptions. Through connection with the E3ME model, we can investigate the macro-economic impacts of realizing carbon neutrality by 2050 in Japan.

1.5. Aim of This Study

The aims of this study are two-fold: (1) to propose a set of policies that mimics the METI's proposed policies and aimed at assisting in promoting hydrogen demand in the Japanese economy, alongside policies aimed at achieving Net-Zero emissions; (2) and what the likely impacts of promoting a hydrogen-based economy would be which is in line with Japan's hydrogen strategy. This study does intend to show the optimal pathway to a hydrogen economy, nor does it make claims about alternative modes of decarbonization (e.g., direct electrification).

2. Methodology

2.1. Outline of E3ME-FTT

We used the Energy–Environment–Economy Macro-econometric (E3ME) model and the submodules of Future Technology Transformation (FTT) to evaluate the response of the Japanese economy to policy packages aimed at decarbonization. The E3ME-FTT model divides the world into 71 regions, with the major economies being represented individually, including Japan. The E3ME is a demand-led macro-econometric simulation model that estimates the components of effective demand, leading to supply through the national accounts framework. Additionally, energy demand in the broad sector is determined econometrically and responds to price feedback, economic activity, and investment [23].

Applying the econometric approach to determine energy use can be problematic, as its energy use relates to technology deployment, and technology diffusion can be sudden, demonstrated by it following the characteristic S-curve [24]. Therefore, FTT was first developed for the power sector (FTT:PG) [25], followed by modules for passenger road transport (FTT:PRT), freight road transport (FTT:FRT), residential heating (FTT:Heat), and the iron and steel sector (FTT:Steel). Each module describes technological changes based on evolutionary economics. Consistent with the evolutionary nature of FTT, technology diffusion is path-dependent. The core mechanism depends on pairwise comparisons of the two technologies by evaluating past market shares, agent preferences, and substitution frequencies [26] to determine technology uptake. The detailed nature of FTT modules allows for various policy interventions to steer decision-making.

Simulation-based modelling is preferred above optimization and/or equilibrium modelling due to the nature of the research objective. Here, the objective is to design a policy scenario to achieve Net-Zero emission with a focus on promoting demand-side hydrogen technologies, and to investigate its effects on technology diffusion, GDP, employment, and emissions. Hydrogen-based technologies are potentially disruptive and optimization and/or equilibrium modelling is then less suited as a tool. See Grubb et al. [27] and Barbrook-Johnson et al. [28] for a more detailed discussion.

Figure 1 presents a schematic overview of the linkages between E3ME and the FTT submodules. Depending on the energy resource depleted (renewable or renewable resources), the costs of primary energy sources can be estimated. This is fed into the individual FTT submodules, which are incorporated into the decision-making process and affect technology diffusion in each represented sector. Moreover, economic consequences, such as investments, price feedback, and final energy use, are fed into the E3ME, which reports back demand (for example, electricity) to the FTT modules. E3ME-FTT allows for a myriad of policies to be incorporated that can interact with each of the subcomponents.

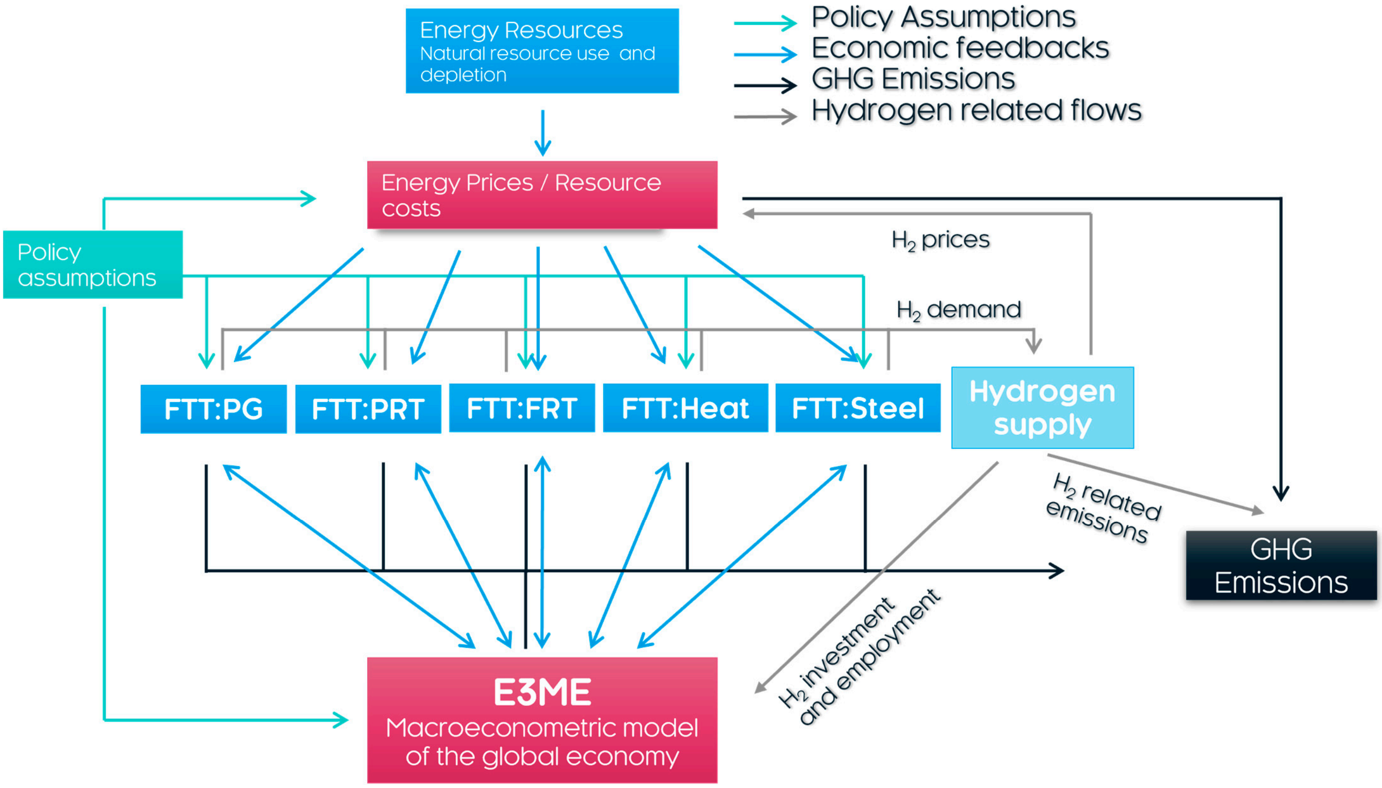

Figure 1. Schematic overview of E3ME-FTT. **Note**: PG: power generation; PRT: private road transport; FRT: freight road transport; Heat: residential heat; Steel: iron and steel industry; GHG: greenhouse gas.

Hydrogen demand and supply determine the price of hydrogen, which affects energy prices/resource costs. Due to limited data constraints, the hydrogen price and supply are set up exogenously to estimate hydrogen demand. The uptake of hydrogen-demanding technologies can be estimated by feeding hydrogen price projections into the FTT submodules. The total hydrogen demand levels determine the utilization of the projected domestic hydrogen production capacity. Investment in ramping up hydrogen production capacity and employment to operate the facilities are fed back to E3ME. Additionally, hydrogen supply leads to hydrogen investment and employment in the E3ME. Therefore, we represented the hydrogen supply industry using exogenous prices, exogenous market share of production methods, and exogenous employment [29] and investment factors [30]. The hydrogen supply sector is represented by the following projections published by the METI.

