Energy Proceedings
Vol 49, 2024
ISSN 2004-2965

Scenario Analysis for Energy Transition Integrating Global and Local Perspectives#

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ABSTRACT

Mitigation pathways are critical in achieving carbon neutrality. However, there is still uncertainty about the potential of these technologies. Therefore, it is necessary to develop possible scenarios for such technologies to facilitate forward-looking decision-making in national energy strategies. In this study, Japan's energy dynamics from 2010 to 2050 are examined, focusing on shifts from fossil fuels to sustainable sources within a declining population and expanding economy context. Utilizing the Glocal Century Energy Environment Planning (G-CEEP) model, Various scenarios for Japan's future energy system to achieve net-zero CO_2 emissions by 2050 were examined. This transition suggests profound impacts on national energy policies and economic strategies, supporting Japan's commitment to sustainable development and environmental stewardship. This research contributes to understanding the integration of energy policy with macroeconomic and environmental objectives in a transitioning economy.

Keywords: carbon neutrality, multiple scenarios, mitigation technologies, integrated energy assessment model, scenario analysis

NONMENCLATURE

Abbreviations	
CCS	Carbon Capture and Storage
CES	Constant Elasticity Substitution
DNE21	Dynamic New Earth 21
G-CEEP	Glocal Century Energy Environment Planning
GDP	Gross Domestic Product
MARKAL	MARKet ALlocation

Symbols	
C	Consumption
E	Electricity
EC	Energy cost
I	Investment
K	Capital
L	Labor
N	Non-electricity
PE	Electricity supply
PN	Non-electricity supply
Y	Production output

1. INTRODUCTION

To enhance environmental health and combat climate change, many countries are actively working to reduce carbon emissions, formalizing these efforts through the Paris Agreement. The Japanese government has pledged to achieve net zero emissions by 2050, necessitating significant decarbonization in the coming decades. Such massive decarbonization will require unprecedented efforts (e.g., deep technological renewal and energy transition in multiple sectors of transportation, power, buildings, and manufacturing to achieve [1]. However, there is a highly uncertainty about the long-term impact of carbon-neutral energy transition options on decarbonization due to their technical feasibility and economic variability. Therefore, energy scenario analysis and integrated energy assessment models are necessary to simulate the energy transition and thus inform policy makers about energy and environmental strategies.

Energy modeling or integrated energy assessment modeling is a popular approach to discuss the future development and implementation directions of various

