A Study of Long-term Energy-mix Optimization Model: A Case Study in Japan

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Abstract – There is a strong need to reduce greenhouse gas emissions to deal with climate change. In the power sector, changing the power generation method in the medium and long term is needed to reduce greenhouse gas emissions. This paper proposes a long-term energy-mix optimization model to obtain the process of carbon neutrality in the power system. The proposed model models power supply and demand at an hourly granularity and determines the generation capacity that minimizes the long-term energy supply cost. Compared with the models proposed in previous studies, the proposed model can determine the installed capacity to maintain the balance of power supply and demand by adding the capacity of regulation reserve required by fluctuations in the output of variable renewable energy as a constraint condition. A Japan energy mix calculation is reported as a case study of the proposed model. This model can clarify the roadmap to achieving each country’s emission reduction target and support the government's decision-making.

Keywords: Energy-mix optimization, Linear programming

1. Introduction

Countries worldwide are required to shift to a carbon-neutral energy supply system as a measure against climate change. Japan has declared itself carbon neutral by 2050 and has set a goal of reducing greenhouse gas emissions to 37% reduction by 2030 from 2013. To achieve this goal, decarbonizing the electricity sector is essential [1]. Although various industry associations have published roadmaps for achieving this goal (e.g., Japan Wind Power Association [2]), a quantitative roadmap from the overall optimization perspective is needed to ensure fair decision-making across the country.

The rapid spread of variable renewable energy (VRE) resources such as solar photovoltaic (PV) and wind power (WP) was motivated by a renewable energy feed-in tariff that went into effect in 2012, prior to the greenhouse gas reduction targets. It has been pointed out that issues such as the lack of various measures are considered to address these issues, including the introduction of grid storage batteries and demand control of consumer-side equipment. Economic calculations that include supply and demand control are necessary to evaluate the cost-effectiveness of these measures. Methods using the optimal power resource configuration model [3] and unit commitment problem (UC) [4] have been proposed to perform these economic calculations.

To clarify the path to achieving a carbon neutral state over several decades, developing a model is needed that can perform the operational analysis of supply and demand over a period of more than one year and optimize the capacity of various power sources and storage facilities.

Several optimization models have been proposed to determine the energy mix on a multi-year scale. Komiyama and Fujii [3] proposed a model that considers Japan as one area and determines the optimal energy resource capacities. H.C. Gils [4] proposed the "REMix" model, an optimal capacity model for electric power and thermal energy equipment. The "REMix" model is modeled by GAMS, an energy analysis software. The "REMix" model is also used to analyze energy supply and demand over a wide area in the EU [5]. In the optimization model for non-power systems, a capacity planning model for energy supply in small areas has been proposed [6].

These previous studies did not include regulation reserves to deal with fluctuations in the output of VRE. Regulation reserves are the "extra power" to maintain power supply and demand by using controllable thermal and hydroelectric power generation to cover the output of VRE that increases or decreases in seconds to minutes, depending on weather conditions.

Therefore, this paper proposes a long-term energy mix optimization model that includes regulation reserve capacity. The optimization results of Japan's energy mix are shown as a case study.

The contributions of this paper can be summarized as follows:
2. Problem Description

Fig. 1 shows the model inputs/outputs and internal processing. Daily load curve, VRE installed capacity scenario, fuel price scenario, generator performance data, time-series data on VRE generation output, and hydro and geothermal/biomass generation output are the model input data. As a result of the optimization, the operating cost, the operation pattern of each generator, the capacity of the regulating power to be supplied, and the marginal hourly fuel cost are obtained.

3. Long-term Energy-mix Optimization Model

The objective function and constraints of the long-term energy mix optimization model are shown in (1)-(38). The proposed model is formulated as a linear programming problem. Table 1 lists the nomenclatures used in the model.

\[
\min \sum_{y=1}^{\text{Num}} \frac{1}{(1+r)^y} AC_y
\]

subject to

\[
AC_y = \sum_{i \in \mathcal{I}} g_i \cdot f_{i,y} \cdot P_{gcap_{i,y}} + \sum_{i \in \mathcal{I}} v_{i,y} \cdot P_{g_{i,y}} + \sum_{j \in \mathcal{I}} ASC_{j,y}
\]

\[
PG_{i,y} + \sum_{j \in \mathcal{J}} (Ps_{out_{ij,y}} - Ps_{in_{ij,y}}) = load_{i,y}
\]

\[
Ru_{i,y} + \sum_{j \in \mathcal{J}} (Rscd_{i,y} + Rsd_{i,y}) \geq rc_{i,y}^-
\]

\[
r_c^{+} = rcl \cdot load_{i,y} + rcp \cdot PG_{i,y}
\]

\[
r_c^{-} = rcl \cdot load_{i,y} + rcp \cdot PG_{i,y}
\]

\[
P_{g_{i,y}} + Ru_{i,y} \leq P_{g_{cap_{i,y}}}
\]

\[
P_{g_{i,y}} - Rd_{i,y} \geq 0
\]

\[
P_{g_{i,y}} = v_{i,y} \cdot P_{g_{cap_{i,y}}}
\]

\[
Ru_{i,y} \leq r_{i}^{upper} \cdot P_{g_{cap_{i,y}}}
\]

\[
Rd_{i,y} \leq r_{i}^{upper} \cdot P_{g_{cap_{i,y}}}
\]

\[
P_{s_{in_{ij,y}}} + Ps_{out_{ij,y}} + Rscu_{ij,y} + Rsd_{ij,y} \leq P_{scap_{ij,y}}
\]

\[
P_{s_{in_{ij,y}}} - Rscd_{ij,y} \geq 0
\]

\[
Ps_{out_{ij,y}} - Rsd_{ij,y} \geq 0
\]

\[
Rscu_{ij,y} + Rsd_{ij,y} \leq r_{j}^{upper} \cdot P_{scap_{ij,y}}
\]

\[
Rscd_{ij,y} + Rsd_{ij,y} \leq r_{j}^{upper} \cdot P_{scap_{ij,y}}
\]
\[ E_{S,j,t} \leq Escap_{j,y} \]
\[ Es_{j,t} \geq 0.2 \cdot Escap_{j,y} \]
\[ E_{S,j,t+1} = \mu s_j \cdot Ps_{in} - \frac{1}{\mu s_j} \cdot Ps_{out} + E_{S,j,t} \]
\[ E_{S,j,t+1} = 0.5 \cdot Escap_{j,y} \]
\[ E_{S,j,t+1} = 0.5 \cdot E_{S,j,t} \]
\[ P_G, \psi_{i,n}, - P_G, \psi_{i,l} + E_{S,j,t} \]
\[ P_G, \psi_{i,n} \leq P_G, \psi_{i,u} \]
\[ P_G, \psi_{i,l} \leq P_G, \psi_{i,u} \]
\[ Escap_{j,y} \leq Escap_{j,y} \]
\[ \sum_{t=0}^{n} P_G, \psi_{i,n} + \sum_{t=0}^{n} P_G, \psi_{i,l} \geq (1 + \delta) \cdot load_{y,t} \]
\[ P_G, \psi_{i,n} \leq P_G, \psi_{i,n} + d^+ \cdot P_G, \psi_{i,n} \]
\[ P_G, \psi_{i,l} \geq P_G, \psi_{i,l} - d^- \cdot P_G, \psi_{i,l} \]
\[ \sum_{t=0}^{n} P_G, \psi_{i,n} \leq c_{f_{i,n}} \]
\[ \sum_{t=0}^{n} P_G, \psi_{i,l} \leq c_{f_{i,l}} \]

Equation (1) is the objective function. The total cost for the entire period is minimized as the objective function. Equation (2) is a constraint on the annual cost. It sums the annual fixed cost for the generation facility, the annual fuel cost, and the annual fixed cost for the energy storage facility. Equation (3) is a constraint on the one-year fixed cost of the energy storage facility. Equation (4) is the supply-demand balance constraint. Equations (5) and (7) are inequality constraints on the amount of regulation reserve capacity provided by generators. Specifically, they are constraints that ensure more capacity than the required regulation reserve capacity shown in equations (6) and (8). Equation (9) is the generation capacity constraint. Equation (10) is the constraint on the capacity of the regulation reserves in the downward direction. Equations (11) and (12) are constraints on the output of PV and WP. The actual power output minus the amount of curtailment is the respective power output. Equations (13)-(16) are constraints on the upper limit of the capacity of regulation reserves provided relative to the rated capacity. Equation (17) is the constraint of the storage system's recharge/discharge power, power capacity, and regulation reserve capacity. In this paper, we consider many energy storage facilities together. For this reason, constraints on the total capacity of charging and discharging power and the amount of regulating power provided are provided. Equations (18) and (19) are the constraints on the relationship between the charging/discharging power and the downward regulation reserve. Equations (20) and (21) represent the upper limit of the regulation reserve capacity that can be provided relative to the power capacity of the storage system. Equations (22) and (23) are the upper and lower constraints on the amount of stored energy. Equation (24) is the constraint for updating the amount of stored energy between periods. Equations (25)-(27) are equality constraints on the amount of stored energy boundary conditions. In this paper, it is assumed that the amount of stored energy is 50% of capacity at the beginning and end of a year. Equations (28)-(30) are upper bound constraints on the amount of capacity. Equations (31)-(33) are equation constraints on the installed capacity for each year. The capacity in each year is the capacity of the existing facilities plus the newly added capacity. Equation (34) is a constraint on operation reserve capacity. Equations (35) and (36) are upper and lower constraints on the change in generation output. Equation (37) and (38) is the upper and lower constraints on the capacity factor of each generating facility.
4. Case Study

In this paper, the energy mix for the Japanese power system was optimized to ascertain the effect of extending the model for the provision of regulation reserve capacity. This case study takes one year as the period of consideration and finds the energy mix that minimizes the total cost for one year.

### 4.1 Input Data

This section describes the data input to the proposed model. The demand data is the sum of hourly electricity demand data for 2019, which is included in the supply-demand data by service area published by the ten general transmission and distribution utilities in Japan.

Assumptions regarding the cost, generator capacity, and installation potential for each type of power generation are...
Table 2. Assumed parameters in a case study.

| Parameter                     | Nuclear [MW] | Coal [MW] | LNG [MW] | Oil [MW] | Hydro [MW] | Geothermal [MW] | PV [MW] | WP [MW] |
|-------------------------------|--------------|-----------|----------|----------|------------|----------------|---------|---------|
| Fixed cost [10^5 JPY/kW]      | 40.0         | 24.4      | 16.1     | 20.0     | 64.0       | 79.0           | 29.4    | 34.7    |
| Existing generator capacity   | 39,561       | 27,708    | 67,251   | 27,858   | 36,065     | 0.134          | 53,269  | 4,043   |
| Minimum capacity factor [%]   | 100          | 30        | 30       | 30       | 11.3       | 0              | -       | -       |
| Maximum capacity factor [%]   | 100          | 85        | 90       | 90       | 55         | 70             | -       | -       |
| Maximum ramping [%]           | 0            | 20        | 20       | 20       | 100        | -              | -       | -       |
| Maximum ramping [%]           | 0            | 20        | 20       | 20       | 100        | -              | -       | -       |

Table 3. Optimal capacity in each case.

| Parameter          | Case 1          | Case 2 (Proposed model) |
|--------------------|-----------------|-------------------------|
| Nuclear [MW]       | 39,561          | 39,561                  |
| Coal [MW]          | 27,708          | 27,708                  |
| LNG [MW]           | 67,251          | 67,251                  |
| Oil [MW]           | 27,858          | 27,858                  |
| Hydro [MW]         | 36,065          | 36,065                  |
| Geothermal [MW]    | 10,375          | 10,375                  |
| PV [MW]            | 53,269          | 53,269                  |
| WP [MW]            | 76,288          | 76,651                  |
| Pump (Power) [MW]  | 26,000          | 26,000                  |
| Pump (Energy) [MWh]| 130,000         | 177,518                 |
| BESS (Power) [MW]  | 1,600           | 1,600                   |
| BESS (Energy) [MWh]| 9,600           | 9,600                   |

4.2 Compared Cases

The model proposed in this paper is unique in that it adds information on the regulation capacity compared to previous studies. In the numerical experiments in this paper, the following two cases were set up to confirm the changes caused by the addition of information on regulation reserve capacity.

- Case 1: Calculate without including constraints on regulation reserve capacity.
- Case 2: Include constraints on regulation reserve capacity (proposed model).

4.3 Calculation Results

First, Table 3 shows the optimal installed capacities calculated for the two cases. From Table 3, the WP capacity and the pumped storage energy capacity were increased.

Next, the annual output curtailment is shown in Fig. 2, which shows an increase in PV output curtailment and a decrease in WP output curtailment. This is because the output is suppressed in Case 2 due to the lack of regulation reserve capacity during the hours when PV output is high. In this paper, the output fluctuation rates of PV and WP are set to 10% and 8%, respectively. Therefore, PV was prioritized for output curtailment, and WP output curtailment was reduced.

As shown in Table 3, the increase in pumped storage energy capacity and WP capacity can be attributed to the fact that the PV output curtailment was covered by WP and pumped storage.

However, the results of numerical experiments conducted by the author with similar input data in the literature [12] showed a minor change in PV and WP output suppression.
when regulation reserve capacity was included in the model. This is because the model proposed in this paper lumps all areas together. In the existing power system, each area is connected by interconnection lines, and each area has a different power supply configuration. Therefore, the regional bias of renewable energy dramatically affects the amount of output curtailment. The results of this paper confirm the necessity of constraints on cross-regional interconnection lines.

5. Conclusion

In this paper, a long-term energy mix optimization model is proposed. A case study for Japan confirms that generators' operation and optimal capacity changed with the addition of the constraint of regulation reserve capacity.

In Japan, interconnection lines connect each area with a different energy mix and renewable energy installable capacity. Literature [12] proposes an efficient method for solving the UC problem for multiple areas connected by interconnection lines. It is thought that the effect of the model proposed in this paper, including the regulation reserve capacity, can be achieved by introducing interconnection lines as a model. This paper compares results from a single year to confirm the effect of the model extension but does not calculate or compare results from multiple years. In the future task, it will be necessary to conduct multi-year case studies and study facilities' transitions to reach the CO2 emission reduction target.

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