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Hydrogen in low-carbon energy systems in Japan by 2050: The uncertainties of technology development and implementation

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ABSTRACT

Low-carbon technologies will play a vital role in the realization of environmentally sustainable economies. However, uncertainties remain as to the feasibility of their development and implementation. Therefore, possible scenarios for the potential of these technologies should be considered to allow for flexible decision-making with respect to long-term energy strategies in Japan. This study evaluates the role of hydrogen in future energy systems in Japan using a MARKet ALlocation (MARKAL) model. A range of uncertainties are considered for nuclear power generation and carbon capture and storage (CCS) from fossil power generation. Our results suggest that an 80% reduction of CO_2 emissions from the 2013 level by 2050 requires emissions from the electricity sector to decrease to nearly zero. Hydrogen power must play a functional role in future energy systems in Japan, but its contribution should depend on nuclear power and CCS.

Abbreviations: AIST, National Institute of Advanced Industrial Science and Technology, Japan; BAU, business-*as*-usual; CCS, carbon capture and storage; CHP, combined heat and power; CIF, cost insurance and freight; EFOM, Energy Flow Optimization Model; EOR, enhanced oil recovery; ETSAP, Energy Technology Systems Analysis Program; FC, fuel cell; FY, fiscal year; GDP, gross domestic product; GHG, greenhouse gas; IEA, International Energy Agency; IGCC, integrated coal gasification combined cycle; IGFC, integrated coal gasification fuel cell combined cycle; INDC, Intended Nationally Determined Contributions; IPCC, Intergovernmental Panel on Climate Change; JRC, Joint Research Center; NGCC, natural gas combined cycle; O&M, operation and maintenance; OAT, one-at-a-time; PV, photovoltaics; MARKAL, MARKet ALlocation; SCPC, super-critical pulverized coal; TIMES, The Integrated Markal-Efom System.

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Introduction

The migration to low-carbon energy systems is a global issue. According to the fifth report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [1], the low-carbon energy share of the global primary energy supply must be increased from 15% (ca. 2010) to 50–70% by 2050, and account for as much as 90% by 2100 to stabilize long-term greenhouse gas (GHG) concentrations at manageable levels (430–480 ppm CO_2eq). Such changes are also necessary to contain global temperature increases below 2 °C for the 21st century relative to pre-industrial levels. In 2015, Japan set a near-future GHG emission reduction target of −26% total GHG emissions by fiscal year (FY) 2030 relative to those in FY 2013 [2]. A new energy strategy was developed that aimed at increasing the low-carbon energy share of primary energy supplies in Japan to 24% by 2030, comprised of 10–11% nuclear energy, and 13–14% renewable energy [3]. Expanding the low-carbon energy supply is also important for increasing energy self-sufficiency, and thus reinforcing the energy security of Japan. As the sum of nuclear and renewable energies only accounted for 9% of the primary energy supply in FY 2015 [4], further development and implementation of low-carbon technologies is essential for reducing GHG emissions in Japan.

Recently, hydrogen has received considerable attention as a low-carbon energy source because of its flexibility as an energy carrier. Hydrogen that is produced from renewable resources and other low-carbon processes is expected to play a key role in future low-carbon energy systems [5–9], while most of hydrogen is currently produced by methane reforming which releases significant amount of CO_2 to the environment. Many studies have been carried out to develop and evaluate renewable and low-carbon hydrogen production processes via water electrolysis [10], thermal pyrolysis [11,12] and photo-thermochemical water splitting [13]. At the other end of the supply chain, end-users in diverse sectors can save energy use and cut their emissions by utilizing hydrogen instead of fossil fuels. In the transportation sector, for example, the hydrogen fuel cell vehicle (FCV) has received attention globally as a next-generation clean vehicle that major motor companies are now developing and releasing on the consumer market [14–16]. Stationary fuel cells have been installed as power and heat sources in both residential dwellings and commercial facilities [17–21]. A commercially operated 12 MW hydrogen turbine began generating power in Italy in 2009 [22,23]. Given this apparent flexibility, hydrogen is expected to play a significant role in diversifying energy sources and mitigating GHG emissions in Japan. In the Japanese strategy to realize hydrogen economy, establishment of an international hydrogen supply chain using energy carriers (e.g., liquid hydrogen, methylcyclohexane, and ammonia) is regarded as a key component because it enables the economic utilization of hydrogen produced from overseas low-carbon energy sources [24]. Japanese companies have thus been engaged in international hydrogen supply chain projects that aim to transport hydrogen produced from overseas renewable or excess energy to Japan [25–28].

Besides the use of hydrogen, there are other promising low-carbon technologies that may drastically cut global GHG emissions [29–31]. Among these technologies, carbon capture and storage (CCS) garners attention as a technology capable of supplying low-carbon energy from fossil fuels. There are 17 large-scale CCS facilities in operation globally: 14 facilities for enhanced oil recovery (EOR), and three dedicated for storage, capturing more than 30 Mt/year of CO_2 [32]. In Japan, a CCS demonstration project began in 2016 to capture up to 0.1 my/year of CO_2 from an oil refinery [33]. The International Energy Agency (IEA) suggested that CCS should reduce ~94 Gt of CO_2 from industry, electricity, and other energy sectors by 2050 to accomplish the IEA's 2 °C scenario in which the mean annual global temperature does not exceed a 2 °C increase relative to pre-industrial conditions [34].

In order to discuss the future directions of the development and implementation of low-carbon technologies, we must understand the effect of these technologies on long-term energy system transitions. Energy modeling is a popular approach for providing necessary information to policy makers on technological development and environmental policies. MARKet ALlocation (MARKAL) and its successor, The Integrated MARKAL EFOM System (TIMES), models are energy modeling methodologies that have been used by national research teams in nearly 70 countries [35]. One of the primary motivations for using MARKAL/TIMES models is to evaluate the impacts of long-term GHG emission reduction targets on energy systems. For example, Chiodi et al. [36] analyzed Irish energy systems under different CO_2 emission reduction targets for 2050 using the Irish TIMES model. Similar analyses were conducted by Sgobbi et al. [37] for European energy systems using the JRC-EU-TIMES model. MARKAL/TIMES models have been also applied to analyze the interactions between multiple energy and environmental policies, such as CO_2 emission reduction, primary energy savings, and renewable obligation [38–41]. Another purpose of analyses that employ MARKAL/TIMES models is to clarify the effect of technological development and implementation on energy systems. Using the Chinese MARKAL model, Larson et al. [42] simulated an energy system transition based on different technological strategies. Since MARKAL/TIMES models are technology-rich, bottom-up models, they have been used to evaluate the contribution of particular technologies, including solar photovoltaics (PV) [43], CCS [44,45], and FCV [46–48] for establishing low-carbon energy systems.

Various low-carbon technologies, including hydrogen utilization, should have functional roles in decarbonizing the Japanese energy systems by 2050. However, each low-carbon technology has some level of uncertainty associated with its development and implementation, which can affect the long-term energy transition of Japan [49]. Multiple possible scenarios for low-carbon technologies should be considered to make flexible decisions given these uncertainties, which have not yet been fully accounted for in the 2030-target energy strategy of Japan [3]. In this study, we aim to clarify the role of hydrogen in the future energy system of Japan using a MARKAL model developed by the National Institute of Advanced Industrial Science and Technology (AIST) [43,46,50–53]. MARKAL parameters were determined based on recent studies and policies. The transition of the energy system of Japan is simulated under various settings for CO_2 mitigation targets, nuclear power generation, and CCS from fossil power

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