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

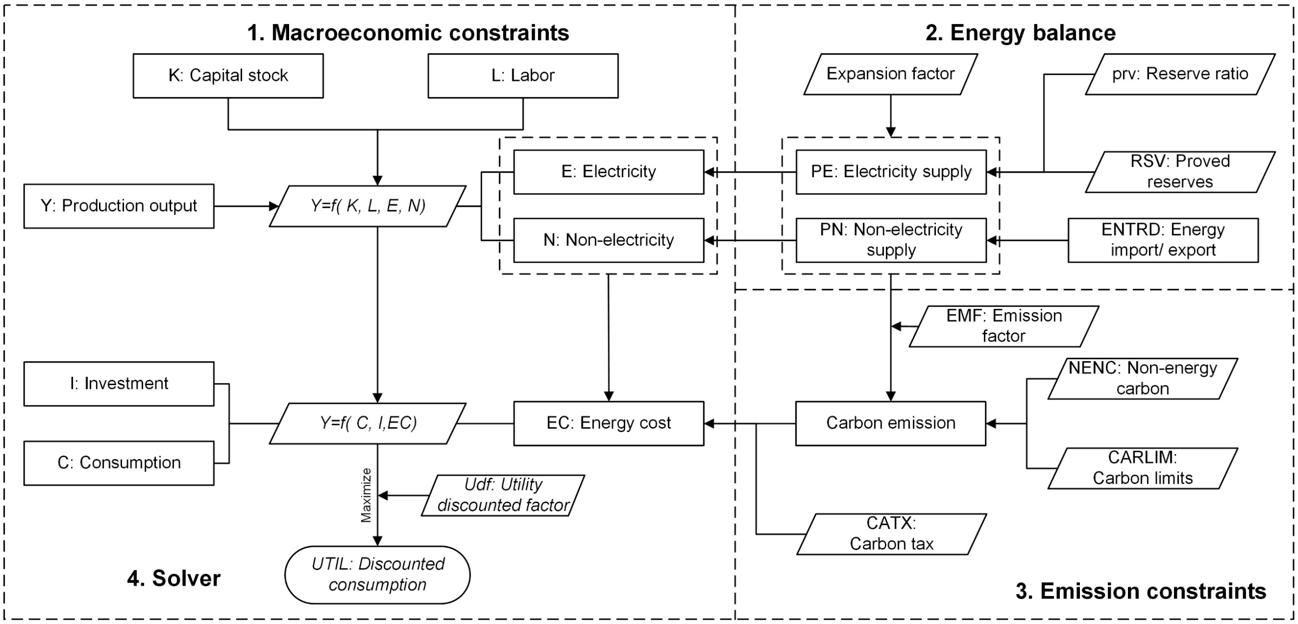

Fig. 1 Overview of the Glocal Century Energy Environment Planning (G-CEEP) model.

low carbon technologies. In this regard, there is a considerable number of available models that can support low carbon scenario analysis. GEM-E3 (General Equilibrium Model of Economy, Energy, and Environment) is a multi-regional, multi-sectoral general equilibrium model. Goods, services, labor, and capital in all markets are represented by constant elasticity of substitution production functions. Ozawa et al. [2] used the MARKAL model to assess the role of hydrogen in Japan's future energy system. The results indicate that hydrogen power generation should play a vital role as a low-carbon energy source in Japan's future energy system, along with renewable energy, nuclear energy, and fossil energy using CCS. In Japan there is also the DNE21 and a modified version of the DNE21+ model, which consists of three sub-models: an energy system model, a macroeconomic model, and a climate change model. K. Akimoto et al. [3] proposed the integrated assessment model DNE21 and suggests the best mitigation strategy to deal with global warming. And they are mostly parameter-driven models developed for large scales and long periods (e.g., one or several countries or even globally). The overall assessment of a country's future adoption of a low-carbon transition is made by looking at the total amount of resources and the possibilities of low-carbon technologies in a country. Their conclusions are often very instructive, such as clarifying that renewable energy should play a dominant role in decarbonizing Japan's power sector. However, the main contribution of different energy types with different technological characteristics in each period, and their interactions with each other, are difficult to visualize.

As an important economic powers in East Asia, Japan drive the economic development of the region, encompassing developed, developing, and mid-developed nations, forming a representative community. The economies of these three countries are dynamic, resilient, and closely interconnected, sharing common challenges as well as opportunities. "Glocal" is a compound word of "global" and "local" which refers to integration of local and global forces. This study built a large scale non-linear integrated planning model, the Glocal Century Energy Environment Planning (G-CEEP) model to evaluate macroeconomic, energy and environmental related issues for building a Glocal Low-carbon Community for Japan.

2. MATERIAL AND METHODS

2.1 Method

To achieve zero or low carbon emissions, upgrading regional energy systems requires not only a technological shift towards renewable energy but also the maintenance of socio-economic systems, known as a low-carbon economy. It comprises three main sub-models: the macroeconomic sub-model, the energy balance sub-model, and the emission constraint sub-model. The methodology flow is shown in **Fig. 1**.

2.2 Macro-economic constraints

Currently, most energy-related macroeconomic models, or energy models with macroeconomic components, are based on a two-level CES production function. The relationship between production, capital, labor, and energy consumption are described by Eq. (1):

$$Y_t = f(K_t, L_t, E_t, N_t) \tag{1}$$

where Y_t, K_t, L_t, E_t and N_t represent production output, capital, labor, electricity and non-electricity in *t* year, respectively. It can be detailed as Eq.(2).

$$\Delta Y_t = \gamma\left[\delta\left(\delta_1 \Delta K_t^{-\rho_1} + (1-\delta_1)\Delta L_t^{-\rho_1}\right)^{\frac{\rho}{\rho_1}} + (1-\delta)\left(\delta_2 \Delta E_t^{-\rho_2} + (1-\delta_2)\Delta N_t^{-\rho_2}\right)^{\frac{\rho}{\rho_2}}\right]^{-\frac{1}{\rho}} \tag{2}$$

where ΔY_t, ΔK_t, ΔL_t, ΔE_t and ΔN_t represent new production output, new capital, new labor, new electricity and non-electricity in *t* year, respectively. δ, δ_1 and δ_2 are distribution parameters. ρ, ρ_1 and ρ_2 are substitution parameters. The accumulation of production factors can be described by Eq. (3) to (7).

