ANALYSIS OF OPTIMAL POWER GENERATION MIX IN JAPAN TO 2050, USING DYNAMIC MULTI-SECTOR ENERGY ECONOMIC MODEL

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Abstract: Today, energy sector is dealing with severe problems, including but not limited to depletion of fossil fuels, CO_2 emissions leading to global warming and so on. These issues deeply link with not only energy sectors but also economic sectors as well. Therefore, it is necessary to develop energy models providing quantitative analysis of energy systems which consider the relationship between energy and economic sectors. In this study, we propose a general economic equilibrium model that elaborates energy sectors with high time resolution. The results of this model could be used to identify the best energy-economic policy.

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Keyword: Energy Economic Model, General Equilibrium Model, Energy System, Optimal Power Generation Mix, GDP

1. Introduction

In order to explore future energy system trajectories of countries and to determine actual energy polices, energy models providing quantitative assessments have been developed all over the world. MARKAL (MARKet ALlocation) model is one of representative energy models, which focuses on the energy system itself and solves the cost minimization problem of the system so that the economic and engineering features of technology could be considered in detail. However, looking at the macro-economy system, it is difficult to consider the economic interaction between uncoordinated producers in models that focuses on only one sector. On the other hand, the general equilibrium model could describe the relationships among each economic agents by dealing with the utility function of society. The MIT EPPA (Emissions Predictions and Policy Analysis) model [1], which is based on the general equilibrium model, plays an important role in the debate on global warming countermeasures. However, unsuitable analysis of specific systems for high-resolution and nonlinearity of production functions are often criticized.

Therefore, a new general equilibrium model has been developed that takes into account the temporal operation of the power supply in electricity sector, mathematically and consistently. In addition, based on the developed model and the calculation results, this paper reports on the optimal power supply operation in Japan up to 2050 and its implications on the economy.

2. Dynamic Multi-sector Energy Economic Model (DMSEE)

2.1 Information and Novelty of DMSEE

The DMSEE model is based on the general equilibrium model, that elaborates the electricity sector with accumulation and refinement of technology. The target sectors are shown in **Table 1**. The 2007 Global Trade analysis Project (GTAP) database[2] is adopted as reference data for these sectors. The target area is Japan, and the target period is from 2015 to 2050 in 5 years increment, and the time resolution of electricity sector is divided into 8,760 hour time points. This model is a dynamic optimization model, and considers the connection between time-points by the investment behavior described later. The electricity sector is divided into the power generation sector and the transmission and distribution sectors, Transmission and distribution losses have also been taken into considerations. Production process in the non-electricity sector follows the CES (Constant of Elasticity Substitution) production function.

The novelty and uniqueness of this model is that it is possible to analyze the optimal deployment and operation of the technology dynamically at detailed time resolution until 2050, which is consistent with economic growth. There is no other existing general equilibrium model that can analyze the optimal technology selection of the power supply with such high time resolution. And our model is not calculated by the link of multiple models, but is completed in one model.

Table 1. Sectors in DMSEE

Non-Electricity sectors (Top-down sectors)	Agriculture, fishing, coal, oil, gas, mining, food/drink, fiber, lumber, paper, petroleum/coal products, chemical, non-ferrous metal, steel, nonmetal, machine, transport machines, other manufacturing, gas distribution, construction, land transport, marine transport, air transport, others
Electricity sectors (Bottom-up sectors)	Nuclear, coal-fired, oil-fired, gas-fired, hydro, wind, solar PV, pumped, short-cycle battery, long-cycle battery, other power, super high, high, low voltage transmission/distribution

2.2 Information of Electricity Sector

Information of each power generation technology is shown on **Table 2, 3**. Each value is referred to the references[3][4][5]. Basically, these exogenous values remain the same throughout all time points, however, the construction costs of solar and wind power generation are set at each time point in consideration of technological progress. First, for wind power generation, 177,000 yen/kW is set as the lowest construction price for 2030 [8] in this model. It is assumed to decrease at the same rate from 2015 to 2030, and thereafter it is set to the same value as the one for 2030. Next, for solar power generation, as with wind, its construction cost is assumed to be 158,000 yen/KW in 2030, and it decreases at the same rate after that. In addition, **Table 4, 5** show the initial installed capacity of each power generation and storage technologies. Regarding the construction of a power plant, the constraints in section ***2.4*** (c) are followed, however the cases of nuclear, wind and solar power generation have been discussed separately in section ***2.4*** (k)(l).

Table 2. Exogenous variables of power plants.

