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Analyzing the necessity of hydrogen imports for net-zero emission scenarios in Japan

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ABSTRACT

With Japan's current plans to reach a fully decarbonized society by 2050 and establish a hydrogen society, substantial changes to its energy system need to be made. Due to the limited land availability in Japan, significant amounts of hydrogen are planned to be imported to reach both targets. In this paper, a novel stochastic version of the open-source multi-sectoral Global Energy System Model in conjunction with a power system dispatch model is used to analyze the impacts of both availability and price of hydrogen imports on the transformation of the Japanese energy system considering a net-zero emission target. This analysis highlights that hydrogen poses a valuable resource in specific sectors of the energy system. Therefore, importing hydrogen can indeed positively impact energy system developments, although up to 19mt of hydrogen will be imported in the case with the cheapest available hydrogen. In contrast, without any hydrogen imports, power demand nearly doubles in 2050 compared to 2019 due to extensive electrification in non-electricity sectors. However, hydrogen imports are not necessarily required to reach net-zero emissions. In all cases, however, large-scale investments into renewable energy sources need to be made.

1. Introduction

With the Paris Agreement, the global community agreed on reducing greenhouse gas emissions in order to keep the global mean temperature increase well below 2 °C [1]. In this regard, Japan also handed in their Nationally Determined Contributions (NDCs). These aim for an emission reduction of 15%–17% until 2030 [2]. Japan's NDCs had been lately updated and additionally aimed for a greenhouse gas reduction of 80% until 2050 with the strife to reach carbon neutrality as soon as possible in the second half of the century [3]. Recently, however, Japan's Prime Minister further increased this ambition by pledging that Japan will reach a net-zero emission society in 2050.[1]

For the decarbonization of its energy system, Japan introduced a variety of policy measures to restructure its feed-in-tariff system, increase electricity from renewable energy sources, and increase its overall energy security [4]. Together with the increased support of renewable energy sources, Japan also plans to establish a "Hydrogen Society" by the mid of this century. This includes a significant promotion of fuel-cell electric vehicles (FCEV), replacement of fossil power generation with hydrogen-based power generation, and fuel-switching towards hydrogen and synthetic gases in the industry sector [5]. To fulfill the future demands for hydrogen, domestic production of green hydrogen via electrolysis is planned to be supported alongside the establishment of international hydrogen markets. In the case of global hydrogen markets, Japan aims for importing around 5-10 mt of hydrogen by 2050, most of which will come from Australia [5,6]. However, importing substantial amounts of hydrogen will not be a solution to the national goal of increased energy security [7], as one of the biggest problems for the Japanese energy system and energy security is the reliance on large shares of imported energy carriers. Currently, the Japanese energy system is highly reliant on mostly imported fossil fuels [8]. This results in a high share of around 87% dependency on fossil fuels on primary energy consumption. With only small amounts of domestic fossil resources, Japan has a low self-sufficiency rate of 9.6% compared to other OECD (Organisation for Economic Co-operation and Development) countries.[2] On the other hand, Japan currently has the

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[1] https://asia.nikkei.com/Politics/Suga-vows-to-meet-Japan-s-zero-emissions-goal-by-2050, last accessed 03.12.2020.

[2] This rate determines how much of the primary energy demand can be fulfilled by domestic resources. For example, Germany has a self-sufficiency rate of around 37%, whereas the USA has a self-sufficiency rate of around 93%.

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globally second-highest installed capacity of solar photovoltaic (PV) plants and the third most generation [9].

2. Literature review

For the Japanese energy system, and more specifically the power sector, a plethora of studies is available, looking primarily at emission reduction scenarios of about 80%–90% by 2050 (compared to 1990). In this regard, studies often promote nuclear power production and carbon capture and storage (CCS)[3] as a valid and necessary option for a decarbonization of the energy system [11–15]. In this regard, Oshiro et al. [11] assess highly increased energy system costs for reaching ambitious climate targets without the availability of bio-energy with carbon capture and storage (BECCS) within their analysis of possible transformation pathways of the Japanese energy system. In their study, even without the deployment of BECCS, large amounts of CCS technologies have to be deployed to meet international climate targets. Similarly, Kato and Kurosawa [12] found with their modeling approach that Japan cannot reach 80% or even 90% emission reduction without large-scale deployment of CCS. Furthermore, a cross-model comparison of 80% reduction scenarios has been carried out by Sugiyama et al. [14]. As a result of this, they present that the industrial sector has a large final energy share and significant residual carbon dioxide emissions under 80% reduction scenarios, which highlights the difficulty of the decarbonization of that sector. Also looking at 80% reduction scenarios, Fujimori et al. [15] link a computable general equilibrium (CGE) model to an energy system and power market model to assess the loss in GDP resulting from the energy transformation with different model setups. Comparing Japan and Germany, Kharecha and Sato [13], analyze the cuts in CO_2 emissions after the Fukushima incident. They advocate that a prolongation of nuclear power and instead of phasing out coal and natural gas would reduce emissions even further and lead to fewer air pollution-induced deaths. However, they also show that despite the phase-out of nuclear power in Germany and Japan, total CO_2 emissions have been reduced due to the large-scale deployment of renewable energies.

Overall, in these previously mentioned studies, the external costs of nuclear power plants [16] or historical and current cost overruns of nuclear power plants [17,18] are often not discussed or neglected. Furthermore, the technological applicability of large-scale deployment of CCS is still uncertain [19,20]. Additionally, there are limited geologically appropriate areas for CCS deployment on Japanese territory [15] and thus, scenarios without the availability of CCS should also be considered. Nevertheless, only a few studies analyze 100% renewables in the power system in Japan, and no study is available looking at net-zero emissions in Japan without the necessity of utilizing CCS or nuclear energy. Esteban et al. [21,22] highlight that 100% renewables are indeed possible with moderate demand assumptions, but will result in large-scale deployment of batteries and overall increased balancing requirements for the power system. In this regard, Neetzow [23] shows that renewable energies are indeed able to first replace flexible generation (e.g., gas-fired power plants) and later inflexible generation (e.g., coal and nuclear). Apart from specifically looking at the Japanese energy system, several studies are available looking at possible transformation pathways for the global energy system [24–28]. Hereby, Bogdanov et al. [26], Ram et al. [27] present a power system based on 100% renewables for the whole world. They show that, in the case of complete decarbonization of the power sector, significant investments into power system flexibility are needed to compensate for the variable and intermittent nature of renewable energy sources. Also incorporating sector-coupling effects and the global energy system, Löffler et al. [25] and Bogdanov et al. [28] present different analyzes looking at the global energy system based on 100% renewables, also incorporating non-electricity sectors and sector-coupling effects. Both studies highlight the importance of low-cost renewable energy sources as a basis for a successful energy transformation. Furthermore, they also emphasize the importance of swift and consequent climate actions, combined with long-term strategic planning of energy and climate policies.

Regarding the importance of flexibility options for the global and Japanese future energy systems, Bogdanov and Breyer [29] present an energy system based on 100% renewables for the North-East-Asian region, where balancing and flexibility will be provided by the deployment of a super-grid encompassing the whole region. Thus, Japan's connection with mainland China allows for large-scale power trade to compensate for the regionally different production patterns of renewable energy sources. Similarly, Ichimura [30] points out that increased cross-regional interconnection inside Japan can prove to be a crucial factor in balancing renewable energies.

Furthermore, flexibility for the power system can also be provided by demand-side measures. In this regard, electricity storage and system flexibility can also be provided by battery electric vehicles (BEV), which provides system-wide benefits, especially in combination with residential solar PV [31]. When BEVs are charged within the peak of solar PV production, the battery of electric vehicles can provide an economical way of storing excess power and later using it via vehicle-to-grid integration [32]. However, public opinion is crucial, as local actors and citizens drive the deployment of solar PV systems in metropolitan areas in conjunction with electric vehicles. However, as Chapman and Okushima [33] showed in their study, lower-income households in Japan are less likely to be interested in a low-carbon energy transition and might favor non-renewable energy options. Therefore, the Japanese government would need to re-distribute the costs and benefits of solar power deployment more progressively and increase subsidies in prefectures with lower incomes to deploy renewable energies effectively throughout the country [34].