$$Y_t = Y_{t-1} \times (1-\mu)^5 + \Delta Y_t \tag{3}$$

$$L_t = L_{t-1} \times (1-\mu)^5 + \Delta L_t \tag{4}$$

$$E_t = E_{t-1} \times (1-\mu)^5 + \Delta E_t \tag{5}$$

$$N_t = N_{t-1} \times (1-\mu)^5 + \Delta N_t \tag{6}$$

$$\Delta K_t = 5 \times [I_t \times (1-\mu)^5 + I_{t+1}] \tag{7}$$

where Y_t, K_t, L_t, E_t and N_t represent production output, capital, labor, electricity and non-electricity in *t* year. I_t is the annual investment. μ is defined as annual depreciate rate. Then, the production output is expressed as the sum of the costs of consumption, investment, and energy system cost.

$$Y_t = C_t + I_t + EC_t \tag{8}$$

The Terminal condition is as follows:

$$K_T \times (\omega + \mu) \le I_T \tag{9}$$

where *T* is the last period in this model. ω is annual growth rate.

2.3 Energy balances

In this model, energy balances primarily take into account energy cost, emission constraints, and energy supply and demand, as follows:

$$EC_t = \sum (EP_{t,e} \cdot PE_{t,e} + NP_{t,e} \cdot PN_{t,e}) \tag{10}$$

where $EP_{t,e}$ is the electricity energy price coefficient. $PE_{t,e}$ denotes the electricity supply. $NP_{t,e}$ is the non-electricity energy price coefficient. $PN_{t,e}$ denotes the non-electricity supply. EC_t denotes the energy cost.

2.4 Constraints

The energy supply of the energy balance sub-model has to satisfy the energy demand of the macroeconomic sub-model, so that the energy supply and demand constraints can be described as：

$$\sum_{e \in ET} PE_{t,e} + \sum_{e \in NT} PN_{t,e} \ge (E_t + N_t) \times \prod_{\tau=0}^{t-1} (1-\omega_\tau)^5 \tag{11}$$

where τ is the Autonomous Energy Efficiency Improvement (AEEI) factor.

2.5 Environment evaluation

The environmental evaluation calculates the emissions of CO_2, SO_2, and NO_x under specific scenarios based on the emission factors of various energy sources and in accordance with relevant environmental policy constraints.

2.5.1 CO_2

Emissions are typically calculated as the product of energy consumption volume and emission factors. Therefore, CO_2 emissions for a specific period and sector can be estimated using the following Eq.(12):

$$E_{CO_2} = Q \cdot EF_{CO_2} \tag{12}$$

where E_{CO2} is the CO_2 emission volume. *Q* denotes energy consumption volume. EF_{CO2} is the CO_2 emission factor.

2.5.2 SO_2

SO_2 emission is estimated according to Eq.(13):

$$E_{SO_2} = 2 \cdot Q \cdot S \cdot \alpha \cdot (1-R) \tag{13}$$

where E_{SO2} is the SO_2 emission volume. *S* is the Sulfur content in specific period. α denotes SO_2 emission factor. *R* is desulfurization rate.

2.5.3 NO_X

NO_X emission is estimated according to Eq.(14):

$$E_{NO_X} = Q \cdot EF_{NO_X} \cdot (1-RE) \cdot (1-DE \cdot RE) \tag{14}$$

where E_{NOX} is the NO_X emission volume. EF_{NOX} is the NO_X content in specific period. *RE* denotes reduction efficiency of NOx emission, and *DE* is De-NOx efficiency of De-NOx equipment.