	Nuclear	Coal	Oil	Gas
Construction cost [k¥/kW]	1000	272	200	164
Annual Average Availability [%]	10-80	80	80	80
Seasonal Peak Availability [%]	20-90	90	95	95
Maximum Increase Rate of Output [1/h]	0.02	0.26	0.44	0.44
Minimum Increase Rate of Output [1/h]	0.02	0.31	0.31	0.31
Life Time [year]	40	40	40	40
Share of Daily Start and Stop	0.8	0.3	0.3	0.3

	Hydro	PV	Wind	Other
Construction cost [k¥/kW]	640	294	284	790
Annual Average Availability [%]	65	-	-	70
Maximum Increase Rate of Output [1/h]	0.05	-	-	0.05
Minimum Increase Rate of Output [1/h]	0.05	-	-	0.05
Life Time [year]	60	15	15	40

Table 3. Exogenous variables of storage technologies.

	Pumped	Long-cycle battery	Short-cycle battery
Construction cost [k¥/kW]	19	-	-
Power Storage Amount[kWh/kW]	6	-	-
C Rate	-	0.14C	2C
Self-discharge Rate [%/hour]	0.1	0.5	0.5
Efficiency [%]	70	85	85
Availability Factor [%]	90	90	90

2.3 Objective Function

The objective function is utility function of household and government consumptions, considering utility loss by taxes. Utility for each time point is capitalized as the current value by a discount rate, and is aggregated in (1). This model is an optimization problem that maximizes this function. Vectors are column vectors have as many components as time points.

$$obj = \sum_{yr} \sigma_{yr} \left(util_{\mathrm{H}_{yr}} + util_{\mathrm{G}_{yr}} - tax_{yr} \right)$$

$$\begin{aligned} \boldsymbol{tax} &= HTaxRate \cdot \boldsymbol{h} + GTaxRate \cdot \boldsymbol{g} + ATaxRate \cdot \boldsymbol{a} \\ &+ ITaxRate \cdot \boldsymbol{i} + PTaxRate \cdot \boldsymbol{p} + KTaxRate \cdot \boldsymbol{k} \\ &+ LTaxRate \cdot \boldsymbol{l} + MTaxRate \cdot \boldsymbol{m} + XTaxRate \cdot \boldsymbol{x} \end{aligned} \tag{1}$$

$\sigma = 1/(1+0.04)$, $util_{\mathrm{H}}$: utility function of household cons., $util_{\mathrm{G}}$: utility function of government cons., $\boldsymbol{h}$: household cons., $\boldsymbol{g}$: government cons., $\boldsymbol{a}$: intermediate cons., $\boldsymbol{i}$: investment, $\boldsymbol{p}$: production, $\boldsymbol{k}$: capital of equipment, $\boldsymbol{l}$: labor, $\boldsymbol{m}$: import, $\boldsymbol{x}$: export. Each coefficient is its tax rate.

2.4 Constraints

This model has the following constraints (a-l). Variables with index T are Top-down (TD), and variables with index B are Bottom-up (BU) constraints.

(a) Balance of demand and supply

$$\boldsymbol{h}_{\mathrm{B}} + \boldsymbol{g}_{\mathrm{B}} + \boldsymbol{a}_{\mathrm{B}} + \boldsymbol{i}_{\mathrm{B}} = \boldsymbol{c}_{\mathrm{B}} \tag{3}$$

$$\boldsymbol{h}_{\mathrm{T}} + \boldsymbol{g}_{\mathrm{T}} + \boldsymbol{a}_{\mathrm{T}} + \boldsymbol{i}_{\mathrm{T}} = \boldsymbol{c}_{\mathrm{T}} \tag{4}$$

$\boldsymbol{c}$: consumption

Buying and selling consumptions between sectors are described as $\boldsymbol{a}$ and $\boldsymbol{i}$ in equation (3) and (4). Intermediate input matrix of TD and BU consumptions consumed by TD and BU activities are defined as $A_{\mathrm{TT}}, A_{\mathrm{BT}}, A_{\mathrm{TB}}, A_{\mathrm{BB}}$ respectively, and investment matrixes are $C_{\mathrm{TT}}, C_{\mathrm{BT}}, C_{\mathrm{TB}}, C_{\mathrm{BB}}$.

$$\boldsymbol{a}_{\mathrm{B}} = A_{\mathrm{BT}} \cdot \boldsymbol{p}_{\mathrm{T}} + A_{\mathrm{BB}} \cdot \boldsymbol{p}_{\mathrm{B}} \tag{5}$$

$$\boldsymbol{a}_{\mathrm{T}} = A_{\mathrm{TT}} \cdot \boldsymbol{p}_{\mathrm{T}} + A_{\mathrm{TB}} \cdot \boldsymbol{p}_{\mathrm{B}} \tag{6}$$

$$\boldsymbol{i}_{\mathrm{B}} = C_{\mathrm{BT}} \cdot \boldsymbol{p}_{\mathrm{T}} + C_{\mathrm{BB}} \cdot \boldsymbol{p}_{\mathrm{B}} \tag{7}$$

$$\boldsymbol{i}_{\mathrm{T}} = C_{\mathrm{TT}} \cdot \boldsymbol{p}_{\mathrm{T}} + C_{\mathrm{TB}} \cdot \boldsymbol{p}_{\mathrm{B}} \tag{8}$$

