CONTRIBUTION OF FUSION ENERGY TO LOW-CARBON DEVELOPMENT UNDER THE PARIS AGREEMENT AND ACCOMPANYING UNCERTAINTIES

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Abstract

The Paris Agreement requires deep reduction of greenhouse gas emissions. The world is moving toward rapid transition not only for climate change mitigation but also for sustainable development. Fusion energy has outstanding characteristics of plentiful resources, no nuclear runaway and zero-carbon emission. Its development has made a remarkable progress thanks to large investment for more than 60 years. However, long-term strategies for fusion energy development will become critically important in order to promote future DEMO projects by another large-scale investment and gain social acceptance. The paper assessed potential contribution of fusion energy to low-carbon development which is prescribed in the Paris Agreement under the combination of uncertainties of future socioeconomic development, probability of the 2 °C target and development of commercial fusion power plants. Global energy systems up to 2100 were analyzed in consideration of uncertainties by combining socioeconomic scenarios, global CO_2 emission pathways and fusion power plants by using a global energy systems model: DNE21+. Three Shared Socioeconomic Pathways (SSPs) were used to express the uncertainty of future socioeconomic development. Assumptions and parameters for DNE21+ were harmonized with the SSP narratives. Four global CO_2 emission pathways were used to simulate the uncertainty of the long-term targets of the Paris Agreement. For the uncertainty of fusion energy development, three scenarios which have different assumptions on parameters of fusion power plants were employed. The parameters were set by considering potential and achievable cost reduction and performance improvement on the extension of DEMO concept design. Global negative CO_2 emission in 2100 by drastic decarbonization of energy systems is required in order to achieve the 2 °C target, and fusion power plants will be installed in the latter half of the 21st century mainly in the countries which have limited potentials of zero-emission energy sources such as Japan, Korea and Turkey. If inexpensive power plants could be developed by enhanced R&D and advanced design in DEMO projects, fusion power plants will also be deployed in the EU28, India and China. Further cost reduction by innovative design and/or alternative concept will become essential to diffuse fusion plants also in zero-emission resource-rich countries.

1. INTRODUCTION

The Paris Agreement which was adopted by 193 governments in December 2015 seeks the long-term objectives to keep global mean temperature increase relative to the pre-industrial level to well below 2 °C and requires all the governments to submit their Nationally Determined Contributions (NDCs) and low-carbon development pathways for greenhouse gas (GHG) emission reduction [1]. Concurrently, Sustainable Development Goals (SDGs) were adopted in September 2015 by the United Nations [2]. The world is moving toward rapid transition not only for climate change mitigation but also for sustainable development.

Fusion energy has outstanding characteristics of plentiful resources, no nuclear runaway and zero-carbon emission. Its development has made a remarkable progress thanks to large investment for more than 60 years. Some countries and regions have started their concrete DEMOnstration Fusion Reactor (DEMO) design activities. Japan established Joint Special Design Team for Fusion DEMO in 2015 and adopted Japan's Policy to promote R&D for a fusion DEMO reactor in 2017 [3] and a roadmap for fusion DEMO development in 2018 [4]. The EU initiated in 2014 a comprehensive design study of a DEMO as a part of the Roadmap to Fusion Electricity Horizon 2020 [5]. China and Korea have made a progress on their DEMO design and R&D activities towards the China Fusion Engineering Test Reactor (CFETR) [6] and K-DEMO [7], respectively. There is a deep discussion with respect to a strategic plan for burning plasma research in the United States [8].

Long-term strategies for fusion energy development will become critically important in order to promote future DEMO projects by another large-scale investment and gain social acceptance. Scenarios can provide possible different futures in the context of fundamental future uncertainties to understand long-term consequences by near-term decisions. In this study, we assessed potential contribution of fusion energy to low-carbon development which is prescribed in the Paris Agreement under the combination of uncertainties of future socio-economic development, probability of the 2 °C target and development of commercial fusion power plants. The objective of this study is to provide comprehensive global energy scenarios for discussion of long-term strategies of fusion energy development.

