International Journal of Sustainable Energy Planning and Management Vol. 31 2021 189–210

International Journal of
Sustainable Energy Planning and Management

Multi-objective analysis of sustainable generation expansion planning based on renewable energy potential: A case study of Bali Province of Indonesia

Rahmat Adiprasetya Al Hasibi*

Department of Electrical Engineering, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya, Kasihan, Bantul 55183, Indonesia

ABSTRACT

This article analyzes the role of renewable energy in producing sustainable generation expansion planning. The generation expansion planning is carried out using an optimization model which has two objective functions, namely the objective function of planning costs and the objective function of emissions. Multi-objective analysis was performed using the epsilon constraint method to produce the Pareto set. Solution points are selected from the Pareto set generated using the fuzzy decision making method. The process of determining the best solution points is based on three scenarios. Furthermore, calculations were carried out to obtain 7 indicators of sustainability covering economic, social, and environmental aspects. The sustainability index is calculated based on several predetermined policy options. The model is implemented using data obtained from the electricity system in Bali Province, Indonesia. From the analysis, the planning scenario by implementing renewable energy sources in the generation of electrical energy, namely scenario 3, results in an increase in the sustainability index with the highest value during the planning period. However, scenario 3 produces two sustainability indices from the economic aspect, namely the unit cost of generation and shared electricity cost to GDP, which is the lowest when compared to other scenarios.

Keywords

Generation expansion planning;
Multi objective;
Renewable energy;
Sustainability;
Global warming potential;

http://doi.org/10.5278/ijsepm.6474

1. Introduction

The demand for electrical energy continues to increase in line with the increase in population and economic activity. Fulfilling the demand for electrical energy at a good quality level of reliability at a minimum cost is a challenge for electrical energy supply companies. On the other hand, the issue of greenhouse gas (GHG) emissions as an impact on the environment resulting from the process of generating electrical energy using fossil fuels is getting more attention. The issue of the impact on the environment poses additional challenges for companies providing electrical energy. This problem must be solved simultaneously by the electricity supply company. The use of renewable energy sources can be optimized to obtain a balanced generation expansion planning (GEP) between the planning costs and the GHG generated.

In 2020, the total population in Indonesia is estimated to reach 271 million people, experiencing a growth of 6.11% from the total population in 2015 [1]. In 2017, Indonesia's Gross Domestic Product (GDP) at constant prices in 2010 reached 666.38 billion USD, which grew by 5.23% of the value of GDP in 2016 [2]. In 2017, the demand for electric energy in Indonesia was 226.01TWh with an average growth between 2012-2017 of 7.37% per year. The biggest demand for electrical energy is found in the Java-Madura-Bali (JAMALI) electricity system with a demand for electrical energy of 167.96TWh in 2017. The demand for electrical energy in the

*Corresponding author - e-mail: r.a.alhasibi@umy.ac.id

JAMALI system is 74.31% of all electrical energy demand in Indonesia [3]. n 2018, the installed power generation capacity in Indonesia was 57.82GW with a fossil fuel power plant of 89.99%. Renewable energy sources in the form of hydropower, solar radiation, wind power, and biomass only played a role of 10.01% [4].

Bali Province has a population in 2020 which is estimated to reach 4.38 million people, which is experiencing a growth of 5.49% when compared to the population in 2015 [1]. From the perspective of Gross Regional Domestic Product (GRDP), Bali Province generated a GRDP of 9.66 billion USD in 2017 or a growth of 5.57% when compared to GRDP in 2016. Population growth and GRDP affect the growth in demand for electrical energy. The electricity system in Bali Province is part of the Java-Madura-Bali (JAMALI) interconnection electricity system. Some of the electricity demand in Bali Province is generated by power plants located outside Bali Province. In 2017, the electricity sold in Bali Province was 5.07TWh or 3.02% of the electricity sold in the JAMALI electricity system.

When compared with the demand for electrical energy in 2016, the demand for electrical energy in 2017 experienced a growth of 10.35% [5]. As one of the provinces with several renewable energy sources, providing electricity through an adequate, affordable, and reliable system in a sustainable manner is a challenge that must be overcome. In addition, the supply of electricity is currently very dependent on the supply of primary energy from outside the Province. Thus, the security aspect of energy supply is one of the factors that must be considered in producing a sustainable GEP.

GEP is performed using optimization calculations to minimize investment costs and operating costs in both the dynamic model [6, 7] and the stochastic model [8]. The optimal planning costs can also be affected by the integration of renewable energy sources into the GEP model. An optimization model is applied to analyze the advantages and disadvantages of several renewable energy integration mechanisms to achieve a zero-carbon power system [9]. By comparing the four mechanisms, the results of this study state that geographic aggregation is the most optimal mechanism.

Integration of the (renewable energy sources) RES into the power system planning is one of the supporting factors to produce sustainable planning. The integration of renewable energy has been applied in a dynamic optimization model for multi-regions [10]. This publication presents an analysis of the integration of variable RES on a large scale. The optimization model in the form of Mixed Integer Linear Programming (MILP) has been used to determine the optimal power system planning with the RES integration scheme and the CO_2 emission reduction targets with a case study in Malaysia [11].

Meanwhile, the RES transition policy and nuclear energy in the GEP model have been published with a case study in Korea [12]. The integration of RES with various types of technology into the GEP model has been implemented into an optimization model that is solved by classical methods [13] and using genetic algorithmic methods [14]. In particular, the integration of the hydropower source into the GEP model has been analyzed using the MILP model [15]. RES integration can be enhanced with policy support through incentive schemes for electric energy providers that use renewable energy [16]. In addition, techno-economy analysis should be carried out in the integration of RES into GEP [17].

The aspects of sustainability that are important to consider in the GEP model are the security of electricity supply, the impact on climate change, and social aspects. By using Long-range Energy Alternative Planning (LEAP) software, sustainability aspects in the form of CO_2 emission reduction have been analyzed for case studies in Indonesia and Thailand [18]. The results of this publication indicate that CO_2 emission reductions can be achieved by 81% and 88% in Indonesia and Thailand, respectively, through the RES integration scenario. Using the same software, the impact on the environment of future electric energy generation is analyzed with a case study in Iraq [19]. By using EnergyPlan, power generation capacity planning has been carried out by taking into account the impact on the environment and the security of energy supply [20] with a high penetration of renewable energy [21].

A GEP model has been developed by considering environmental, social, and economic aspects as a dimension of sustainability where the environmental aspects that are concerned are water pollution, land use, emission costs, radioactive impacts [22]. This model has shown that a country with large fossil energy reserves will inhibit the commercialization of RES unless the country implements an incentive policy towards RES development. The use of carbon capture and storage (CCS) technology has been analyzed in the GEP model to reduce CO_2 emissions by taking into account uncertainty variables [23]. A model and algorithm to solve optimization problems in power plant planning have been developed based on the aspects of sustainability [24]. The model that has been developed uses a life-cycle assessment to analyze the impact on the environment.

Policies in the GEP are determined by several important factors such as renewable energy targets, mitigation of climate change, and security of energy supplies. To accommodate all these parameters, the GEP model was completed in a multi-objective form. For energy systems in general, the application of a multi-objective algorithm has been used with objective functions in the form of planning costs and CO2 emissions in energy planning [25]. A GEP model with multi-objective optimization has been published with a case study of the Brazilian power system [26]. The model in the publication considers three objective functions, namely minimizing total planning costs, maximizing the non-hydro RES contribution, and maximizing the generation of electrical energy during peak loads. By using the GEP optimization model which has two objective functions, the wind power and solar panel penetration rates are evaluated for an isolated system [27]. Apart from these two renewable energy sources, the model in this publication uses a diesel generator and a battery storage system.

The intermittence nature of RES has also been included in the analysis of the multi-objective GEP model [28]. In this publication, the objective functions used are minimizing total planning costs and maximizing the contribution of RES to the peak load during winter and summer. A multi-objective GEP model has also been used to increase the return on investment against RES in electric power systems [29]. The objective function used in this publication is to maximize profit by paying attention to RES generation curtailment. The reliability of the electric power system is one of the objective functions that have been analyzed along with cost-optimization with respect to the RES target [30].

An analytical procedure to complete the optimization with multiple objectives has been proposed to solve a mixed integer linear programming (MILP) model [31]. Integration of multi-objective analysis with Energy Plan software has been used to produce a Pareto Optimal that illustrates the relationship between planning costs and carbon emissions [32], energy efficiency in building [33], long-term energy planning with an hourly step [21], and energy planning at the regional level with several electric vehicle penetration scenarios [20]. The integration of electric vehicles in energy planning has been analyzed through a multi-objective approach with a high level of resolution [25]. However, these publications have not systematically included the sustainability aspect in the multi-objective analysis. Thus, the contribution made through this research is

1. the integration of sustainability analysis in power generation capacity planning through a multi-objective approach.
2. In addition, the GEP model and analytical procedures developed in this article focus on the optimization of locally available energy sources.

This article aims to develop a GEP model to support decision-making for power system planning by taking into account the aspects of sustainability by optimizing available renewable energy sources. The analysis carried out is a multi-objective analysis so that it can provide flexibility for decision makers to determine policies in planning power generation capacity. Furthermore, the model is applied using data on the electricity system of a province, namely Bali Province in Indonesia. The Province of Bali is used as a case study in this publication because the need for electrical energy in this province is met through power plants with primary energy sources imported from outside the province. On the other hand, renewable energy sources exist in this province and can be developed in the provision of electrical energy.