Intermediate input matrixes are GTAP data, and investment matrixes are calculated based on Japanese fixed capital matrix. Electricity sector in the matrix is not divided into each power generation matrix [3]. $\boldsymbol{c}_{\mathrm{B}}$ is given by equation (9). $\boldsymbol{d}_{\mathrm{B}}$ is domestic consumptions, and $LossG$ is the rate of transmission loss of international transmission lines. Japan has no international transmission line at this moment. Therefore, import member of equation (9) equals zero, and this model assumes that the member equals zero until 2050, the end of calculation time points. $\boldsymbol{c}_{\mathrm{T}}$ is determined by the formulation explained in (l).

$$\boldsymbol{c}_{\mathrm{B}} = \boldsymbol{d}_{\mathrm{B}} + (1 - LossG) \cdot \boldsymbol{m}_{\mathrm{B}} \,. \tag{9}$$

(b) Balance of materials

$$\boldsymbol{p}_{\mathrm{B}} = (1 - Loss) \cdot \boldsymbol{d}_{\mathrm{B}} + \boldsymbol{x}_{\mathrm{B}} \,. \tag{10}$$

$Loss$ is the rate of domestic transmission loss. $\boldsymbol{p}_{\mathrm{T}}$ is determined by the formulation explained in (l).

(c) Investment and capacity

$$\boldsymbol{k}_{\mathrm{B}_t} = \boldsymbol{k}_{\mathrm{B}_0} + \sum_{t'=0}^{t} F_{\mathrm{B}_{t,t'}} \eta_{\mathrm{I}_{t'}} \boldsymbol{i}_{\mathrm{B}_{t'}} \,. \tag{11}$$

$\boldsymbol{k}_{\mathrm{B}}$: installed capacity, F: matrix for investment, η_{I}: construction cost

TD sectors have no defined unit of capacity, like [GW] for electricity sector, therefore, this model applied a distinctive method to consider unique unit of capacity (capital stock) for TD sectors as follows. Generally, the value of capital stock is expressed as the amount of money, called 'Rental Payment'(V). Then, the unique unit of capital stock of sector n, one of the TD sectors, is set as 'nUnit', and the absolute value of initial capital stock, which has unique unit, equals the production amounts for each sector in GTAP. The value of 1 nUnit is defined as rental price, RP, and, the following equation is satisfied:

$$V_{n,0} = RP_n \cdot k_{\mathrm{T}_{n,0}} . \tag{12}$$

Rental Payment, V, is can be given by GTAP, therefore, we can obtain the rental price of each TD sector. Using this rental price, capital stock having unique unit can be updated by investment as following:

$$k_{\mathrm{T}_{t+1}} = (1-\delta)^{\tau} k_{\mathrm{T}_t} + \tau \cdot i_{\mathrm{T}_t} / RP_n . \tag{13}$$

δ: depreciation rate (4%), τ: time interval, this model sets $\tau = 5$

(d) Labor force

DMSEE considers labor force as explained in [6]. Let the number of labor be l', let the efficiency of labor be e, then, labor force l is $e \cdot l'$. Each grows at the rate of population growth, θ, and the rate of technology progress, ζ, respectively, then, l is given as following:

$$\begin{aligned} l_{t+1} &= (1+\zeta)e_t \cdot (1+\theta)l'_t \\ &\approx (1+\zeta+\theta)l_t \\ &= (1+\gamma)l_t \ \ (\gamma = \zeta + \theta). \end{aligned} \tag{14}$$

Assuming a stationary equilibrium state of the solution, equation (15) is derived from the relationship between investment and capital stock and equation (14).

$$(\gamma + \delta)V_{n,0} = i_{\mathrm{T}_{n,0}} . \tag{15}$$

This means that , theoretical value of γ could be calculated by considering the ratio of rental payment to investment.

(e) Production and facility

$$\eta \cdot \boldsymbol{p}_{\mathrm{B}} \leq \boldsymbol{k}_{\mathrm{B}} \tag{16}$$

$$\eta \cdot p_{\mathrm{B}_{n,t}} \leq Cu_{n,t} \cdot k_{\mathrm{B}_n} \ \ (n \in \{Wind, Solar, Hydro\}) \tag{17}$$

η: coefficient to convert TWh to GW

For solar- and wind-power generation, the upper limit was set by using the capacity factor Cu every hour, and output suppression could be implemented like equation (17). For hydropower generation, the daily maximum operation rate was set because its maximum output depends on natural conditions [4]. Furthermore, the capacity factor was set to 40% based on the amount of power generated by hydropower in Japan in recent years and the capacity of existing facilities, and Cu was set in combination with the above-mentioned operating rate. The relationship between production and facility of TD sectors follows (l).