2.2. Reference Scenario

The reference scenario in this study is calibrated to the reference scenario of the IEEJ Outlook 2021 and aligns with "current policies", indicating a continuation of the current policies. Additionally, the reference scenario does not involve staying in the current situation or using additional special technology. Additional special technology that would lead to an exit of the trajectory which was not considered. Thus, the reference scenario will clarify the trajectory and future effects of current policies and technology. Therefore, it is counterfactual for investigating policies to achieve Net-Zero emissions by 2050 in Japan.

Groups of policies were established in the policy scenarios. Next, we compared the reference scenario with the policy scenarios to determine whether the policy scenarios cause energy, economy, and industry changes, the extent of their effect, and whether carbon neutrality can be achieved by 2050.

The important indicators of the reference scenario are listed in Table 1, including gross domestic product (GDP), final energy consumption, power generation, and CO_2 emissions. Under the IEEJ Outlook 2021 reference scenario [31], the global economy experienced negative growth in 2020 due to the impact of COVID-19. However, COVID-19 is not expected to affect the global economy significantly after 2021. Additionally, positive growth and the economic growth rate will return. Under this assumption, the Japanese GDP growth rate from 2018 to 2050 will be 0.7%, as the GDP growth rate from 1990 to 2018 was 1.0%. Japan's GDP will increase from USD 6190 billion in 2018 to USD 7740 billion in 2050 (based on 2015 prices). Primary energy consumption includes oil, natural gas, coal, and renewables, including nuclear energy and hydropower. Japan's final energy consumption will decline from 283 Mtoe in 2018 to 224 by 2050. Moreover, the two largest power generators, coal- and LNG-fired, will decrease to 198 and 288 TWh in 2050, respectively. To make up for the reduction in coal-fired, oil-fired, and LNG-fired power generation, power generation from other sources will be increased; notably, wind power generation was increased to 7.5 TWh in 2018 and 64 TWh in 2050. Furthermore, energy-related CO_2 emissions at the reference scenario will fall gradually from 1080 million tons in 2018 to 738 million tons in 2050.

Table 1. Important indicators of the Japanese economy and energy prediction by IEEJ Outlook 2021 [31].

	2018	**2030**	**2040**	**2050**
GDP (USD billion, 2015 prices)	4485	4850	5242	5611
Final energy consumption (Mtoe)	283	263	244	224
Power generation (TWh)	1050	1079	1093	1082
Coal-fired	339	291	289	262
Oil-fired	52	21	2.0	-
LNG-fired	378	329	330	288
Nuclear	65	157	141	141
Hydroelectric	81	91	94	94
Geothermal	2.5	6.0	9.7	13
Solar	63	87	106	123
Wind	7.5	18	32	64
Biomass Waste	44	60	70	78
CO_2 emissions (million tons)	1081	940	852	738

Source: IEEJ [31].

2.3. Hydrogen-Based Net-Zero Scenario

This study investigates the economic and environmental impacts of promoting a hydrogen economy to achieve Net-Zero emissions by 2050 in Japan. We included policies announced by the Japanese government that align with the Net-Zero trajectory. Table 2 provides an overview of the scenario settings. Various policies were included, from penalizing taxes to promoting subsidies aimed at decarbonization through electrification and hydrogen-based solutions. Therefore, the policies focus on decarbonizing the power and hydrogen supply sectors.

Hence, we followed the Government Power Mix Plan (GPMP) for specific power generation technologies. Other low-carbon and renewable power generation sources were promoted through these policies. The hydrogen supply was represented exogenously. Policies promoting hydrogen demand have focused on transportation, iron, and steel. The Net-Zero scenario is based on a decarbonization policy scenario (policy scenario I) for achieving carbon neutrality in Japan [32]. Moreover, we implemented additional policies to promote hydrogen-based technologies.

Table 2. Summary of policy inputs in the policy scenario.

Policy/Setting	Sectors	Description
Carbon tax (from 2021 onward)	All sectors	Carbon tax gradually increasing from USD 50/tCO_2 in 2023 to reach USD 410/tCO_2 in 2040 (2010 prices), and constant thereafter.
Government power mix plan	Power	Government power mix plan of 2030 and 2050.
Kick-start for BECCS and hydrogen	Power	A program to support BECCS and hydrogen plants by setting up a small-size demonstration plant in the first few years.
Hydrogen or ammonia blending in coal and gas power plants	Power	From 2025 a mix of fossil fuels and ammonia or hydrogen is used in fossil-fueled power plants. The blending percentage grows to 25% by 2050.
Ban on petrol and diesel engines by regulation	Road transport	Ban sales from 2035 onward.
Biofuel mandate	Freight and air transport	Increase the share of biofuels in the fuel mix.
ZEV subsidies for LDV	Passenger road transport	Subsidies given to EVs and FCEVs in the first few years. Battery EV: USD 8000, 10,000, 12,000/veh for economy, medium, and luxury vehicles, respectively. Plug-in hybrid EV: USD 4000, 5000, 6000/veh for economy, medium, and luxury vehicles, respectively. Fuel cell EV: USD 24,000/veh for all classes.
ZEV subsidies for HDV	Freight road transport	Subsidies given to EVs and FCEVs in the first few years. USD 30,000/veh on small trucks and USD 60,000/veh on large freight trucks.
FCEV mandates for HDV	Freight road transport	Mandate to kick-start FCEV HDV in the system. 10% of all truck sales are mandated to be FCEV by 2030 and 20% by 2035.
Energy efficiency investment	Buildings and industry	Similar level of investment under the IEA Sustainable Development Scenario.
Coal, gas, and oil boiler regulations	Buildings	Gradual ban of fossil fuel boilers by 2050.
Steel sector	Steel	Regulation of blast furnaces to gradually reduce to zero by 2050.
Kick-start for H2-DR-EAF	Steel	A program to support H2-DR-EAF plants by setting up a small-size demonstration plant in the first few years
Support for low-carbon steelmaking	Steel	Subsidies on low-carbon steelmaking (hydrogen-based and steel recycling); 50% on the upfront investment costs of hydrogen-based steelmaking, 40% of hydrogen energy, and 25% of electricity costs.
Hydrogen use in other industries	Industry	Substitution towards hydrogen for process heating. In line with the METI's strategy.
Processed emissions	Industry	Assume processed emission intensity reduced by 4% pa in the Net-Zero scenario.
Exogenous representation of hydrogen supply	Hydrogen supply	Based on targets set by METI, an exogenous pathway of hydrogen technologies is implemented.

Source: Produced by the authors. **Note**: BECCS, bioenergy with carbon capture and storage; EV, electric vehicles; FCEVs, fuel cell electric vehicles; HDV, heavy-duty vehicle; IEA, International Energy Agency; METI, Ministry of Economy, Trade and Industry.

The upfront costs of light- and heavy-duty FCEVs were subsidized. The biofuel and e-fuel blending mandates were added. Notably, heavy-duty vehicle manufacturers are exposed to sales mandates that require them to offer zero-emission vehicles. Additionally, subsidies have been implemented for hydrogen-based steelmaking and other low-carbon steelmaking technologies.

The power mix in the policy scenario aligns with the power mix plan of the sixth Strategic Energy Plan for 2030 and the proposal of the Growth Strategy Meeting [33] for

2050. This strategy envisions that the share of nuclear power in the electricity generation mix will grow to 20–22% by 2030, from a 6.2% share today. By 2050, the share of nuclear power decreases to 10% of the electricity supply. Renewables are envisioned to grow from 20% to 36–38% by 2030 and 60% by 2050. Additionally, a carbon tax was set up based on the current Climate Change Tax (JPY 289/CO_2t) [33].