2. METHODOLOGY

2.1. Framework for assessment of global energy systems

We analyzed global energy systems up to 2100 in consideration of uncertainties by combining socioeconomic scenarios, global CO_2 emission pathways and fusion power plants by using a global energy systems model: Dynamic New Earth 21+ (DNE21+) as shown in Figure 1. We used three Shared Socioeconomic Pathways (SSPs) to express the uncertainty of future socioeconomic development. Four global CO_2 emission pathways were used to simulate the uncertainty of the long-term targets of the Paris Agreement. For the uncertainty of fusion energy development, we set three scenarios, i.e., No Fusion, Conventional R&D (Conv) and Advanced R&D (Ad) which have different assumptions on parameters of fusion power plants.

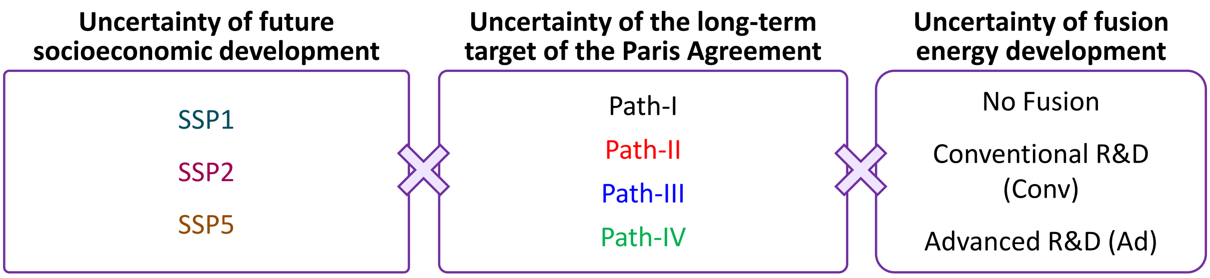


FIG. 1. Analytical frewework and uncertainties considered in this study.

2.2. Global energy systems model: Dynamic New Earth 21+ (DNE21+)

The DNE21+ model [9] is an intertemporal linear programming model for assessing global energy systems and global warming mitigation options which minimizes the world energy systems cost and covers a time horizon from 2000 to 2100. This model disaggregates the world into 54 regions to represent regional difference and assesses detailed energy technologies. Energy production, interregional trade, conversion and consumption are explicitly described in the model with existing facility vintages. Resource potentials and supply costs of fossil fuel reserves and renewable energies, energy conversion efficiency and plant costs in energy conversion sectors and power sector, and capacity of carbon capture and storage (CCS) are assumed based on a wide range of literature. Energy end-use technologies are selected to satisfy the extent of service demand cost-efficiently. Capital costs and efficiency of energy technologies including cost reduction by region are explicitly assumed. See RITE (2015) [10] for more details.

2.3. Shared Socioeconomic Pathways (SSPs)

Five Shared Socioeconomic pathways (SSPs) have been developed by global climate change research community to assess climate change impact, adaptation and mitigation consistently and comprehensively considering socioeconomic uncertainties. SSPs are composed of two dimensions: socioeconomic challenges for mitigation and those for adaptation. SSPs storylines describe qualitative narratives in terms of motivating forces, policies, institutions and social conditions, human development, economy and lifestyle, population and urbanization, technology, and environment and resources [11]. They were implemented to Integrated Assessment Models (IAMs) for quantitative assessment according to the SSPs guideline [12].

In this study, we used three SSPs (SSP1: Sustainability, SSP2: Middle of the Road, SSP5: Fossil-fueled Development). Table 1 shows narratives related to energy systems and population and GDP scenarios. Assumptions and parameters for DNE21+ were harmonized with the SSP narratives.