(f) Maintenance operation

Nuclear power plants and thermal power plants shut down their facilities at an appropriate time of year for maintenance. In this research, the maintenance pattern of each day was expressed by superimposing the seasonal maintenance pattern set every four seasons [4].

$$\boldsymbol{ap}_{pl,d} + \sum_{m=0}^{3} Ur_{m,d}\boldsymbol{mk}_{m,d} = \boldsymbol{k}_{\mathrm{B}_{pl}}\,, \tag{18}$$

$$\sum_{m=0}^{3} Ur_{m,d}\boldsymbol{mk}_{m,d} \geq \left(1 - Up_{pl}\right)\boldsymbol{k}_{\mathrm{B}_{pl}}\,, \tag{19}$$

$$\sum_{m=0}^{3}\sum_{d=0}^{364} \frac{Ur_{m,d}\boldsymbol{mk}_{m,d}}{365} = \left(1 - Ua_{pl}\right)\boldsymbol{k}_{\mathrm{B}_{pl}}\,. \tag{20}$$

$Ur_{m,d}$: rate at which the plant shuts down on day d in the repair seasonal pattern m, $ap_{pl,d}$: operation capacity at day d of plant $pl \in \{NuclearE, coalE, oilE, gasE\}$, $mk_{m,pl}$: Capacity at which plant pl stops according to repair seasonal pattern m, Up_{pl}: maximum daily operation rate of plant pl, Ua_{pl}: average annual operation rate of plant pl

As the amount of power generation is limited to the operating capacity $ap_{pl,d}$, the following equation need to be satisfied;

$$\eta \cdot \boldsymbol{p}_{\mathrm{B}_{pl,d,t}} \leq \boldsymbol{ap}_{pl,d} \tag{21}$$

t: hourly time points

(g) Load following operation

Let the upper and lower limits of the load following operation be $MaxLF, MinLF$ respectively, then, the followings need to be set in order to consider load following operation;

$$p_{\mathrm{B}_{pl,t}} \leq \left(1 + MaxLF_{pl}\right)p_{\mathrm{B}_{pl,t+1}}\,, \tag{22}$$

$$p_{\mathrm{B}_{pl,t}} \geq \left(1 + MinLF_{pl}\right)p_{\mathrm{B}_{pl,t+1}}\,. \tag{23}$$

Nuclear, solar, wind, pumped and batteries are excluded from these constraints.

(h) Reserve capacity

Sum of all power generation capacity is assumed 5% more than expected maximum demand $MaxLOAD$.

$$\sum_{pl} \boldsymbol{k}_{\mathrm{B}_{pl}} \geq (1 + 0.05) \cdot \eta \cdot \boldsymbol{MaxLOAD}\,. \tag{24}$$

(i) Other constraints of nuclear power generation

Today, almost all nuclear power plants in Japan are not being operated. As of September 2017, the capacity factor of nuclear power in Japan is 11.1% [7], and it is difficult to restart all 42 units immediately. Therefore, assuming that all existing nuclear power plants will be reactivated by 2030, the upper limit of approved maximum capacity in 2020 and 2025 is set to 30% and 60% of that in 2015 respectively. In addition, new construction of plants is carried out after 2030, and investment for it is permitted only after 2030.

(j) Other constraints of wind- and solar-power generation

Consideration of intra and inter-regional interconnections is indispensable for the expansion of wind-power generation. In this model, only simple power transmission and distribution has been taken into account, and the problems of interconnection were not addressed adequately. Therefore, an upper limit is set for the installed capacity of wind-power generation at each time point. Specifically, the upper limit is 32.5 GW in 2030 and 70.0 GW in 2050, as in the case of wind-power generation introduction high-order cases set by the Ministry of the environment. For solar power generation, in order to suppress unrealistic large-scale introduction in a single year, the upper limit of the facility increase rate compared to the previous time point is set to 80% at each time point.