This tax will be increased proportionally from 50 USD/tCO_2 in 2021 to 410 USD/tCO_2 in 2041 and remain constant after 2041. The carbon tax targets all sectors, including those not directly targeted by the policies listed in Table 2, and reduces residual emissions elsewhere in the economy to achieve Net-Zero emissions by 2050.

Carbon taxes generate revenue; however, most of the policies listed in Table 2 incur additional public spending. The treatment in the E3ME-FTT model assumes the revenue neutrality of the government balances. The key elements of the model are as follows:

- Policy revenues: carbon tax is in relation to taxable emissions.
- Policy costs: public energy efficiency investment, low-carbon technology subsidies, and stranded power plant assets costs.
- Net revenues are equal to the total policy revenues minus the total policy costs.

If the net revenues are positive, it is assumed that the will be to lower non-environmental tax rates. These revenues include income tax, value-added tax, and employer's social security contributions. However, if the difference is negative, the government is assumed to respond by increasing the same fiscal tax levers. Income tax affects consumer spending. VAT (value-added tax) rates affect end-use prices. Lastly, employer's social security contributions affect the cost of employment.

2.4. Hydrogen Supply Assumptions

We investigated a decarbonization scenario involving a push toward a hydrogen economy. This has consequences for the electricity and hydrogen supply sectors. Notably, E3ME-FTT does not include a detailed representation of the latter. Therefore, the representation of the hydrogen supply sector was based on the hydrogen price and supply target projections reported by METI (see Figure 2) [5]. The hydrogen price starts at JPY 100 JPY/Nm^3 and is expected to decline swiftly to 30 JPY/Nm^3 by 2030 and end finally at 20 JPY/Nm^3 in 2050. Over the same period, the hydrogen supply is projected to increase from 2000 kt in 2020 to 3000 kt in 2030, to 12,000 kt in 2040, and finally to 20,000 kt in 2050 [10].

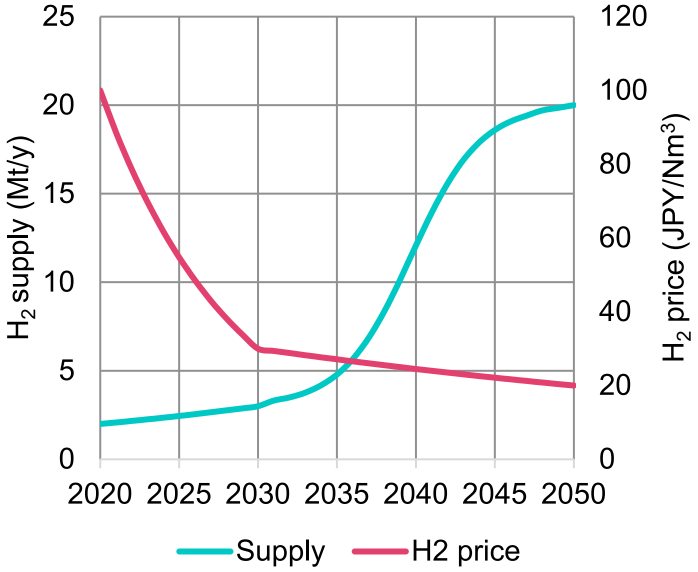

Figure 2. Projections of total hydrogen supply (left axis) and price (right axis). **Source**: METI [5].

Without a technology diffusion submodule, exogenous assumptions had to be made regarding the technology composition within the hydrogen demand and supply markets. In broad terms, the demand market can be divided into the feedstock market and the energy market. The former has already been established and hydrogen demand for feedstocks predominantly originates from the chemical industry, to produce ammonia and methanol, and from the oil refining industry in the hydrocracking process. The main issue with hydrogen supply statistics is that the bulk of hydrogen is presently produced on-site where it is needed—in the captive market. In these cases, hydrogen is used as a feedstock rather than an energy vector. The hydrogen supply statistics of captive markets are missing because hydrogen is the intermediary [21]. They have estimated that the captive market in Japan mostly consists of stream methane or naphtha reforming (approximately 1400 kt/y capacity in 2017); the merchant market was estimated to be considerably smaller (13 kt/y capacity, mostly steam methane reforming).

However, in this study, we investigated the transition toward an energy-based hydrogen economy in Japan. Therefore, a split should be assumed between the hydrogen supply destined for the non-energy and energy markets within the bounds of the hydrogen supply projection offered by the METI [5]. We assumed that the hydrogen demand of the non-energy market segments will grow with the combined economic activity of the chemical and oil refining sectors, which are expected to grow by 50% between 2020 and 2050 in the reference scenario setting. This implies that of the 20,000 kt of hydrogen expected by 2050, 17,000 kt will be potentially available for the energy market. In this study, we assumed that 17,000 kt of hydrogen is the maximum potential domestic production capacity. The split between hydrogen supply for the energy and feedstock (non-energy) markets is depicted in Figure 3. Figure 4 depicts market splits.

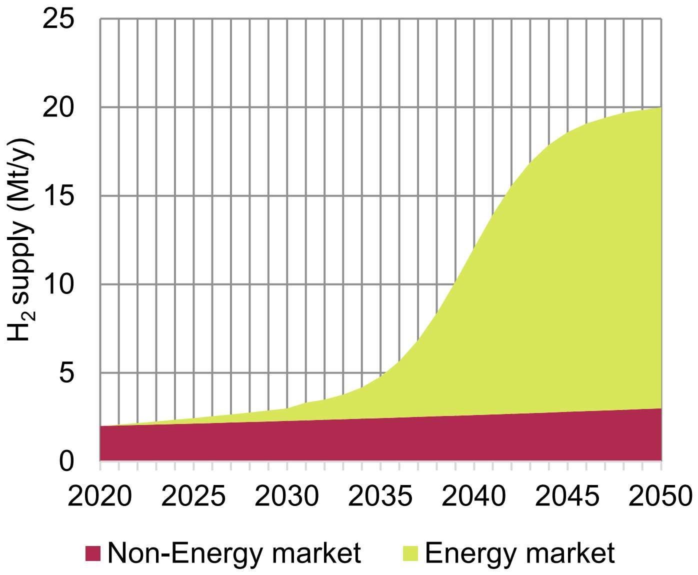

Figure 3. Market division of hydrogen supply flows. **Source:** Produced by the authors. **Note**: Supply to the energy market represents the maximum potential and its utilization depends on the simulated scenarios that dictate the hydrogen demand for energy purposes.

Without a hydrogen model, assumptions were also needed on the supply side of the equation. The International Energy Agency (IEA) hydrogen project database [34] shows that 2 kt/y of electrolysis capacity is currently operational through various demonstration projects. In 2019, a project with a capacity of 9.9 kt/y for steam methane reforming combined with CCS was demonstrated. These capacities are a fraction of the total current supply of 2000 kt/y H_2. In the 2023 version of the Basic Hydrogen Strategy, an electrolyzer capacity target of 15 GW by 2030 was quoted [10]. We assumed that the incumbent unabated steam methane reforming process will not decline before 2025. Only afterwards will it be gradually phased out by the abated variant and electrolysis. Furthermore, electrolyzer capacity will increase to slightly more than 100 GW by 2050. We fitted an S-shaped curve through the starting point, 2030 target, and assumed 2050 capacity level to electrolyzer diffusion. Together with assumptions about load hours and efficiencies, this leads to 6 Mt of green hydrogen production. Blue hydrogen increases to 8 Mt by assuming an average annual capacity growth rate of 26%. With a gradual phase-out of grey hydrogen, the bulk of the remaining hydrogen supply is sourced abroad (2.6 Mt by 2050). Note that the assumed imports in Figure 4 are developed to be in line with the supply projections reported by METI. In our scenario, the domestic production potential is fixed while demand is simulated. Hydrogen imports are calculated as the difference between demand and supply if the demand is greater than the supply.