TABLE 1. NARRATIVES AND POPULATION AND GDP SCENARIOS FOR SSP1, SSP2 AND SSP5

	SSP1: Sustainability	SSP2: Middle of the Road	SSP5: Fossil-fueled Development
Challenges on mitigation/adaptation	Low / Low	Middle/ Middle	High / Low
Narratives related to energy systems (highlights) [11]	The world shifts toward a more sustainable path; management of the global commons improves; educational and health investments lead to a relatively low population; the emphasis on economic growth shifts toward a broader one on human well-being; improved resource efficiency reduces overall energy and resource use and improve environmental conditions; renewable energy becomes more attractive; consumption is oriented toward low material growth and lower resource and energy intensity.	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns; development and income growth proceed unevenly; institutions work toward but make slow progress in achieving sustainable development goals; environmental systems experience degradation, although overall the intensity of resource and energy use declines; there is no reluctance to use unconventional fossil resources; global population growth is moderate and levels off in the second half of the century.	This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital; global markets are increasingly integrated; the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles; rapid growth of the global economy is lead; global population peaks and declines in the 21st century.
Population in the world (2030-2050-2100)	8.1 – 8.6 – 7.0 [billion people]	8.4 – 9.2 – 9.3 [billion people]	8.2 – 8.7 – 7.5 [billion people]
GDP in the world (2030-2050-2100)	76 – 120 – 230 [trillion US$2000]	73 – 112 – 220 [trillion US$2000]	79 – 135 – 406 [trillion US$2000]

2.4. Global CO_2 emission pathways corresponding to the 2 °C target

In terms of the long-term targets, the Paris Agreement contains the following phrases: “To hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels.” There is neither statement with respect to time points to achieve the goal nor temperature pathways. In addition, scientific uncertainties regarding earth systems remain. For example, equilibrium climate sensitivity (CS) which is defined as the global annual mean surface air temperature change experienced by the climate system after it has attained a new equilibrium in response to a doubling of atmospheric CO_2 concentration is estimated to be 1.5-4.5 °C according to the Intergovernmental Panel on Climate Change fifth assessment report [13]. Its best estimate could not be agreed among experts. The temperature target cannot convert to GHG concentrations or emissions level and pathways target straightforwardly.

We set four representative global CO_2 emissions pathways by assuming different climate sensitivities and temperature pathways as shown in Figure 2. All pathways correspond to the 2 °C target from the viewpoint of current scientific knowledge.

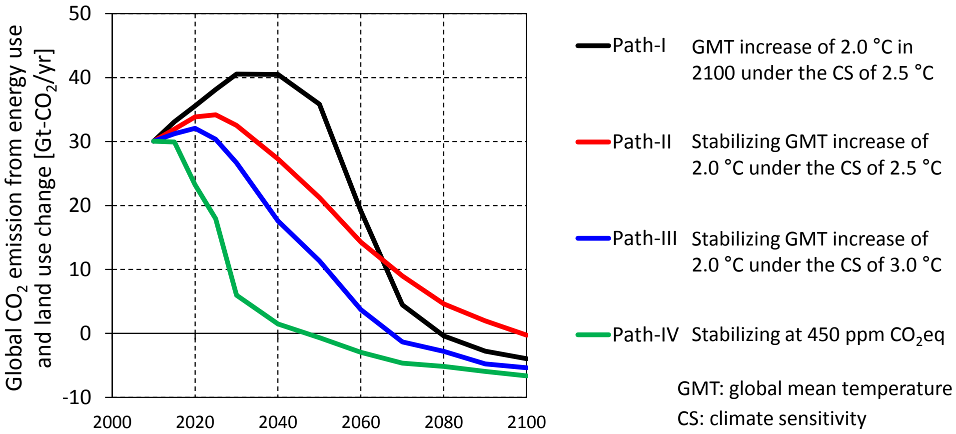


FIG. 2. Global CO_2 emissions pathways corresponding to the 2 °C target.