The following sections of this article are organized as follows. Section 2 describes the methods used in this study. The GEP model, the algorithms used, and the sustainability parameters are described in detail in the sections. Furthermore, section 3 describes the data and data sources used. The results analysis and discussion are presented in section 4. Conclusions and further research are presented in section 5.

2. Research Method

The research flow diagram is shown in Figure 1. Multi objective analysis is carried out to minimize the objective function of electricity generation costs and the objective function of emissions. The results obtained from the multi objective analysis are used as input for the sustainability analysis. Furthermore, the results of the sustainability analysis are used to have the best scenario to be applied in the development of power generation capacity.

2.1. Generation expansion planning model

2.1.1. Objective functions

The GEP model in this study is an optimization model with two objective functions, the first is the cost

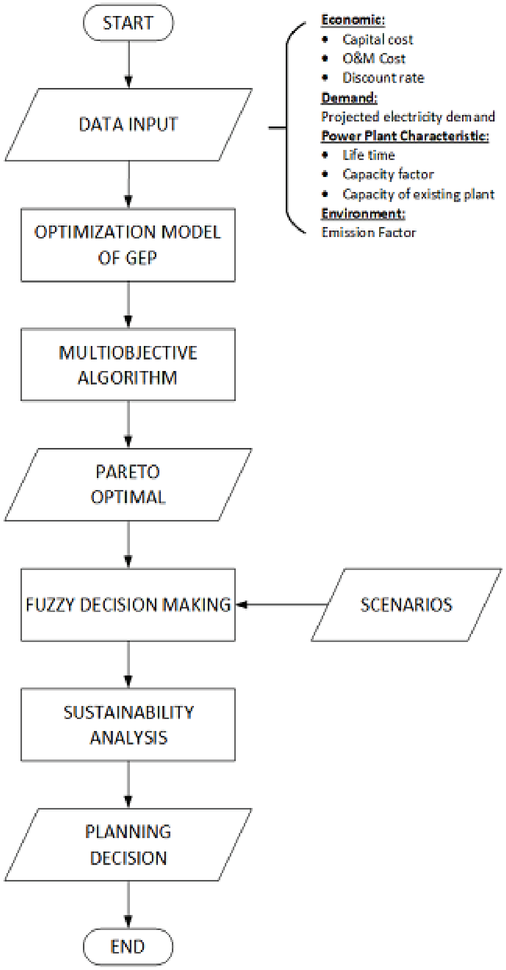

Figure 1. The research flowchart

objective function and the second is the objective function of emissions. The objective planning cost function (Z_{cost}) can be expressed as investment costs and O&M costs, expressed as

$$Z_{cost} = \sum_{t=1}^{T}\sum_{g=1}^{G}(1+r)^{-t}(E_{g,t}^{NG} \times LCOE_{g,t}^{new} + E_{g,t}^{EG} \times LCOE_{g,t}^{ext}) \quad (1)$$

where $E_{g,t}^{NG}$ and $E_{g,t}^{EG}$ respectively represent electrical energy generated by new and installed power generation units (in MWh), $LCOE_{g,t}^{new}$ and $LCOE_{g,t}^{ext}$ respectively are levelized cost of energy (LCOE) for new and installed power generation units (in \$/MWh), and r is the discount rate (in%). LCOE for new power plants is expressed as

$$LCOE_{g,t}^{new} = \left(\frac{(C_{gt}^{new} \times CRF_g)O_{gt}^{Fix}}{8760 \times CF_{gt}}\right) + O_{gt}^{Var} \quad (2)$$

and LCOE for installed power plants is expressed as

$$LCOE_{g,t}^{new} = \left(\frac{O_{gt}^{Fix}}{8760 \times CF_{gt}}\right) + O_{gt}^{Var} \quad (3)$$

where C_{gt}^{new} is the investment cost for a new power plant (in \$/MW O_{gt}^{Fix} is a fixed operating cost (in \$/MW), O_{gt}^{Var} is a variable operating cost (in \$/MWh), and CF_{gt} is the capacity factor for each type of generating technology electricity. CRF_g is the capital recovery factor (CRF) (in%) which is used to annualize the investment cost of a new power generation unit. A constant of 8760 is the number of hours in a year. CRF is expressed as

$$CRF_g = \frac{r \times (1+r)^n}{(1+r)^n - 1} \quad (4)$$

where n is the number of annuities represented by the technology lifetime of the power generating unit. The index t is the index for the planning year and the index g is the index for power generation technology.

Emissions in the form of global warming potential (GWP) generated from each generating unit technology are directly proportional to the electrical energy generated from a generating unit. Thus, the emission objective function used in the GEP model is expressed as

$$Z_{emission} = \sum_{t=1}^{T}\sum_{g=1}^{G}\sum_{e=1}^{E}\left(EF_{g,e} \times \left(E_{g,t}^{NG} + E_{g,t}^{EG}\right)\right) \quad (5)$$

where $EF_{g,e}$ is the emission factor for the types of pollutants e produced by each generating unit technology g (in Ton CO_2 Equivalent). Emission factors and conversion of emission factors to Ton CO_2 Equivalent units will be presented in the Data and Data Sources section.

2.1.2. Constraints functions

Overall, the electrical energy generated by all generating units must be able to meet the projected demand for electrical energy after deducting losses in the transmission and distribution network. Fulfilling the demand for electrical energy is one of the constraint functions in the GEP model which is expressed as

$$\sum_{g=1}^{G}\left(E_{g,t}^{NG} + E_{g,t}^{EG}\right) \geq E_t^D \times (1 + L^{TD}), \forall (t \in T) \quad (6)$$

where E_t^D is the demand for electrical energy in each planning year (in MWh) and L^{TD} is the losses in the transmission and distribution network (in%).

The electrical energy generated by each generating unit must not exceed the available capacity and must exceed the minimum load allowed by each generating unit technology. Thus, the generation of electrical energy by the installed generating unit can be expressed as

$$8760 \times \underline{P}_g^L \times P_{g,t}^{EG} \leq E_{g,t}^{EG} \leq 8760 \times CF_{g,t} \times P_{g,t}^{EG}, \forall(t \in T) \quad (7)$$

where $\underline{P}_g^L$ is the minimum allowable load power (in MW) and $P_{g,t}^{EG}$ is the installed power generation power for each technology g in year t (in MW). As for new generating units, the generation of electrical energy is expressed as

$$8760 \times \underline{P}_g^L \sum_{t'|t' \leq t, t-t' < LT_g}^{T} P_{g,t'}^{NG} \leq E_{g,t}^{EG} \leq 8760 \times CF_{g,t} \times \sum_{t'|t' \leq t, t-t' < LT_g}^{T} P_{g,t'}^{NG}, \forall\left(t \in T\right) \quad (8)$$

where $P_{g,t'}^{NG}$ is the new generating capacity (in MW) and LT_g is the lifetime parameter for each technology of generating unit g (in years).

In equation (8), the new power generation capacity for each technology g and in each year t, $P_{g,t}^{NG}$, is determined by

$$P_{g,t}^{NG} = N_g \times P_{g,t}^{Option}, \forall(g \in G), \forall(t \in T) \quad (9)$$

where N_g is the number of new generating units and $P_{g,t}^{Option}$ is the increase in the available capacity for each generating technology g (in MW). Equation (9) s used to determine in an integer manner the additional capacity of the new power generation unit.

For new power plants with renewable energy sources, the capacity that can be developed is limited by the availability of these renewable energy sources. Thus, the power generation capacity with renewable energy sources cannot exceed the potential energy sources which is stated in the constraint function as

$$\sum\nolimits_{t'|t' \leq t, t-t' < LT_g}^{T} P_{re,t'}^{NG} \leq RE_{re}^{Limit}, \forall(t \in T), \forall(re \in G) \quad (10)$$

where RE_{re}^{Limit} is the potential source of renewable energy available (in MW) and re is an index for generation technology with renewable energy sources.

As a reference, the GEP optimization model can be summarized as

$$\min_{\Delta} Z_{cost} = \sum_{t=1}^{T}\sum_{g=1}^{G}(1+r)^{-t}\left(E_{g,t}^{NG} \times LCOE_{g,t}^{new} + E_{g,t}^{EG} \times LCOE_{g,t}^{ext}\right)$$

subject to

$$\text{Equations (6)–(10)}$$

where $\Delta = \{E_{g,t}^{NG}, E_{g,t}^{EG}, P_{g,t}^{NG}, N_g\}$ is the set of decision variables from the two objective functions. The resulting optimization model is a mixed integer linear programming (MILP) model. This is the result of using a variablel, N_g, which is an integer in equation (9). This optimization model produces output in the form of additional generating capacity needed to meet the demand for electrical energy each year. Based on the objective function of planning costs that have been presented, determining the type and capacity of the power plant to be built is that the type of plant configuration has the lowest overall planning cost. As such, no priority is given to the specific types of power generation used in this GEP model.