The production of hydrogen presents another cost-efficient way of providing flexibility for the energy system by storing and later utilizing excess renewable energy via electrolysis. Linking the electricity and gas networks may provide the flexible resources and necessary infrastructure to absorb the increasing renewable energy production [35,36]. Excess renewable energy can be profitable to transform to hydrogen and provide energetic benefits for decarbonizing the energy system, although significant cost barriers remain [37]. Nevertheless, hydrogen and hydrogen storages are suitable for storing excess renewable energy production for an extended period of time, and hydrogen storages by themselves pose to be economically competitive with battery storages in Japan [38]. When targeting net-zero emissions in the power sector, and CCS and nuclear are not available, electricity generation from hydrogen can play a significant role [39]. In general, hydrogen can be burned in gas turbines and has the same ramping and cycling capabilities as natural gas based power generators. However, hydrogen production is still costly, and in order to decrease the costs for electrolysis, governmental incentives are necessary to increase the profitability of hydrogen systems [40]. Also, utilizing a multi-sectoral approach for analyzing hydrogen systems seems essential, as hydrogen can not only provide electricity, but energy in the industrial (i.e., as a chemical component or energy carrier), buildings, and transportation sectors. Globally, hydrogen is assumed to play a critical role in the transportation sector, especially for heavy-duty road-based transportation via fuel-cell electric vehicles in 2050, as hydrogen and hydrogen electrofuels pose a more cost-competitive alternative to biofuels [41–43]. Specifically, hydrogen and hydrogen-based ammonia can also provide the means to decarbonize the maritime shipping sector [44,45]. Additionally, hydrogen could also be used in a large variety of applications in local smart grids in future energy systems for generating electricity, as energy storage, or for producing heat. However, integrating hydrogen in smart grids still faces many challenges from a demand-side and market perspective, but also from a technological side [46].

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[3] Also promoted as carbon capture, transport, and storage or carbon capture, transport, and sequestration (CCTS) in certain studies [10].

In this paper, the value of hydrogen for reaching net-zero emissions without the deployment of CCS or additional nuclear generators under different assumptions regarding the prices and availability of hydrogen imports is assessed. In this research, a novel stochastic version of the open-source multi-sectoral Global Energy System Model (GENeSYS-MOD) [25,47,48] is used to examine the case of Japan. Furthermore, to generate further insights about the flexibility of hydrogen in the power sector and to assess the feasibility of the results of the energy system model, a full-hourly power system dispatch model is used in conjunction with GENeSYS-MOD.

Although the modeling work of this paper is focused on the region of Japan, the findings presented in this paper can also be of interest to international policy- and decision-makers as well as energy system modelers. In general, uncertainty is widely acknowledged as a key issue for energy systems planning. However, it is often neglected in energy system models [49,50]. In fact, in all of the studies mentioned above analyzing either the global or the Japanese energy system, no formal techniques of uncertainty modeling have been applied, although several methods exist. Most commonly, two methods of analyzing uncertain elements to quantitative models are applied: stochastic programming [51] or deterministic and stochastic sensitivity analyses (i.e., Monte-Carlo simulations) [52–54]. This paper contributes to the existing literature gap regarding long-term energy system analyses by applying stochastic programming to address uncertainties in energy system modeling.

Furthermore, it specifically investigates the inter-linkage between ambitious climate targets and hydrogen imports, which is also an actual topic for possible hydrogen-exporting as well as future hydrogen-importing countries. Although hydrogen can play an important and broad role in future energy systems, current research often only focuses on narrow use-cases or only in certain sectors. As of now, a comprehensive analysis of hydrogen production and consumption in a multi-sectoral energy system model on a detailed technological level is missing in the literature. Especially, as the topic of net-zero emissions is gaining interest in various countries [55–57].

3. Methods

For this research, the multi-sectoral open-source Global Energy System Model (GENeSYS-MOD) by Löffler et al. [25] has been enhanced and reformulated into a multi-horizon two-stage stochastic linear optimization problem [51] and has been applied to the Japanese energy system. Additionally, the results from GENeSYS-MOD are used in a power system dispatch model to check the general feasibility of the resulting power system for 2050.

3.1. Stochastic energy system model

In general, GENeSYS-MOD is a linear cost-optimizing techno-economic model based on the Open Source Energy Modeling System (OSeMOSYS) [58,59]. GENeSYS-MOD builds upon this framework and extends its core functionalities as well as its sectoral coverage [47,48]. Besides the power sector, non-electricity sectors such as industrial, residential and commercial buildings, and mobility are incorporated into the model. Overall, this allows for an extensive analysis of sector-coupling aspects and assessment of electrification efforts in the future energy system.

For this analysis, the industrial sector has been extensively reformulated. Instead of the previous demands for specific heating ranges (buildings heat, low industrial heat, medium industrial heat, high industrial heat, compare [48]), different industrial sub-sectors are now modeled in greater detail: Aluminum, Copper, Ammonia, Chlorine, Steel, Lime, Glass, and Cement production, as well as their primary intermediate products. Additionally, the buildings sector has been split into residential and commercial sub-sectors, each with their own set of technologies. In this regard, the presentation of combined heat and power (CHP) plants, as well as district heating (DH) in general, has been improved.

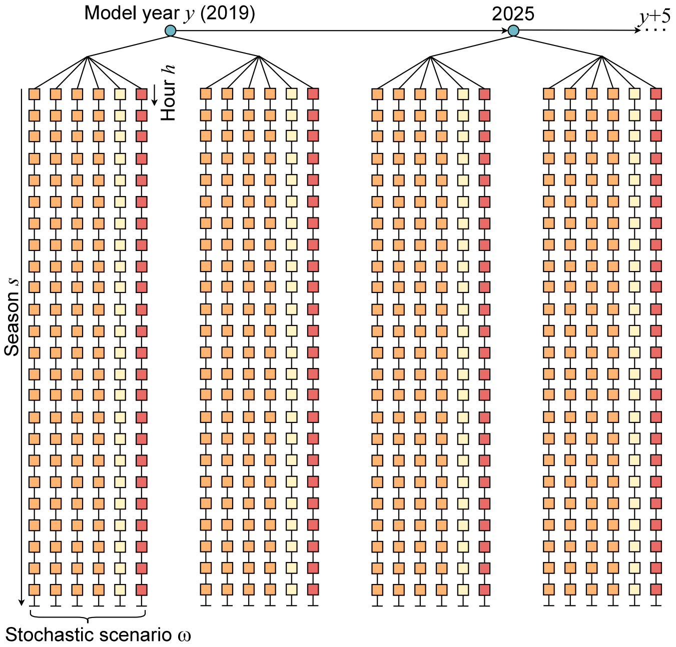

Fig. 1. Example visual representation of the temporal and stochastic structure of the stochastic version of GENeSYS-MOD with two stochastic scenarios. Blue circles represent the model years, each of which has two stochastic scenarios associated in this example. Each stochastic scenario is divided into six seasons (four regular and two special) consisting of 24 consecutive hours (represented by orange, yellow, and red squares) each. The actual structure utilized within the model is presented in Section 3.1.1.

To add elements of uncertainty, GENeSYS-MOD has been extensively reformulated into a two-stage stochastic program with recourse [51]. Additionally to the changes in the technological representation, the temporal resolution has also been adjusted for a better implementation of the stochastic variables. In general, the temporal structure now follows Skar et al. [60]. In this regard, the principles of multi-horizon stochastic programming as presented by Kaut et al. [61] are applied. Therefore, stochastic and operational uncertainty is represented by independent stochastic processes. It is also assumed that current operational decisions do not directly affect future strategic or operational decisions. This allows to isolate current operational decisions from future decisions and reduce the scenario tree's total size.