2.5. Fusion energy development scenarios

We assumed two types of commercial fusion power plants which have different capital costs as shown in Table 2. The parameters were set by considering potential and achievable cost reduction (70-80% reduction relative to DEMO) and performance improvement, based on the proposed conceptual designs of a tokamak fusion power plant, CREST [14] and Slim-CS [15]. Assumption on available regions of fusion energy is shown in Figure 3. It should be noted that plasma performance (such as a normalized beta value) applied in the fusion energy development scenarios is higher than that of the experimental reactor ITER and has to be developed even in the DEMO phase in the support of JT-60SA etc. The parameters should be considered tentative and they need to be revised in the future according to the update of the fusion energy development scenarios.

TABLE 2. ASSUMPTION ON FUSION POWER PLANTS

	Conventional R&D (Conv)	Advanced R&D (Ad)
Capital costs per unit [US$2000/W]	8.5	6.6
Major radius [m]/Aspect ratio	5.5 / 2.6	5.4 / 3.4
Normalized beta value	4.3	5.5
Plant availability [%]	90	
Life time [yr]	40	
Annual expense ratio [%]	12	
Fuel and back-end costs [US$2000/MWh]	2.0	
Capacity constraint	Maximum limit of annual capacity introduction of 2 GW/yr by region.	

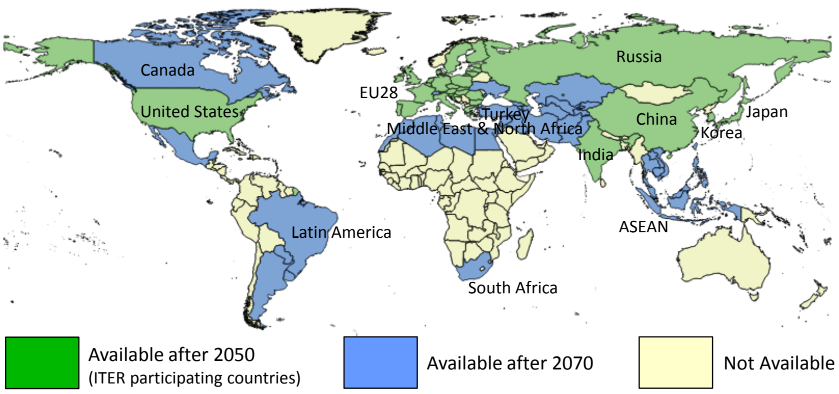


FIG. 3. Assumption on available regions of fusion energy.

3. RESULTS

3.1. Energy systems transition in the 2 °C target scenarios

Figure 4 shows global primary energy consumption, electricity generation and final energy consumption in Conv cases for SSP1, SSP2 and SSP5. Drastic fuel transition from conventional fossil fuels to low-/zero-emission energy sources in both energy supply and end-use sectors while supplying doubled final energy demand is required for the low-carbon development in the world. Measure costs become a few to ten-plus % per GDP even in the ideal cases. Electricity generation triples or sextuples in 2100, and zero-emission energy sources comprise more than 70%.

