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# Policy design for diffusing hydrogen economy and its impact on Japanese economy by 2050 carbon neutrality: Analysis using E3ME-FTT model

August 2023

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**Abstract:**
The purpose of this study is to investigate the diffusion of hydrogen technology and extend the utilization of hydrogen in Japanese economy by 2050. By simulating E3ME-FTT model and comparing policy scenarios with baseline, the economic and environmental impact of policy scenarios for hydrogen diffusion can be analyzed. Moreover, when carbon neutrality is tried to be realized by 2050, the impact on Japanese economy can be also measured. The results have shown that large-scale decarbonization with hydrogen diffusion is possible without losing economic activity. Investment in new hydrogen-based and other low-carbon technologies in the power sector, freight road transport, and iron and steel industry contributes to the positive GDP results as it invokes economic activity and requires additional employment.

**Keywords**

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

# 1. Background and purpose of the study

In order to achieve carbon neutrality in Japan in 2050, decarbonization of energy consumption is an unavoidable issue. The Japanese government's 2050 energy plan calls for a 100% decarbonization for the power sector; in the non-power sector, decarbonized electricity should be focused on and the remainder should be hydrogen, methanation, and synthetic [1].

It is necessary to promote renewable energy as the main energy source on a large scale to achieve Japan's decarbonization ambitions. Using FITs (Feed-in tariffs), Japan aims to promote the uptake of renewables, such as solar, wind and biobased power generation. However, there are barriers for the whole economy to decarbonize energy because there are constraints of location, decreasing of learning effect (cost down effect by technological advances) in the diffusion of renewable energy in the power generation sector, and the limitations of decarbonization in non-power generation sector.

In recent years, the potential of hydrogen is highly rated for overall economic decarbonization (e.g. [2]). In Japanese government tactical planning, 10% of power generation comes from hydrogen or ammonia in the power sector. Besides, hydrogen should also play a role in the non-power sector. Due to the widespread use of renewable energy power, acquiring green hydrogen at a low cost will become possible in the future. Along with that, the possibility of hydrogen to be the overall economic decarbonized energy is also increased, for instance, hydrogen reduction steelmaking in industrial sectors, household fuel cell in and household sector, FCEV (Fuel Cell Electric Vehicle) in transportation sector. Hydrogen is expected as a trump card of achieving overall economic decarbonization or realization of hydrogen economy.

Nevertheless, there is a limitation of achieving overall economic decarbonization at current stage, because the cost of hydrogen is 100 JPY/Nm3 [1] which is 22 ~ 60 times higher than fossil energy. In a publication of 2023 by Agency for Nature Resource and Energy [3], based on the CIF price per 1,000 kcal in March 2015, the price of crude oil, LNG, and coal are 4.51 JPY, 5.81 JPY and 1.65 JPY, respectively. The cost of green hydrogen which is made from renewable energy is particularly high. That makes realization of hydrogen economy to be a challenging topic.

This study designs hydrogen policies for realizing hydrogen economy which is one of the Japanese government targets (the cost of hydrogen is 20 JPY/Nm3 in 2050 and the supply of hydrogen is 20 million ton/year are shown at [1]). By using the E3ME-FTT model, this study simulates hydrogen economy of Japan in 2050 including hydrogen reduction steelmaking, FCEV (for both freight and private road transport), and the diffusion of hydrogen-based power generation. E3ME-FTT model is also used to estimate the impact on overall economics.

To increase the amount of hydrogen supply, the prices of hydrogen cost are set in policy scenario Ⅱ as 100 JPY /Nm3 in 2020, 30 JPY /Nm3 in 2030 and 20 JPY/Nm3 in 2050 estimated by METI [1]. In addition, hydrogen/Ammonia power share, subsidies for FCEV, EV are also set in power generation sector and transport sector etc. By simulating E3ME-FTT model and comparing policy scenarios with baseline, the economic and environmental impact of policy scenarios can be analyzed. The hydrogen supply to support the hydrogen economy by 2050 can be estimated. Moreover, when carbon neutrality is tried to be realized by 2050, the impact on Japanese economy can be also measured.

In the next section, hydrogen utilization status of Japan will be explained, and scenarios will be set up for realization of hydrogen economy. The simulation results of the scenario setting in E3ME model will be presented in the third section. Ultimately, the conclusion will be summarized in the last section.

# 2. Summary of basic hydrogen strategy and subsidies in Japan

## 2.1. Hydrogen Strategy in Japan

In Japan's Roadmap to "Beyond-Zero" Carbon, Japan intends to use hydrogen in transportation, industry and power production sectors, etc. to realize carbon neutrality by 2050. In addition, The National Hydrogen Strategy [4] and the Environment Innovation Strategy [5] which include hydrogen technology innovation are also established for carbon neutrality. Hydrogen is used as the secondary energy [6] in electricity, transportation, industry, residential, commercial and public services sectors, etc. It is necessary to broaden hydrogen applications to ships, trains, trucks, and other transportation modes to improve the hydrogen eco-system. Industrial CCS (carbon capture and storage) is used for capturing and storing carbon which is generated by blue hydrogen. Blue hydrogen is generated from methane and coal. There is 10 – 20% of carbon cannot be captured in blue hydrogen. However, Green hydrogen does not generate carbon which is generated from renewable electricity through electrolysis process.

Not only was the Basic Hydrogen Strategy published in 2017 [2], but also the First strategic plan, the 2030 Action Plan toward 2050, and the 2050 Vision toward realization of hydrogen society were also published since, highlighting Japan's focus on a hydrogen economy in its attempt to decarbonize its economy. The 2030 Action Plan toward 2050 is about "development of international supply chains and development of domestic technology for producing hydrogen derived from renewable energy" [7]. On the other hand, the 2050 Vision toward realization of hydrogen society is for "Realization of CO2-free hydrogen" [7]. In Hydrogen Basic Strategy [2], there are three phases to realize a hydrogen society step by step:

1. Phase 1：Fast extension of utilization of hydrogen
   Extensive diffusion of stationary fuel cell and FCEV. Leading role in the global market in hydrogen and fuel cell.
2. Phase 2：Introduce hydrogen power generation／Establishment of large scale hydrogen supply system (in the late 2020s)
3. Phase 3：Establishment of CO2 free hydrogen supply system using renewable energy source or with CCS (realize in 2040)"

The outlines of Japan's long-term strategy for sectors are clarified by METI (2019) [7]. Energy sector will realize a "Hydrogen Society" and promote CCS&CCUS/carbon recycling. Industry sector will use CO2-free hydrogen such as a challenge towards "zero-carbon steel". Besides, transport sector will achieve the highest level of environmental performance of Japanese vehicles by 2050 to achieve the "Well-to-Wheel Zero Emission".

There are goals in the Basic Hydrogen Strategy which include the goals on the use side (mobility, power and fuel cell) and on the supply side (fossil fuel + CCS and green hydrogen). In order to achieve goals in the

Basic Hydrogen Strategy, it is necessary to set up targets to achieve and approach to achieve target, such as increasing efficiency of hydrogen-fired power generation from 26% to 27%. The goal of green hydrogen is also setup. The system cost of water electrolysis for producing green hydrogen should be 50,000 JPY/kW in the future. There are 2 setting of targets to achieve this goal by 2030. The first one is decreasing the cost of electrolysis from 200,000 JPY/kW to 50,000 JPY/kW. The second one is changing the efficiency of water electrolysis from 5 kWh/Nm3 to 4.3 kWh/Nm3. The approach to achieving target is made such as demonstration in model regions for social deployment utilizing the achievement in the demonstration of Namie in the Fukushima Prefecture. [7]

## 2.2. Hydrogen Subsidies in Japan

According to [8], the Japanese government provides robust funding for RDD&D (research, development, demonstration, and deployment), while also keeping its technology options open. In 2020, the funding for hydrogen includes JPY 24.7 billion for clean energy vehicles, JPY 4 billion for residential fuel cells and fuel cell innovation, JPY 5.25 billion for innovative fuel cell R&D, JPY 3 billion for hydrogen supply infrastructure R&D, JPY 12 billion for FCEV refueling stations, JPY 14.1 billion for the development of hydrogen supply chains, and JPY 1.5 billion for hydrogen production, storage, and usage technology development [8]. In the newest news which is published by METI's Tokyo "Beyond-Zero" Week 2021 Held [9], a Green Innovation Fund, JPY 2 trillion, has been established to encourage companies to do R&D and to facilitate the deployment for carbon neutrality by 2050.