Yearly investment decisions represent the strategic stages. With this, perfect foresight about strategic data is assumed and strategic uncertainty neglected. Instead, each year has several stochastic scenarios ω, each represented by different seasons l. Each year and stochastic scenario has the same amount of seasons associated. Also, each season for each scenario has the same amount of consecutive hours h. An exemplary visual representation of this structure is shown by Fig. 1, whereas the actual setup used in this article is presented in Section 3.1.1.

In contrast to using a yearly full-hourly time-series consisting of 8760 annual time-steps, this formulation has a largely reduced problem size. Still, it allows for a representation of short-term operation planning while representing the seasonal intermittency. Operational uncertainty is represented by uncertain hourly variable renewable infeed (i.e., solar PV, wind, run-of-river hydropower) and uncertain hourly demands. Other techno-economic parameters such as costs, fuel prices, emission budgets, and efficiencies are assumed to be strategic data.

The model was solved using different amounts of stochastic scenarios (compare Section 4.2). Common for all model runs, stochastic scenarios, and years is the temporal structure. Each stochastic scenario is divided into six seasons, each of which has 24 consecutive hours. The model's storage formulation has been adjusted to this new temporal structure, and only long-term storages (e.g., pumped hydro, compressed air energy storage) are allowed to store energy from one season to another.

3.1.1. *Stochastic scenario generation*

The data used for the stochastic scenarios $\omega \in \Omega$ comes from a sample of consecutive hours from historical data, and all data types (e.g., solar PV infeed, residential demand, etc.) used the same sample of consecutive hours. This preserves auto-correlation and correlation between data series. The samples are randomly chosen for each season and stochastic scenario.

To generate the stochastic data, first, for each modeled year $y \in Y$ and stochastic scenario $\omega \in \Omega$, a random data year $k \in K$ is chosen (compare Algorithm 1). Data is chosen from historical data from 2010 until 2019. For each regular season $s \in S$, a random number θ_s^{rnd} between $(s-1)\frac{8760}{|S|}+1$ and $s\frac{8760}{|S|}-24$ is chosen.[4] Then, it is ensured that each season starts with the first hour of the day by calculating $\theta_s = \theta_s^{rnd} - (\theta_s^{rnd} \ mod \ 24)$. Therefore, all stochastic scenarios for all seasons start in the same hour of the day- and night-time hours are equal in all cases. For all regions, the data for the 24 consecutive hours starting from θ_s are taken as data for the season and stochastic scenario from the existing historical data $\xi_{k,r,h}^{data}$. Lastly, for each region, two special seasons with extreme cases are added. First, a season containing the 24 consecutive hours with the highest variable renewable infeed based on the chosen historic year is added, and consequently, a season with the lowest variable renewable infeed is included as well.

Algorithm 1 Stochastic scenario generation

```
for $y \in Y$, $\omega \in \Omega$ do
    select random data year $k \in K$
    for each regular season $s \in S$ do
        select random number $\theta_s^{rnd} \in [(s-1)\frac{8760}{|S|}+1, s\frac{8760}{|S|}-24]$
        calculate $\theta_s = \theta_s^{rnd} - (\theta_s^{rnd} \ mod \ 24)$
        for $r \in R$, $h \in H$ do
            select hourly data sample $\xi_{y,\omega,s,r,h}^{sample} = \xi_{k,r,h'}^{data}$
            with $h' = \theta_s + h + 1$
        end for
    end for
    for $r \in R$ do
        add 24 consecutive hours with highest variable infeed as season $|S|+1$
        add 24 consecutive hours with lowest variable infeed as season $|S|+2$
    end for
end for
```

The resulting sampled data points $\xi_{y,\omega,s,r,h}^{sample}$ are then assigned their respective actual model parameters. For this research, cases of the model have been run, ranging from 1 stochastic scenario up to 5 stochastic scenarios with 4 regular and 2 special seasons each. The model itself is implemented in GAMS, and each model run has been calculated by using the commercial solver CPLEX on a high-performance cluster. For a model run with 5 stochastic scenarios, 410 GB of RAM and a calculation time of roughly 120 h have been needed. Model runs with only one stochastic scenario represent model runs without uncertainty, as the probability for the realization of the only existing scenario is always 100%. The scenario generation algorithm was executed once before the actual model runs. Hence, cases with 5 stochastic scenarios contain the same scenarios as the cases with 4 stochastic scenarios plus 1 additional one.

3.2. *Dispatch model*

A full-hourly power system dispatch model has been used in addition to GENeSYS-MOD to investigate the general feasibility of the resulting power system for 2050. The dispatch model is implemented in GAMS, too, and its mathematical formulation loosely follows Schill and Zerrahn [62]. The mathematical formulation of the dispatch model can be found in Appendix C. In general, it is implemented as a linear optimization program focusing on generation planning in the power sector, minimizing the dispatch costs for each hour and each region. Key parameters, such as power demand for each hour, existing power generation capacities, power transmission lines, and electricity storages are obtained from GENeSYS-MOD results. In this paper, the power system dispatch model uses a linear net-trade flow formulation for power trade instead of a more sophisticated dc load flow formulation. Ramping constraints are represented in the model and considered while optimizing the hourly dispatch. Additionally, the dispatch model can generate electricity via an extremely costly *Infeasibility* technology to consistently meet the electricity demand if GENeSYS-MOD installs not enough installed capacities. Therefore, the dispatch model can always generate a feasible solution, and the results of the different model runs can be benchmarked against each other.

3.3. *Key data*

In this research, Japan is divided into 8 regions based on the operation area of major power companies. However, to reduce the total number of regions, Okinawa has been included in the Kyūshū region, and Hokuriku is included in the Chūbu region. Transmission capacities between these regions, as well as current network extension plans, are considered. Regional energy demand data for all sectors has been obtained on a prefectural level from the Japanese Agency for Natural Resources and Energy[5] and has been aggregated to match the modeled regions.

Hourly capacity factors of solar PV, wind, and heat pumps were calculated based on a 50 × 50 km grid of Japan of *renewables.ninja* [63] for the historic years 2010 to 2019. The resulting data points have been statistically classified in different categories (e.g., inferior, average, and optimal solar PV locations) and aggregated for the corresponding regions. Installable potentials of solar PV and wind power have been taken from Kojima [64], Bogdanov and Breyer [29] and Jacobson et al. [65]. These potentials have been compared and checked with own calculations based on average capacity factors and land utilization rates. Other technology parameters have been taken from Simoes et al. [66], Burandt et al. [47], and Ram et al. [27].

3.4. *Scenario assumptions*

For this paper, the main focus was on analyzing the impacts of hydrogen imports on reaching net-zero emissions in Japan in 2050. Thus, all scenarios that have been calculated aim for net-zero emissions in 2050. In this regard, negative emission technologies, CCS, and prolongation of nuclear power plants and investments into newly built generators are disabled for this analysis. Overall, 9 cases with different hydrogen import prices, ranging from 2 €/kg to 6 €/kg in 2050, have been considered, and one case without the possibility of importing external hydrogen. The prices for hydrogen imports start at a price of 9.5 €/kg in 2019 and are linearly interpolated until the target price in 2050. This analysis does not assess the origin of the imported hydrogen, but it is assumed to come solely from renewable sources. Therefore, the carbon content of the imported hydrogen is assumed to be zero. For further sensitivity analyses, all cases have been run

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[4] E.g., for a total of 4 seasons, the range for a random number for season 2 is between 2191 and 4356.

[5] In Japanese: https://www.enecho.meti.go.jp/statistics/, last accessed: 21.12.2020.