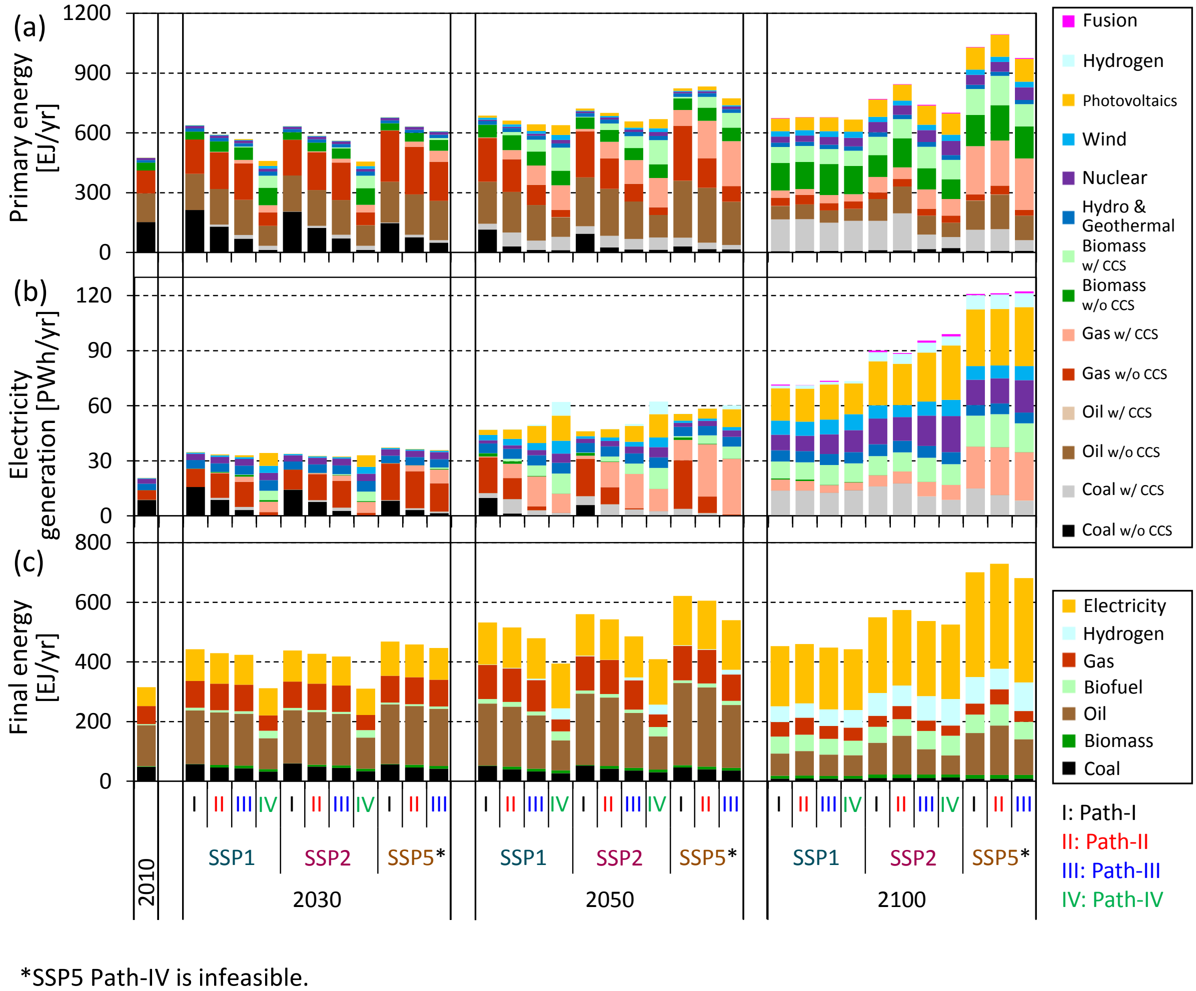