(k) Other constraints of pumped and battery storage

Pumped and battery storage are limited by the following constraints. Battery 1 and 2 means long- and short-cycle fluctuation adjustment battery respectively;

$$\boldsymbol{p}_{\mathbf{B}_j} = \boldsymbol{dis}_j - \boldsymbol{cha}_j\,, \tag{25}$$

$$cha_{j,t} + dis_{j,t} \le Us\_W_{j,t} \cdot k_j\,, \tag{26}$$

$$ss_{j,t} \le Us_{Wh\,j,t} \cdot k'_j\,, \tag{27}$$

$$k'_j \le MStorage_j \cdot k_j\ (j = \{"Pumped"\}) \cdot, \tag{28}$$

$$k_j \le CRate_j \cdot k'_j\ (j = \{"Battery1", "Battery2"\})\,, \tag{29}$$

$$ss_{j,t+1} = \left(1 - Sd_j\right)ss_{j,t} + \sqrt{Eff_j} \cdot cha_{j,t} - \frac{1}{\sqrt{Eff_j}} \cdot dis_{j,t}\,. \tag{30}$$

$\boldsymbol{dis}$: output, $\boldsymbol{cha}$: input, Us_W: kW operation rate, Us_{Wh}: kWh operation rate, $\boldsymbol{ss}$: storage capacity, $\boldsymbol{k'}$: kWh capacity, $MStorage$: storage capacity per installed capacity, $CRate$: C rate, Sd: self-discharge rate per hour, Eff: efficiency of charge and discharge

(l) Approximation of CES function to the primary inequality as Leontief type

Since general CES function is a nonlinear function, it needs to be approximated to a linear function in order to be treated in a linear programming, and in this model, the utility function and the production function, which are given as CES function, are approximated to the primary inequality as Leontief type. Let the utility function or the production function be z, let the variables of CES function be y, let coefficients, which can be derived from problems to minimize the cost of the production process and the lemma of Shepherd, be β, then, the following is the approximated primary inequality;

$$\beta_{i,j,t} \cdot z_t \le y_{i,j,t} \tag{31}$$

This model was solved repeatedly, and β was updated with the solutions and the shadow prices of the previous calculation.

3. Results

3.1 Cases

(a) BAU(Business As Usual) Case: no constraint is imposed other than the constraints described in section 2.
(b) $50 Case: Carbon tax of $ 50 per ton of carbon dioxide is imposed at all times from 2025.
(c) $300 Case: Carbon tax of $ 300 per ton of carbon dioxide is imposed at all times from 2025.
(d) $300_noN Case: Carbon tax of $ 300 per ton of carbon dioxide is imposed at all times from 2025 and nuclear power plants are prohibited at all time points.

3.2 Scenario

In this model, household consumptions are given exogenously. Consumptions of electricity are expected to increase at a rate of 1.5% annually in anticipation of future electrification. Since consumptions of non-electricity commodities are difficult to predict, they are set to as fixed from the beginning. With regard to trade, the exports are constant from the beginning, and imports are treated endogenously and their price is considered constant from the beginning.

3.3 Optimal Power Generation, Installed Capacity and CO_2 Emissions

Figures 1 to 4 show the optimal power generation mix for each case (a to d as explained in ***3.1***), **Figure 5** shows the optimal power generation and CO_2 emissions for each case in 2050, and **Table 4, 5** show the installed capacity for each power generation and storage technology. As described in ***2.1*** above, since this model is calculated every five years, **Figures 1 to 4** show the optimal power generation mix every five years. The total power generation is, for example, 1.12 PWh in 2030. Although the household power consumption is given exogenously, the amount of power consumed by firms is determined endogenously. The power demand of firms is almost flat, and therefore, as the power consumption of households increases, the power demand as a whole tends to increase. If we consider energy saving technology and electrification technology, carbon tax is expected to reduce the demand for electricity. In that case, the best mix would also change, and the share of renewable energy is expected to increase. Along with that, investment behavior in the economy becomes active. It is necessary to consider the appropriate price of the carbon dioxide tax, taking these effects into consideration.

Focusing on the best mix, in the BAU case, there is no restriction on environmental load, therefore, nuclear power and renewable energy, which hold high fixed costs, shrink, and coal and gas power dominate. As a result, CO_2 emissions amounted to 1.3 Gt, an increase of approximately 9.2% from the current level in 2015. Moreover, in the case where carbon tax is imposed, nuclear power generation functions as an important base load power source. Not only reactivation of existing power plants but also new construction is required. Furthermore, the growth of solar power is remarkable, accounting for 52% of the total power generation as of 2050. With the entry of nuclear and solar power that do not emit CO_2, the emissions can be reduced by approximately 25%, to 0.9 Gt. Looking at the $ 300 case, thermal power generation has almost stopped its operation due to the high carbon tax. Along with that, expansion of renewable energy and further construction of nuclear power plants are carried out. However, looking at CO_2 emissions, it was 0.86 Gt as of 2050, which was not much different from the $ 50 case. In the $ 300_N case, which prohibits the establishment of new nuclear power plants, the existing nuclear power plants are fully operated, and solar power supports the supply. Looking at **Figure 5**, the long-period storage battery plays a major role in each case except for the BAU case, which contributes to the expansion of solar power generation that can generate electricity only during the daytime.

