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Multi-objective optimization of a multiregional electricity system in an archipelagic state: The role of renewable energy in energy system sustainability

Yoga Wienda Pratama[a], Widodo Wahyu Purwanto[a,*], Tetsuo Tezuka[b], Benjamin Craig McLellan[b], Djoni Hartono[c], Akhmad Hidayatno[d], Yunus Daud[e]

[a] Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia
[b] Department of Socio-Environmental Energy Science, Graduate School of Energy Science, Kyoto University, Kyoto 606-8501, Japan
[c] Department of Economics, Faculty of Economics and Business, Universitas Indonesia, Depok 16424, Indonesia
[d] Department of Industrial Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia
[e] Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Indonesia, Depok 16424, Indonesia

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ABSTRACT

Indonesia, the world's largest archipelagic state, has sizeable fossil and substantial renewable energy resources; however, high disparity in population density, infrastructure, economic level, and distance between energy sources and consumers inflict a discrepancy in electricity system performance among regions. In the present study, a multi-objective optimization model was developed to support decision makers in selecting the most sustainable scenario for Indonesian power generation planning through 2050. To capture regional characteristics more accurately, the model was developed with a multiregional approach by dividing Indonesia into six regions, and a single-regional approach is set as a reference for comparison. Five development scenarios based on economic–environmental trade-off were proposed, and four policy options were incorporated to evaluate the scenario preferences within various priority sets. Generation mixes obtained from the optimization model were input into a sustainability assessment model consisting of eleven indicators, representing three sustainability aspects: economic, social, and environmental. The results show that for most policy options, the most sustainable electricity system can be achieved by the highest orientation on environmental protection, which results in significant advantages regarding most indicators of sustainability; however, this scenario shows high economic disadvantages relative to the social and environmental benefits. The results indicate that optimization with a multiregional approach can capture regional characteristics of an archipelagic state better than that of a single-regional approach, thereby providing more realistic scenarios for the archipelagic state.

1. Introduction

Energy has an enormous impact on economic, environmental, and social development, and the provision of adequate, affordable, and reliable energy services in a sustainable manner is becoming the primary challenge facing sustainable energy policy. In the future, this issue will become even more important because energy demand is predicted to continue growing at a high rate, sometimes even higher than economic growth [1], as is often the case in developing countries.

Indonesia abounds with energy resources, but the complexity of its geography as an archipelagic country, coupled with the lack of electrical infrastructure and investment, creates challenges with regard to its electricity development. For the five years from 2008 to 2013, Indonesia's electricity demand increased rapidly at an annual average rate of approximately 7.8% [2,3]. Indonesia's current electrical capacity of 50.6 GW is mainly supplied by fossil fuels—coal (51.6%), gas (23.6%), oil (12.5%) and renewable hydro and geothermal energy of 7.9% and 4.4%, respectively. Currently, the average grid emission factor is 0.867 kg CO_2/kWh, which will continue to increase through 2018 owing to the addition of primarily coal-based power generation and the delay of geothermal electricity projects. The domination of coal is anticipated to continue based on the electricity development plan owing to its low cost of generation [4–6]. Indonesia's electricity demand is unevenly spread across the archipelago; the islands of

* Corresponding author.
E-mail addresses: yoga.wienda@che.ui.ac.id (Y.W. Pratama), widodo@che.ui.ac.id (W.W. Purwanto), tezuka@energy.kyoto-u.ac.jp (T. Tezuka), b-mclellan@energy.kyoto-u.ac.jp (B.C. McLellan), djoni.hartono@gmail.com (D. Hartono), akhmad@eng.ui.ac.id (A. Hidayatno), ydaud@sci.ui.ac.id (Y. Daud).

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Nomenclature

f1	objective function 1, min costs of generation ($)
f2	objective function 2, min CO_2 emissions (Mt)
w1	weighting factor of *f1*
w2	weighting factor of *f2*
C	capital expenditure ($/MW)
O	operating and maintenance cost ($/MW.year for fixed, $/MW h for variable)
F	fuel cost ($/MW h)
G	electricity generated (MW h)
R	discount rate (%)
CE	levelized cost of electricity ($/MW h)
CF	capacity factor (%)
ε	heat rate ($MW h_e/MW h_t$)
EF	emission factor (ton/MW h)
D	electricity demand (MW h)
L	losses by transmission and distribution (%)
Fs	fuel supply (MW h/year)
P	capacity (MW)
Imp	imported fossil fuel (MW h/year)
CRF	cost recovery factor

Subscripts/superscripts

i	index of technology type
t	index of time horizon
z	index of region
I	number of technology candidate
T	number of considered time horizon
Z	number of region
ext	index of existing power plant
new	index of new power plant
RE	index of renewable energy