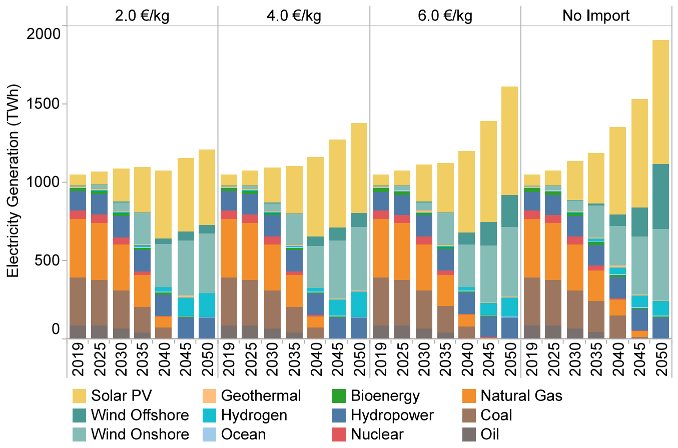

Fig. 2. Power system development in the energy system model until 2050 with 5 stochastic scenarios. The annual results present the average of all stochastic scenarios.

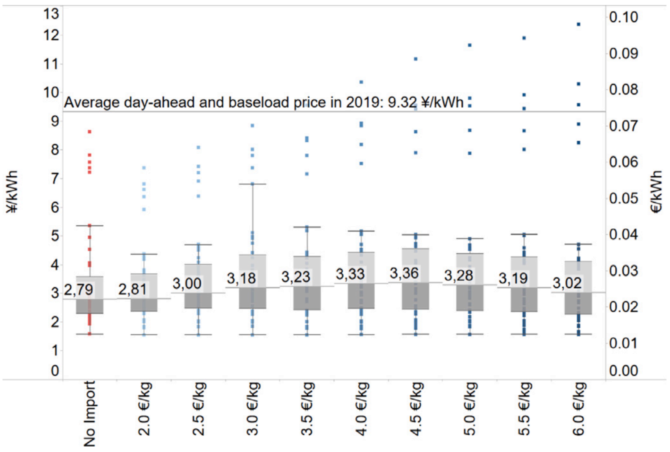

Fig. 3. Average of annual average power generation prices in Japan for all regions and all 5 stochastic scenarios in 2050. In all cases, the topmost outlier represent the Kantō region.

with and without the availability of methane pyrolysis. Despite being a promising technology to produce emission-free hydrogen, methane pyrolysis is currently not commercially available, and future development still sees specific challenges that have to be overcome before a large-scale deployment could be possible [67,68]. Therefore, the results presented in this paper assume no availability of methane pyrolysis.

Furthermore, there is no limit set on the amounts of hydrogen imports, such that the model can freely choose the amount of imported hydrogen that would be beneficial from a system optimization perspective. Furthermore, a major reactivation of the nuclear reactors shut down after the Fukushima Daiichi incident is prohibited in this analysis. Nuclear power generation is limited to 2019 levels to explore the possibility of an energy system decarbonization without nuclear power generation.

The model is calibrated to the base year 2019 and runs in 5-year steps until 2050 (6-year step between 2019 and 2025). Existing and planned capacities for power generation technologies are included in all scenarios. The primary energy consumption, power production, and electricity demands in the base year have been validated by using official government statistics (compare Appendix B).

4. Results

This section presents the key results of this analysis starting with the results for the general energy system development in Section 4.1. Afterwards, the influence of uncertainty and stochasticity on the results is presented.

4.1. Energy system development in Japan

Firstly, the impact of hydrogen imports on the power system, electricity prices, general import dependency, and other industry branches is discussed. As presented in Fig. 2, allowing hydrogen imports has a tremendous impact on the power system development. Overall, a significant shift towards renewable energy sources, such as solar PV, onshore and offshore wind, and hydropower, can be observed in all scenarios. Subsequently, fossil power generators will need to be phased out by 2050 to reach the goal of net-zero emissions.

Commonly for all cases, solar PV will become the primary source of electricity, with a power generation of 40%–45% of the total electricity production. The large amount of solar PV will be complemented by significant amounts of onshore wind power. Further baseload electricity will be provided by hydropower in all cases. However, extensive efforts to electrify other sectors or produce hydrogen from electricity have to be pursued in the case without any hydrogen imports. This results in significantly increased power demands from other sectors, and therefore the total power production nearly doubles from 2015 towards 2050 in the case without hydrogen imports from around 1050 TWh to 1900 TWh. Also, in this case, offshore wind power plays a more prominent role as opposed to the other cases, since despite being a rather costly option, it can complement the large amounts of solar and onshore wind.

Furthermore, power production from hydrogen sees differences between the cases. Although all cases utilize electricity from hydrogen to a certain degree, the importance of hydrogen for the power sector differs. With cheaply available hydrogen (2 €/kg), 12% of electricity will be directly produced via hydrogen (150 TWh) and thus will be providing baseload. In contrast, without hydrogen imports, only 4% (92 TWh) of electricity will be produced by hydrogen utilization. Without the possibility of importing external hydrogen, the domestically produced hydrogen will be more valuable to use in the other sectors, with batteries, seasonal storages, and increased transmission capacity providing flexibility in the power system.

Due to the large amounts of variable renewable energy sources in all cases, the prices for producing electricity will generally be lower than today's prices (compare Fig. 3). The overall lowest levelized cost of electricity (LCOE) can be found in the case without any hydrogen imports, as large amounts of renewables and cheap domestic produced hydrogen have a positive effect on the power generation price. When hydrogen imports with a price of 2 €/kg are possible, nearly as low power generation costs can be observed in the model. Again, renewables pose a cost-efficient way to decarbonize the power system and reduce power generation prices. In this case, electricity produced from hydrogen is nearly as cost-efficient as renewable power production.

Furthermore, hydrogen imports positively impact the average power generation prices in the Kantō region (where the metropolitan area of Tōkyō is situated). In this region, the average LCOE in the case with 2 €/kg hydrogen imports is 6.6 ¥/kWh instead of 7.5 ¥/kWh in the case without hydrogen imports. Mainly because of the limited area for renewable energy sources, this region is always relying on power transmission and electricity produced from hydrogen and hydropower. Hence, cheap imported hydrogen poses a valuable alternative for power production in heavily urbanized regions as a substitute for local renewable energy. On the other hand, the highest LCOE could be observed in cases with hydrogen imports of 4.0–4.5 €/kg. Here, imported hydrogen will be used in the power sector, which increases the power price, but at the same time, large amounts of hydrogen are used in non-electricity sectors. Therefore, using hydrogen in non-electricity sectors positively affects the electricity sector, as electrification in the buildings and industrial sectors is reduced and substituted by hydrogen-based

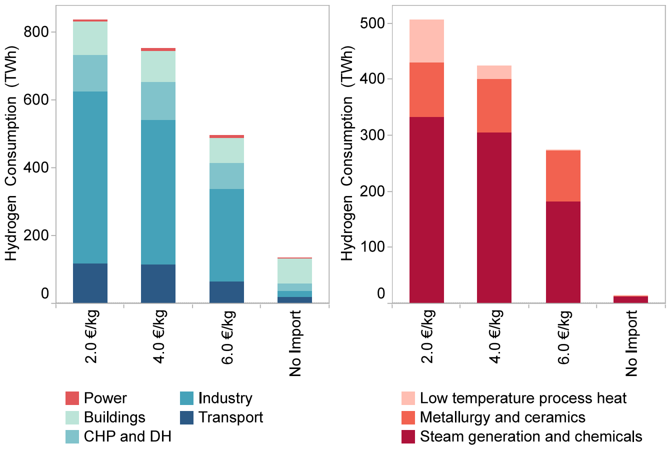

Fig. 4. Overall hydrogen consumption (left) and aggregated industrial use (right) of hydrogen in GENeSYS-MOD in the case with 5 stochastic scenarios.

technologies. Hence, a positive effect on the overall system costs can be observed, although average power generation prices are 20% higher than in the case without hydrogen imports.