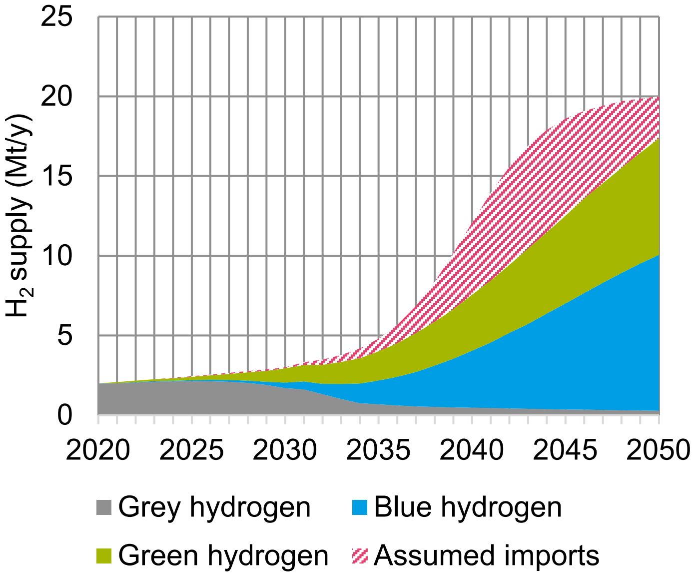

Figure 4. Representation of exogenous hydrogen supply in the Net-Zero scenario based on assumptions and targets set by METI. **Source:** Produced by the authors.

If the simulated hydrogen demand exceeds the potential domestic production capacity, we assumed that the remainder would be imported from partner regions that can supply hydrogen at lower costs. However, due to the lack of data, we assumed that such countries could produce hydrogen at 1 USD/kg or 12 JPY/Nm^3—an estimation within the range that was reported by the IEA [35]. Therefore, Japan's trade partners will likely be the ASEAN (The Association of Southeast Asian Nations) countries and Australia, implying that hydrogen will be transported over a distance of 3000–10,000 km.

According to the European Commission's Joint Research Center (Ortiz et al.), transport costs over such distances are estimated to be approximately 1 EUR/kg or 13.5 JPY/Nm^3 [36]. Converting these prices to per unit of ton of oil equivalent (toe), we estimate an initial hydrogen import price of 940 USD/toe. This is three times cheaper than the current hydrogen price of 2800 USD/toe (or 100 JPY/Nm^3). Figure 5 presents the import and domestic producer price projections used in this study. The LNG import price range between 2019 and 2022 is added for reference. It shows that it is unlikely that the hydrogen price will decline to below the LNG prices prevailing before the pandemic and the war in Ukraine.

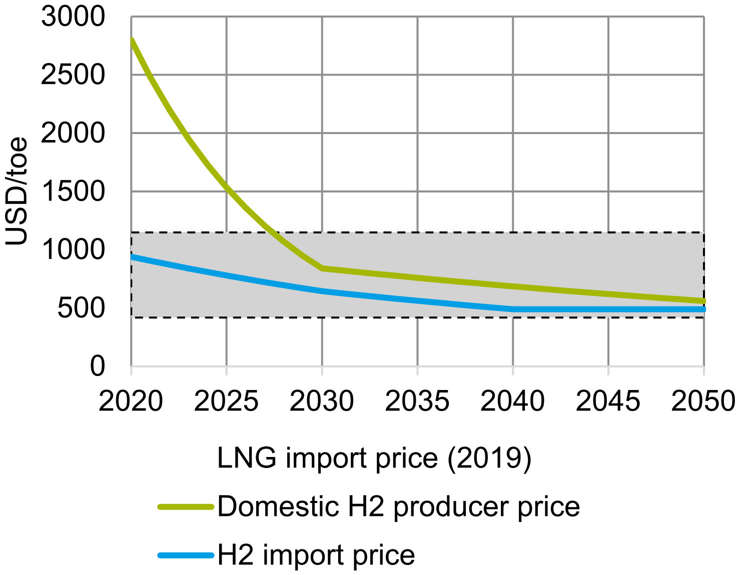

Figure 5. Comparison of the hydrogen price offered by the domestic hydrogen supply sector (dashed line) and the market prices faced by end-users. **Sources:** Compiled by authors. Import prices are based on the International Energy Agency [35] and European Commission's Joint Research Center [36] and assumptions. Domestic producer prices are in line with METI targets [5].

3. Results and Discussion

3.1. Technology Deployment

As shown in the reference scenario in Figure 6, current policies do not promote hydrogen-based technologies; therefore, the status quo is maintained and little to no diffusion of hydrogen-demanding technologies was observed. This changes when the policies supporting low-carbon technologies with a focus on hydrogen-based technologies are enabled.

While declining, power generation remained to be dominated by fossil-fueled technologies. Wind and solar experienced a gradual increase in their market share. However, when the decarbonization policies were enacted, wind and solar power quickly gained in market share as their comparative advantage increases due to carbon taxes and subsidies. From 2030 onward, stationary fuel cells diffused into the system as well as CCS applications of fossil-fueled power plants. Over the course of 2028 to 2050, the share of hydrogen blending into coal and gas power plants increased, which achieves further abatement of emissions.

Steel production gradually transitioned to recycling-based production in the reference scenario, but the conventional blast furnace-based process (BF-BOF) maintained a dominant market share as well. Only minute amounts of novel technologies were able to diffuse into the system in the policy context of the reference scenario. In the Net-Zero scenario, similar recycling levels were observed. Scrap recycling is limited by the availability of scrap and in both scenarios the availability was nearly exhausted. Decisions by steelmakers to transition away from carbon-intensive processes are mostly driven by the cost of inputs. Without policies to suppress those costs for low-carbon alternatives, it is unlikely that a widespread transition will occur. The policies in the Net-Zero scenario therefore assisted in the uptake of hydrogen-based steelmaking (DR-EAF-H2) and CCS applications. By 2050, a 23% market share of DR-EAF-H2 was achieved.

The residential heating sector saw a gradual increase in heat pumps without any policy support in the reference scenario. However, fossil-fueled boilers remained dominant with a 40% market share by 2050. The uptake of heat pumps was sped up by the policies in the Net-Zero scenario and led to a complete disappearance of fossil-fueled boilers. Under these conditions, there was also growth in the number of solar thermal installations.