For establishment of hydrogen supply chain and green hydrogen, the found will be used USD 2.7 billion and USD 700 million, respectively. In addition, Japan aims to expand hydrogen market from 2 million tons per year to 3 million tons per year by 2030 and 20 million tons per year by 2050. Japan also plans to decrease 1/3 of the hydrogen cost by 2030 [8].

Furthermore, the subsidy's upper limit for promoting the introduction of clean energy vehicle EV, Light EV, PHEV and FCEV are 650,000 JPY, 450,000 JPY, 450,000 JPY and 2.3 million JPY, respectively [10].

The Japanese government will develop include 1,000 hydrogen refueling stations for FCV [11]. From Japan's Roadmap to "Beyond-Zero" Carbon [6], to become a full-fledged hydrogen energy source, Japan must overcome several challenges. For example, Japan should broaden applications, including ships, trains, trucks, etc., and build a ubiquitous hydrogen eco-system. By establishing a global supply chain, building on-site storage facilities and validating hydrogen production setups, hydrogen will be more affordable in Japan. Strengthening research and development is also important, including strategically developing human resources. NEDO (The New Energy and Industrial Technology Development Organization) is searching for 500 researchers to oversee the Zero Emissions Creators 500 program [6].

Japan is seeking to access hydrogen securely, so that various sources for hydrogen are tested. The fossil fuel is based on hydrogen supply chains by now [12]. Japan is also "planning to establish a manufacturing technology base by 2030 to produce hydrogen from domestic renewable sources" [8]. However, METI [7] writes 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 expend industrial use".

## 3. Outline of E3ME-FTT

In this study we will use E3ME-FTT to evaluate the response of the Japanese economy to policy packages aimed at decarbonization. E3ME-FTT divides the world into 71 regions with major economies being represented individually, among them Japan. E3ME is a demand-led macro-econometric simulation model that estimates the components of effective demand which leads to supply through the national accounts framework. Energy demand by broad sector is also determined econometrically and responds to price feedback, economic activity, R&D spending, and investment [13].

Applying econometrics to determine energy use can be problematic as it energy use relates to technology deployment, and technology diffusion can be sudden as it is often found to follow the characteristic S-curve [14]. To that end, FTT was developed first for the power sector (FTT:PG) [15], followed by modules for passenger road transport (FTT:PRT), freight road transport (FTT:FRT) [16], residential heating (FTT:Heat) [17], and the iron & steel sector (FTT:Steel) [18]. FTT is a group of models of technological change and designed for different sectors to match characteristics of sectors and different situations. Levelised cost is used in E3ME-FTT. Sectoral technologies and policies are included into FTT module. The feedbacks from FTT module are put into the E3ME model. FTT:PG pairwises comparisons of levelized cost of electricity which is a cost of various electricity generation technologies. The feedbacks from FTT:PG to E3ME model are electricity price, investment, fuel demand of power generation and so on. Both FTT:PRT and FTT:FRT are modules for transport sector which include 25 technologies and have endogenous technology diffusion. FTT:Heat uses the levelised cost of heating to pairwise comparison of all available heating technologies. FTT:Heat is modeling residential heat decisions by households. FTT:Steel is modeling investor choices for steelmaking technologies. There are many policies in FTT:Steel such as carbon tax, regulations, subsidies on capital and technology investment. Each of these modules describes technological change based on evolutionary economics. In line with the evolutionary nature of FTT, technology diffusion is path dependent. The core mechanism depends on pair-wise comparisons of two technologies by evaluating the past market shares, the agent's preference, and substitution frequencies [19] to determine technology uptake. The detailed nature of the FTT modules allows for a range of policy intervention to steer decision-making.

Figure 1 illustrates a schematic overview of the linkages between E3ME and the FTT submodules. Depending on energy resource depletion (including renewable and non-renewable resources), prices or costs of primary energy sources are estimated. This feeds into the individual FTT submodules where it is incorporated into the decision-making process and therefore affects technology diffusion in each of the represented sectors. The economic consequences such as investments, price feedback, and final energy use feed into E3ME, which reports back demand (e.g. electricity) to the FTT models. E3ME-FTT allows for a myriad of policies which can interact with each of the subcomponents. Hydrogen demand and supply will decide hydrogen price which effect on energy prices/resource cost. However, there is no hydrogen supply and demand data. Thus hydrogen price and supply are set up exogenously to estimate hydrogen demand. 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 into E3ME. Therefore we represented the hydrogen supply industry by exogenous prices, exogenous market shares of production methods, and exogenous employment [20] and investment factors [21]. The hydrogen supply sector is represented by the following projections published by the METI.

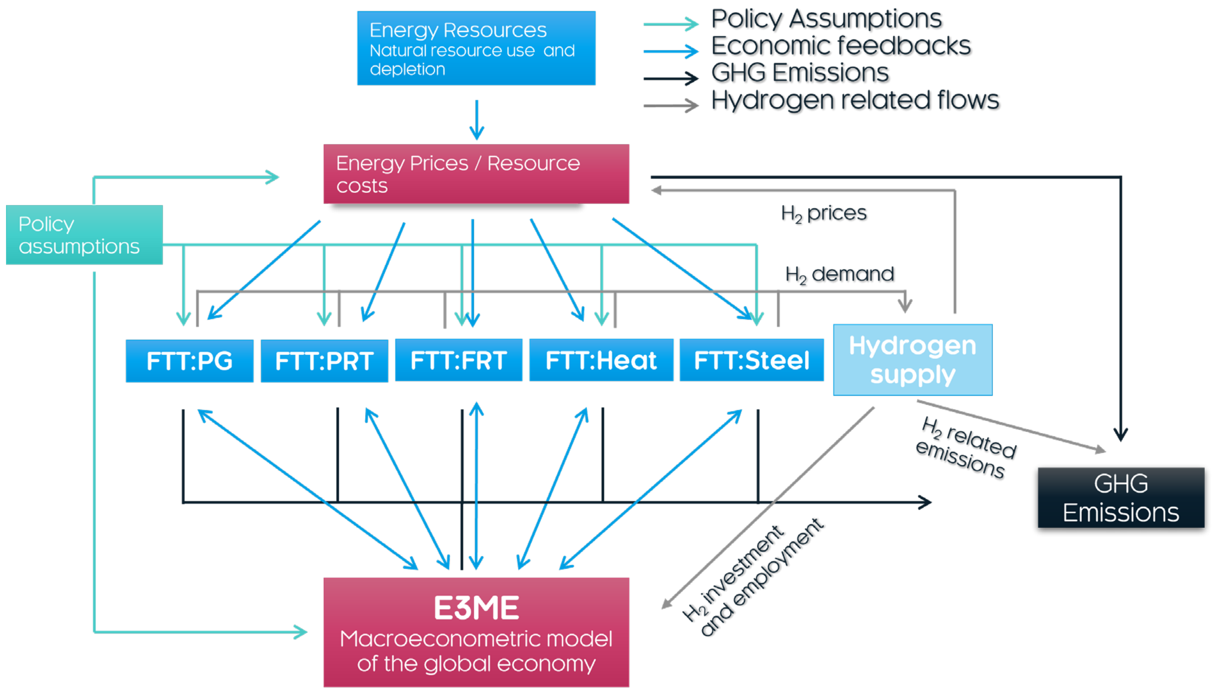


**Figure 1.** Schematic overview of E3ME-FTT. PG: Power generation; PRT: Private road transport; FRT: Freight road transport; Heat: Residential heat; Steel: Iron and steel industry.

This study builds on the study presented by [22] where the economic impacts of Japan's government plan for the power sector was evaluated. Here, we add proposed hydrogen economic related policies in the mix with additional model functionality. New to this study are the inclusions of FTT:Freight and an exogenous representation of hydrogen supply. The government of Japan is highly focused on creating a hydrogen-based economy, so the economic and environmental consequences of hydrogen demand need to be accounted for. The hydrogen supply sector is represented by following projections published by METI.

# 4. E3ME-FTT model simulation toward 2050 hydrogen economy in Japan

## 4.1. Reference and policy scenarios

### 4.1.1. Reference scenario

The Reference scenario in this study is calibrated to the reference scenario of the IEEJ Outlook 2021 and is in line with "current policies" which shows a continuation of the policies currently in place. Reference scenario does not mean staying at current situation or using additional special technology. The additional special technology which will lead to the exit of the trajectory are not considered. Thus, baseline scenario will make clear about the trajectory and the effect of current policy and technology in the future, etc. It therefore forms a counter-factual in order to investigate the policies to achieve Net-Zero emissions by 2050 in Japan.