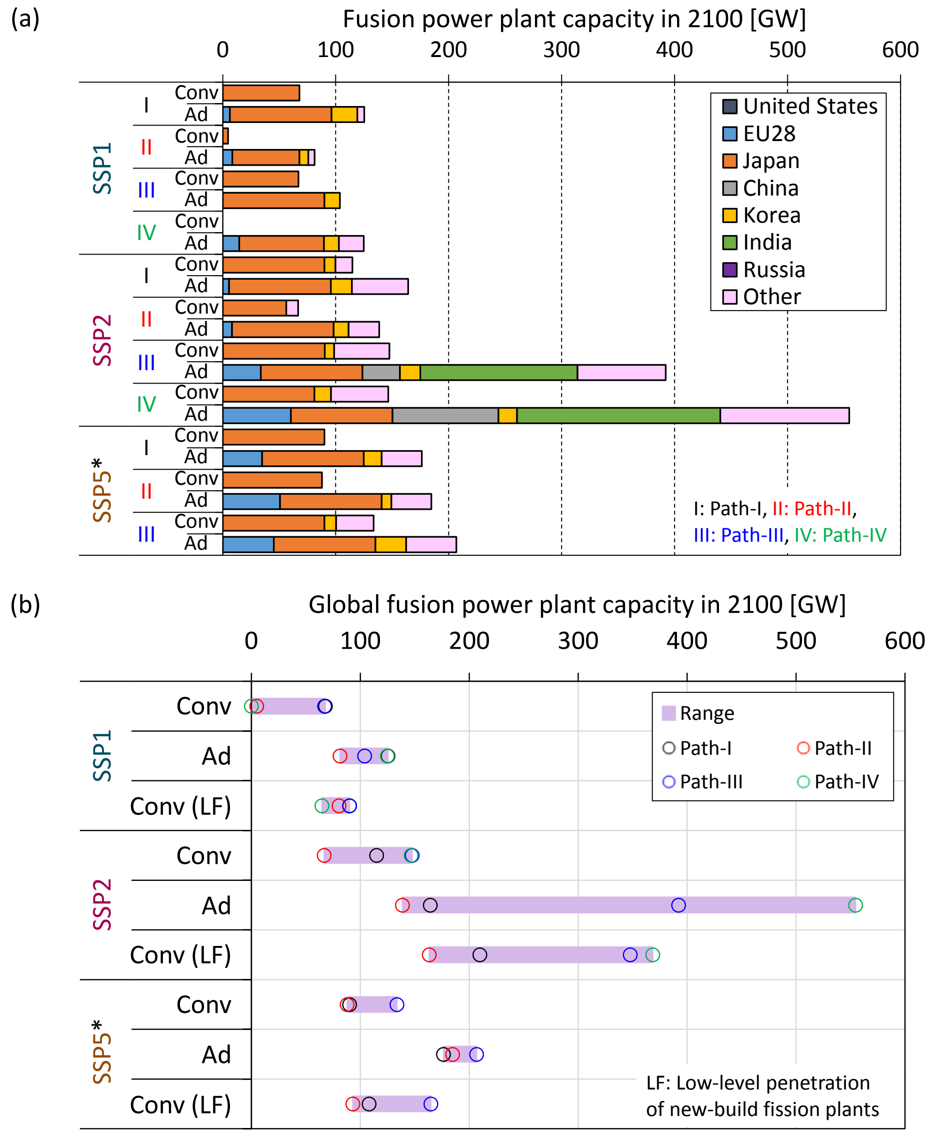