Java, Madura and Bali account for approximately 71% of Indonesia's total electricity demand, and the other islands combine for only 29%. In addition to the Java–Madura–Bali (Jamali) transmission system, other transmission systems are found on the main islands: Sumatra, Kalimantan, and Sulawesi. The remaining generating capacity is spread across 600 isolated systems. At the country level, the electrification ratio reached 81.4% in 2014 with average annual electricity consumption of 746 kWh per capita; however, this ratio is still below the average of other countries in the Southeast Asian Nations (ASEAN). There is a disparity of annual electricity consumption among different regions: approximately 200 kWh/cap in Maluku, Nusa Tenggara and Papua, approximately 400 kWh/cap in Sumatra and Kalimantan, and approximately 1000 kWh/cap in Jamali. According to the national electricity development plan [4,5], over the next ten years, Indonesia's electricity demand is expected to grow significantly at an average rate of 8.7%; at the same time, the country is pushing to improve electricity access rates from 81.4% of the population in 2014 to close to 100% in 2020. This corresponds to an addition of 50 MW from the current capacity by 2020.

In an archipelagic country, such as Indonesia, there are many barriers to the development of the electricity system, particularly in the eastern region. The key obstacles are a mismatch among the primary energy sources, electricity demand distribution, and power generation infrastructure across different regions in Indonesia [4,7]. This situation has led to the limited development of power generation in this area, with the use of small-scale distributed power generation and the usual risk of higher-cost electricity generation. The Jamali system has relatively good infrastructure and high electricity demand but limited fossil energy resources. An interchange of energy resources among islands is still possible for fossil sources but not for renewable sources because renewable energy is locally-bound and typically untradeable unless in the form of an energy carrier in a well-connected grid. This situation indicates the necessity of a holistic approach that supports long-term electricity generation planning for this complex geography. Analysis of the complex system requires optimization tools considering the different regional characteristics to improve electricity access and increase the renewable energy-based generation portfolio.

Optimization studies for electricity generation planning have been conducted to minimize the cost of electricity generation [8,9]. Moura and Almeida minimized the cost of generation and maximized the contribution of renewable energy to a system's technical performance [10]. Scenarios of renewable energy penetration have been assessed by Poulikas, et al. [11] to optimize electricity tariffs, CO_2 emissions, and system failures. Goal-based modeling studies to obtain optimal generation mix and power plant location have been performed by Cristóbal [12] and Chang [13]. Cong [14] conducted a study to optimize maximum renewable energy and its impact on the energy system by considering renewable energy technology diffusion. Economic and environmental analysis for power generation planning in Japan [15] and specifically for the Tokyo area [16] after the Fukushima nuclear accident were studied via multi-objective optimization, by developing four nuclear expansion scenarios. A multi-objective optimization model for Indonesia's electricity system to analyze economic, environmental, and energy availability issues has also been developed [17]. Multi-regional optimizations of electricity systems generation have been conducted for areas with interconnected grids [18–26]. Research about electricity generation planning also varies in scale, from district [27] up to global levels [28]. Electricity system performance and technology are commonly evaluated using sustainability indicators. The sustainability of power generation technology has been assessed [29,30], and various sustainability concepts and indicators have been introduced for the assessment of developing [31–39] and developed countries [40] as well as for the globe [41–45]. The relevant studies in multiregional energy systems modeling and sustainability assessment are summarized in Table 1. To our knowledge, the concept of a generation planning scenario based on multi-objective, multiregional optimization integrated with sustainability assessment for an archipelagic state is novel.

The aims of this work are to develop a multi-objective optimization and sustainability assessment of a multiregional electricity system to provide decision support for the selection of the most sustainable scenario, to assess the impact of renewable energy on the sustainability

Table 1
Relevant studies on energy modeling and sustainability assessment.

No.	Remarks	Articles
1.	Least cost optimization	[9]
2.	Least cost optimization with clean and renewable energy share and/or CO_2 emissions reduction target	[8,10,11,14,27]
3.	Multi-objective optimization: cost and CO_2 emissions minimization, location selection	[12,13,15–17]
4.	Multiregional optimization with energy/electricity trading among regions	[18–26]
5.	Multiregional optimization for global electricity supply with CO_2 emissions reduction	[28]
6.	Optimization with multiple time scales: considering operational pattern of technology generation and renewable energy intermittency	[10,16,21,22,26]
7.	Sustainability assessment in developing countries	[31,33,34,36–39]
8.	Sustainability assessment in developed countries	[40]
9.	Sustainability assessment of energy technology	[29,30]
10.	Sustainability assessment of energy system of multiple countries	[39,41]
11.	Guidelines and reviews for assessing energy systems sustainability	[42–45]