Groups of policies will be set up in policy scenarios. To figure out energy, economy and industry changes are caused by policy scenarios, how big is the effect, and whether carbon neutrality can be achieved in 2050, baseline scenario will be compared with policy scenarios.

Important indicators of baseline scenario are shown in Table 1, for instance, GDP, final energy consumption, power generation and CO2 emission. Under the IEEJ Outlook 2021 reference scenario [23], the global economy experiences negative growth in 2020 due to the impact of COVID-19. However, COVID-19 is not expected affect the global economy too much after 2021. Positive growth will return, and the economic growth rate will also return. In the assumption, Japanese GDP grows rates from 2018 to 2050 is 0.7% (GDP grows rates from 1990 to 2018 is 1.0%). GDP of Japan changes from USD 6,190 billion in 2018 to USD 7,740 billion 2050 (based on 2015 prices). Primary energy consumption includes oil, natural gas, coal, other renewables, nuclear and hydro. Japan's final energy consumption will decline from 283 Mtoe in 2018 to 224 Mtoe in 2050. In power generation, the two largest power generation, coal-fired and LNG-fired, will decrease until 198 TWh and 288 TWh in 2050, respectively. To make up for the coal-fired, oil-fired power and LNG-fired reduction, the generation of other methods was increased, notably wind power generation was increased to 7.5 TWh in 2018 and 64 TWh in 2050. Furthermore, in baseline, energy-related $CO_2$ emissions fall gradually from 1080 million tons in 2018 to 738 million tons in 2050.

**Table 1.** Important Japanese indicator of economy and energy prediction by IEEJ Outlook 2021[23]

| | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| **GDP (USD billion, 2015 prices)** | 6,190 | 6,693 | 7,234 | 7,740 |
| **Final energy consumption (Mtoe)** | 283 | 263 | 244 | 224 |
| **Power generation (TWh)** | 1,050 | 1,079 | 1,093 | 1,082 |
| 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)** | 1,081 | 940 | 852 | 738 |

**Source**: IEEJ [23].

### 4.1.2. Net-Zero scenario with a focus on hydrogen economy

This study revolves around investigating the economic and environmental impacts of promoting a hydrogen economy to achieve Net-Zero by 2050 in Japan. We include policies announced by the government of Japan intended to be in line with a Net-Zero trajectory. Table 2 provides an overview of the scenario settings. Various policies are included, ranging from penalizing taxes to promoting subsidies. The policies are aimed at decarbonization through electrification and hydrogen-based solutions. Therefore, the focus also lies on the decarbonization of the power and hydrogen supply sectors.

To that end, we follow the Government Power Mix Plan (GPMP) for specific power generation technologies. Other low-carbon or renewable power generation sources are promoted through policies. Hydrogen supply is represented exogenously and has been set to follow the deployment set out by figure 3 and figure 4. Policies promoting hydrogen demand are focused on transport and iron & steel. The Net-Zero scenario is based on [24] the decarbonization policy scenario (policy scenario I) for achieving carbon neutrality in Japan. In this study, additional policies are implemented to promote hydrogen-based technologies.

The upfront costs of light-duty and heavy-duty FCEV are subsidized. Besides a biofuel blending mandate, a e-fuel blending mandate is added. Heavy-duty vehicle (HDV) manufacturers are exposed to sales mandates that require them to offer zero emission vehicles FCEV. Subsidies are also implemented for hydrogen-based steelmaking and other low-carbon steelmaking technologies.

The power mix in policy scenario is along the power mix plan of The 6th Strategic Energy Plan in 2030 and the proposal of The Growth Strategy Meeting [25] in 2050. The share of nuclear power is 6.2% in 2019. The share will increase to 20% in 2030 (20 ~ 22% in the power mix plan) and decrease to 10% in 2050. In the meantime, the share of renewable energy power is 19.8% in 2020. The share will increase to 38% in 2030 (36 ~ 38% in the power mix plan) and 60% in 2050. Carbon tax is set up on top of current Climate Change Tax (JPY 289/CO2t).

This tax will be increased proportionally from 50 USD/t$CO_2$ in 2021 to 410 USD/t$CO_2$ in 2041. After 2041 it is kept constant. The carbon tax targets all sectors, including those not directly targeted by the policies listed in Table 2, and acts to reduce residual emissions elsewhere in the economy in order to achieve Net-Zero emissions by 2050.

Carbon tax generate revenues while most of policies listed in Table 2 incur additional public spending. The treatment in E3ME-FTT is to assume revenue neutrality of the government balances. Its key elements in the model are:

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

If the net revenues are positive, then it is assumed that the response is to lower non-environmental tax rates. These are income tax, VAT (value-added tax), and employers’ social security contribution. If the difference is negative, then the government is assumed to respond by increasing the same fiscal tax levers.

**Table 2.** Summary of policy inputs in Policy Scenario.

| Policy/setting | Sectors | Description |
|---|---|---|
| Carbon tax (from 2021 onward) | All sectors | Carbon tax gradually increasing from $50/tCO2 in 2023to reach around $410/tCO2 in 2040 (2010 prices). Fixed rate in constant term after 2040. |
| Government power mix plan | Power | Government power mix plan of 2030, 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. |
| Ban on petrol & diesel engines by regulation | Road transport | Ban sales from 2035 onward |
| Biofuel mandate | Freight and air transport | Increase share of biofuels in the fuel mix |
| E-fuel blending mandate | All transport | Increase share of e-fuels in the fuel mix |
| ZEV subsidies for LDV | Passenger road transport | Subsidies given to EVs and FCEVs in the first few years.<br>Battery EV: 8,000, 10,000, 12,000 $/veh for economy, medium, and luxury vehicles respectively.<br>Plug-in hybrid EV: 4,000, 5,000, 6,000 $/veh for economy, medium, and luxury vehicles respectively.<br>Fuel cell EV: 24,000 $/veh for all classes. |
| ZEV subsidies for HDV | Freight road transport | Subsidies given to EVs and FCEVs in the first few years.<br>30,000 $/veh on small trucks and 60,000 $/veh on large freight trucks. |
| FCEV mandates for HDV | Freight road transport | Mandate to kick-start FCEV HDV into the system.<br>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 furnace 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 costs and 25% of electricity costs. |

| | | |
|---|---|---|
| Hydrogen use in other industries | Industry | Substitution towards hydrogen for process heating. In line with 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 authors

## 4.2. Hydrogen supply assumptions

The purpose of this study is to investigate a decarbonization scenario involving a push towards a hydrogen economy. This involves consequences to the electricity and hydrogen supply sectors. E3ME-FTT does not include a detailed representation of the latter. Therefore, the representation of the hydrogen supply sector is based on hydrogen price and hydrogen supply projections offered by [26]. Figure 2 shows these projections. The hydrogen price starts at 100 JPY/Nm$^3$ and is expected to decline swiftly to 30 JPY/Nm$^3$ in 2030 and finally ends at 20 JPY/Nm$^3$. Over the same period, hydrogen supply increases from 2,000 kt in 2020, to 3,000 kt in 2030, and finally to 20,000 kt in 2050. In this study we will assume that the supply projection is the maximum potential of domestic hydrogen supply.

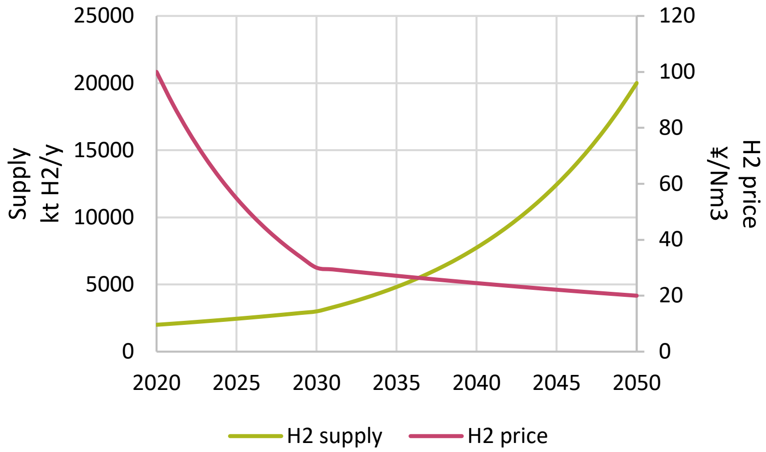


**Figure 2.** Projections of total hydrogen supply (left axis) and hydrogen price (right axis).

**Source**: METI [26].

Without a technology diffusion submodule, exogenous assumptions will have to be made on the technology composition within the hydrogen supply market. Here, we follow a simple approach by setting exogenous market share developments(see figure 3). The IEA hydrogen projects database [27] shows that 2 kt/y of electrolsis capacity is operational in the form of various demonstration projects. Up to 2019, a project with a capacity of 9.9 kt/y of steam methane reforming in combination with CCS was being demonstrated. These capacities are a fraction of the total current supply of 2,000 kt/y.