FIG. 4. Global (a) primary energy consumption, (b) electricity generation and (c) final energy consumption in Conv cases.

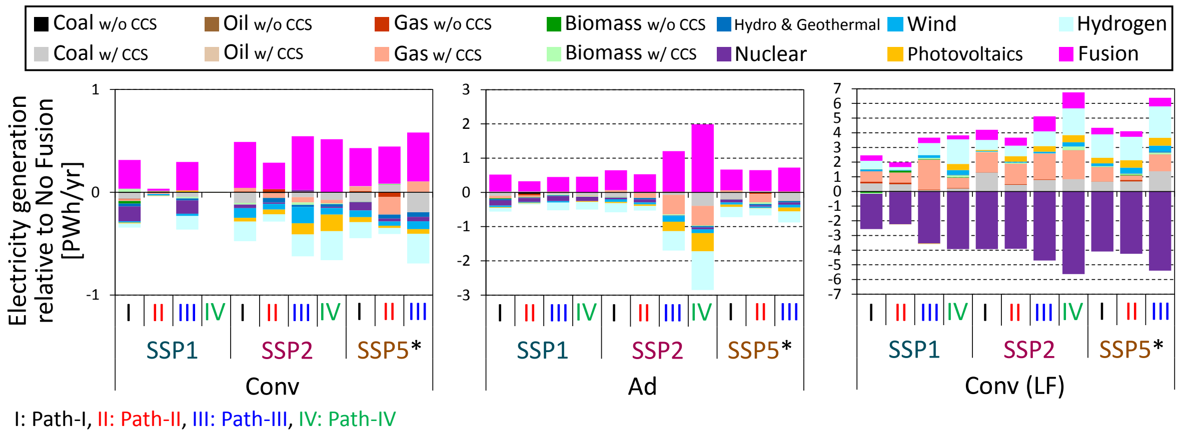
3.2. Fusion power plant capacity

Figure 5(a) shows installed fusion power plant capacity by region in 2100. In Conv cases, fusion is mainly introduced in Japan, Korea and Turkey where potentials of zero-emissions energy sources such as solar and wind and storage areas for CCS are limited. The EU28, China and India will deploy fusion power plants in Ad cases especially for Path-III and Path-IV which radical emission reduction is required. Potential of fusion energy introduction depends on both the socioeconomic scenarios and CO_2 emission pathways. The result that there is no fusion introduction in the United States and Russia implies that alternative and innovative approach which contributes to further cost reduction compared with the parameters shown in Table 2 is pivotal for zero-emission resource-rich countries.



*SSP5 Path-IV is infeasible.

FIG. 5. (a) Fusion power plant capacity by region and (b) global fusion power plant capacity in 2100.



*SSP5 Path-IV is infeasible.

FIG. 6. Difference of average global electricity generation in 2050-2100 relative to No fusion cases.

3.3. Sensitivity analysis: the case of low-level penetration of new-build nuclear fission plants

Competitiveness of fusion power plants also depends on the availability of other zero-emission energy sources. Nuclear fission energy is one of the most controversial issues for energy systems. In the 2 °C target scenarios, capacity of nuclear fission plants in 2050 are in the range of IAEA projections [16] but it increases significantly in the latter half of the 21st century. Although difference of public acceptance against nuclear fission energy is already included in the SSP1 storylines and IAM implementations, we conducted additional sensitivity analysis for the case of low-level penetration of new-build nuclear fission plants (LF) by reducing the maximum capacity introduction constraint of nuclear fission power plants to one third from the default setting of DNE21+.

Figure 5(b) shows total fusion power plant capacity in the world in 2100. For SSP1, Japan increases fusion capacity in Conv (LF) cases compared with Conv cases. Global fusion plant capacity doubles in Conv (LF) cases compared with Conv cases for SSP2 because China installs fusion plants and Japan, Korea and Turkey increase them. The constraint of low-level penetration of nuclear fission plants has little impact for SSP5 because natural gas is relatively affordable.

Figure 6 depicts difference of average global electricity generation in 2050-2100 relative to No Fusion cases. Fusion generation accounts for 0.5 (0-2.5)% and generate 0.4 (0-2.0) PWh/yr on average in the world. Fusion energy could substitute a part of inefficient zero-emission sources in power sector such as hydrogen generation, variable renewables and uneconomic fossil-fueled power plants with CCS.

3.4. Effect on whole energy systems by fusion introduction in Japan

Fusion introduction will affect whole energy systems especially in Japan. As shown in Figure 7, substantial amount of hydrogen is used in the 2 °C scenarios in Japan after 2050. Cost-efficient fusion energy can substitute fossil-fueled power generation with CCS, renewables and hydrogen generation, and increases total electricity generation simultaneously. The incremental electricity is not directly used in the end-use sectors but it is utilized to produce hydrogen by water electrolysis. In consequence, average imported hydrogen is reduced by half and average annual energy import costs are reduced by 33 billion US$2000/yr at most in the latter half of the 21st century by fusion introduction for SSP2 Path-III case. Energy self-sufficiency can be improved to 70% in 2100 at most in Japan. This systematic transition suggests an alternative option of fusion energy development which directly produces hydrogen by high-temperature steam electrolysis.