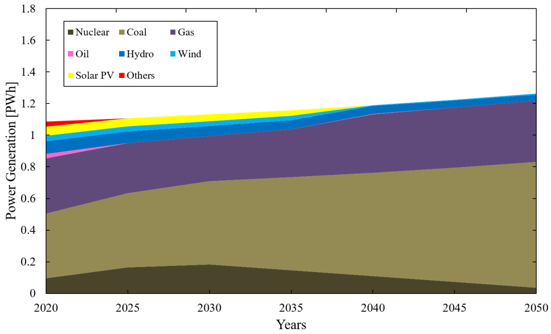

Figure 1. Power generation mix in BAU case.

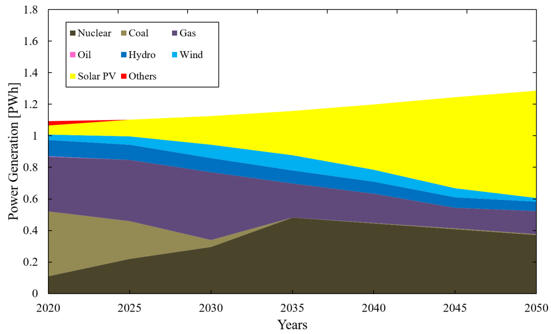

Figure 2. Power generation mix in $50 case.

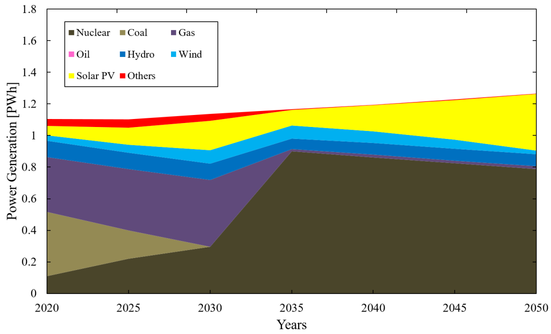

Figure 3. Power generation mix in $300 case.

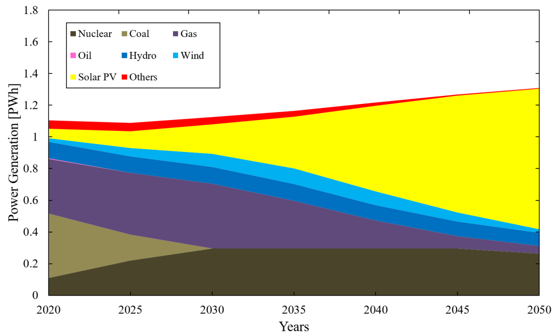

Figure 4. Power generation mix in $300_noN case.

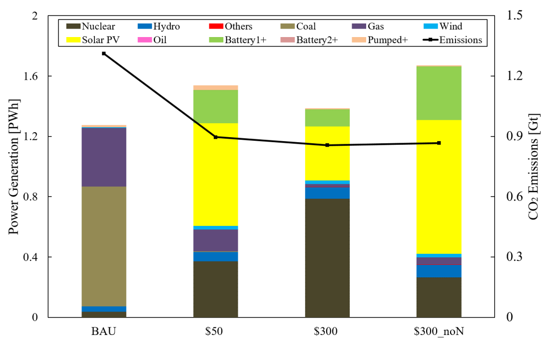

Figure 5. Power generation mix and CO_2 emissions in 2050.

Table 4. The capacity of power generation technologies.

[GW]		BAU	50$	300$	$300_noN
Nuclear	2015	42.0	42.0	42.0	42.0
	2030	26.3	42.0	42.0	42.0
	2050	5.3	53.1	112.5	37.8
Coal	2015	51.4	51.4	51.4	51.4
	2030	75.0	45.7	45.0	45.1
	2050	113.4	20.0	19.3	19.3
Oil	2015	42.3	42.3	42.3	42.3
	2030	26.4	26.4	26.4	26.4
	2050	5.3	5.3	5.3	5.3
Gas	2015	94.4	94.4	94.4	94.4
	2030	95.6	102.3	121.6	130.2
	2050	117.5	71.9	74.4	83.0

Hydro	2015	49.5	49.5	49.5	49.5
	2030	37.1	51.2	59.5	59.5
	2050	20.6	34.7	43.0	47.1
Wind	2015	3.1	3.1	3.1	3.1
	2030	13.1	35.6	35.6	35.6
	2050	2.6	10.2	10.2	10.2
Solar PV	2015	34.3	34.3	34.3	34.3
	2030	44.6	200.3	200.3	200.3
	2050	0.1	1173.4	1071.7	2102.3
Other	2015	4.2	4.2	4.2	4.2
	2030	2.6	2.6	5.7	5.7
	2050	0.5	0.5	3.6	3.6

Table 5. The capacity of storage technologies.