Based on these numbers, we let low-carbon hydrogen supply technologies diffuse into the system in line with the splits of past low-carbon hydrogen supply capacities. The change will first be dominated by “blue hydrogen”, which is produced using natural gas feedstocks where the emissions are sequestered using CCS technology. Towards 2030, “green hydrogen” is set to diffuse into the system at an increased pace. “Green hydrogen” is the production pathway that electrolyzes water using electricity from renewable sources. The remainder of hydrogen supply is produced via the “grey hydrogen” supply chain, which also builds on steam methane reforming with natural gas as input but does not include abatement of emissions. By 2050, “grey hydrogen” is set to completely phase out in favour of low-carbon hydrogen production. “Green hydrogen” is set to grow to 55% market share, while “blue hydrogen” is set to capture the remainder 45%.

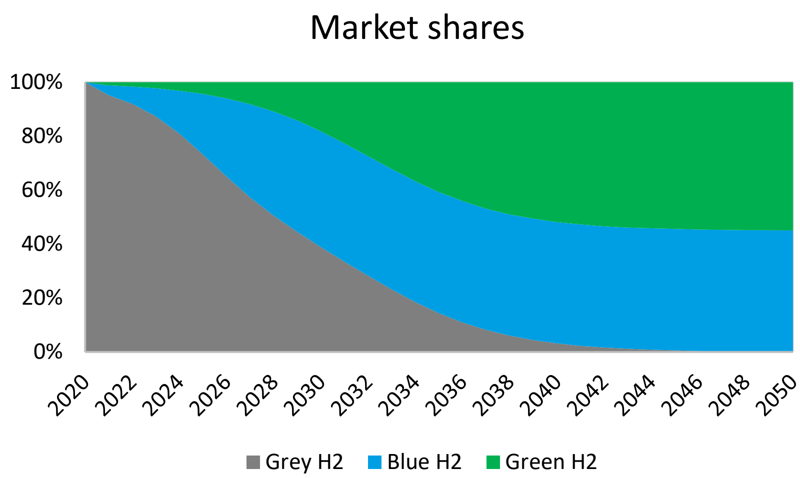


**Figure 3.** Exogenous market share development aligned with a Net-Zero setting within the hydrogen supply market supplying the energy markets

**Note:** Figure excludes other sectors that require hydrogen as a feedstock.

**Source:** Produced by authors.

An additional issue with hydrogen supply statistics is that the bulk of hydrogen demand is presently produced onsite where it is needed (i.e. the captive market). In those cases, hydrogen is not used as an energy vector, but rather as a feedstock. Examples are onsite hydrogen use to facilitate oil refining and to bulk chemicals such as ammonia and methanol in the chemical industry. Energy statistics specific to the hydrogen supply of captive markets are embedded with the statistics of the sector they are embedded in. The Pacific Northwest National Laboratory has launched the Hydrogen Tools Portal which tracked captive and merchant hydrogen markets. They estimated that the captive market in Japan mostly consisted of stream methane or naphtha reforming (~1,400 kt/y capacity in 2017), while the merchant market was estimated to be considerably smaller (13 kt/y capacity, mostly steam methane reforming).

However, in this study we will be investigating a transition towards a hydrogen economy in Japan. Therefore, the need arises to assume a split between hydrogen supply destined for the non-energy market and the energy market while remaining within the bounds of the hydrogen supply projection offered by METI [28]. We will assume 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 is expected to grow by 40% between 2020 and 2050 in a reference scenario setting. This means that of the 20,000 kt of hydrogen by 2050, 17,000 kt is potentially available for the energy market. Figure 4 depicts the market split. In this study we will assume that the 17,000 kt of hydrogen is the maximum potential domestic supply.

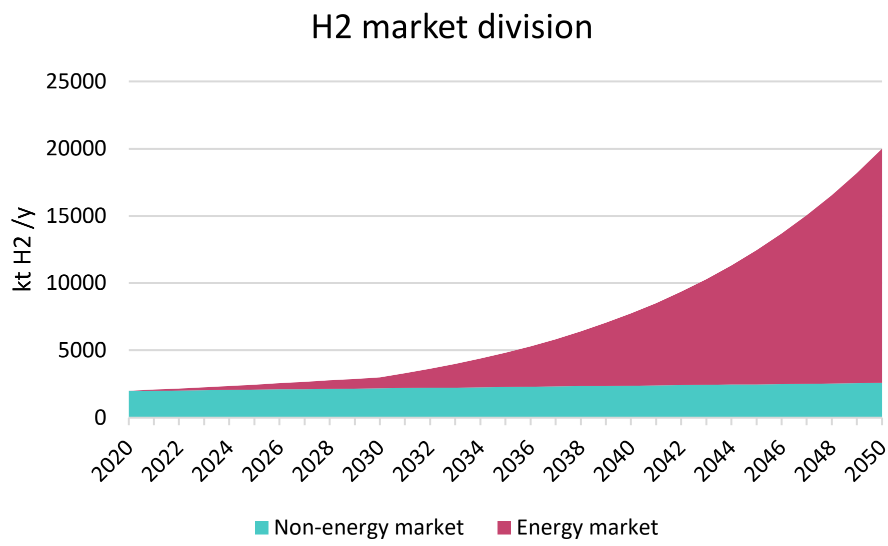


**Figure 4.** Market division of hydrogen supply flows.

**Note:** The supply to the energy market represents the maximum potential. Actual volumes of supply to the energy market depends on the simulated hydrogen demand in the scenarios.

**Source:** Produced by authors.

If the simulated hydrogen demand exceeds the potential domestic supply, then we assume that the remainder is imported from partner regions that can supply hydrogen at lower costs. Since data is lacking on this account, we assume that such countries can produce hydrogen at 1 USD/kg or 12 JPY/Nm3, an estimate that falls within the range of what the IEA finds [29]. It is likely that Japan's trade partners will be located in ASEAN countries and Australia. This means that hydrogen needs to be transported over a distance of 3,000 to 10,000 kilometres.

According to the European Commission's Joint Research centre, it is estimated that the transport costs over such a distance will be around 1 $/kg [30]. Countries with more favourable resource costs can produce hydrogen for a price of 2 $/kg. It is 3 $/kg or 36.5 JPY/Nm3 in total. Based on those numbers, we assume that the hydrogen import price is 25.5 JPY/Nm3. In 2020, the import price is about 4 times cheaper than the domestic producer price in Japan. On top of this, we assume that there is an innovation happens on the importer's side and the import price declines to 22 JPY/Nm3 due to economies of scale and innovation effects. This implies that only towards 2050, the domestic producer price will drop below the import price. It is further assumed that the difference between the import price and the domestic producer price is subsidised by the Japanese government. Figure 5 depicts the import price and domestic producer price projections used in this study.

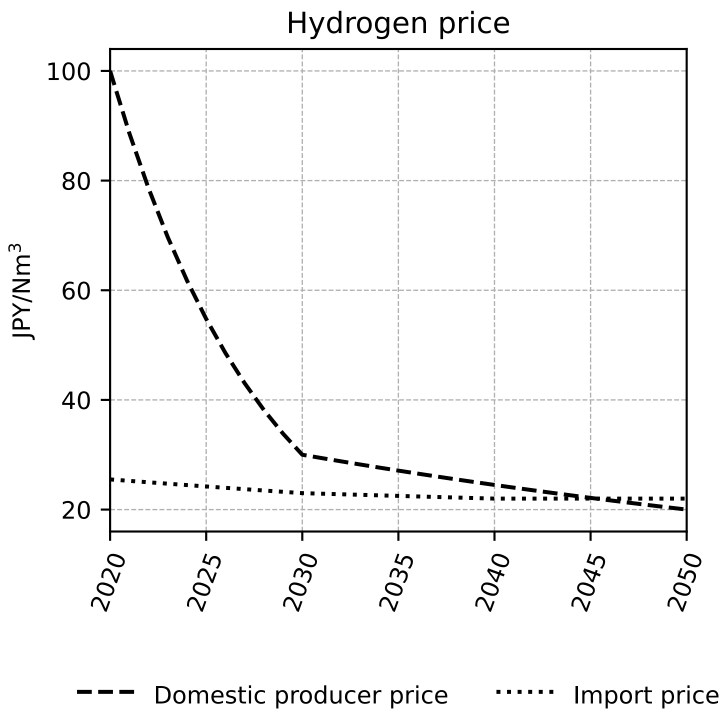


**Figure 5.** Comparison of the hydrogen price as offered by the domestic hydrogen supply sector (dashed line) and the market prices faced by end-users.