2.2. Multi objective optimization

lti objectives analysis for the optimization model that has been developed is carried out using the ε-constraint algorithm. This algorithm will produce a Pareto set of two conflicting objective functions. The ε-constraint algorithm is shown in Figure 2. The process of this algorithm is as follows:

- Step 1: Lexicographic optimization is performed to calculate the pay-off table. The pay-off table is a table with a size of *m x m*. The value returned by the objective function z_i will be the element of the *i*th column of the pay-off table.
- Step 2: The next step is to determine the interval for the objective function z_i (i = 2,3, …, y) which is determined using

$$r_i = z_i^{Max} - z_i^{Min} \quad (11)$$

- Step 3: the intervals for the objective function $y - 1$ are separated into equal intervals, namely y_i (i = 2,3, …, y) where y is the index for the objective functions.
- Step 4: Analysis of multiple objective functions is carried out to solve the optimization sub-problem to produce a Pareto optimal point.

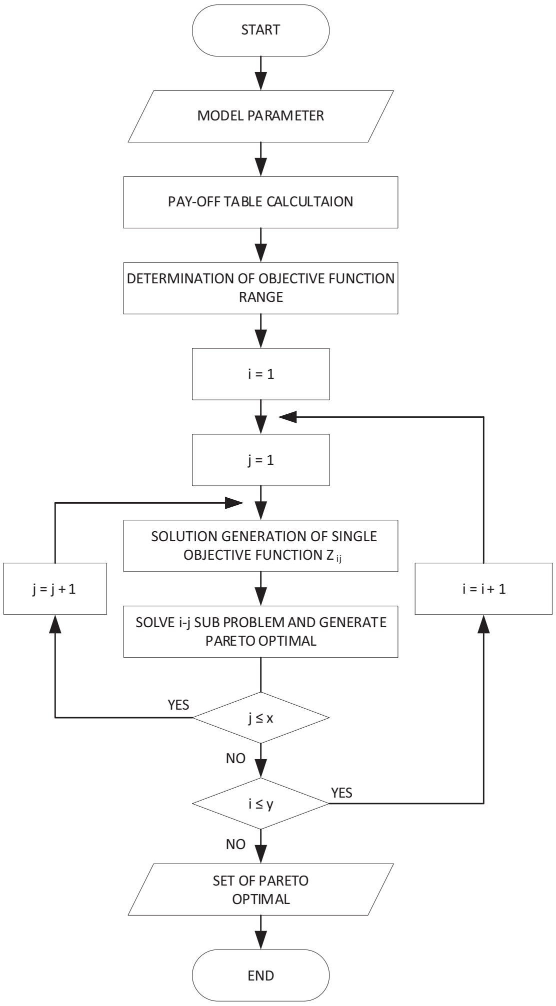

Figure 2. ε-constraint algorithm.

The result obtained from the implementation of the ε-constraint algorithm is a Pareto set. The optimal points contained in the Pareto set have not been able to show the level of importance of each objective function. Thus, a decision cannot be determined based solely on this Pareto set. A decision must be selected from the Pareto set that has been obtained. One method that is often used is fuzzy decision making (FDM).

Determination of the solution point can be done by implementing FDM. The resulting Pareto set is an input for FDM and the best solution point is determined based on the weighting factor for each objective function involved. The FDM method uses a linear membership function definition for all objective functions. For minimized objective functions, the membership function is defined by

$$\mu_i^r = \begin{cases} 1, & z_i^r \le z_i^{Min} \\ \dfrac{z_i^{Max} - z_i^r}{z_i^{Max} - z_i^{Min}}, & z_i^{Min} \le z_i^r \le z_i^{Max} \\ 0, & z_i^r \ge z_i^{Max} \end{cases} \tag{12}$$

where z_i^r is the rth Pareto optimal solution related to the membership function μ_i^r. The total membership function, μ^r, is defined on the basis of individual membership values. μ^r determined by

$$\mu^r = \frac{\sum_{i=1}^{y} w_i \mu_i^r}{\sum_{i=1}^{y} w_i} \tag{13}$$

where w_i is the weighting of ith objective function and y represents the set of the objective function. The value of μ^r obtained is then used to determine the solution point of the Pareto set. The best solution point is determined with the highest μ^r value based on the weight that has been determined for each objective function. In detail, the application of the ε-constraint algorithm combined with FDM has been described in [34].

2.3. Proposed scenarios

In this study, the scenario used is a combination of weighting factors given to each objective function in determining the solution point using FDM. There are three scenarios analyzed, namely scenarios by giving greater weighting to the objective function of planning costs, scenarios by giving the same weighting to both objective functions, and scenarios by giving greater weighting to the objective function of emissions. The three scenarios are summarized in Table 1.

Table 1. Proposed senarios for multi objective analysis.

Scenario	Objective Weight Factor	
	Z_{cost}	$Z_{Emission}$
Scenario 1	75%	25%
Scenario 2	50%	50%
Scenario 3	25%	75%

2.4. Stainability indicators

Seven indicators are used to analyze the level of sustainability of the electric power system to be developed. These indicators represent three dimensions of sustainability, namely economic, social, and environmental. The sustainability indicators in this study are summarized in Table 2.

Table 2. Sustainability indicators.

Dimension	Indicator
Economic	Unit Cost of Generation (EC1)
	Self-sufficiency (EC2)
	Electricity cost to GDP (EC3)
Social	Electricity consumption per capita (S1)
	Average Employment Index (S2)
Environmental	GWP intensity of electricity (EN1)
	GWP intensity of GDP (EN2)

The unit cost of generation indicator represents the amount of costs required to produce one unit of electrical energy. This indicator has a unit of \$/MWh which is based on the LCOE value of each electrical energy generation technology and is expressed as

$$EC1 = \frac{\sum_{g=1}^{G} E_{g,t}^{NG+EG} \times LCOE_{g,t}}{\sum_{g=1}^{G} E_{g,t}^{NG+EG}}, \forall \left(t \in T \right) \quad (14)$$

Self-sufficiency indicators are expressed as

$$EC2 = \frac{\sum_{g=1}^{G} E_{g,t}^{(NG+EG)local}}{\sum_{g=1}^{G} E_{g,t}^{NG+EG}}, \forall \left(t \in T \right) \quad (15)$$

where the numerator part in equation (15) is the production of electrical energy using local energy sources. This indicator states the percentage of energy production from local energy sources to the total electricity production in each year (in %).

The Electricity cost to GDP indicator is a comparison between the cost of generating electrical energy and the value of GDP in each year which is expressed as

$$EC3 = \frac{\sum_{g=1}^{G} E_{g,t}^{NG+EG} \times LCOE_{g,t}}{GDP_t}, \forall (t \in T) \quad (16)$$

where the lower the value of this indicator the better the impact on economic growth. This indicator is expressed in%.

Electricity consumption per capita indicator states the consumption of electrical energy for each resident in each year (in MWh/Capita). This indicator is a comparison of the total electrical energy produced compared to the population in each year. This indicator is expressed as

$$S1 = \frac{\sum_{g=1}^{G} E_{g,t}^{NG+EG}}{NP_t}, \forall (t \in T) \quad (17)$$

where NP_t is the total population in year t. This indicator is closely related to the Human Development Index (HDI).

In [35, 36], the generation of electrical energy using renewable energy sources can provide access to jobs, either directly or indirectly. The Average Employment Index indicator states the average jobs generated for each power generation unit capacity, both conventional and those using renewable energy sources (Jobs-yr/MW). This indicator is defined as

$$S2 = \frac{\sum_{g=1}^{G} E_{g,t}^{NG+EG} \times JF_g}{\sum_{g=1}^{G} E_{g,t}^{NG+EG}}, \forall (t \in T) \quad (18)$$

where JF_g is a parameter which states the number of jobs that can be generated for each MW capacity of a power plant unit with g technology.

The indicator of GWP intensity of electricity states the amount of GWP emissions produced for each unit of electrical energy produced by all power plants (in Ton CO_2 Equivalent/MWh). This indicator is expressed as

$$EN1 = \frac{\sum_{g=1}^{G} \sum_{e=1}^{E} E_{g,t}^{NG+EG} EF_{g,e}}{\sum_{g=1}^{G} E_{g,t}^{NG+EG}}, \forall (t \in T) \quad (19)$$

The GWP intensity of GDP indicator is a comparison between the amount of GWP emissions produced against the value of GDP (Ton CO2 Equivalent/\$). This indicator is expressed as

$$EN2 = \frac{\sum_{g=1}^{G} E_{g,t}^{NG+EG} EF_g}{GDP_t}, \forall (t \in T) \quad (20)$$

Then, the normalization process is carried out for each sustainability indicator. There are three normalization methods that are often used, namely min-max, distance to reference, and standardization. The advantages and disadvantages for these three data normalization methods are detailed in [37]. In this publication, normalization is carried out using the distance to reference method using the min or max values which depend on positive or negative orders. The mathematical equation used in this method is expressed as

$$\hat{I} = \frac{I_1}{\max I} \quad (21)$$

for positive order, and

$$\hat{I} = \frac{\min I}{I_1} \tag{22}$$

for negative order, where $\hat{I}$ is the normalized value, I_1 is the data to be normalized, max I is the maximum value of indicator I, and min I is the minimum value of indicator I. This normalization value is used to aggregate the sustainability indicators. The weighting method used is the equal weighting method [38, 39]. Then to obtain the sustainability index, the aggregation method used is linear aggregation which is expressed as

$$SI_t = \sum_{j=1}^{n} Is_{j,t} \times \omega_j \tag{23}$$

with $\Sigma_j \omega_j = 1$ and $Is_{j,t}$ is expressed as

$$Is_{j,t} = \sum_i \hat{I}_{i,j,t} \times \omega_{i,j} \tag{24}$$

with $\Sigma_i \omega_{i,j} = 1$. In equations (23) and (24), SI_t is the sustainability index for each planning period t, ω_j is the weight for the dimensions of the indicator, $Is_{j,t}$, is the sustainability sub-index of the indicator group I, $\hat{I}_{i,j,t}$ is the normalized i^{th} indicator value in the indicator group j, and $\omega_{i,j}$ is the weight of each indicator i in the indicator group j. Since the equal weighting method is applied in each indicator group j, $\omega_{i,j}$, has the same value.