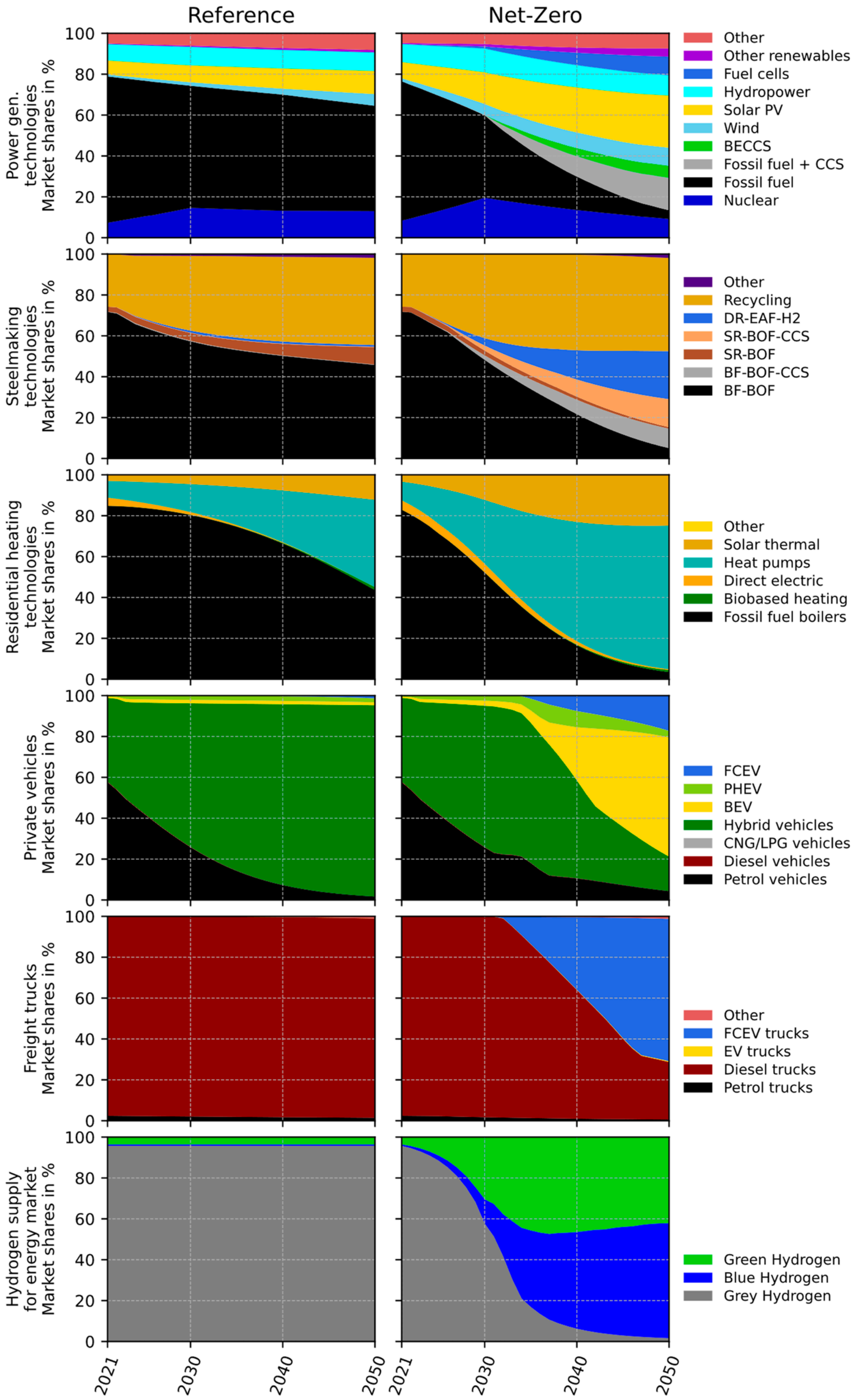

Figure 6. Market share developments related to hydrogen technologies within the relevant sectors. **Source**: Produced by authors. **Note**: CCS: carbon capture and storage; BECCS: bioenergy with carbon capture and storage; PV: photovoltaics; BF-BOF: the blast furnace-basic oxygen furnace; SR-BOF: smelting reduction-basic oxygen furnace; DR-EAF: direct reduced iron electric arc furnace; H2: hydrogen; CNG: compressed natural gas; LPG: liquefied petroleum gas; BEV: battery electric vehicle; PHEV: plug-in hybrid electric vehicle; FCEV: fuel cell electric vehicles; EV: electric vehicle.

In the passenger vehicle market, only a small number of FCEVs diffused into the passenger vehicle market in the reference scenario (from 0.01% in 2021 to 1.3% in 2050). At the moment, Japanese vehicle manufacturers are primarily focused on hybrid vehicles. Currently, nearly half of all vehicles driven in Japan are hybrid and our scenario shows that the diffusion of hybrid vehicles continues. This occurs despite rapidly falling battery costs which seems to lead to a tipping point in certain regions in favor of battery electric vehicles (BEVs) [37]. The lack of BEVs and FCEVs in the reference scenario can be linked to the limited number of BEV or FCEV options available to the Japanese car market [37]. In the Net-Zero scenario, the stagnant trend of BEV and FCEV uptake was overturned and driven by a ban on internal combustion engine vehicle (ICEV) sales. However, by 2030, we notes 40,000 FCEVs, which is much less than the 800,000 FCEV target set by METI [3]. Most of the vehicle sales by 2050 will be BEVs due to a better cost performance compared to alternatives. By 2050, the passenger vehicle market was simulated to consist of 80% BEVs and 18% FCEVs.

In the freight transport market, a homogenous technology configuration was observed which prevailed over the simulated timeline. FCEV trucks and EV trucks were too uncompetitive to gain any sizeable market share in the reference scenario. However, with policy support in the Net-Zero scenario, FCEV trucks diffused to a significant market share of 70%. This was predominantly driven by FCEV truck mandates on sales. Electric trucks were less likely to diffuse due to batteries being less suitable for heavy-duty vehicles. Emissions were further abated due to the remaining diesel-powered trucks running on a diesel fuel blend consisting of 50% biofuel.

Finally, hydrogen production is represented by exogenous assumptions. In the reference scenario, grey hydrogen was the dominant technology and mainly applied in the non-energy market segment as the hydrogen demand for energy purposes only constituted minute amounts. This was not the case in the Net-Zero scenario where a significant number of hydrogen-based technologies diffused into their respective markets due to policy support. The much larger volumes of demand were satisfied through an increasing share of low-carbon processes based on interpretations of the METI targets.

3.2. Energy Demand

The technology composition is determined via the FTT models, which leads to specific energy demand profiles (Figure 7). In the reference scenario, coal and gas demand remained dominant in the power sector, albeit with a gradual decline. This will change when the Net-Zero policy package is enabled, which shows a transition to renewables, BECCS, and hydrogen-powered fuel cells, leading to an increased energy input of solar energy, biofuels, and hydrogen (33 Mtoe/y by 2050). The remaining fossil fuel inputs will flow primarily into power plants with CCS systems and fossil fuel inputs are partially displaced through hydrogen blending; hence, emissions will be abated.

In the iron and steel sector, 23% of steel production will be hydrogen-based by 2050 in the Net-Zero scenario, amounting to 4 Mtoe/y of hydrogen demand. Other energy streams will move toward electricity due to the addition of electric arc furnaces, which are required for steel recycling and are part of hydrogen-based steelmaking. In residential heating, we noted a transition to heat pumps, leading to large-scale efficiency gains, as heat pumps can deliver 2–4 units of heat for every unit of electricity. This leads to lower overall energy demand.

In the reference scenario, the private vehicle market showed a small transition to BEVs and a large transition to hybrid vehicles. However, implemented subsidies, sales mandates, and biofuel blending mandates will increase the demand for biofuels and hydrogen (2 Mtoe/y by 2050) and nearly completely phase out oil ICEV and hybrid vehicles. Furthermore, since electric powertrains are more efficient than internal combustion engines, the total energy demand will be much lower (reduced by 30% in 2050 compared to the reference scenario). Due to subsidies and sales mandates, FCEV systems will gain traction in freight road transport; by 2050, freight road transport will require 3.6 Mtoe/y of hydrogen.

Similar to the private vehicle market, transitioning to electric powertrains (in the form of FCEVs) will lead to efficiency gains (a 62% reduction compared to the reference scenario in 2050).