**Sources:** Compiled by authors.

# 5. Results and discussions from the model simulation

## 5.1. Technology deployment

As shown in the reference scenario in Figure 6, hydrogen-based technologies are not promoted by current policies and therefore we note little to no diffusion of hydrogen-based technologies throughout the various sectors. Only a small number of FCEV diffuse into the passenger vehicle market, growing from 10,000 vehicles in 2021 (0.01% of all vehicles) to 700,000 by 2050 (1.3% of all vehicles). Passenger road transport will likely see a gradual phase-out of conventional petrol and diesel vehicles as preferences slowly gravitate towards hybrid vehicles.

The only other sector that sees some uptake of a hydrogen-based technology is the iron and steel industry, although hydrogen-based steelmaking does not breach the 1% market share if there are no policies to support this technology. Instead, the blast furnace coupled to the basic oxygen furnace (BF-BOF) route remains dominant but loses some market share to steel recycling other smelt reduction technologies (SR-BOF).

In the residential heating sector, a steady increase of heat pumps is noted, but fossil fuel boilers remain dominant to provide space and hot water heating, although losing market share over time. Freight transport is locked-in to diesel powered vans and trucks. In general, most hydrogen-based technologies are still in the early commercialization phase and therefore found in the initial flat part of the S-curve of diffusion.

However, as shown in Net-Zero scenario in Figure 5, incentivizing hydrogen-based technologies in the power generation, iron and steel, passenger road transport, and freight road transport sectors does lead to significant diffusion. First, in line with the GPMP, 10% of the electricity will be supplied via fuel cells. Solar PV, wind power, fossil fuel + CCS, and BECCS also gain greater market shares. Second, hydrogen-based steelmaking becomes a viable option due to subsidies, and in the Net-Zero scenario it grows to a market share 23% by 2050. Scrap recycling becomes the most dominant steelmaking path. Third, about 40% of all passenger vehicles are FCEVs by 2050 with another 45% being EVs (BEVs + PHEVs). Fourth, FCEV trucks and vans see a substantial growth to a 70% market share, which is primarily driven by the sales mandates in combination with large subsidies. Freight road transport is technologically homogenous as it is dominated by diesel-powered vans and trucks. With FCEV trucks are very expensive compared to diesel trucks in 2021, high subsidies are therefore required to make them cost competitive. In addition, due to a lack of FCEV trucks in the system presently, sales mandates are required to force them into the system. In Net-Zero scenario, 65% of all trucks are powered by fuel cells. The remainder diesel-powered trucks run on a diesel fuel blend consisting of 50% biofuels.

Market shares of technologies in the hydrogen supply market is shown in the last low of Net-Zero scenario in Figure 5. In the Reference scenario we have assumed constant market shares, while in the Net-Zero scenario a transition is set towards low-carbon hydrogen technologies, as outlined in section 4.2.

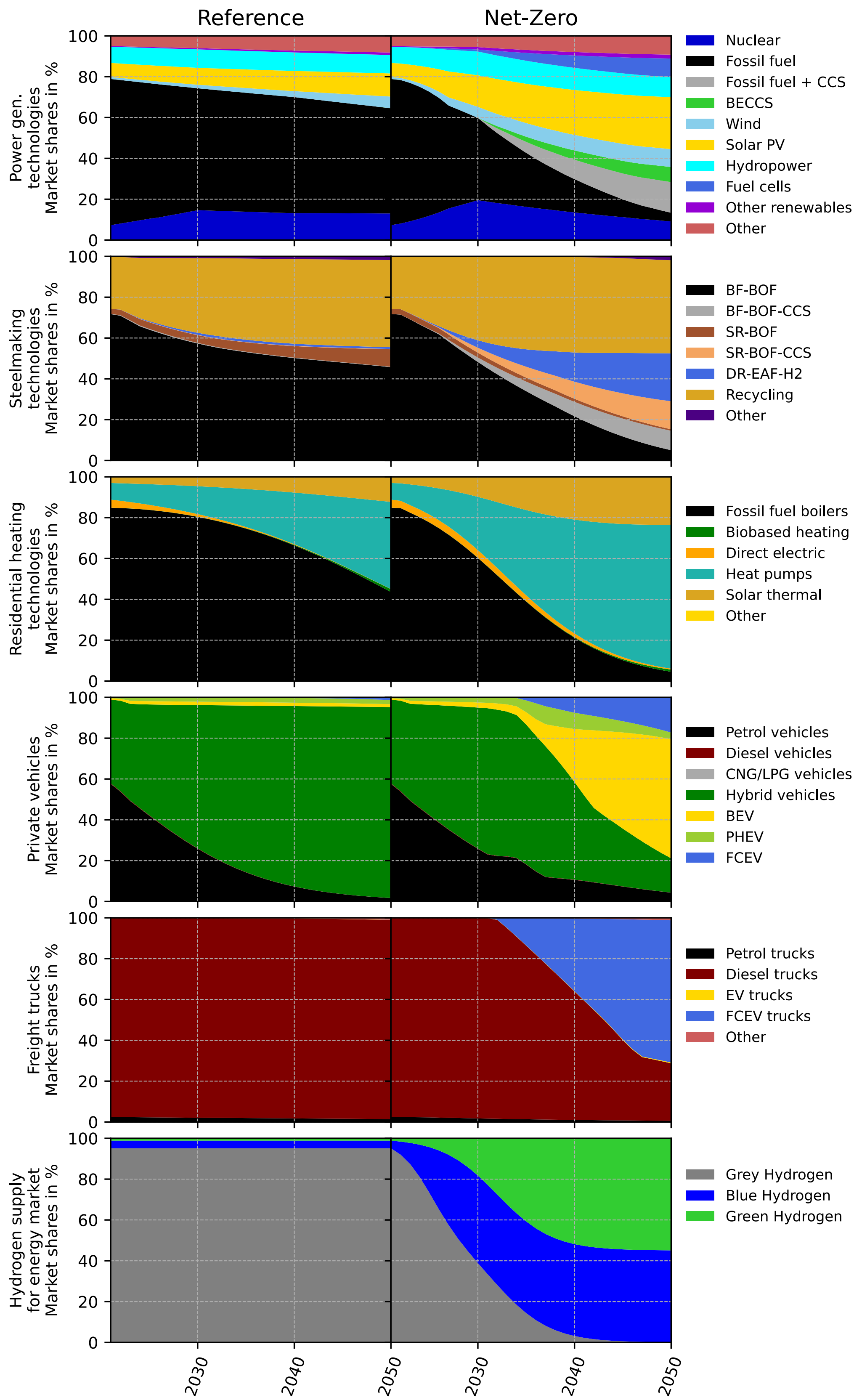


**Figure 6.** Market share developments related to hydrogen technologies within the relevant sectors

**Source:** Produced by authors.

## 5.2. Energy demand

The technology composition as determined by the FTT models leads to specific energy demand profiles (see figure 7). In the Reference scenario, we note that coal and gas demand maintain its dominant position but declines gradually. This changes when the Net-Zero policy package is enabled which shows a transition to renewables, BECCS, and hydrogen-powered fuel cells which leads to increased energy input of solar energy, biofuels, and hydrogen (12 Mtoe/y by 2050). The remaining fossil fuel inputs primarily flow into power plants with CCS systems, and therefore the emissions are abated.

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

The private vehicles market shows a tiny transition to EVs and a large transition to hybrid vehicles in the Reference scenario. Implemented subsidies, sales mandates, and biofuel blending mandates, we see increased demand for biofuels and hydrogen (2.7 Mtoe/y in 2050), while oil is nearly completely phased out, in line with the phase-out of ICEV and hybrid vehicles. Due to electric power trains being more efficient than internal combustion engines, the total energy demand is also much lower (by 30% compared to the Reference in 2050). Due to subsidies and sales mandates, FCEV systems also gain traction in the freight road transport sector. By 2050, freight road transport requires 3.6 Mtoe/y of hydrogen. Similar to the private vehicles market, a transition to FCEVs leads to efficiency gains (62% reduction compared to the Reference scenario in 2050).