3. Data and Data Sources

In this section, the data and data sources used in this study are discussed. This section consists of three sub-sections, namely the first sub-section discusses the current state of the island's electricity system, the second sub-section discusses available energy sources, and the third sub-section contains the characteristics of the power generation unit technology.

3.1. Current situation of bali's electrical systems

In 2018, The total power of the household and commercial sectors in 2018 was 1,633.26MW and 1,524.12MW, respectively. Meanwhile, the social, public, and industrial sectors are 130.8MW, 104.36MW, and 100.13MW, respectively. Overall, the customer power that must be served by the Balinese electricity system in 2018 is 3,492.67MW [4].

In 2018, the amount of energy sold was dominated by the household and commercial sectors, reaching 2.15TWh and 2.63TWh, respectively. The use of electrical energy for the social, public, and industrial sectors is 0.15TWh, 0.18TWh and 0.19TWh, respectively. Overall, the energy sold to meet demand in 2018 was 5.30TWh [4].

To meet this energy need, the power plant capacity installed in the Bali electricity system is 1,290MW consisting of a Coal Powered Power Plant with a capacity of 380MW and gas-powered power plants with a capacity of 910MW. Because the Bali electricity system is part of the Java-Madura-Bali electricity system, a shortage of electricity supply is provided from outside the island of Bali. The losses of transmission and distribution networks in the Bali electrical system are 8.00% [40].

3.2. Energy sources

The energy source used for electricity generation using coal and natural gas is obtained from outside the island of Bali. The energy sources available on the island of Bali are renewable energy sources consisting of geothermal energy, biomass, solar energy and wind. The technical potential for each renewable energy source is shown in Table 3 [41].

Table 3. The potential of renewable energy in Bali.

Renewable Energy Type	Technical Capacity (MW)
Geothermal	262
Biomass	191.6
Solar	1,254
Wind	1,091

3.3. Power plant characteristic

The characteristics of the power plant used for analysis in this study consist of cost characteristics, technical characteristics, environmental characteristics, and social characteristics. Cost characteristics consist of investment costs, fixed operating costs and variable operating costs. The technical characteristics consist of the capacity factor, the service life of the power plant and the minimum allowable load. The environmental characteristics used are the emissions produced by each generation unit technology for each unit of electrical energy produced. Meanwhile, social characteristics illustrate additional employment opportunities resulting from the addition of power generation capacity. In detail, the cost and technical characteristics for each power generation technology are shown in Table 4 [42] and the environmental characteristics are shown in Table 5 [43].

Table 4. The cost and technical characteristics of power generation technology.

Type	Investment Cost (USD/kW)	Fix OM Cost (USD/kW-yr)	Var OM Cost (USD/MWh)	Capacity Factor (%)	Life Time (yr)	Minimum Load (%)
Geothermal	5,940	-	31	95	30	-
Biomass	3,830	95	15	78	20	-
CSP	4,540	50	-	45	25	-
WT Onshore	1,980	60	-	34	25	-
PC	3,040	23	4	84	35	60
PC CCS	6,560	35	6	84	35	60
NGCC	1,230	6	4	90	35	50
NGCC CCS	3,750	18	10	90	35	50
Solar PV	3,070	45	-	18	25	-

The value of the capital recovery factor is calculated based on the cost characteristics using a discount rate of 5%. Emissions shown in Table 5 are then converted into units of global warming potential (Ton CO_2 Equivalent) using the coefficients for pollutants CO2, CH4, and N2O, which are 1, 30, and 265, respectively.

Table 5. Environmental characteristics of power generation technology.

Type	CO_2 (Ton/MWh)	CH_4 (g/MWh)	N_2O (g/MWh)
PC	0.33	9.88	13.8
PC CCS	0.05	13.3	18.6
NGCC	0.18	7.07	9.9
NGCC CCS	0.03	10.6	14.9

In addition to the cost, technical and environmental characteristics, each additional power generation capacity, for both conventional and renewable energy power plants, will result in additional jobs. Additional employment for each type of power generation technology is shown in Table 6 [44].

Table 6. The potential job creation for each power plant technology.

No.	Power Plant Type	Jobs-yrs/MW
1	Coal Power Plant	0.14
2	Natural Gas Power Plant	0.14
3	PV Utility Scale	1.4
4	CSP	0.6
5	Wind onshore	0.3
6	Wind offshore	0.2
7	Biomass	1.5
8	Geothermal	0.4

4 Result and Discussion

4.1. Electricity demand projection

The projection of demand for electrical energy is based on the elasticity of demand for electrical energy on GDP growth using the econometric method as described in the equation

$$E_t = E_{t-1} + E_{t-1} * G \tag{25}$$

where E is electricity demand, G is the GDP growth, and t is year index. GDP data [2] and GDP growth projection [41] are shown in Figure 3. The projection of demand for electricity is based on the projection of GDP. Demand data for electric energy [3] and the projection results are shown in Figure 4. During the projection period, the average growth in demand for electrical energy is 4.06%. This will result in the demand for electrical energy in 2050 to 18.95TWh. The projection result of electric energy demand is used as one of the input parameters in the GEP model.

4.2. Optimization results

4.2.1. Pareto optimal

The Pareto set generated by applying the ε-constraint algorithm is shown in Figure 5. This Pareto set shows the trade-off between the two objective functions. At the time the power generation capacity development is based on the least planning costs will produce the most emissions. On the other hand, planning based on the least emissions will generate the greatest planning costs. This results in a pay-off table which is denoted as

$$\begin{bmatrix} 1.60 & 80.43 \\ 12.81 & 25.66 \end{bmatrix} \tag{26}$$

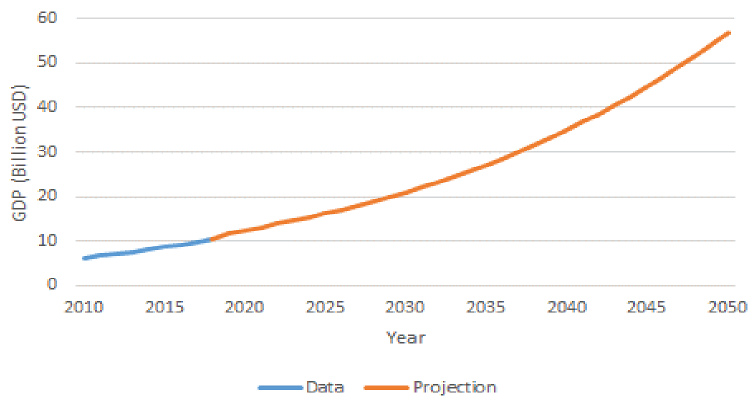

Figure 3. The GDP data and projection.

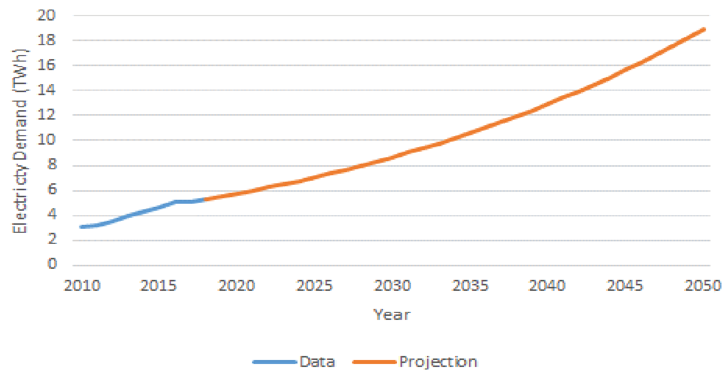

Figure 4. The electricity data and projection.

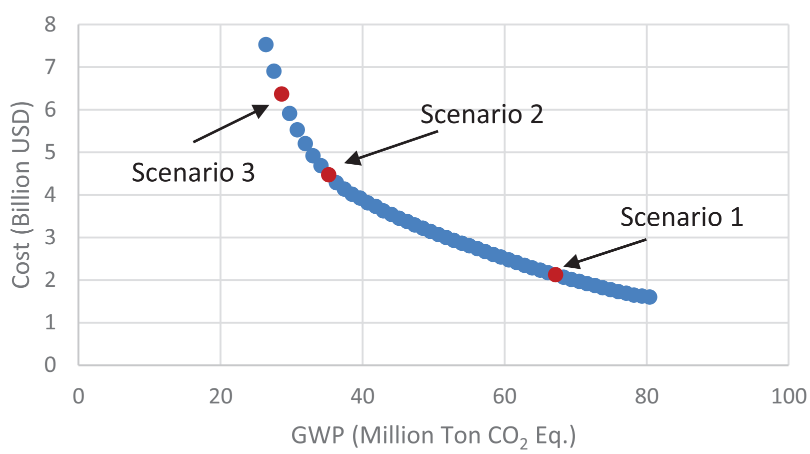

Figure 5. Pareto optimal.

where the first column is the value of the objective function of planning costs and the second column is the value of the objective function of emissions. Furthermore, the pay-off table in (26) is used as an input parameter to determine the best solution point using FDM.