[GW]		BAU	50$	300$	$300_noN
Pumped	2015	54.1	54.1	54.1	54.1
	2030	63.3	74.7	42.1	36.8
	2050	71.9	168.4	34.0	33.3
Battery1	2015	0.0	0.0	0.0	0.0
	2030	0.0	0.0	71.7	65.0
	2050	0.0	1159.7	594.1	1869.0
Battery2	2015	0.0	0.0	0.0	0.0
	2030	0.0	0.0	0.0	0.0
	2050	0.0	0.0	0.0	0.0

3.4 Optimal Power Generation Pattern

Figure 6 shows the hourly power generation pattern for the $50 case (left: July 2030, right: July 2050). Compared with 2030 and 2050, there is a big difference in the amount of battery usage. In 2030, gas-fired is dominant, and solar and batteries do not spread, almost only pumped is used as the storage facility. On the other hand, in 2050, long-period storage batteries are actively used. It is probable that this is due to the difference in charge and discharge efficiency in equation (30).

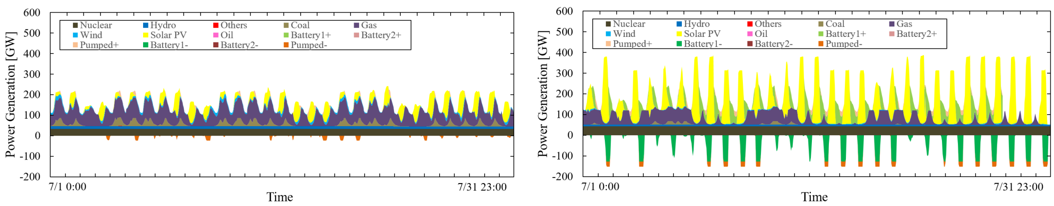

Figure 6. Power variation of $50 case in July 2030 (left), 2050 (right).

3.5 GDP and Utility

Since this model is also an economic model based on the general equilibrium model, it is possible to create an Input/Output (I/O) table at each time point. **Figure 7** shows the GDP growth rate calculated from the table. In each case where CO_2 tax is imposed is imposed, investment in renewables contributes significantly to GDP growth. Especially, in the $ 300 case, approximately 30 trillion yen is invested into the construction of a new nuclear power plant, and the expansion of production in each sector through investment contributes significantly too. Comparing the $ 300 case with the $ 300_noN case, the former has higher GDP levels until 2030, and the latter is higher thereafter. Even if the existing nuclear power generation is restarted, the GDP level after 2035 is high due to the investment in renewable energy. However, from the perspective of the GDP growth rate, the result is 13% at most, and there is a large discrepancy (39% and 41%, respectively) with those assumed in [12] and [13]. In this model, as mentioned earlier, consumptions are set by scenarios, and in particular, consumptions of non-electricity commodities are fixed from the beginning, which is the cause of low growth. In the future, we plan to consider establishing some consumption scenarios and treating consumptions endogenously.

More importantly, it is not necessarily said that the increase in GDP brings benefits to people's lives. **Figure 8** shows the utility of each case when the utility of the BAU case at the initial point is 1. The very high carbon tax of \$300/t-CO_2 contributed to the growth of GDP as shown in **Figure 7**, however, the utility of each household is reduced by about 25% compared to the initial. Although what the decrease means is difficult to be interpreted on this discussion, the fact is important that economic growth is not always directly proportional to utility, and in this analysis, it was suggested that the introduction of high CO_2 tax should be treated carefully.

In addition, the use of energy saving technology is expected to reduce energy consumption due to the introduction of CO_2 tax, but as mentioned earlier, since the energy saving technology is not considered in the current model, it is difficult to argue the effect of CO_2 tax accurately. Furthermore, it is also possible to return CO_2 tax revenue to other taxes and subsidies, however, it is difficult to discuss accurate tax process, which is one of the future works,

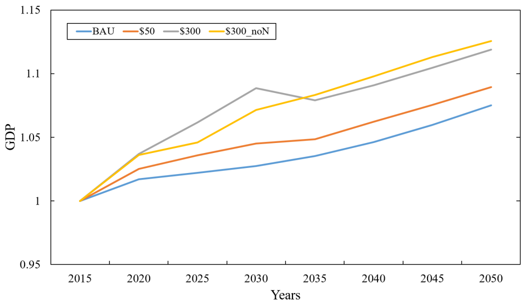

Figure 7. GDP growth (standardized by value in 2015).