2.6 Objective function

Following the previous approach, for each region, there is a representative producer-consumer. The savings decision is modeled by choosing a consumption sequence for each region that maximizes the sum of the discounted "utilities" of consumption. To optimize the investment and consumption patterns over successive

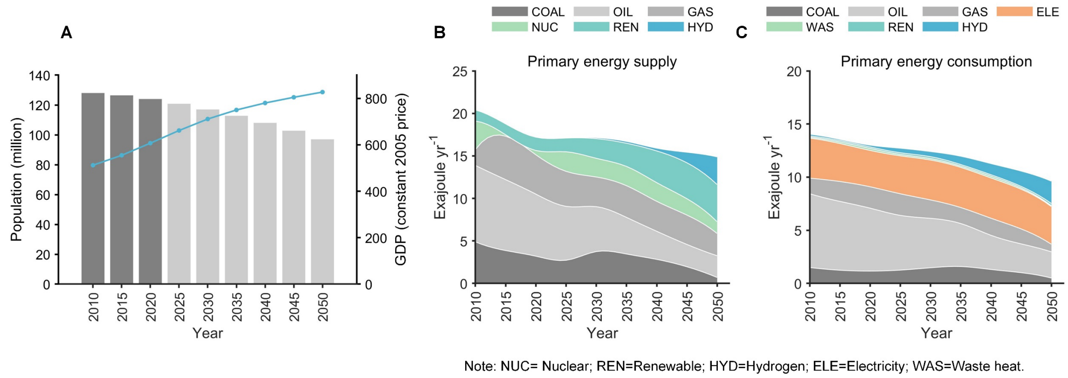

Fig. 2 Assumed GDP, population and calculated energy scenario in the study. (A) GDP and population in Japan. (B) Primary energy supply. (C) Primary energy consumption.

time periods, the utility function is the logarithm of consumption.

$$UTIL = \sum_{t=1}^{T} (5 \times \prod_{t=1}^{t-1} (1 - udr)^5 \times \log(C_t)) \qquad (15)$$

where *UTIL* is discounted utility. *C* is Annual consumption. *udr* denotes Utility discount rate.

3. RESULTS AND DISCUSSION

To estimate energy service demands, GDP and population projections were made based on the assumptions of the New Energy and Industrial Technology Development Organization and the Institute of Energy Economics (NEDO), as shown in **Fig. 2(A)**. This graph presents a projection of Japan's population and GDP growth from 2010 to 2050. The left y-axis, which aligns with the bars, shows the population forecast in millions. It indicates a decline in population over the period, decreasing from approximately 128 million in 2010 to about 100 million by 2050. The right y-axis, which aligns with the blue line, represents the GDP in constant 2005 prices. The GDP shows an upward trend, increasing from about 500 billion in 2010 to roughly 800 billion by 2050.

Fig. 2(B) shows the transition of the primary energy supply in the case scenario between 2010 and 2050. **Fig. 2(C)** shows the transition of the primary energy consumption in the case scenario. **Fig. 2(B)** shows the primary energy supply, with a visible decrease in coal, oil, and gas usage over time, and an increase in renewable and hydroelectric sources, particularly after 2030, indicating a shift toward more sustainable energy sources. **Fig. 2(C)** illustrates the primary energy consumption, highlighting significant growth in the consumption of electricity and energy from waste, along with a relative decrease in the use of traditional fossil fuels.

4. CONCLUSIONS

As Japan's population is projected to gradually decrease while its GDP continues to grow, there is a noticeable shift in energy demand and consumption patterns. In terms of energy supply, Japan is moving away from reliance on traditional fossil fuels such as coal, oil, and gas, towards increased use of renewable and hydroelectric sources. This indicates that Japan will focus more on sustainable energy solutions over the next few decades, responding to environmental protection needs. Additionally, the increase in electricity and energy consumption from waste highlights improvements in energy efficiency and technological advancements. These shifts will have significant implications for Japan's energy policies and economic development in the future.

ACKNOWLEDGEMENT

This study was supported by the Asia-Japan Research Institute of Ritsumeikan University within the research project titled “Research on Green Recovery and the Realization of Carbon Neutrality in East Asia”.

REFERENCE

[1] Li, Y., Wang, Y., Fukuda, H., Gao, W., & Qian, F. (2022). Analysis of energy sharing impacts in a commercial community: A case of battery energy storage system deployment for load leveling. *Frontiers in Energy Research*, 10, 929693.

[2] Ozawa, A., Tsani, T., & Kudoh, Y. (2022). Japan's pathways to achieve carbon neutrality by 2050–Scenario analysis using an energy modeling methodology. *Renewable and Sustainable Energy Reviews*, *169*, 112943.

[3] Akimoto, K., Tomoda, T., Fujii, Y., & Yamaji, K. (2004). Assessment of global warming mitigation options with integrated assessment model DNE21. *Energy Economics*, *26*(4), 635-653.