Determination of the best solution point using FDM is carried out based on the membership values generated for the two objective functions. The value of this membership is very dependent on the weighting factor assigned to the two objective functions. FDM uses the maximum total membership value to determine the best solution point of each predetermined scenario. The maximum total membership value obtained for each scenario is shown in Table 7. The best solution points for the

Pareto set that have been generated for each scenario are shown in the third column in Table 7. These solution points are then used as the basis for planning the power generation capacity.

Table 7. Maximum value of total membership for each scenario.

Scenario	Maximum Total Membership	Pareto's Number
Scenario 1	0.7651	38
Scenario 2	0.7492	10
Scenario 3	0.8248	3

4.2.2. Power plant investment cost

Based on the FDM results, the investment costs in each year in the planning period for new power plants based on scenarios are shown in Figure 6, Figure 7, and Figure 8 respectively for Scenario 1, Scenario 2, and Scenario 3. Investments in new power plants are strongly influenced by the scenario. For scenario 1 where the objective function of planning costs is more concerned with the objective function of emissions, investment is made to increase capacity by building natural gas combined cycle (NGCC) and NGCC with carbon capture and storage (NGCC-CCS) power plants. During the planning period, the investment costs for the NGCC and NGCC-CSS power plant were 1.97 Billion USD and 6.75 Billion USD, respectively.

Scenario 2, where the planning cost objective function and the emission objective function have the same weight, resulting in different investment cost calculations as shown in Figure 7. Scenario 2, where the planning cost objective function and the emission objective function have the same weight, resulting in different investment cost calculations as shown in Figure 11. The investment cost under Scenario 2 is only used to increase capacity by building the NGCC-CCS power plant. The investment cost required in Scenario 2 is 10.13 billion USD which is 16.14% higher than the investment cost for Scenario 1. Assigning equal weight values to both objective functions results in calculations in Scenario 2 to increase the power generation capacity with cleaner technology when compared with Scenario 1. This is the reason why the investment costs in Scenario 2 are higher than the investment costs in Scenario 1.

Figure 8 shows the results of the calculation of investment costs for Scenario 3. The investment costs generated

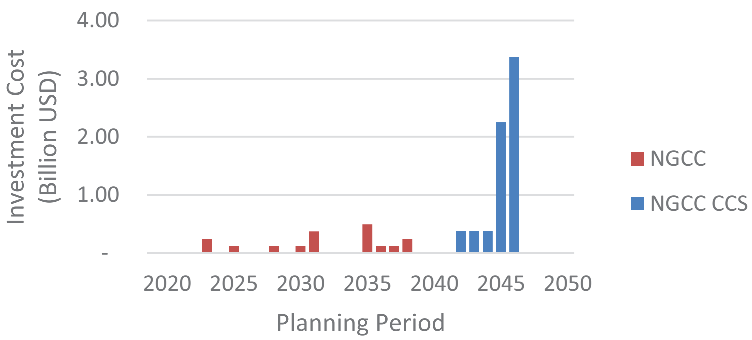

Figure 6. Investment cost based on Scenario 1.

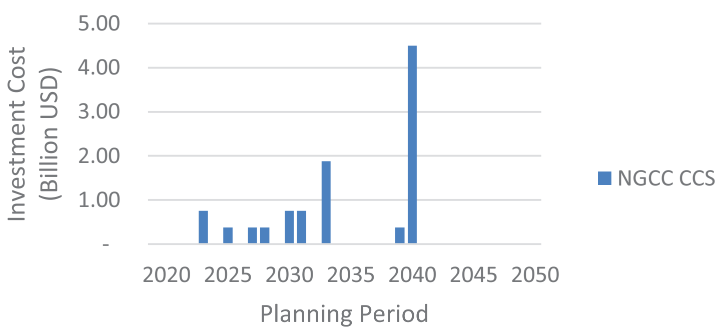

Figure 7. Investment cost based on Scenario 2.

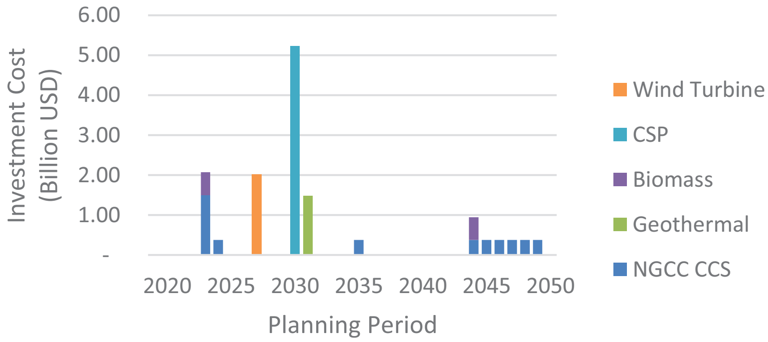

Figure 8. Investment cost based on Scenario 3.

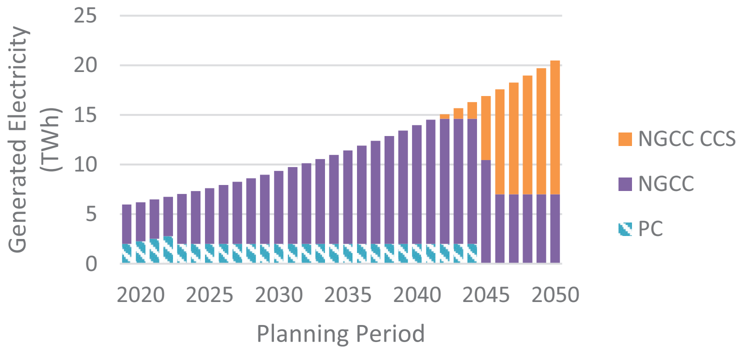

Figure 9. Generated electricity based on Scenario 1.

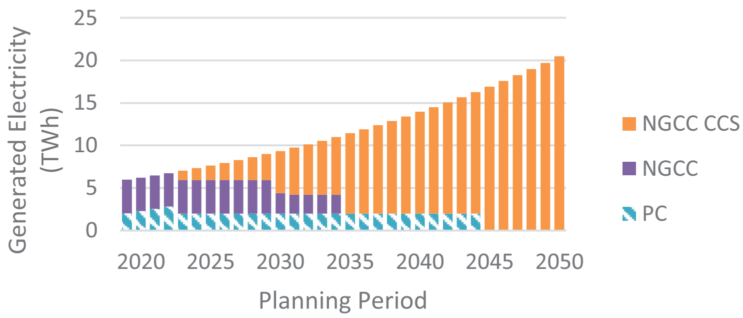

Figure 10. Generated electricity based on Scenario 2.

by Scenario 3 are used to increase capacity by building 5 types of power generation technology, namely NGCC-CCS, geothermal, biomass, concentrated solar panel (CSP), and wind turbine. Overall, the investment cost generated by Scenario 3 is 14.38 Billion USD. Scenario 3 results in 42.03% and 64.96% higher investment costs, respectively when compared to the investment costs generated by Scenario 2 and Scenario 1. It can be said that Scenario 3 produces the highest investment cost. This is because the weighting of the objective function of emissions is higher than that of the objective function of planning costs. Therefore, the power plant technology chosen by the optimization process is cleaner generation technology when compared to the technology selected in Scenario 1 and Scenario 2.

4.2.3. Electricity generation

The electrical energy generated by each power plant unit based on the scenario is shown in Figure 9, Figure 10, and Figure 11, respectively for Scenario 1, Scenario 2, and Scenario 3. The results of the generation of electrical energy by all scenarios produce the same value. And when compared with the projection of demand for electrical energy in Figure 6, the amount of electrical energy generated is 8.00% higher due to losses in the transmission and distribution network. These three figures show

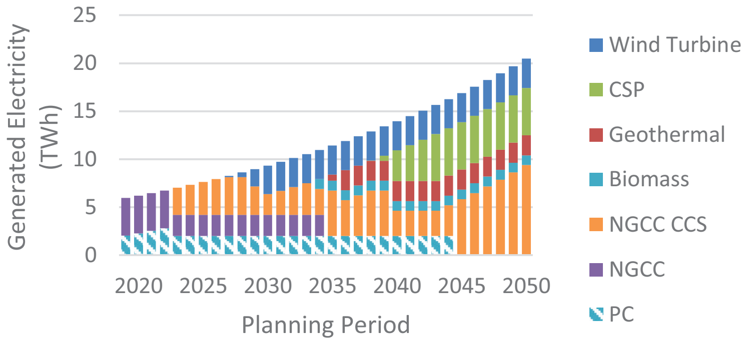

Figure 11. Generated electricity based on Scenario 3.