The usage of hydrogen across all sectors in general and specifically in the industrial sub-sectors is depicted in Fig. 4. As previously mentioned, the effect on the power sector is generally minor in all cases, regardless of hydrogen import availability. In all cases, significant amounts of hydrogen will be used by dedicated district heating plants (DH) and by residential homes and commercial buildings for direct heat generation. With decreasing hydrogen import prices, the role of hydrogen in the transportation sector increases, although this primarily impacts freight transport, as passenger transportation will tend towards the usage of battery electric vehicles in the model. However, allowing hydrogen imports allows for higher usages of hydrogen, especially in the industry sector. Up to 500 TWh (roughly 12 mt of hydrogen) will be used in the industrial sector alone in the case with the cheapest hydrogen imports. Overall, in this case, 19 mt of hydrogen will be imported, which exceeds current governmental plans for importing 10 mt hydrogen in 2050 [5].

Without any imports, only small amounts are used for steam generation and in the chemical sector. This amount is significantly increased the cheaper the imported hydrogen becomes available, as steam generation via hydrogen becomes the primary consumer of hydrogen. However, only with hydrogen imports, hydrogen plays a significant role in the metallurgy sector. As a result of this, the largest share is being used in the steel production sector with direct reduced iron produced via hydrogen combined with steel-making in electric arc furnaces. Second are generic high-temperature furnace appliances used in specific industrial sub-sectors (e.g., glass, ceramics, etc.). Also, alumina refineries utilizing hydrogen are used when hydrogen imports become available. In the case without hydrogen imports, the metallurgy sub-sectors will opt for direct electrification of most products (e.g., molten electrolysis, electric (arc) furnaces, etc.). When hydrogen import prices get as low as 4.0 €/kg, hydrogen will also be used in other industrial sub-sectors where low-temperature process heat is required (e.g., food production).

Overall, importing hydrogen will also increase the import dependency of the Japanese energy system towards 2050 compared to the cases without any possibility to import hydrogen (compare Fig. 5). Without hydrogen imports, the Japanese energy system will depend only on 4% foreign fuel imports. These fuels will be used in industrial processes, where no carbon will be embodied in the final product, and no direct emissions occur. However, when hydrogen imports are allowed, the import dependency will be around 20% to 40%. An import dependency of 40% is still significantly less than today's levels and positively impacts the Japanese government's energy security goals. However, for maintaining overall energy security with such import dependency levels, diversification of suppliers is needed. Furthermore, the scenario without hydrogen imports still sees higher overall energy security, with most energy carriers being produced domestically.

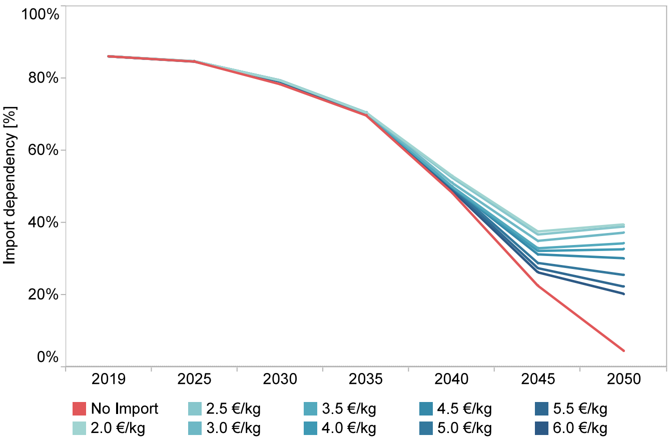

Fig. 5. Import dependency of the Japanese energy system from 2019 until 2050 in the case with 5 stochastic scenarios.

Table 1
Remaining global and Japanese carbon budgets in Gt based on [69]. The remaining carbon budgets for Japan were obtained using different metrics.

Approximate global warming		Global 2018	Japan 2019 *Population*	Japan 2019 *GDP*	Japan 2019 *Current emissions*
1.5 °C	66%	420	5.81	15.81	11.56
	50%	580	8.48	22.29	16.42
1.75 °C	66%	800	12.16	31.20	23.10
	50%	1040	16.17	40.92	30.39
2 °C	66%	1170	18.34	46.18	34.34
	50%	1500	23.85	59.55	44.37

Furthermore, it can still be observed that a transformation of the energy system towards renewable energy sources, hydrogen, and electrification increases energy security. Currently, the Japanese energy system is dependent on 86%–87% foreign energy supports, utilized in most of the sectors. Hydrogen imports in the model only play a role from 2035 onward, with only marginal impacts in the years before 2035. In cases with cheap hydrogen imports available, the import dependency in 2050 is slightly increasing compared to 2045. It can be assumed that the trend of importing hydrogen will either further increase or at least stay stable in the years from 2055 onward if enough global hydrogen exporting capacities exist. Import dependency levels in today's magnitude seem unlikely considering the energy system developments presented in this paper.

The accumulated model period emissions in all cases with 5 stochastic scenarios range from 20.2 to 21.4 Gt CO_2. Based on different metrics as presentedin Table 1, this is still in line with a 1.5 °C compatible pathway (global emissions divided by GDP) or at least 2 °C (global emissions divided by population). However, it becomes clear that net-zero emission does not necessarily represent a well-below 2 °C compatible energy transition pathway as agreed on by the global community in the Paris Agreement [1]. Therefore, having a significant chance of keeping the global mean temperature increase at 1.5 °C, even stricter and globally coordinated climate actions are needed.

In the case of 5 stochastic scenarios, hydrogen imports with 2.0 €/kg have a decreased objective value of 0.54% compared to not allowing hydrogen imports, as shown in Fig. 6. Thus, although it shows that introducing hydrogen imports has a marginally positive effect on the overall system costs, the overall costs of planning an energy system without hydrogen are not much more costly than relying on large-scale hydrogen imports in the future. Nevertheless, hydrogen imports

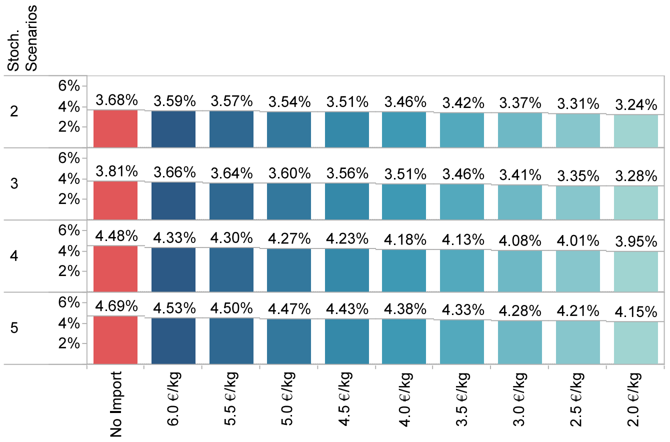

Fig. 6. Increase of total system costs compared to the case with 1 stochastic scenario and no hydrogen imports.

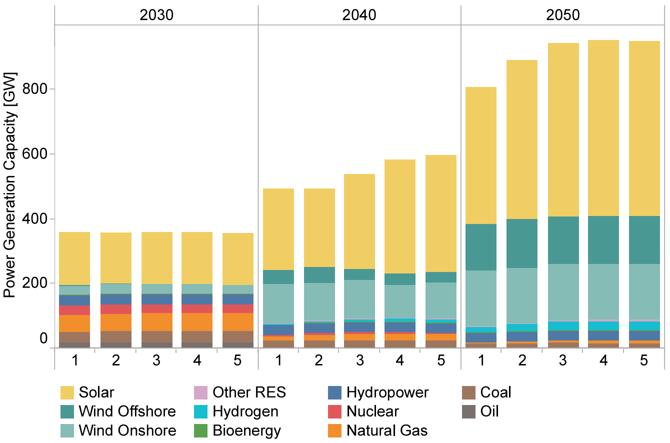

Fig. 7. Power generation capacities in the case without hydrogen imports for the different stochastic scenarios in GENeSYS-MOD.

can still have an essential role in specific sectors of the energy system. However, the results also highlight that the cost increase for increased self-sufficiency is relatively insignificant from a whole system perspective.