Lastly, the hydrogen supply sector delivering to the energy market does not require energy as there are virtually no demand technologies diffusing in the Reference scenario. However, in the Net-Zero scenario, hydrogen-based technologies are promoted and therefore demand for hydrogen increases. This invokes sizeable demand for natural gas (in “grey” and “blue” hydrogen supply) and electricity (due to “green” hydrogen supply) to meet the hydrogen needs by 2050.

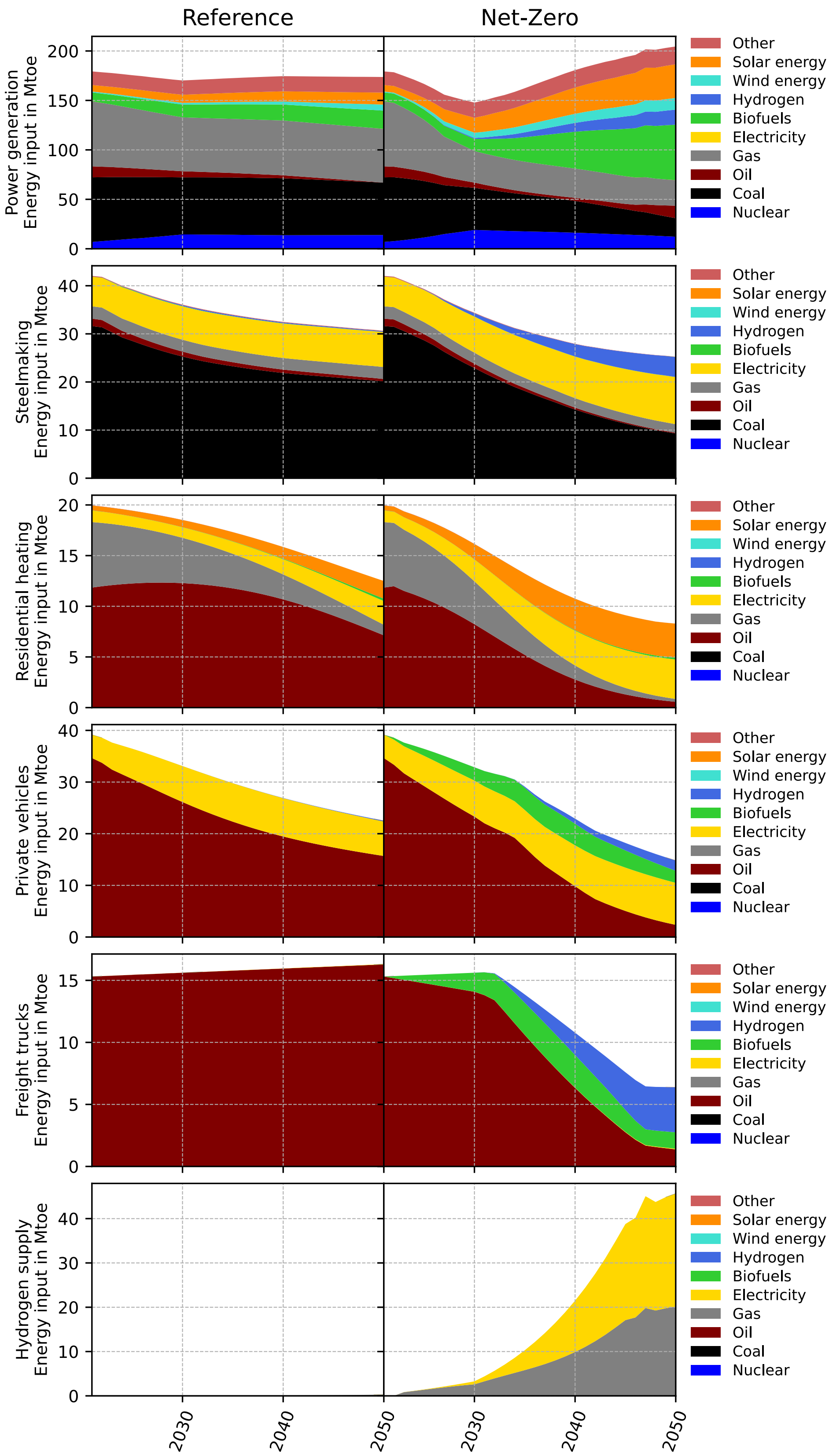


**Figure 7.** Energy input to the relevant sectors in the Reference and Net-Zero scenarios

**Source:** Produced by authors.

While figure 7 showed energy inputs to the sectors represented by the FTT models, energy demand of other sectors is described by E3ME. Demand for hydrogen is increased in those sectors as well and uses other FTT sectors as a proxy. Figure 8 depicts hydrogen demand across all sectors in a different level of aggregation. The total demand for hydrogen initially outpaces METI's hydrogen supply profile. This means that between 2020 and 2045, at least a portion of hydrogen needs to be imported, with consequences on energy trade balances.

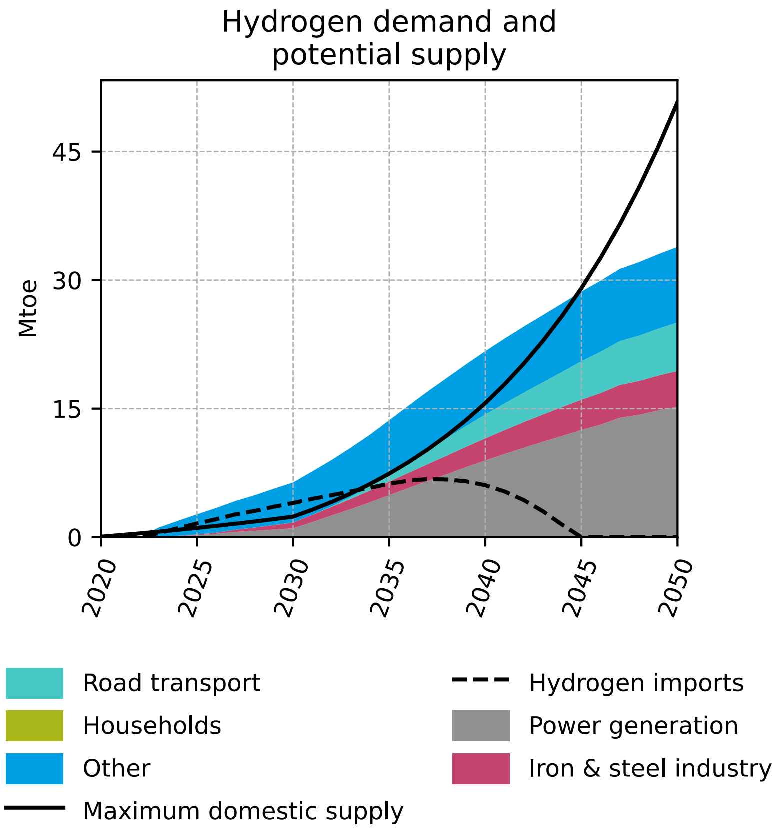


**Figure 8.** Hydrogen demand versus supply.

**Note:** The colored wedges indicate hydrogen demand by broad sectors. The black solid line indicates the maximum potential domestic supply, while the dashed line indicates hydrogen that needs to be imported.

**Source:** Produced by authors.

### 5.3. Emissions

The decline in fossil fuel demand in the Japanese economy in the Net-Zero settings leads to a large-scale reduction in emissions. Any remaining fossil fuel use is abated via CCS. Figure 9 illustrate the energy-related emission profiles of the reference and Net-Zero scenario, and the relative differences between them. In the reference scenario, the power sector remains to be the largest $CO_2$ emitter, but it shows a gradual decrease of 30% between 2020 and 2050. This is largely driven by continued uptake of renewables and nuclear energy. Emissions in the household sector halves in the same period, which is primarily driven by uptake of heat pumps. In total, emissions decline steadily by 32% between 2020 and 2050 in the reference scenario.