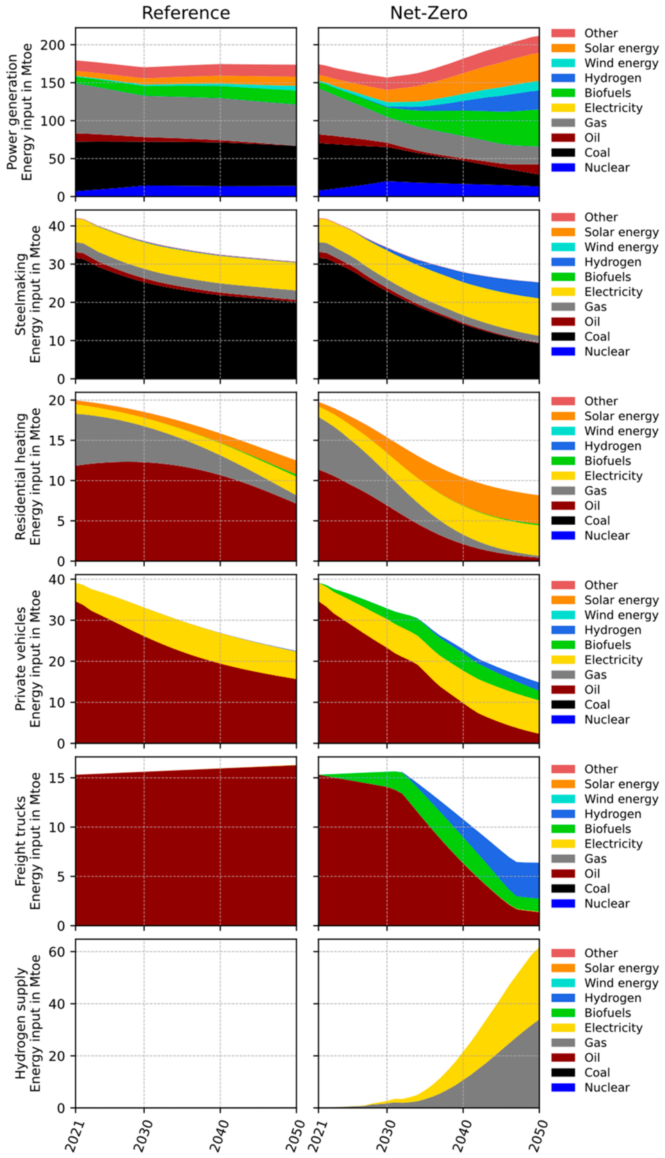

Figure 7. Energy input to the relevant sectors in the reference and Net-Zero scenarios. **Source:** Produced by authors.

Lastly, the hydrogen supply sector delivering energy to the energy market does not require energy, because there is no demand technology diffusion in the reference scenario. However, hydrogen-based technologies are promoted in the Net-Zero scenario; therefore, the demand for hydrogen increases. This invokes a sizeable demand for natural gas (in grey and blue hydrogen supply) and electricity (due to green hydrogen supply) to meet hydrogen needs by 2050. The total energy demand of the newly established hydrogen supply market for energy purposes will amount to 62 Mtoe/y by 2050.

Figure 7 shows the energy inputs to the sectors represented by the FTT models, but the excluded energy demand of the other sectors is represented by E3ME. The demand for hydrogen increased in these sectors, and it used other FTT sectors as a proxy. Furthermore, Figure 8 depicts the hydrogen demand across all sectors. The total demand for hydrogen outpaced the domestic production projection as interpreted from the METI's targets. In fact, the hydrogen demand outpaced the METI's total supply target between 2027 and 2038. All of this implies that hydrogen imports form a sizeable portion of the hydrogen supply.

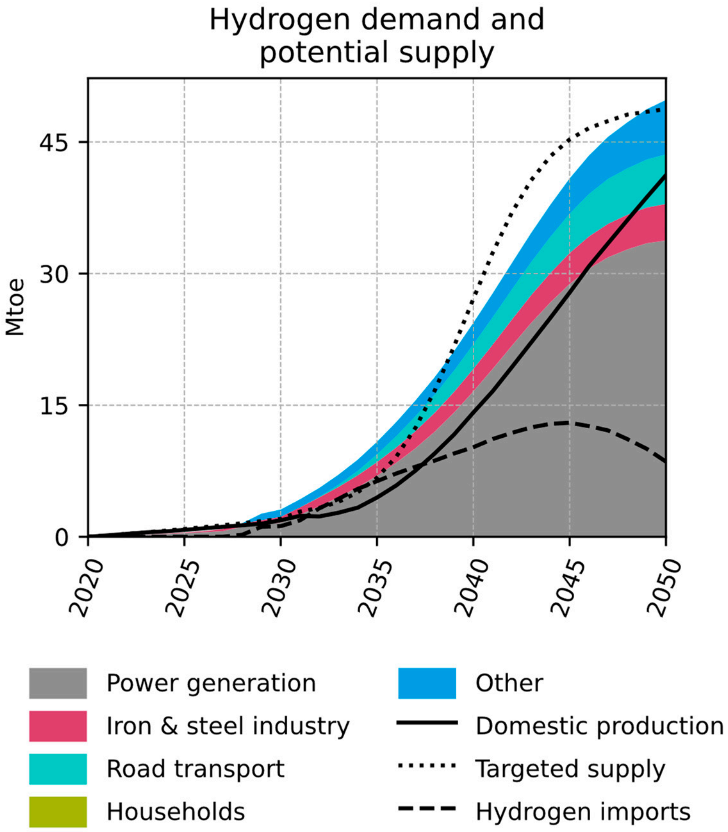

Figure 8. Hydrogen demand by segment versus domestic production, imports, and the METI supply targets. **Source:** Produced by authors. **Note:** Colored wedges indicate hydrogen demand by sector. The black solid line indicates the maximum potential domestic production, and the dashed line indicates the amount of hydrogen that needs to be imported.

3.3. Emissions

The decline in fossil fuel demand in the Japanese economy in the Net-Zero setting will lead to a large-scale reduction in emissions. Any remaining fossil fuels will be abated via CCS. Figure 9 illustrates the energy-related emission profiles of the reference and Net-Zero scenarios and the relative differences between them. In the reference scenario, the power sector remained the largest CO_2 emitter but gradually decreased by 30% between 2020 and 2050. This was largely driven by the continued uptake of renewable and nuclear energy. Moreover, emissions in the household sector halved during the same period, primarily driven by the use of heat pumps. Overall, the emissions declined steadily by 32% between 2020 and 2050 in the reference scenario.

The rate of decline will accelerate once the Net-Zero policy package is implemented. Due to the invoked technology diffusion, the power sector will be nearly completely decarbonized by 2050. Compared to the reference scenario in 2050, the iron and steel industry will show a reduction of 93% owing to the increased uptake of hydrogen-based steelmaking and scrap recycling. Furthermore, emissions from road transport (passenger and freight road transport) will decrease by 80% due to a transition toward FCEVs. Emissions will decrease by 90% in 2050 compared to the reference scenario. This leaves residual emissions of 78 Mt of CO_2, which we assume would be absorbed by land-use-related emission mitigation.