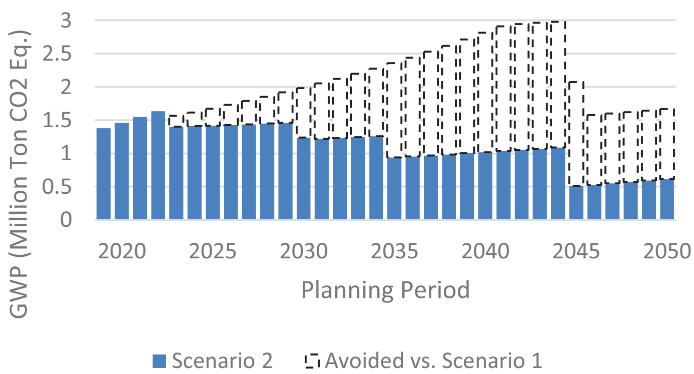

Figure 12. Avoided emission by Scenario 2 vs. Scenario 1.

the amount of electrical energy generated from both the installed and newly built power plants. The installed power plants consist of NGCC, which will be retired in 2034, and Pulverized Coal (PC), which will be retired in 2044.

Based on Scenario 1 in Figure 9, electrical energy is generated by a power plant system with PC, NGCC, and NGCC-CCS technologies. However, the PC power plant will not be rebuilt after it is retired in 2044. The NGCC-CCS power plant generates electrical energy in 2040. Based on Scenario 2 in Figure 10, the NGCC-CCS power plant is built early in the planning period and starts generating electrical energy. in 2023. Scenario 2 results in the NGCC-CSS power plant, which is an environmentally friendly power plant, contributing more dominantly when compared to Scenario 1. This is due to the higher emission objective function weight in Scenario 2 when compared to the weighted value in Scenario 1.

The source of electrical energy in Scenario 3 is more varied when compared to the other two scenarios. Based on Scenario 3 in Figure 11, electricity generation with renewable energy sources has a significant contribution to the supply of electrical energy. At the end of the planning period, renewable energy sources contributed 43.72% of the total electricity generated. The contribution of wind turbine and solar CSP in supplying electrical energy was 17.34% and 13.46%, respectively. The contribution of geothermal and biomass in supplying electrical energy was 8.35% and 4.57%, respectively.

4.3. Avoided global warming potential

As explained in the previous section, electrical energy is generated from a combination of different power generation technologies for each scenario. As a consequence, each scenario produces a different amount of emissions from the process of generating electrical energy. Scenario 1, where the cost objective function is more concerned with the objective function of emissions, produces the most when compared to the emissions produced by other scenarios. When compared with Scenario 1, the avoided emissions generated by Scenario 2 and Scenario 3 are shown in Figure 12 and Figure 13. These two figures show the emissions produced in each year in the planning period.

In Figure 12, the emissions produced by Scenario 2 are lower than those produced by Scenario 1. This occurs during the planning period other than the first to the fourth year, where at the beginning of the planning period, electricity is still generated by the installed generator, namely the PC and NGCC. At the end of the planning period, the emissions produced by Scenario 1 have decreased. This is due to the operation of a more environmentally friendly generating unit, namely the NGCC CCS. After the fourth year, Scenario 2 could produce lower emissions than Scenario 1. The emission reduction at the beginning of the planning period by Scenario 2 resulted from the operation of the NGCC CCS generating unit.

The average annual emission reduction that can be generated by Scenario 2 is 0.95 Million Tons CO_2 Equivalent. The emission reduction produced by Scenario 3 against scenario 1 is shown in Figure 13. The average annual emission reduction produced by Scenario 3 is 1.17 Million Tons of CO2 Equivalent. The emission reduction produced by Scenario 3 is higher than that in Scenario 2 where this is due to the contribution of generation from renewable energy sources. Cumulatively, the emissions resulting from the electricity generation process for each scenario are shown in Figure 14. At the end of the planning period, Scenario 2 and Scenario 3 can reduce emissions by 46.11% and 56.49% respectively when compared to the emissions produced by scenario 1.

4.4. Sustainability Analysis

The sustainability indicator in the form of unit cost of generation (UCG) for each scenario is shown in Figure 15. During the planning period, Scenario 1 produces the lowest UCG when compared to other scenarios. On the other hand, Scenario 3 produces the highest UGC when compared to other scenarios. UCG in Scenario 1 decreases until 2040 and then increases until the end of the planning period. The increase in UCG is due to the investment that must be made to replace the power plant that will stop operating in 2040.

In Scenario 2, the resulting UCG has decreased relatively during the planning period. Most investments for new power plants are made at the beginning of the planning period. Whereas in Scenario 3, the peak of investment is carried out in 2040 so that the resulting UCG increases from the beginning of the planning period to 2040. After 2040, UCG in Scenario 3 experiences a

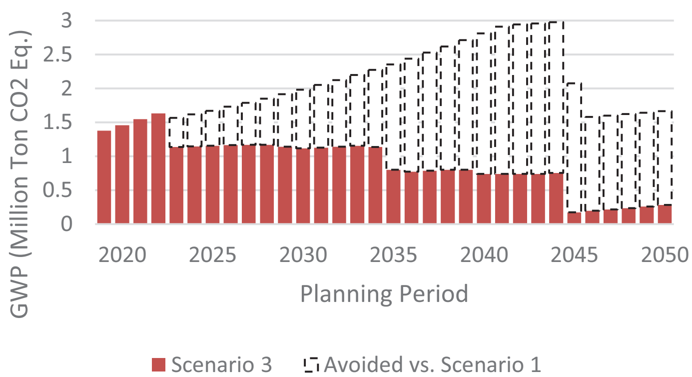

Figure 13. Avoided emission by Scenario 3 vs. Scenario 1.

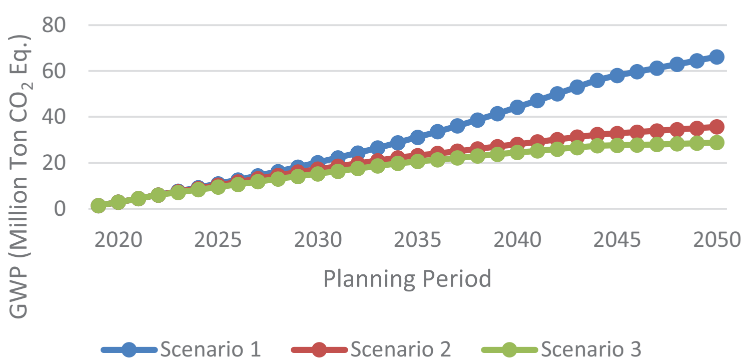

Figure 14. Cumulative GWP for each scenario along planning period.

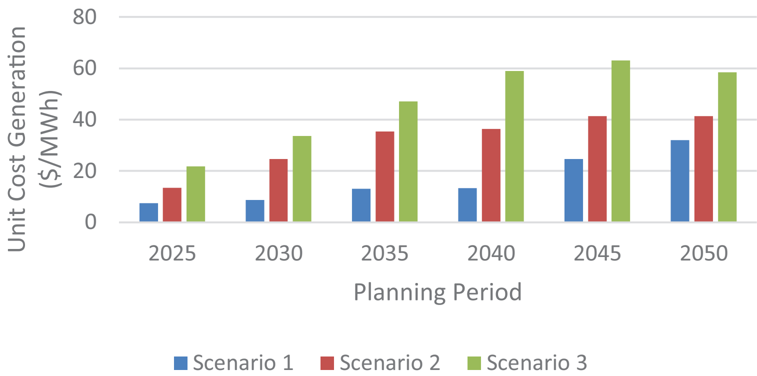

Figure 15. The indicator of unit cost of generation.

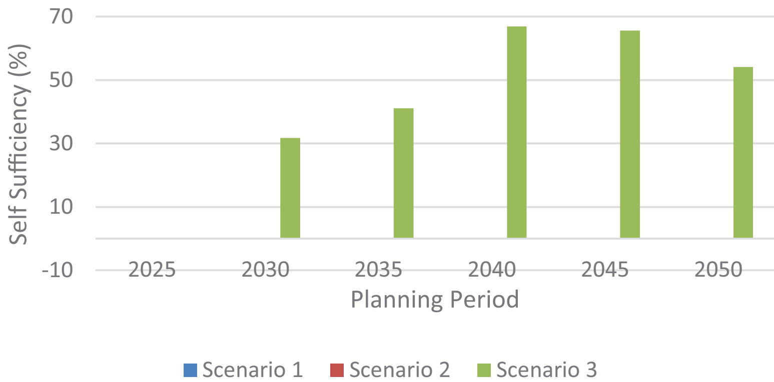

Figure 16. Self-sufficiency indicator.

decrease due to reduced investment for new power plants. During the planning period, Scenario 3 produced the highest UCG compared to other scenarios. This is because Scenario 3 produces the highest investment cost to build the most environmentally friendly power plant.

The self-sufficiency indicator is only produced by scenario 3 as shown in Figure 16. Scenario 1 and Scenario 2 result in a power plant capacity planning using coal and natural gas, where both fuels are exported from outside Bali Island. Thus, these two scenarios produce a self-sufficiency indicator that is worth 0. Meanwhile, Scenario 3 produces a power plant capacity plan that combines fuel from outside Bali and local energy sources. Between 2040 and 2045, Scenario 3 produces the highest self-sufficiency indicator, which is around 65%. In the period 2045 - 2050, the self-sufficiency indicator based on Scenario 3 has decreased. This is because the contribution of the NGCC-CCS power plant in generating electrical energy has increased (Figure 11). The increase in the contribution of the NGCC-CSS power plant is due to the retirement of the coal-fired power plant (PC). In addition, renewable energy sources have reached their maximum production capacity.