The rate of decline is accelerated once the Net-Zero policy package is enabled. The power sector nearly completely decarbonizes by 2050 due to the invoked technology diffusion. Compared to the reference scenario in 2050, the iron and steel industry shows a reduction of 93% due to increased uptake of hydrogen-based steelmaking and scrap recycling. Emissions in the road transport (as a combination of passenger and freight road transport) decrease by 80% due to a transition towards FCEVs. In total, emissions decrease by 90% compared to the reference scenario in 2050. This leaves residual emissions of 78 Mt $CO_2$, which are assumed to absorbed by land-use related emission mitigation.

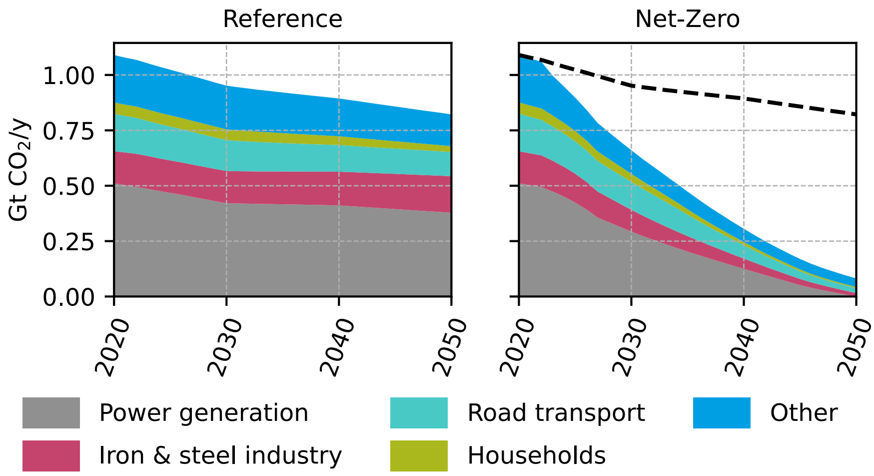


**Figure 9.** $CO_2$ emission levels in the Reference and Net-Zero scenarios

**Sources:** Produced by authors.

## 5.4. Gross Domestic Product and employment

The detailed simulation presented in this study leads to many economic feedbacks affecting GDP. Figure 10 shows the absolute differences of GDP and its components between the Net-Zero scenario and reference scenario. Investment in new buildings ( power plants, electrolysis capacity, etc.) and equipment (heat pumps, FCEVs, etc.) drive positive GDP impacts. The investment boost leads to job creation which – together with wage effects – lead to increased disposable income and that is reflected in consumer expenditure. The government spending such as subsidies will have a stimulating effect on the economy. At the same time, the policies do lead to inflated price levels which have a slight negative effect. Increasing energy price which is induced by carbon tax and high hydrogen price will give negative impact on the economy. These allow GDP to grow until 2027 and then fall between 2030. However, decarbonization technological innovation and renewable energy cost down by diffusion and learning effect will ease cost burden of the economy. Besides, the trade balance improvement by substantial fossil fuel import reduction will have a positive impact on the GDP.

Of course, the main target of the Net-Zero policy package is to transition to hydrogen-based and decarbonized economy. This goes hand in hand with a reduction in energy imports of fossil fuels. Up to 2045 some hydrogen imports are required to meet growing demand. However, it is expected that exports decline as the inflated price levels affect the trade competitiveness. Overall, the trade balance develops beneficially for Japan.

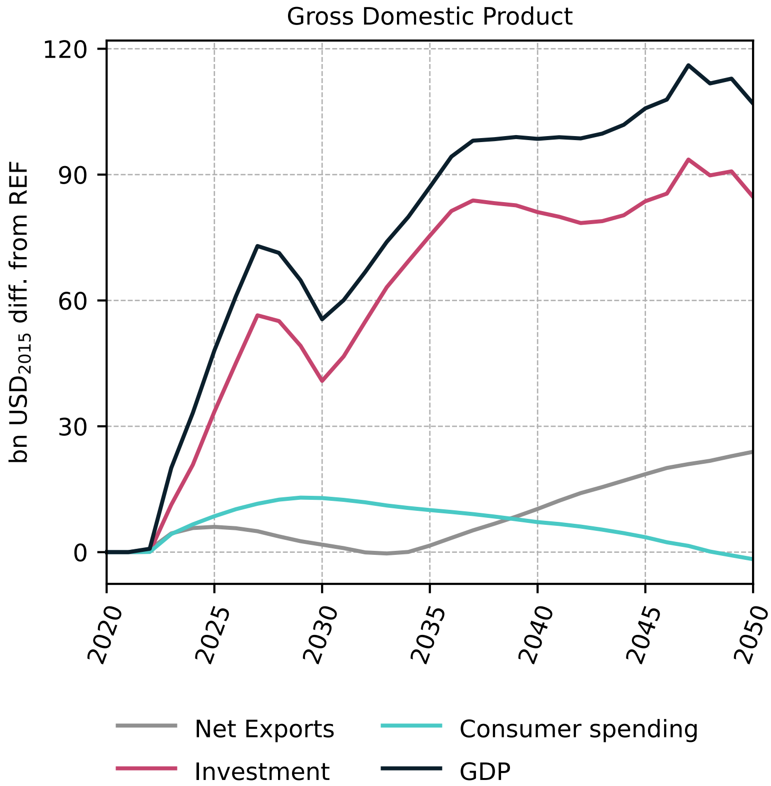


**Figure 10.** Absolute difference of GDP and its components between the Net-Zero and Reference scenarios

**Source:** Produced by authors.

The Net-Zero policy package presented in this study leads to a widespread change in the energy system through technology substitution and energy efficiency. It reshapes demand and supply profiles which has consequences on employment. As Figure 11 points out, a transition to low-carbon technologies will likely lead to positive job impacts, most notably in the power and hydrogen supply sectors and construction sectors. The power and hydrogen supply sectors stand to gain due to an increase of variable renewables in the power sector which is associated to higher employment factors and due to the creation of a novel hydrogen supply sector. Employment in construction increases in line with additional fixed gross investment, which involves building new power plants, installation of solar PV panels, and electrolysis for hydrogen production. Employment in the fossil fuel related industries decrease compared to the reference scenario.