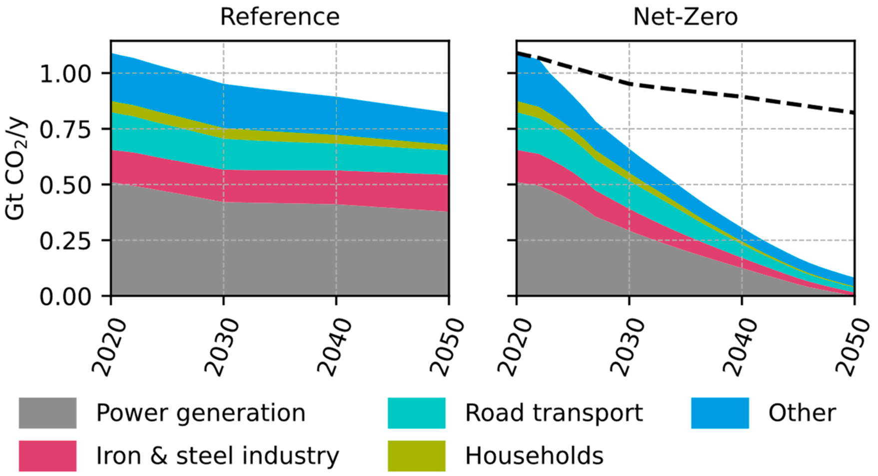

Figure 9. CO_2 emission levels in the Reference and Net-Zero scenarios. **Sources:** Produced by the authors. **Note:** The "Other" category includes agricultural, manufacturing, commercial and service industries. "Road transport" includes both passenger road transport and freight road transport.

3.4. Gross Domestic Product and Employment

The detailed simulation presented in this study leads to economic feedback that affects GDP. Figure 10 shows the absolute differences in GDP and its components between the Net-Zero and reference scenarios. Investment which are propelled by the policies in new buildings (power plants and electrolysis capacity) and equipment (heat pumps and FCEVs) will positively impact GDP. Additionally, this investment will create jobs which, together with wage effects, will increase disposable income, as reflected in consumer expenditure.

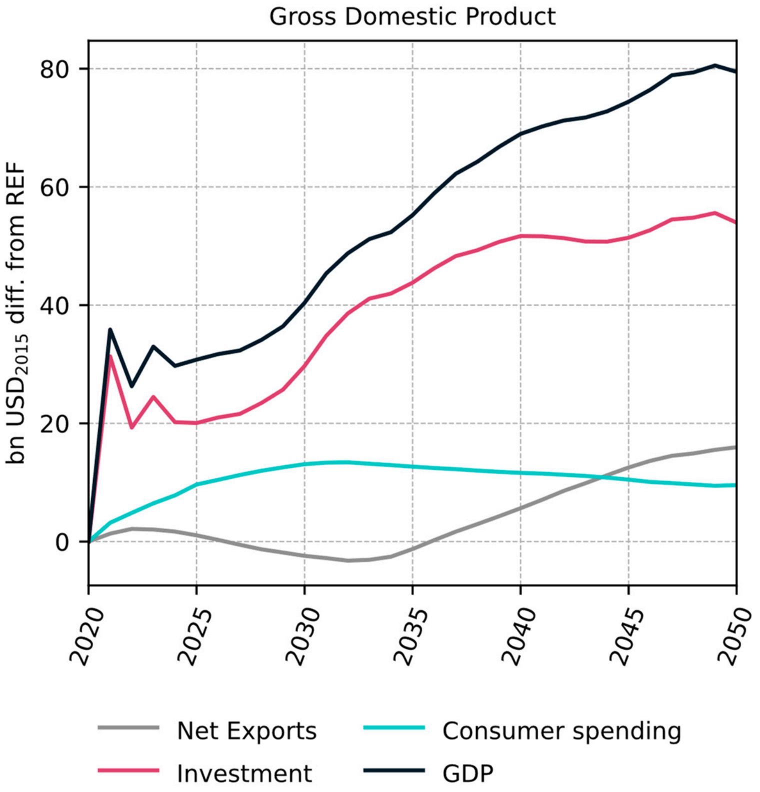

Figure 10. Absolute difference of GDP and its components between the Net-Zero and Reference scenarios. **Source**: Produced by the authors.

However, there is also a negative effect on consumer expenditure. Price levels increase due to the carbon tax and exposure to higher energy costs, initially. This is counteracted by lower fiscal rates as the carbon tax revenues are greater than the policy costs up to 2043 (see Appendix A). The transition also leads to job creation and increases households' disposable income. Overall, consumer spending changes are positive compared to the reference scenario over the simulation period, with a peak around 2030.

The net trade balance also improves by 2050 due to prevented fossil fuel imports. However, Japan will require sizeable hydrogen import volumes to satisfy demand. This will lead to a negative trade balance between 2030 and 2035, as there will also still be a reliance on fossil fuel imports during that period. Afterwards, fossil fuel imports will decline rapidly, tipping the balance in favor of Japan.

The Net-Zero policy package presented in this study will lead to widespread changes in the energy system through technology substitution and energy efficiency. Additionally, the package will reshape demand and supply profiles, which will have consequences for employment. As shown in Figure 11, transitioning to low-carbon technologies will likely impact jobs positively, most notably in the power, hydrogen supply, and construction sectors. Additionally, this development will benefit the power and hydrogen supply sectors due to an increase in variable renewables in the power sector, associated with high employment factors and the creation of a novel hydrogen supply sector. Employment in construction will increase due to the additional fixed gross investment, which involves building new power plants, installing solar PV panels, and electrolysis for hydrogen production. Finally, employment in fossil fuel-related industries will decrease compared to the reference scenario.

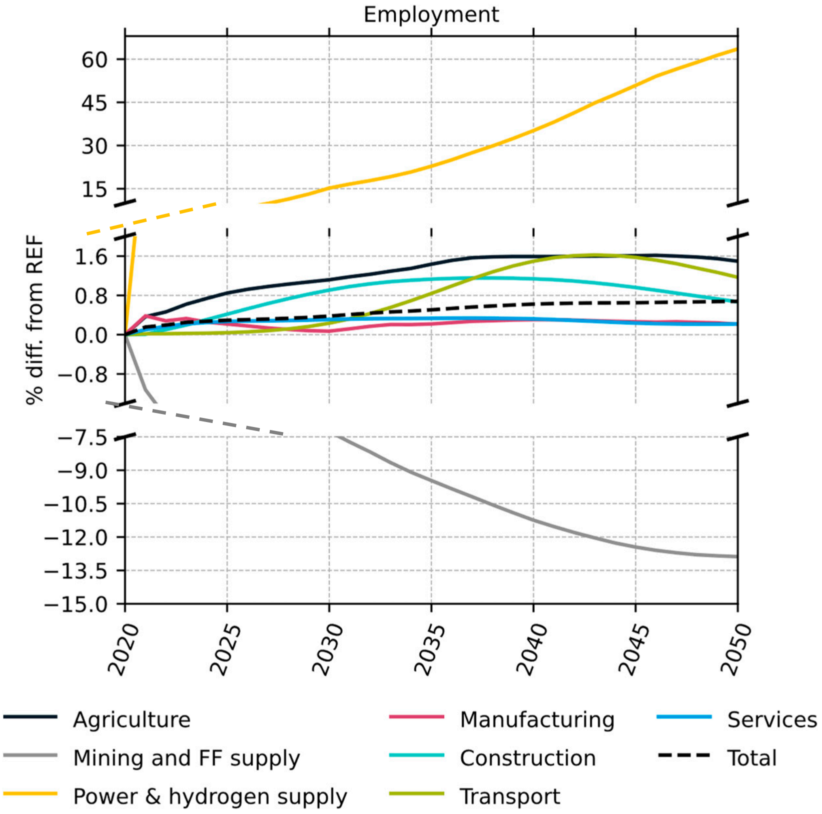

Figure 11. Relative employment differences between the Net-Zero and Reference scenarios. **Source:** Produced by authors.