Figure 17 shows the share of electricity to GDP indicator. Scenario 1 and Scenario 2 produce the value of this indicator which tends to decrease. This is because the installed power generation capacity is still dominant in the supply of electrical energy. Different results are shown by Scenario 3 where the value of this indicator has increased in the interval between 2025 and 2035. This is due to the investment made to build environmentally friendly power plants. However, the value of this indicator based on Scenario 3 begins to decline from 2035 to the end of the planning period. This is due to the reduced contribution of coal-fired power plants in electricity generation and replaced by renewable energy generators that do not require fuel.

The job creation indicator as a result of the power plant development is shown in Figure 18. Scenario 1 and Scenario 2 produce the same value for this indicator. This is because the types of power plants used for these two scenarios are the same, namely PC, NGCC, and NGCC CCS. In addition, these three types of power

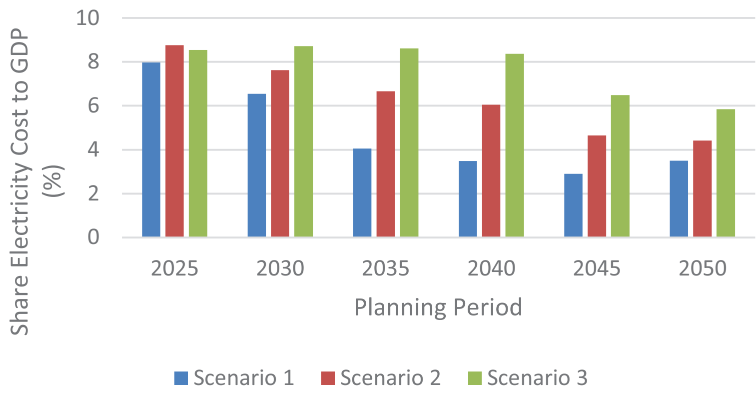

Figure 17. The indicator of share electricity cost to GDP.

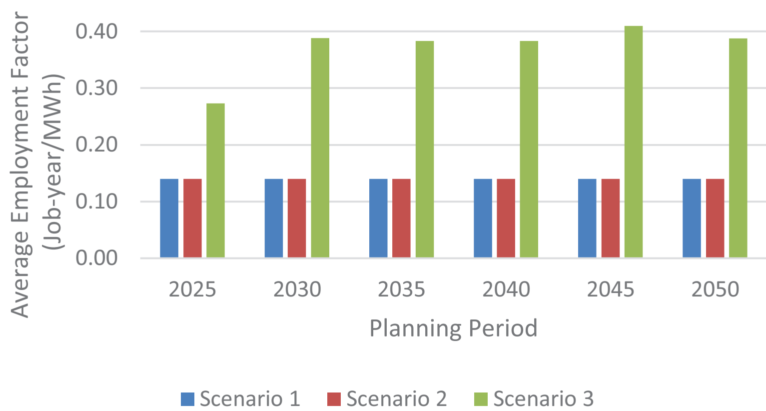

Figure 18. The indicator of average job creation.

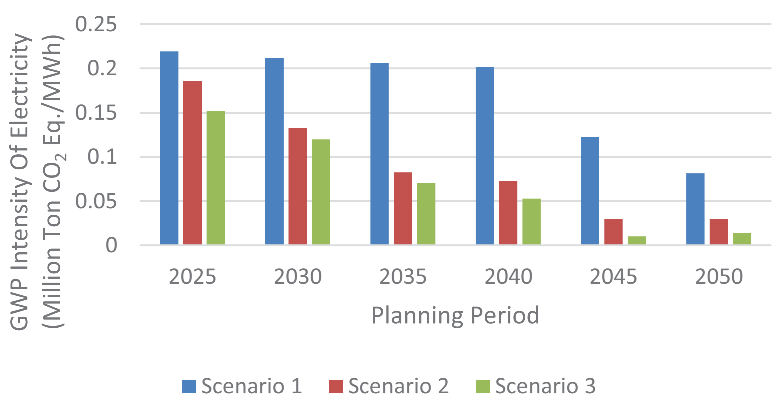

Figure 19. The indicator of GWP intensity of electricity.

generation technology have the same coefficient in terms of additional employment (Table 6). The job creation indicator produced by Scenario 3 has the greatest value when compared to the other two scenarios. This shows that the increasing role of renewable energy in the supply of electrical energy will generate bigger jobs when compared to power generation with conventional technology.

From an environmental point of view, indicators that represent environmental aspects are indicators of GWP intensity of electricity and GWP intensity of economy. These two indicators are shown in Figure 19 and Figure 20, respectively. In these two figures, Scenario 1 produces the highest value for the two environmental indicators when compared to the other scenarios. After 2040, the values of the two environmental indicators for

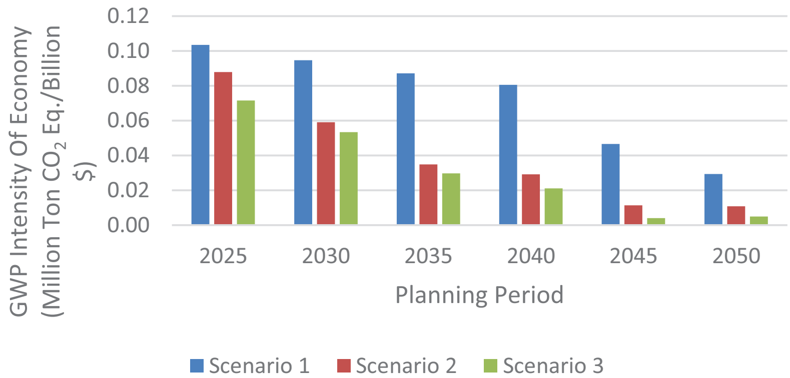

Figure 20. The indicator of GWP intensity of economy.

Scenario 1 will experience a significant decline. This is because the old power plant has stopped operating and has been replaced by a more environmentally friendly power plant, namely NGCC-CCS.

In the same way, the NGCC-CCS power plant plays a role in reducing GHG emissions in Scenario 2 where the NGCC-CCS power plant starts providing electricity at the beginning of the planning period. Based on Scenario 2, the NGCC-CCS power plant has the most dominant contribution when compared to other power generation technologies in the provision of electrical energy. In fact, after the old plant stopped operating, all demand for electrical energy was provided by the power plant with NGCC-CC technology. This results in the environmental indicators produced by Scenario 2 having a lower value when compared to the indicator values generated by Scenario 1.

The environmental indicator value generated by Scenario 3 is the lowest when compared to the value generated by the other scenarios. The provision of electrical energy generated by Scenario 3 consists of installed power plants, namely NGCC and PC, and new power plants, namely NGCC-CC and power plants with renewable energy sources. Based on Scenario 3, the type of power plant that has been installed does not experience additional capacity and the two power plants are operated at their minimum load limit.

To meet the increasing demand for electrical energy, Scenario 3 results in an additional environmentally friendly power generation capacity, namely the addition of NGCC-CCS power plant capacity at the beginning of the planning period and power generation with renewable energy sources from 2030 to the end of the planning period. When the power generation capacity with renewable energy sources has reached its maximum limit, the NGCC-CC power plant must be added again to meet the demand for electrical energy. This is why the environmental indicator value in Scenario 3 has the lowest value when compared to the values generated by the other scenarios.

The development of power generation capacity is determined by policies in giving weight to the sustainability aspects consisting of economic, social, and environmental aspects. The sustainability indicators that have been generated are normalized using equations (21) and (22). Furthermore, the normalized value of sustainability indicators is used to produce a sustainability index using equation (23). In this study, three policies that give different weights to each aspect of sustainability are used as assumptions in determining the sustainability index during the planning period. The three policies with weight values for each aspect of sustainability are shown in Table 8.

Table 8. Weighting factor policy

Option	Economy	Social	Environment	Total
Policy 1	33.33	33.33	33.33	100
Policy 2	40	40	20	100
Policy 3	45	45	10	100

Figure 21 shows the results of calculating the aggregated normalized sustainability index. The values obtained in this figure are weighted equally for each aspect of sustainability. If the weighting for the sustainability aspect has different values, the results of the calculation of the sustainability index are shown in Figure 22. From Figure 21, from an economic, social and environmental perspective, Scenario 3 is the best scenario to be implemented. This can be seen with the highest sustainability index value during the planning period when compared to other scenarios. The value of

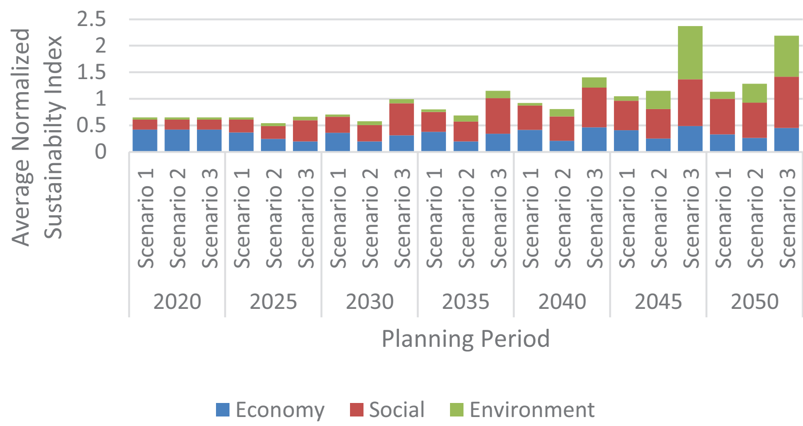

Figure 21. Aggregated normalized sustainability index.