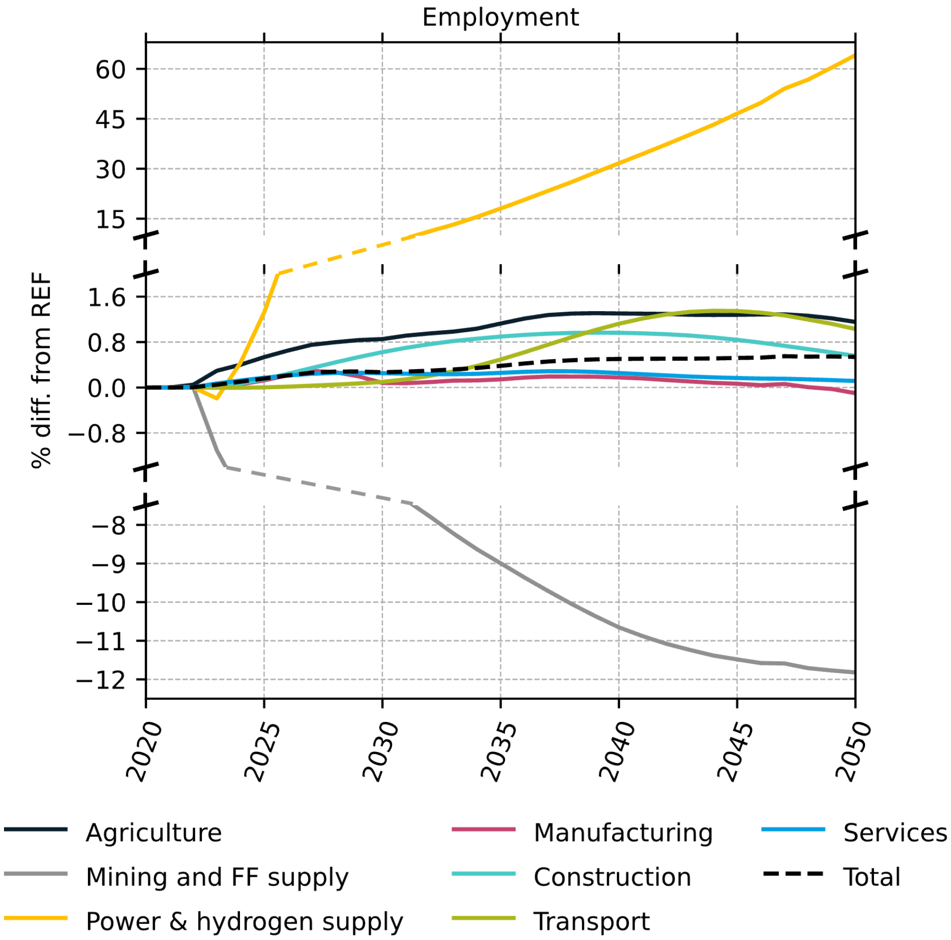


**Figure 11.** Relative employment differences between the Net-Zero and Reference scenarios.

**Source:** Produced by authors.

## 6. Conclusions and challenges

The results have shown that Japan has a lot to gain from decarbonization in a Net-Zero scenario involving a focused transition towards a hydrogen economy. First and foremost, the hydrogen diffusion scenario (Net-Zero scenario) shows that large-scale decarbonization is possible without losing economic activity. In fact, economic benefits can be expected according to our simulations. Second, many policies are focused on electrification and hydrogen-based application and both technology groups see a large increase in the relevant energy systems. Hydrogen technologies on the demand-side especially gain traction in the power sector, freight road transport, and iron and steel industry. About 12% and 34% of all energy input is hydrogen and electricity respectively. Third, the economic impacts are positive across the board as the Net-Zero policy package indicates that employment and most of the components of GDP show favorable results compared to the reference. Investment in new hydrogen-based and other low-carbon technologies contributes to the positive GDP results as it invokes economic activity and requires additional employment. However, this study does not analyze the impact on existing fossil energy sector. The precondition is carbon neutral but not limited to fossil energy. The reason for not analyzing the existing fossil energy sector is that it is not the center of the analysis. This study focuses on, the renewable energy sector like hydrogen replacing fossil energy as the center of energy, which also has the effect of economic growth.

However, there are some caveats. The simulation suggests that the transition to a Net-Zero economy requires a lot of investment. In fact, investment drives most of the positive outcomes. E3ME allows for money creation through lending without leading to full crowding out elsewhere. The model remains agnostic on the source of finance. While real-world evidence exists to support this, there are still caveats to this treatment (see e.g. [31]and therefore the simulation results need to be interpreted carefully. Our scenario showed the level of investment required to achieve Net-Zero by 2050 in Japan, but it does not indicate the likelihood of obtaining such investments. It also showed that a lot of public investment is required to facilitate the diffusion of low-carbon technologies, such as electricity charging stations for EV. However, most of these investments can be recouped via carbon tax revenues. Future work will focus on including an amplified mechanism to track financial flows and potential consequences of investment stimuli such as presented in this study.

Then, technology diffusion models such as FTT are well-suited to determine uptake trajectories of established technologies but dealing with novel technologies that are currently not included in the model system because of sparse data is a challenge. In addition, the rate of diffusion is highly uncertain for completely novel technologies such as electrolysis for green hydrogen production, as it outlined by Odenweller et al. [32].

**References**


1. METI *2050 Carbon Neutral Growth Strategy*; 2021;
2. METI *Hydrogen Basic Strategy*; 2017;
3. Section 1. The Situation of Energy Cost Available online: https://www.enecho.meti.go.jp/about/whitepaper/2015html/1-3-1.html (accessed on 10 January 2023).
4. The Federal Government *The National Hydrogen Strategy*; 2020;
5. METI *Environment Innovation Strategy*; 2020;
6. METI Japan's Roadmap to "Beyond-Zero" Carbon Available online: https://www.meti.go.jp/english/policy/energy_environment/global_warming/roadmap/innovation/thep.html (accessed on 4 October 2022).
7. METI *Recent Trends in Energy and the Progress of Policies toward Energy Transition and Decarbonization*; 2019;
8. Nakano, J. Japan's Hydrogen Industrial Strategy Available online: https://www.csis.org/analysis/japans-hydrogen-industrial-strategy (accessed on 6 October 2022).
9. Tokyo "Beyond-Zero" Week 2021 Held.
10. METI Purchase Subsidy for EV・LEV・PHV・FCV Available online: https://www.meti.go.jp/policy/mono_info_service/mono/automobile/cev/cevr3/file2.pdf (accessed on 1 October 2023).
11. Japan Targets 1,000 Hydrogen Stations by End of Decade Available online: https://asia.nikkei.com/Economy/Japan-targets-1-000-hydrogen-stations-by-end-of-decade (accessed on 28 May 2023).
12. Japan's Hydrogen Industrial Strategy Available online: https://www.csis.org/analysis/japans-hydrogen-industrial-strategy (accessed on 6 October 2022).
13. Cambridge Econometrics *E3ME Model Manual*; 2022.
14. Nakicenovic, N. The Automobile Road to Technological Change: Diffusion of the Automobile as a Process of Technological Substitution. *Technol Forecast Soc Change* **1986**, *29*, 309–340, doi:10.1016/0040-1625(86)90021-1.
15. Mercure, J.F. FTT:Power A Global Model of the Power Sector with Induced Technological Change and Natural Resource Depletion. *Energy Policy* **2012**, *48*, 799–811, doi:10.1016/j.enpol.2012.06.025.
16. Mercure, J.F.; Lam, A. The Effectiveness of Policy on Consumer Choices for Private Road Passenger Transport Emissions Reductions in Six Major Economies. *Environmental Research Letters* **2015**, *10*, doi:10.1088/1748-9326/10/6/064008.
17. Knobloch, F., P.H., C.U., L.R., H.M.A., M.J.F. A Technical Analysis of FTT:Heat-A Simulation Model for Technological Change in the Residential Heating Sector: Technical Study on the Macroeconomics of Energy and Climate Policies. *Energy Policy* **2021**, *153*, 112–249.
18. Vercoulen, P.; Lee, S.; Han, X.; Zhang, W.; Cho, Y.; Pang, J. Carbon-Neutral Steel Production and Its Impact on the Economies of China, Japan, and Korea: A Simulation with

E3ME-FTT:Steel. *Energies (Basel)* **2023**, *16*, 4498, doi:10.3390/en16114498.

19. Mercure, J.-F. An Age Structured Demographic Theory of Technological Change. *J Evol Econ* **2015**, *25*, 787–820, doi:10.1007/s00191-015-0413-9.
20. CE Delft *Jobs from Investment in Green Hydrogen*; 2021;
21. Capros, P.; De Vita, A.; Kannavou, M.; Fotiou, T.; Siskos, P.; Tsiropoulos, I.; Katoufa, N.; Mitsios, I.; Evangelopoulou, S.; Asimakopoulou, G.; et al. *EU Reference Scenario 2020: Energy, Transport and GHG Emissions - Trends to 2050*; Brussels, 2021;
22. Lee, S.; He, Y.; Suk, S.; Morotomi, T.; Chewpreecha, U. Impact on the Power Mix and Economy of Japan under a 2050 Carbon-Neutral Scenario: Analysis Using the E3ME Macro-Econometric Model. *Climate Policy* **2022**, *22*, 823–833, doi:10.1080/14693062.2022.2061406.
23. IEEJ *IEEJ Outlook 2021*; 2020;
24. Kato, S.; Lee, S.; He, Y.; Yoshioka, T.; Morotomi, T.; Chewpreecha, U. Study on Economic and Industrial Impact by 2050 Carbon Neutral in Japan, Assuming GHG Reduction Target and Power Supply Composition in 2030. *Analysis using E3ME Macro Econometric Mode, Research Project on Renewable Energy Economics of Kyoto University* **2022**, *43*, 1–28.
25. METI *Strategic Energy Plan*; 2021;
26. METI *Recent Trends in Hydrogen Policy*; 2021;
27. International Energy Agency Hydrogen Projects Database Available online: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database#license (accessed on 27 January 2023).
28. METI *Recent Trends in Hydrogen Policy*; 2021;
29. International Energy Agency *Global Hydrogen Review 2021*; Paris, 2021;
30. Ortiz Cebolla, R.; Dolci, F.; Weidner Ronnefeld, E. Assessment of Hydrogen Delivery Options. **2022**, doi:10.2760/869085 (online).
31. Pollitt, H.; Mercure, J.-F. The Role of Money and the Financial Sector in Energy-Economy Models Used for Assessing Climate and Energy Policy. *Climate Policy* **2018**, *18*, 184–197, doi:10.1080/14693062.2016.1277685.
32. Odenweller, A.; Ueckerdt, F.; Nemet, G.F.; Jensterle, M.; Luderer, G. Probabilistic Feasibility Space of Scaling up Green Hydrogen Supply. *Nat Energy* **2022**, *7*, 854–865, doi:10.1038/s41560-022-01097-4.