4.2. Impact of uncertainty on long-term energy system planning

This sub-section explores the value a stochastic model can provide for long-term energy system planning. Starting with the total system costs in GENeSYS-MOD, it can be observed that introducing stochasticity increases the total system costs (compare Fig. 6). Introducing only one additional stochastic scenario increases the total system costs by 3.7%, whereas introducing further 4 stochastic scenarios (so, 5 in total) only increases the total system costs by an additional 1% (4.7% from 1 to 5 stochastic scenarios).

For long-term planning of the power system, introducing stochasticity significantly affects capacity planning, as depicted by Fig. 7. Without stochasticity and perfect foresight, much less renewable capacity is being invested in. However, with an increasing amount of stochastic scenarios, solar PV capacities are vastly increased (namely by 28% in the case with 5 stochastic scenarios compared to only 1 stochastic scenario). Also, the introduction of stochasticity has an additional incremental effect on power generation capacities utilizing hydrogen and energy storages in general, as more flexibility options are needed to cover the uncertainty of renewable electricity generation. The increased need for flexibility options and power generation capacities is the primary source of increased system costs in the cases with more stochastic scenarios.

However, the impacts of stochasticity on long-term power system planning only play a role in cases without substantial conventional generation. In 2030, introducing stochasticity only has a limited effect on capacity planning, as uncertainty in renewable production can nearly always be met by ramping up conventional generators, and only from 2040 onward, substantial differences can be seen. The conventional generators still existing in 2050 in all scenarios are not being used by the model due to the constraint of having net-zero emissions and 2050 and no negative emission technologies available in this analysis. In this research, the existing conventional capacities in 2050 cannot be run and end up stranded in the model. Nuclear power generation capacities are subsequently phased out until 2050, with only 5 GW of nuclear capacity still existing in 2040.

Overall, the differences in existing capacities also play a significant role in the operational planning of the actual power system dispatch. Using the capacities resulting from the model runs in GENeSYS-MOD, a power system dispatch model has been used to calculate the feasibility of the resulting power system. As seen in Fig. 8, calculating a dispatch with the capacities planned while using only 1 stochastic scenario is only possible using *Infeasibility* power generation. Thus, it would not be possible to actually meet the power demand in that case in all hours. However, with 5 stochastic scenarios, the capacity planning is adequate to meet the demand for the whole year without using any *Infeasibility* power generation. Sensitivity analyses showed that this behavior could also be observed using various meteorological time-series as a data basis.[6]

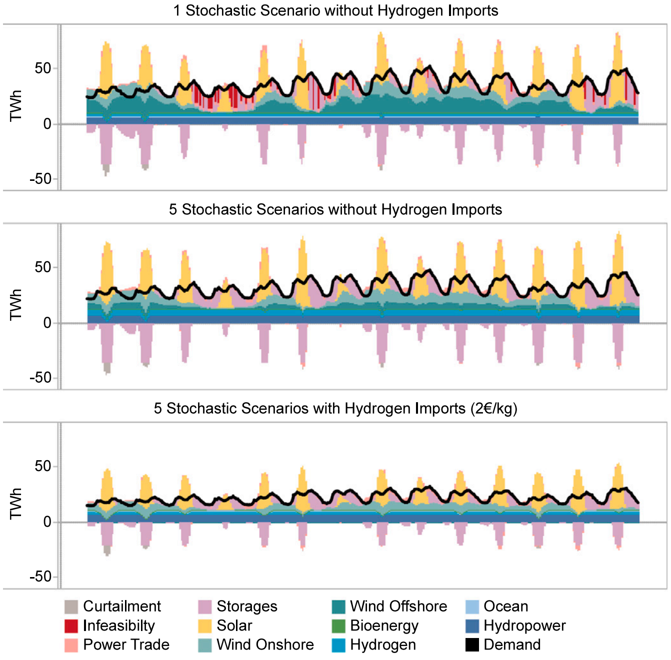

Fig. 8. Power system dispatch for the 2nd and 3rd week of January in 2050 using renewable generation patterns from the meteorological year 2018.

Furthermore, it can be observed that with the increasing amount of stochastic scenarios, a cannibalizing effect of hydrogen and wind offshore can be observed. For the chosen time frame in Fig. 8, hydrogen

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[6] Fig. 8 only shows a possible dispatch for the meteorological year 2018. However, the dispatch has been calculated and is feasible for different historical years when using 5 stochastic scenarios.

needs to run as a base-load technology and storages providing peak-load flexibility or electricity when little wind or solar are available. Fig. 7 shows that overall wind offshore and hydrogen capacities do not change substantially between the scenarios. However, the actual location and region where certain technologies are deployed changes with increasing amount of stochastic scenarios. It can be observed that hydrogen imports reduce the overall burden on the power system, as the overall power demand level is reduced, comparing the case with hydrogen import to the one without hydrogen imports. Hydrogen imports also result in less storage and flexibility capacity, as hydrogen and hydropower can produce a higher share of base-load power compared to the peak generation of renewables.

However, increasing the number of stochastic scenarios significantly increases the matrix size and computation time of GENeSYS-MOD. The actual matrix size increases nearly linearly from 100 GB (1 stochastic scenario) towards 410 GB (5 stochastic scenarios), the computation time increases exponentially. Consequently, a model run with 3 stochastic scenarios took 20 h, 4 scenarios took 38 h, and 5 scenarios took 120 h of computation time. Due to the limit set by the utilized solving environment, a model run with 6 stochastic scenarios could not be run successfully in the available time frame.

4.3. Discussion of results and assumptions

Although this analysis provides sophisticated outlooks until 2050 for different cases with and without the possibility of hydrogen imports by using a stochastic large-scale open-source energy system model combined with a full-hourly power system dispatch model, several key limitations of the modeling approach exist. First of all, both utilized models belong to the class of linear optimization models. As such, critical features of macroeconomic models are missing. Hence, the model results are strongly dependent on exogenous assumptions such as GDP, population growth, or modal choice of transportation. For future analysis, coupling GENeSYS-MOD to a macroeconomic model can further enhance and validate the model results. Being a linear model, modeling decisions are often binary as soon as inherent prices reach certain thresholds. Furthermore, GENeSYS-MOD also acts as a system-optimizing social planner, neglecting competing interests of actions of firms, behaviors of individuals, and other participants of the energy transition.

Using stochastic scenarios compared to a full hourly time resolution for energy system planning poses advantages and disadvantages. Using a full-hourly resolution for all years might increase the feasibility of the power system development, as short-term variability and long-term intermittency are inherently included in the data. However, using the time-series of just one historical year bears a data bias for the future generation of renewable energy sources, especially in times of a constantly changing climate. Instead, using different historical years for producing stochastic scenarios adds a level of uncertainty for the future renewable generation that also increases the robustness of model results. Obviously, using different full-hourly time series as stochastic scenarios might further increase the feasibility of energy system and power system planning, with the downside of further increasing the computational complexity of the model.

Limited by computational resources, this analysis was carried out using aggregated regions of Japan instead of a detailed prefectural or nodal representation. However, a more detailed regional aggregation can indeed change the choice of technologies built or utilized, as shown by Burandt et al. [48] and Oei et al. [70]. Therefore, future research should either increase the regional coverage of the energy system model or alternatively utilize an even more sophisticated power system dispatch model with preferably a non-convex representation of power transmission flows (e.g., using an optimal dc load flow model).

A further caveat of the modeling approach is the method of using constant hydrogen prices for different cases and unlimited capacities for hydrogen imports. In reality, prices are based on supply and demand and variable for given quantities of demand. However, this relationship cannot be expressed in a linear model, and, therefore, I opted for running several scenarios with different hydrogen import prices instead. The goal of this analysis was to look into the effects and implications resulting from large-scale hydrogen imports. For future analyses, coupling GENeSYS-MOD to a hydrogen market equilibrium model would undoubtedly lead to further insights.