4. Conclusions and Challenges

Our results showed that Japan has much to gain from decarbonization in a Net-Zero scenario with a focused transition toward a hydrogen economy. First, the hydrogen diffusion (Net-Zero) scenario showed that large-scale decarbonization is possible without losing economic activity; notably, economic benefits are expected in our simulations. Second, many policies are focused on electrification and hydrogen-based applications, and both technology groups will see a large increase in the relevant energy systems. Hydrogen technology demand will gain traction in the power, freight road transport, and iron and steel industries. Approximately 12% and 34% of all energy inputs will be hydrogen and electricity, respectively. Third, the economic impacts were positive across the board, as the Net-Zero policy package indicates that employment and most GDP components had favorable results compared to the reference scenario. Investments in new hydrogen-based and other low-carbon technologies improved GDP as they invoke economic activity and require additional employment. Moreover, transitioning away from fossil fuel imports leads to a favorable energy trade balance, despite requiring hydrogen imports, which is supported by Mercure et al. [38].

However, this study has some caveats. The simulation suggests that transitioning to a Net-Zero emissions requires considerable investment; notably, investments have the most positive outcomes. E3ME allows for money creation through lending without leading to full crowding out elsewhere; however, the model remains agnostic of sources of financing. Although real-world evidence exists to support this treatment, it has some caveats [34]; therefore, the simulation results must be interpreted carefully. Moreover, our scenario indicated the level of investment required to achieve Net-Zero by 2050 in Japan; however, it did not indicate the likelihood of obtaining such investments. Additionally, our model showed that a large amount of public investment is required to facilitate the diffusion of low-carbon technologies, such as electricity charging stations for EVs. However, most of these investments can be recovered through carbon tax revenues. Future work will focus on including an amplified mechanism to track financial flows and the potential consequences of the investment stimuli required for the transition, such as those presented in this study.

Furthermore, technology diffusion models such as FTT are well-suited for determining the uptake trajectories of established technologies; however, dealing with novel technologies that are currently not included in the model system is challenging because of sparse data. Finally, the diffusion rate is highly uncertain for completely novel technologies, such as electrolysis for green hydrogen production, as outlined by Odenweller et al. [39].

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Data Availability Statement: The historical macro-economic data and exogenous projections used to develop econometric relationships in E3ME originate from various sources. See the Technical Manual for an overview [23]. E3ME-FTT is operated and owned by Cambridge Econometrics and therefore not publicly available. However, stand-alone versions of the FTT models are available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

FITs	feed-in tariffs.
METI	the Japanese Ministry of Economy, Trade and Industry.
R&D	research and development.
CCS	carbon capture and storage.

NEDO	New Energy and Industrial Technology Development Organization.
FCEV	fuel cell electric vehicle. Also called FCV.
CCUS	carbon capture, usage, and storage.
EV	electric vehicles.
PHEVs	plug-in hybrid electric vehicles.
REI	Renewable Energy Institute.
GENeSYS-MOD	the multi-sectoral open-source Global Energy System Model.
GRAPE	a global and long-term intertemporal optimization energy model.
FTT:PG	FTT model for power generation.
FTT:PRT	FTT model for private road transport.
FTT:FRT	FTT model for freight road transport.
FTT:Heat	FTT model for residential heat.
FTT:Steel	FTT model for iron and steel industry.
E3ME model	Energy-Economy-Environment Macro-econometric model.
FTT model	Future Technology Transformations model.
GHG	greenhouse gas.
GDP	gross domestic product.
GPMP	the Government Power Mix Plan.
VAT	value-added tax.
BECCS	bioenergy with carbon capture and storage.
LDV	light-duty vehicle.
HDV	heavy-duty vehicle.
H2-DR-EAF	hydrogen direct reduction and electric arc furnaces.
IEA	International Energy Agency.
ASEAN	the Association of Southeast Asian Nations.
PV	photovoltaics.
BF-BOF	the blast furnace-basic oxygen furnace.
SR-BOF	the smelting reduction-basic oxygen furnace.
DR-EAF	direct reduced iron electric arc furnace.
H2	hydrogen.
CNG	compressed natural gas.
LPG	liquefied petroleum gas.
BEV	battery electric vehicle.
PHEV	plug-in hybrid electric vehicle
ICEV	internal combustion engine vehicle.

Appendix A. Fiscal Implications of the Policy Scenario

Due to Japan's government debt, it was considered unlikely that a large-scale transition would be able to be funded. Therefore, we assumed net-neutrality of the government budget. To achieve net neutrality, the net spending on policy costs minus carbon tax revenues are balanced by changing fiscal rates such as VAT, income tax, and employers' social security contributions. The former affects consumer expenditure, while the latter two effectively affect the cost of employment.

Up to 2043, the carbon tax revenues outweigh the policy cost, which leads to a lowering of the fiscal rates. Afterwards, the policy costs outweigh the carbon tax revenues as most emissions have already been removed from the economy. Figure A1 illustrates how the policy costs develop compared to the carbon tax revenues.

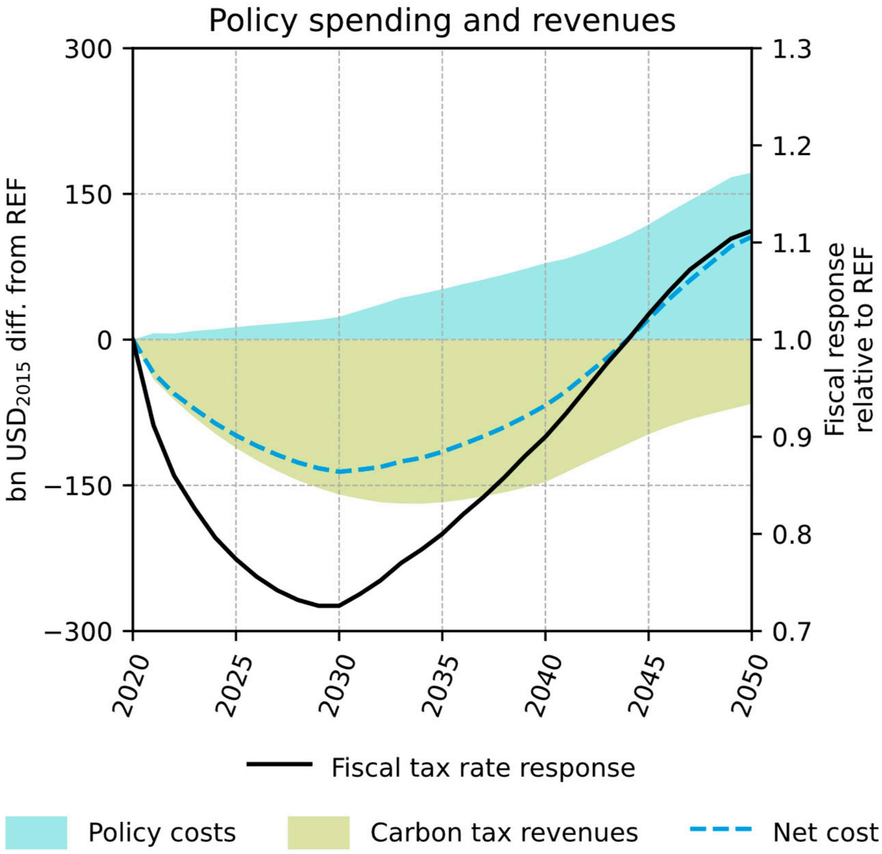

Figure A1. Policy costs versus carbon tax revenues (left *y*-axis) and the net effect on fiscal tax rates (right *y*-axis), where 1 indicates no change from baseline; less than 1 indicates a proportional decrease in tax rate, and greater than 1 indicates a proportional increase in tax rate.

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