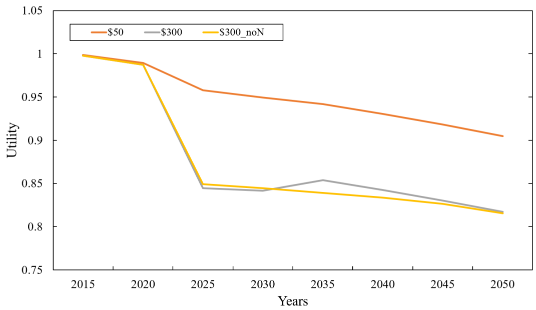

Figure 8. Utility growth (value in 2015 in BAU case as 1).

Table 6. Change of consumptions in 2050 compared with ones in BAU case, and its share of GDP [%].

	construction	coal	machine	gas	Marine transport
\$50	7.3 (1.0)	-76 (0.074)	1.8 (0.69)	-44 (0.38)	-4.3 (0.48)
\$300	7.3 (1.1)	-76 (0.073)	8.3 (0.70)	-68 (0.16)	-5.1 (0.47)
\$300_noN	8.3 (1.1)	-76 (0.073)	10 (0.70)	-62 (0.20)	-4.5 (0.48)

3.6 The scope of update of DMSEE

The current version of DMSEE could only elaborate electricity sector, and there is provision to update it in order to non-electricity energy sectors and material sectors. Non-electricity sectors need to be elaborated in order to consider electrification technology on the demand side, and material sectors occupy 36.6% (4.95×10^{18} J) of the total energy consumptions and technological development is expected in order to reduce CO_2 emissions.

Non-electricity energy sectors are defined as ‘coa’, ‘oil’, ‘gas’, ‘p_c’ (petroleum, coal products), and ‘gdt’ (gas manufacture, distribution) in GTAP. In order to deal with the process of energy consumptions accurately, it is needed to consider petroleum and coal products separately, therefore, we elaborate non-electricity energy sectors based on the classification of activities and commodities shown on **Table 7**, referring to Comprehensive Energy Statistics, published by Ministry of Economy, Trade and Industry (METI) in Japan. **Table 8** shows the activities and commodities of cement and steel sectors. The classification and methods to elaboration are based on the report[14] published by Research Institute of Innovation Technology for the Earth (RITE).

Table 7. Activities and commodities of non-electricity energy sectors.

GTAP	Activity	Commodity
‘coa’, ‘oil’, ‘gas’	coal, oil	coal, oil
‘p_c’	oil product	raw material oil, gasoline, jet fuel, kerosene, diesel oil, heavy oil, other petroleum products
	coal product	cokes, COG, BFG, LDG
‘gas’	gas	natural gas, city gas

Table 8. Activities and commodities of cement and steel sectors.

GTAP	Activity	Commodity
‘nmm’	Type I~IX	cement
‘i_s’	converter (low, middle, high efficiency), next generation converter (low, middle, high efficiency), electric furnace (low, middle, high efficiency), direct reduction (low, middle, high efficiency)	slag, crude ore, steel products

4. Conclusions and Future Works

In this paper, we developed a model, named DMSEE, based on a general equilibrium model that handles multiple sectors, that elaborates electricity sector with a very high time resolution (8,760 hour points for a year). As a policy to reduce CO_2 emissions, we evaluated changes of the energy system and its impact on the economy when the carbon tax was introduced. As a result of solution of the current model, it was suggested that nuclear power generation and photovoltaic power generation could play important roles. In particular, nuclear power plants need to be considered not only for restart but also for new construction. In addition, the introduction of electricity storage equipment is also key to the spread of solar power generation. However, it is also suggested that carbon tax increase and emissions reduction are not in direct proportion, and the contribution of carbon tax increase to emissions reduction could slow down. The reason why this emission reduction effect gradually saturates is that by raising the carbon tax amount, the technology with the emission reduction effect will gradually spread and the reduction effect will plateau.

Also, considering this problem from the economic aspects, we have obtained the result that active investment in nuclear and solar power generation contributes to the boost of GDP. Moreover, contrary to the increase in GDP, the utility of the society as a whole has decreased, and it has been suggested that the discussion on the whole society is necessary when analyzing on the economic side. In addition, we are developing a new model, which elaborates energy sectors (including electricity sector elaborated by the current model) and material sectors. The refinement is needed in order to consider accurate process of energy consumptions and electrification technology.

As the future works, we would like to complete the development of an updated DMSEE model and analyze the optimal selection of technology of the material industry and the impact on other industries when environmental load measures such as carbon tax are introduced. And we introduce electrification technologies such as electric car and greenhouse gas reduction technology such as CO_2 Capture and Storage (CCS) and fuel cell car into this model, and we would like to quantitatively investigate whether we can achieve some challenging targets of CO_2 emission reduction in near future.

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