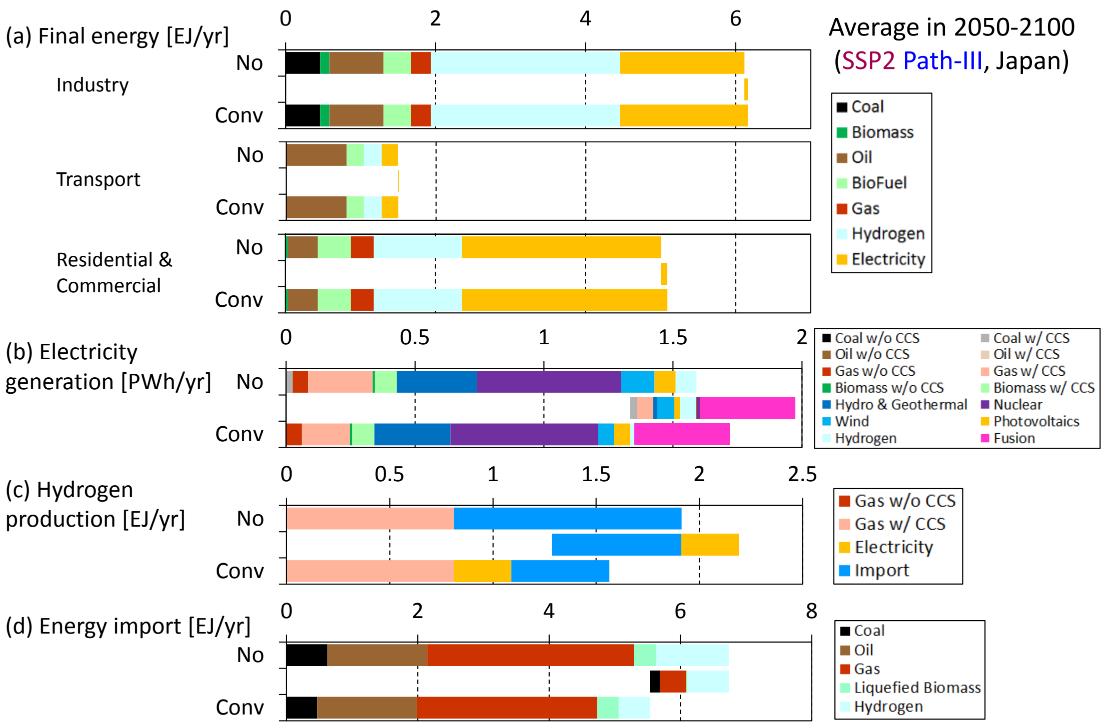


FIG. 7. Average (a) final energy consumption by sector, (b) electricity generation, (c) hydrogen production and (d) energy import in 2050-2100 in No Fusion and Conv cases and their difference for SSP2 Path-III in Japan.

4. CONCLUSIONS AND DISCUSSIONS

Potential contribution of fusion energy to global long-term energy systems transition up to 2100 toward low-carbon development was assessed under uncertainties of future socioeconomic development, CO_2 emission pathways corresponding to the long-term target of the Paris Agreement and fusion energy development scenarios by using a state-of-art technology-rich global energy systems model.

Drastic decarbonization of energy systems and global negative CO_2 emission in 2100 are required in order to achieve the 2 °C target, and fusion power plant will be installed in the latter half of the 21st century mainly in the countries which have limited-potentials of zero-emission energy sources such as Japan, Korea and Turkey if it follows moderate cost reduction. If inexpensive power plants could be developed by enhanced R&D and advanced design in DEMO projects, fusion power plants will also be deployed in the EU28, India and China. Further cost reduction by innovative design and/or alternative concept will become essential to diffuse fusion plants also in zero-emission resource-rich countries.

There are huge uncertainties surrounding future energy systems. However, it is plausible that decarbonization, digitalization and decentralization are three key directions where global energy systems aim to. Fusion energy development needs long-term and large-scale investment. In order to gain social acceptance to promote future DEMO projects and spread commercial fusion plants within the 21st century, clear strategies for fusion energy development which maximize its economic competitiveness and pursue economy of scope of its derivatives are pivotal. This study provides important information for long-term strategic planning of fusion energy development. Further studies involving stakeholders are vital to consider unique and broader objectives of energy policies for each country which aim for ensuring the energy trilemma, i.e., energy security, energy equity and environmental sustainability.

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