As presented in this research article, substantial shares of renewable energies need to be deployed in Japan for reaching ambitious climate targets. With Japan being an insular state with limited land availability, the actual amounts of usable area for solar PV and wind can be discussed. In this study, most of the available potentials for variable renewable energy sources have been utilized in the case without hydrogen imports. Still, the potentials have been calculated using today's efficiencies and land utilization rates and thus, higher potentials might be assumed for the future. Also, Esteban et al. [22] conclude similar capacities and production levels of renewable energies in their study. They also do not consider hydrogen imports and furthermore only assess the power sector. In contrast, in the results presented in this study an integrated approach to modeling sector-coupling effects is included and thus, even higher demand levels for electricity can be observed. Similarly, in other studies of the Japanese energy system [12,14,15] only 80% emission reduction scenarios have been analyzed, naturally resulting in much less power generation from renewable energy sources. Furthermore, in studies focusing 80% emission reduction targets, less electrification and sector-coupling technologies have to be deployed, resulting in less overall power demand.

All in all, I want to stress that the results of this analysis should not be considered foresight in a traditional sense. In general, numerical models should only be used to generate insights and not exact numbers for future predictions [71]. Nevertheless, this analysis still provides novel and valuable insights about both the role of hydrogen imports in a multi-sectoral energy system model, especially for the case of Japan, as well as the impact of stochasticity on long-term energy system planning. However, this paper only looks at the time frame until 2050, as the Japanese Prime-Minster set this date for reaching net-zero emissions. Therefore, it could also be beneficial to look into long-term energy system analyses for the years after 2050 in future research work.

5. Recommendations

Overall, this research highlights that the ambitious target of net-zero emissions in 2050, which the Japanese Prime-Minister has announced, can generally be achieved. These findings are relevant for Japan and other countries and regions aiming at net-zero emissions, such as e.g., the USA, the European Union, China, Germany. Complying with these ambitious goals of net-zero emissions by the mid of the century is required to keep global warming below 1.5 °C [72]. In this regard, this research also explored the decarbonization of all sectors of the energy system without the deployment of carbon capture and storage and nuclear energy. Even without hydrogen imports, such decarbonization seems possible, even though immediate and large-scale deployment of additional renewable energy sources together with short-term and long-term energy storages would be needed. To prevent large-scale lock-in effects and to achieve ambitious climate goals, investments in fossil fuels need to be reduced as soon as possible. This again is not only true for Japan, but also for other regions that are currently relying on large shares of fossil fuels as their primary energy sources (e.g., China, Germany, USA, compare Burandt et al. [48], Bartholdsen et al. [73], Zozmann et al. [74]).

For reaching net-zero emissions, the hydrogenification of industrial sectors and the transportation sector is often deemed key. Not only for Japan but also for Germany, importing substantial amounts of hydrogen is presented as necessary in some studies [56]. In general, hydrogen poses a valuable resource in specific sectors of the energy system, and importing hydrogen can positively impact energy system developments. Still, policy- and decision-makers should move away from portraying hydrogen as the one and only savior for the energy system and instead focus on the large-scale deployment of readily available and cost-efficient variable renewable power generation technologies to reach ambitious decarbonization targets. Regarding infrastructure investments, hydrogen is often used as an excuse by incumbent actors to keep existing gas infrastructure alive by promising a switch to hydrogen at a later stage. However, unnecessary additional investments into natural-gas-based infrastructure might create unwanted path dependencies and lock-in effects. Hence, it needs to be ensured that the fuel switch from natural gas to hydrogen can realistically happen without the need for additional retrofitting costs [75,76].

In contrast, in sector-coupled energy systems, the power sector will always play a crucial role as it will provide energy either for direct use in non-electricity sectors or for the generation of hydrogen and synthetic fuels. Only cheap and broadly available renewable energy sources provide the basis for cost-efficient hydrogen production and electrification of the heat, transport, and industrial sectors. Especially in light of the radical steps needed for decarbonization of all sectors, ambitious actions in the power system are needed.

Lastly, the decarbonization of the energy system is relevant not only for Japan but for the whole global community. Decarbonization of the energy system requires a global context, but regional solutions, as climate change is a global issue but relevant on local scales. Thus policy- and decision-makers should aim for further international coordination. Furthermore, importing hydrogen from countries producing it either via fossil power or via steam methane reforming technologies (without CCS) alleviates the ambitions to fight climate change. The goal for policy- and decision-makers should be to plan global hydrogen markets solely focused on green or blue hydrogen.[7]

6. Conclusions

This analysis explored the impact of the availability of hydrogen imports and their effects on the development of the Japanese energy system. With the combination of a stochastic energy system model and a power system dispatch model, technological developments in specific sectors resulting from the possibility of hydrogen imports have been explored. Furthermore, the value of using a stochastic energy system model for long-term energy system planning has been presented in the research. Key results include that hydrogen can indeed play a significant role in the industry sector if enough cheap hydrogen can be imported. However, even in the case with the cheapest hydrogen import prices (2 €/kg), renewable energy sources still provide the largest share of the Japanese primary energy consumption. Thus, the Japanese energy system will never transition towards a full “Hydrogen Society”, where hydrogen provides the primary energy carrier in most of the sectors of an energy system. Instead, utilizing domestic renewable energy sources and electrification of most sectors prove the most cost-efficient way of decarbonizing the energy system. Without hydrogen imports, the deep decarbonization of the energy system results in significant electrification means in most of the sectors, and thus, the overall power demand of the Japanese energy system will almost double compared to 2019 levels. Furthermore, based on modeling results, hydrogen will always play just an ancillary role in the power system, as most of the domestic and imported hydrogen is more valuable to be used in other sectors. However, fuel cells and combined heat and power plants pose a cost-efficient way of producing electricity and heat for commercial and residential buildings and provide cycling and ramping capabilities for the power system.

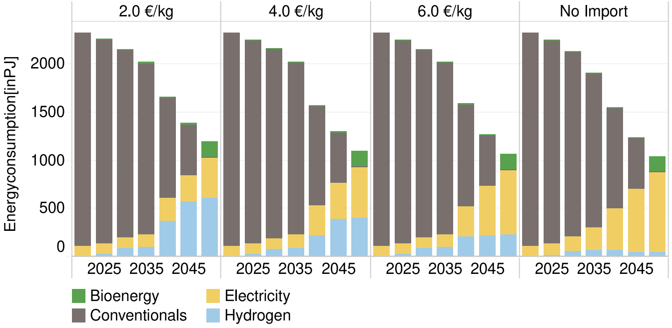

Fig. 9. Development of the transportation sector in the case without hydrogen imports compared the case with hydrogen imports priced at 2/kg.

Secondly, this research also highlights that using stochasticity in large-scale multi-sectoral energy system models can result in more robust results, especially regarding power system developments. Using stochasticity and uncertainty is advantageous for power system planning, as variable renewable energy sources have an uncertain power generation pattern in reality. Coupling a multi-sectoral energy system model with a dedicated power system dispatch model allows for a further assessment of the feasibility of the resulting power system.

CRediT authorship contribution statement

Thorsten Burandt: Conceptualization, Investigation, Data curation, Model runs, Validation, Visualization, Writing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and model can be found in Burandt [77].

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Appendix A. Transport sector results

As shown in Fig. 9, cheap hydrogen imports allow for a substantial increase in hydrogen usage in the transportation sector. Furthermore, utilizing hydrogen will slightly increase the final consumption in the transportation sector, as hydrogen-fueled transportation technologies are less efficient compared to technologies directly utilizing electricity. In both cases, an increase in transportation via rail can be observed.

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[7] Green hydrogen represents hydrogen produced from renewable energies via water electrolysis and blue hydrogen represents hydrogen produced via steam methane reforming with CCS.