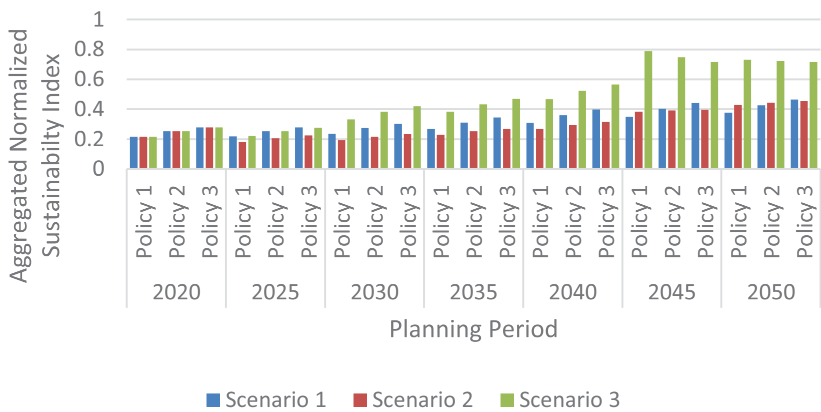

Figure 22. The comparison of sustainability index based on various policy.

the sustainability of Scenario 3 is strongly influenced by the benefits obtained from social and environmental aspects.

In Figure 22, the sustainability index generated by Scenario 3 has the highest value for each policy option in line with the implementation of renewable energy in electricity supply. On the other hand, the sustainability index generated by Scenario 1 and Scenario 2 did not experience a significant increase. This is due to the absence of the role of renewable energy generated by Scenario 1 and Scenario 2. Meanwhile, Scenario 3 produces the EC2 indicator value in the year in which local energy sources, namely renewable energy sources, begin to play a role in supplying electrical energy.

Currently, planning for generating capacity development carried out in Indonesia, in general, and in the Province of Bali uses calculations that prioritize economic aspects, in this case, is to develop a power system with minimal costs to meet the growth of the electricity load. This is shown in document [5] where the planning of generating capacity is still dominated by the use of power plants with fossil fuels in the Java-Madura-Bali (JAMALI) system. In addition, this document does not include the development of local energy in Bali Province. Changing the power plant capacity planning policy from Scenario 1, which prioritizes the objective planning cost function, to Scenario 3, which is more concerned with the objective function of emissions, will result in benefits in every sustainability indicator except for EC1 and EC3 indicators.

5. Conclusion

This research has discussed the planning of power generation capacity through an optimization model which has two objective functions, namely the objective function of planning costs and the objective function of emissions. Fuzzy decision making methods have been implemented to determine the best solution point from the three proposed scenarios. In addition, sustainability indices have been analyzed for the three scenarios. The model and analysis procedure presented in this study have been implemented with real data, namely data on the power system in Bali Province. From the results obtained, Scenario 1 results in planning the power generation capacity with the lowest cost. However, Scenario 1 produces the highest emissions compared to other scenarios. On the other hand, Scenario 3 produces the lowest emissions when compared to the other two scenarios, which is 56.49% lower than the emissions generated by Scenario 1. However, Scenario 3 requires the highest cost, which is 64.96% higher when compared to with the costs generated by Scenario 1.

From a sustainability perspective, Scenario 3 has a better sustainability index throughout the planning period when compared to other scenarios. Likewise, for several different policy options, Scenario 3 produces the best sustainability index. The sustainability index produced by Scenario 3 is mainly influenced by sustainability from social and environmental aspects. From the analysis results, there are two unfavorable sustainability indices generated by Scenario 3, namely the cost of unit generation and shared electricity cost to GDP.

The model and analysis procedure proposed in this study can be further developed by including several uncertainty variables such as the availability of primary energy, both fossil and renewable energy, variations in the electrical load that may occur, and variations in investment and operational costs of each power generation technology. The model that has been developed in this study can also be used for different areas. Furthermore, a sustainability analysis can be carried out for the energy system as a whole.

Acknowledgement

This research was conducted using research funds originating from a research grant from the Universitas Muhammadiyah Yogyakarta in 2020.

This article was accepted for publication in the IJSEPM special issue "Latest Developments in 4th generation district heating and smart energy systems" [45].

References

[1] BPS-Indonesia. "Statistics Indonesia-Population Projection by Province," October 22, 2019; https://www.bps.go.id/statictable/2014/02/18/1274/proyeksi-penduduk-menurut-provinsi-2010---2035.html.

[2] BPS-Indonesia. "Statistics Indonesia-Gross Regional Domestic Product at 2010 Constant Market Prices by Province," October 22, 2019; https://www.bps.go.id/dynamictable/2015/10/07/956/-seri-2010-produk-domestik-regional-bruto-atas-dasar-harga-konstan-2010-menurut-provinsi-2010-2018-miliar-rupiah-.html.

[3] BPS-Indonesia. "Statistics Indonesia-Electricity Distributed by Province (GWh)," October 22, 2019; https://www.bps.go.id/dynamictable/2019/03/13/1593/listrik-yang-didistribusikan-menurut-provinsi-gwh-2011-2017.html.

[4] PLN. "Statistik PLN 2018," https://web.pln.co.id/statics/uploads/2019/07/Buku-Statistik-2018-vs-Indo-Final.pdf.

[5] KESDM, *Rencana Usaha Penyediaan Tenaga Listrik*, 2019. http://gatrik.esdm.go.id/assets/uploads/download_index/files/5b16d-kepmen-esdm-no.-39-k-20-mem-2019-tentang-pengesahan-ruptl-pt-pln-2019-2028.pdf

[6] B. Alizadeh, and S. Jadid, "A dynamic model for coordination of generation and transmission expansion planning in power systems," *International Journal of Electrical Power & Energy Systems,* vol. 65, pp. 408-418, 2015, http://doi.org/10.1016/j.ijepes.2014.10.007

[7] F. Bayatloo, and A. Bozorgi-Amiri, "A novel optimization model for dynamic power grid design and expansion planning considering renewable resources," *Journal of Cleaner Production,* vol. 229, pp. 1319-1334, 2019, http://doi.org/10.1016/j.jclepro.2019.04.378

[8] S. Li, D. W. Coit, and F. Felder, "Stochastic optimization for electric power generation expansion planning with discrete climate change scenarios," *Electric Power Systems Research,* vol. 140, pp. 401-412, 2016, http://doi.org/10.1016/j.epsr.2016.05.037

[9] B. A. Frew, S. Becker, M. J. Dvorak, G. B. Andresen, and M. Z. Jacobson, "Flexibility mechanisms and pathways to a highly renewable US electricity future," *Energy,* vol. 101, pp. 65-78, 2016, http://doi.org/10.1016/j.energy.2016.01.079

[10] R. Komiyama, and Y. Fujii, "Optimal Integration of Variable Renewables in Electric Power Systems of Japan," *Journal of Energy Engineering,* vol. 143, no. 2, 2017, DOI. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000361

[11] Z. A. Muis, H. Hashim, Z. A. Manan, F. M. Taha, and P. L. Douglas, "Optimal planning of renewable energy-integrated electricity generation schemes with CO2 reduction target," *Renewable Energy,* vol. 35, no. 11, pp. 2562-2570, 2010, http://doi.org/10.1016/j.renene.2010.03.032

[12] J. Kwon, S. Hwang, and B. H. Kim, "A study on generation expansion planning onsidering transition of nuclear and renewable policy," *International Conference on Sustainable Energy and Environmental Engineering,* vol. 291-294, pp. 575-580, 2013, http://doi.org/10.4028/www.scientific.net/AMM.291-294.575

[13] D. Min, J.-h. Ryu, and D. G. Choi, "A long-term capacity expansion planning model for an electric power system integrating large-size renewable energy technologies," *Computers & Operations Research,* vol. 96, pp. 244-255, 2018, http://doi.org/10.1016/j.cor.2017.10.006

[14] M. Ozcan, S. Ozturk, and M. Yildirim, "Turkey's long-term generation expansion planning with the inclusion of renewable-energy sources," *Computers & Electrical Engineering,* vol. 40, no. 7, pp. 2050-2061, 2014, http://doi.org/10.1016/j.compeleceng.2014.07.001

[15] Tumiran, L. M. Putranto, A. Priyanto, and I. Savitri, "Generation expansion planning for high-potential hydropower resources: The case of the Sulawesi electricity system," *Int J Sustain Energy Plan Manag,* vol. 28, pp. 37-52, 2020, http://doi.org/10.5278/ijsepm.3247

[16] S. Pineda, and A. Bock, "Renewable-based generation expansion under a green certificate market," *Renewable Energy,* vol. 91, pp. 53-63, 2016, http://doi.org/10.1016/j.renene.2015.12.061

[17] R. A. R. Candia, J. A. A. Ramos, S. L. B. Subieta, J. G. P. Balderrama, V. S. Miquélez, H. J. Florero, and S. Quoilin, "Techno-economic assessment of high variable renewable energy penetration in the Bolivian interconnected electric system," *Int J Sustain Energy Plan Manag,* vol. 22, pp. 17-38, 2019, http://doi.org/10.5278/ijsepm.2659

[18] S. Kumar, "Assessment of renewables for energy security and carbon mitigation in Southeast Asia: The case of Indonesia and Thailand," *Applied Energy,* vol. 163, pp. 63-70, 2016, http://doi.org/10.1016/j.apenergy.2015.11.019

[19] I. M. