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Green Energy Management System Built by AI Technique to Support the Regional Sustainable Development in Japan

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Abstract. To support regional decarbonization, this study focuses on designing an optimal green energy management system in which renewable energy (onshore, offshore wind power, solar power, and biomass power) are made as prioritized sources to meet the temporal energy demand. The optimization algorithm is applied in the Kitakyushu City of Japan. At first, the annual renewable energy supply and energy demand were estimated and disaggregated to an hourly level, considering the temporal patterns. The storage battery is introduced to rebalance the supply and demand sides. Through its control, the surplus of balance between renewable energy and demand is stored by the battery without supplying from grid power. Meanwhile, the grid power is only supplied when the total green energy supply is less than the demand. The minimum carbon dioxide (CO_2) emission is defined as the objective function. The constraints are considered as including the battery capacity, charging and discharging balance, hourly and annual supply potential for each type of energy, and hourly supply should meet the demand. As our solution, 99.9% of onshore wind power, 56.8% of offshore wind power, 69.8% of solar power, and 45.4% of biomass power were essential in a year to meet each hourly demand and achieve the minimum CO_2 emissions.

Keywords. Decarbonization, energy balance analysis, green energy management system, optimization problem, sustainable development

1. Introduction

Global warming problems caused by greenhouse gas (GHG) emissions have become more and more serious in recent years, which forced humans to take action towards emission adaptation and mitigation. Most global nations including Japan issued their zero-GHG emissions goal by the middle of the 21st century, declared as the Convention, the Conference of the Parties in 2021 (COP26) [1-3]. To support the achievement of the zero-GHG emissions goal by 2050, Japanese municipalities including 46 prefectures, 531 cities, 21 special wards, 290 towns, and 46 villages (covering 125.77million citizens) have declared their action plans by 31st March 2023 [4]. Therefore, energy saving and lower carbon emission style developments will be more highlighted in future society.

In Japan, the fossil fuel-based power supply accounted for 72.8% of the total in 2021

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[5]. There has been considered a large potential for emission mitigation from the energy supply system (ESS) due to the fact that its environmental performance would determine the generation of process-based emissions and emission intensity by the final consumers. With the development of renewable energy (green energy) generation and storage (rebalance function) technologies, there is an opportunity for the optimization of the ESS, contributing to a lower-carbon society. However, the effect of optimization especially to the decarbonization is still not clear.

To support regional decarbonization, this study focuses on designing an optimal energy supply system in which renewable energy (onshore, offshore wind power, solar power, and biomass power) are made as prioritized sources to meet the temporal energy demand. The optimization algorithm is developed to detect the optimal supply amount for each energy source at an hourly level and evaluate the carbon dioxide (CO_2) emissions for the whole system. It is demonstrated in the city of Kitakyushu Japan.

2. Optimization on Energy Balance Model

2.1. Workflow

The workflow of this study is shown in Figure 1. At first, the energy demand (grid power consumption) and supply by renewable energy were estimated at an annual level. Then, the annual values were downscaled to hourly ones so as to discuss the energy balance at an hourly level. The storage battery was introduced here to rebalance the supply and demand sides. Due to our research purposes, two different objective functions were designed and the relevant constraints including the control pattern of the battery were prepared. The optimal algorithm was developed based on a linear programming approach by using Python. Based on the optimal solutions of hourly values (supply, charge, and discharge), we finally made system evaluations and applications.

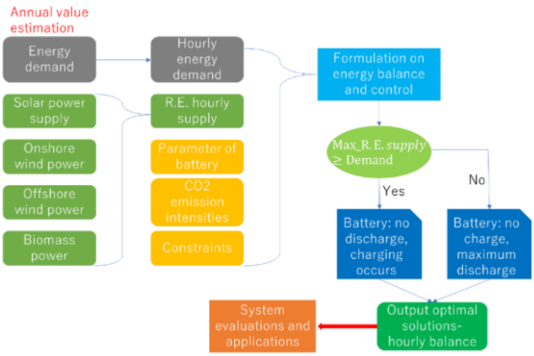

Figure 1. Work flow on optimization of green energy management system.

2.2. Data Preparation

2.2.1. Energy Demand

The energy demands from residential and commercial sectors are obtained from a previous study [6]. The annual demands from these sectors are derived from the past energy consumption intensity and activity data as follows:

Residential:

ED_R = annual energy consumption per household × total household number

Commercial:

ED_C = annual energy consumption per area × total floor area

2.2.2. Energy Supply

Here, the energy supply includes grid power, discharged power from storage battery, and renewable energy, i.e., solar power, onshore, offshore wind power, and biomass power. The annual supplies of solar power and wind power in Kitakyushu were obtained from the database reported by the Ministry of the Environment Government of Japan (MOE) [7]. The summarized annual energy supply and demand are shown in Table 1. The annual supply of biomass power was calculated by a technical guideline [8] as follows:

ES_B = annual growth volume of trees × rate of trees for biomass power use × energy density × power generation efficiency

Table 1. Summarization on the estimation results of annual energy demand and supply.

Item		**Annual potential-PJ year-1**
Energy supply	Onshore wind power	0.67
	Offshore wind power	20.9
	Solar power	14.5
	Biomass power	1.8
Energy demand	Residential	12.8
	Commercial	16.9

2.2.3. Downscale Processing

As we focused on analyzing the hourly energy balance, the estimated annual demand and supply were then downscaled to hourly values (Table 2) based on the relevant indexes [7, 9, 10]. The annual values were first disaggregated into daily values and then hourly ones. See the summarized examples of the downscaled energy demand from two sectors in Figure 2. We could find that there are significantly different monthly trends of energy demands between residential and commercial sectors.

Table 2. Relevant indexes used to downscale the annual energy demand and supply values.

Item		**Daily variation index**	**Hourly variation index**
Energy supply	Onshore wind power	Daily values of wind velocity from the renewable energy potential database by MOE [7]	Hourly values of wind velocity from the renewable energy potential database by MOE [7]
	Offshore wind power		
	Solar power	Daily values from the solar radiation database by NEDO [9]	Hourly values from the solar radiation database by NEDO [9]
	Biomass power	No variation	No variation
Energy demand	Residential	Daily values from the District Heating and Cooling Technical Manual [10]	Hourly values from the District Heating and Cooling Technical Manual [10]
	Commercial		

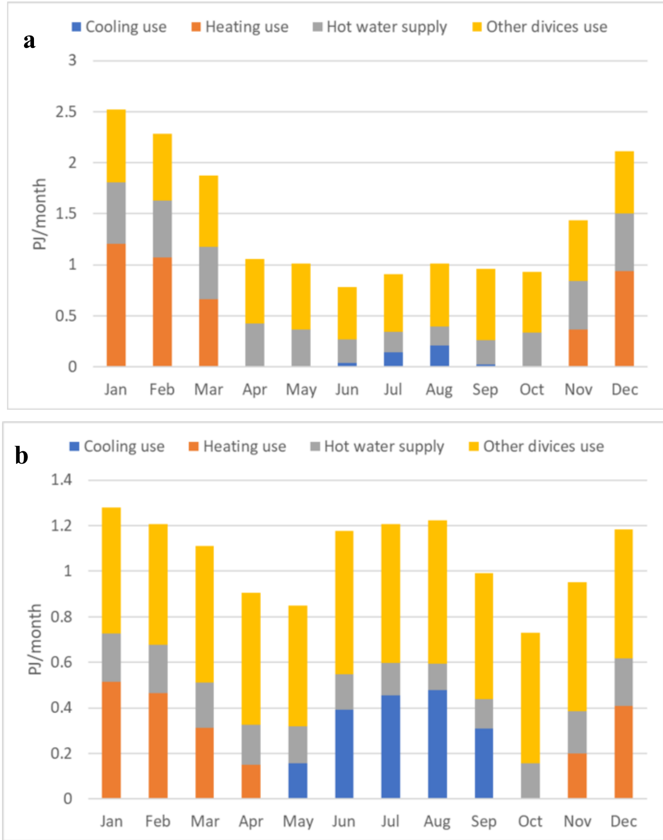

Figure 2. Monthly trend of energy demand by categories from two kinds of sectors. (a) Residential sector; (b) Commercial sector. (unit: PJ month^{-1}).

2.2.4. The Introduction of Storage Battery

With the development of energy storage technology, the storage battery is highlighted in energy management systems due to it could ensure the maximum utilization of renewable energy. The lithium-ion battery was introduced to the current energy system due to its higher energy efficiency [11]. The storage battery is used to store surplus renewable energy when it is applicable. The technical parameters used to estimate intensities of it are listed in Table 3.

Table 3. Technical parameters used to estimate the CO_2 emission for Lithium-ion battery [11].

Sources	Value for emission intensity estimation	Unit
Capacity	44	kWh
Energy efficiency	85	%
Lifespan	10	years
Conversion factor	3.6	MJ/kwh
Intensity_CO_2	188	gCO_2/kWh

2.2.5. The Estimation of Emission Intensity

In this study, the emission intensities used for all energy sources were derived from their total energy supply and environmental performances in the whole life cycle i.e., material extraction, transportation, assembly & manufacture, and operation processes. The estimations on emission intensities for all energy sources are as follows:

Intensity_CO_2 = (CO_2_material extraction + CO_2_transportation + CO_2_ assembly & manufacture + CO_2_ operation in lifespan)/power generation in lifespan

The estimated and collected intensities are listed in Table 4. Except for the intensity values of storage battery, the emission intensities of other energy sources are obtained from a technical report [12], academic paper [13], and reported value by the power company.

Table 4. CO_2 emission intensity by energy sources (tCO_2 PJ^{-1}).

Sources	**Emission intensity-t$CO_2$$PJ^{-1}$**
Onshore wind power	7000
Offshore wind power	28,000
Solar power	16,000
Biomass power	37,328
Grid power	126,111
Storge battery	52,226

2.3. Optimization Problems Design

To solve the optimization problem [14], an objective function was designed as minimizing the total emissions. The optimal solutions for hourly supply and charging & discharging in a year are detected by a linear programming algorithm. The storage battery is used to store surplus renewable energy when it is applicable. Through its control, the surplus of balance between renewable energy supply and demand (when total supply is more than demand) is stored by the battery without supplying from grid power. Meanwhile, the grid power is only supplied when the total green energy supply is less than the demand. The objective function and constraints by relevant factors were defined as follows:

$$\text{Minimum } CO_2 \text{ emissions} = Min \sum_{i,t}\left(RE\_S_{i,t} \times ef_i + BT\_DCH_t \times ef_i\right) \quad (1)$$

subject to

$$\sum_t\left(RE\_S_{i,t} + BT\_DCH_t + G\_S_t\right) = \sum_t(D_t + BT\_CH_t) \quad (2)$$

$$RE\_S_{i,t} \leq S_{i,t} \quad (3)$$

$$BT\_DCH_t \leq BT\_CH_t \leq C\_BT \quad (4)$$

where equation (1) is the objective function (minimum total emissions). i is the types of energy sources, t is the hourly time in a year, $RE\_S_{i,t}$ is the hourly supply of renewable energy by types, ef_i is the emission intensities by types, BT_DCH_t is the hourly discharge by battery, G_S_t is the hourly supply of grid power, D_t is the hourly demand, BT_CH_t is the hourly charge by battery, $S_{i,t}$ is the hourly supply potential of energy by types, C_BT is the capacity of the battery. Equation (2) expresses the constraint that the energy balance should be met at each hour. Equation (3) expresses the constraint that hourly renewable energy supply should not exceed its potential. Equation (4) shows the constraint that hourly charge and discharge should not exceed the capacity of the battery.

3. Results and Discussion

As mentioned above, the objective function was solved by using Python. Based on the optimal solutions, we evaluated the environmental performances for all sources as listed in Table 5.

Table 5. Environmental performances for all energy sources in optimal results.

	Sources	For minimum CO_2 emission
Energy supply-PJ year^{-1}	Onshore wind power	0.67
	Offshore wind power	11.59
	Solar power	10.11
	Biomass power	0.82
	Grid power	6.74
	Storge battery	0.42
Renewable energy supply total-PJ year^{-1}		23.18
Energy supply total (equals to total demand)-PJ year^{-1}		29.92
Annual CO_2- ktCO_2 year^{-1}		1393.31

Compared with the supply potential of renewable energy sources (Table 1), most of the onshore wind power was supplied to achieve the optimal objectives of the system, due to its least intensities (see Table 4). In contrast, other renewable energy sources were partially supplied in the optimal results due to their larger intensities. Meanwhile, the determined individual hourly demands also resulted in the needed supply of other renewable energy sources is less than their supply potential. The supply by the storage battery accounted for only 1.1% of all renewable energy potential (37.8 PJ yr^{-1}) due to its significantly larger intensities than renewable energy. The battery started its charge and discharge functions together with the supply of grid power where the gap of balance occurred between all renewable energy supply and demand (when total supply is less than demand).

The optimal results before and after the introduction of the storage battery are shown in Figure 3. Before the introduction of storage battery, the needed supply of renewable energy accounted for 76.2% and grid power accounted for 23.8% of the demand to achieve the minimum annual emissions (1408.44 ktCO_2). After the introduction of storage battery, the needed supply of renewable energy increased to 77.5% and grid power decreased to 22.5% of the demand. These changes in the energy supply were caused by the usage of the battery (discharge) which also made the whole system with a lower total emission (1393.31 ktCO_2). It implies that the introduction of battery could ensure more utilization of renewable energy in the optimization so as to use less grid power, contributing to a greener energy management system.

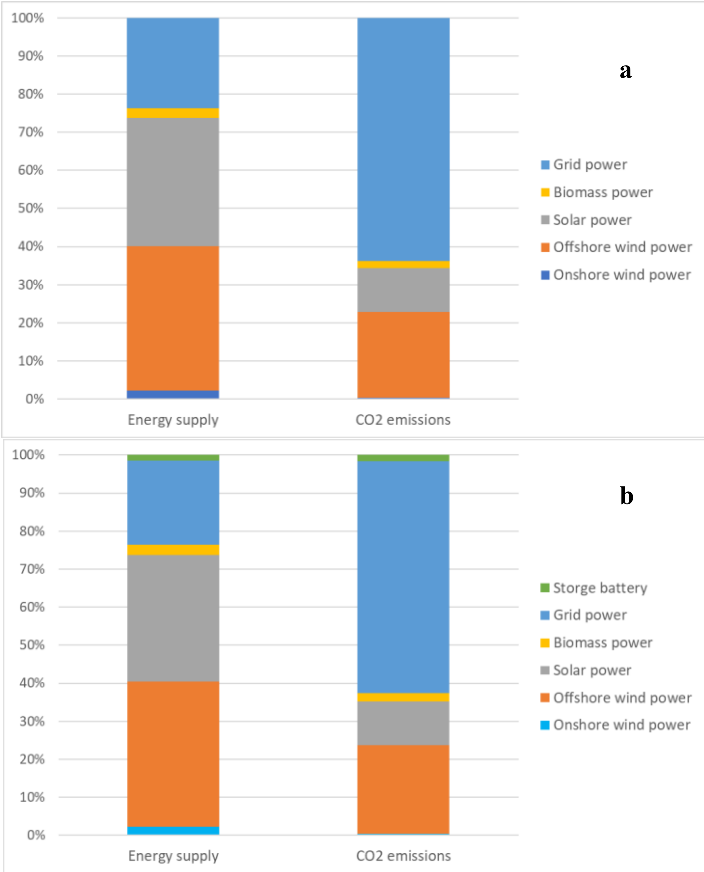

Figure 3. Optimized results on detailed composition (percentage) of energy supply and CO_2 emissions. (a) Before the introduction of storage battery; (b) After the introduction of storage battery.

4. Conclusions

In this study, an optimization algorithm was developed and applied in the ESS of Kitakyushu City, Japan to support regional decarbonization. A framework including renewable energy supply estimation, downscaling of energy supply and demand, estimation of emission intensities, optimization problem design, and solutions was provided in detail. As our solution, 99.9% of onshore wind power, 56.8% of offshore wind power, 69.8% of solar power, and 45.4% of biomass power were essential in a year to meet each hourly demand and achieve the minimum CO_2 emissions. The supply by the storage battery accounted for only 1.1% of all renewable energy potential (37.8 PJ yr^{-1}). We found that decreasing the emission intensity of battery could increase the share of renewable energy during the ESS optimization.

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22.5% of the demand. These changes in the energy supply were caused by the usage of the battery (discharge) which also made the whole system with a lower total emission (1393.31 ktCO_2). It implies that the introduction of battery could ensure more utilization of renewable energy in the optimization so as to use less grid power and gave less total CO_2 emissions, contributing to a greener energy management system. Future works will be done to improve the accuracy of the relevant data and model, discuss complex scenarios, and explore more objectives from other aspects e.g., cost.

Acknowledgment

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