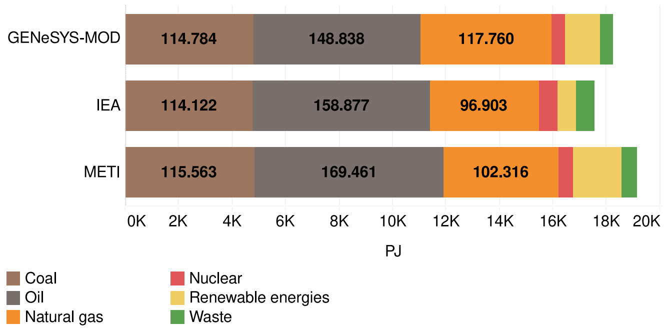

Fig. 10. Comparison of GENeSYS-MOD primary energy consumption results for 2019 with data from METI and IEA.

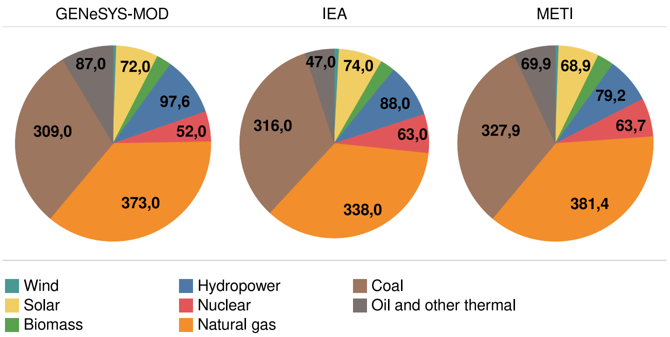

Fig. 11. Comparison of GENeSYS-MOD power generation results for 2019 with data from METI and IEA.

Appendix B. Model validation graphs

The model results for the base year have been validated by data available from the International Energy Agency (IEA) and the Japanese Ministry of Economy, Trade and Industry (METI) (compare Figs. 10 and 11).

Appendix C. Dispatch model

In the following subsections, the mathematical equations of the dispatch model are displayed. The utilized sets, variables, and parameters are presented in Tables 2–4.

Objective function

$$
\begin{aligned}
Z = &\sum_{r,p,h} G_{r,p,h} \cdot vc_{r,p} \\
&+ \sum_{r,p,h} G_{r,p,h} \cdot co2^{act}_{p} \cdot co2^{price} \\
&+ \sum_{r,sto,h} ST^{out}_{r,sto,h} \cdot \varepsilon \\
&+ \sum_{r,h} LOSTLOAD_{r,h} \cdot \varepsilon \\
&+ \sum_{r,rr,h} (FLOW^{pos}_{r,rr,h} + FLOW^{neg}_{r,rr,h}) \cdot \varepsilon \\
&+ \sum_{r,h} G^{inf}_{r,p,h} \cdot inf^{penalty}
\end{aligned}
\tag{1}
$$

Table 2
Sets.

Set	Element	Description
$\mathfrak{H}$	$\ni h$	Hour
$\mathfrak{R}$	$\ni r, \ni rr$	Region
$\mathfrak{P}$	$\ni p$	Dispatchable power plants
$\mathfrak{I}$	$\ni i$	Non-Dispatchable power plants
$\mathfrak{S}$	$\ni sto$	Storage technologies

Table 3
Parameters.

Parameter	Description
$vc_{r,p}$	Variable costs
$dem_{r,h}$	Demand in hour h
$p^{inst}_{r,p}$	Installed capacity of power plant p
$i^{inst}_{r,i}$	Installed capacity of variable power generator i
$cf_{r,i,h}$	Capacity factor of var gen i in hour h
$sto^{inst,e}_{r,sto}$	Installed storage energy capacity
$sto^{inst,p}_{r,sto}$	Installed storage power capacity
sto^{eff}_{sto}	Storage roundtrip efficiency
rf_{p}	Ramping factor: Allowed (de)activation of conventional capacity per hour
$t^{cap}_{r,rr}$	Power trade capacity from regions r to rr
$co2^{act}_{p}$	Carbon intensity of power plant
$co2^{price}$	Carbon price
$inf^{penalty}$	Infeasibility Penalty
ε	Machine epsilon

Table 4
Variables.

Variable	Description
Z	Objective variable
$G_{r,p,h}$	Dispatchable generation
$G^{inf}_{r,h}$	Infeasibility generation
$G^{up}_{r,p,h}$	Upwards change in dispatchable generation
$G^{up}_{r,p,h}$	Downwards change in dispatchable generation
$V_{r,i,h}$	Non-Dispatchable generation
$ST^{in}_{r,sto,h}$	Storage charging
$ST^{out}_{r,sto,h}$	Storage discharging
$SOC_{r,sto,h}$	Storage state-of-charge
$CURTAIL_{r,h}$	Curtailed load
$FLOW^{pos}_{r,rr,h}$	Positive trade flow from regions r to rr
$FLOW^{neg}_{r,rr,h}$	Negative trade flow from regions r to rr
$FLOW_{r,rr,h}$	Net trade flow from regions r to rr

Energy balance

$$
\begin{aligned}
&\sum_{p} G_{r,p,h} + G^{inf}_{r,h} + \sum_{i} V_{r,i,h} \\
&\sum_{sto} ST^{out}_{r,sto,h} - \sum_{sto} ST^{in}_{r,sto,h} + \sum_{rr} FLOW_{rr,r,h} \\
&= dem_{r,h} + CURTAIL_{r,h} \quad \forall r, h
\end{aligned}
\tag{2}
$$

Power generation

Power generation for dispatchable generators is limited by the installed capacity, whereas for variable renewable generators, the production has to equal the installed capacity times the hourly capacity factor.

$$Gr,p,h \le p^{inst}_{r,p} \quad \forall r,p,h \tag{3}$$

$$Vr,i,h = i^{inst}_{r,i} \cdot cf_{r,i,h} \quad \forall r,i,h \tag{4}$$

Storages

The following equations represent the storage formulation included in the dispatch model.

$$SOC_{r,sto,h} = SOC_{r,sto,h-1} + \frac{1 + sto^{eff}_{sto}}{2} ST^{in}_{r,sto,h} - \frac{2}{1 + sto^{eff}_{sto}} ST^{out}_{r,sto,h} \quad \forall r, sto, h \tag{5}$$

$$ST^{in}_{r,sto,h} \leq sto^{inst,p}_{r,sto} \quad \forall r, sto, h \tag{6}$$

$$ST^{out}_{r,sto,h} \leq sto^{inst,p}_{r,sto} \quad \forall r, sto, h \tag{7}$$

$$ST^{out}_{r,sto,h} \leq SOC_{r,sto,h-1} \quad \forall r, sto, h \tag{8}$$

$$ST^{in}_{r,sto,h} + SOC_{r,sto,h-1} \leq sto^{inst,e}_{r,sto} \quad \forall r, sto, h \tag{9}$$

Ramping

The following equations present the ramping constraints for dispatchable power generators.

$$Gr, p, h - Gr, p, h - 1 = G^{up}_{r,p,h} - G^{down}_{r,p,h} \quad \forall r, p, h \tag{10}$$

$$G^{up}_{r,p,h} \leq p^{inst}_{r,p} \cdot rf_{p} \quad \forall r, p, h \tag{11}$$

$$G^{down}_{r,p,h} \leq p^{inst}_{r,p} \cdot rf_{p} \quad \forall r, p, h \tag{12}$$

Trade

The power trade formulation is generally based on a net-trade/net-flow formulation, with the raw-flow components ($FLOW^{pos}_{r,rr,h}$ and $FLOW^{neg}_{r,rr,h}$) only used in the objective function.

$$FLOW_{r,rr,h} = -FLOW_{rr,r,h} \quad \forall r, rr, h \tag{13}$$

$$FLOW_{r,rr,h} \leq t^{cap}_{r,rr} \quad \forall r, rr, h \tag{14}$$

$$FLOW_{r,rr,h} \geq -t^{cap}_{r,rr} \quad \forall r, rr, h \tag{15}$$

$$FLOW_{r,rr,h} = FLOW^{pos}_{r,rr,h} - FLOW^{neg}_{r,rr,h} \quad \forall r, rr, h \tag{16}$$

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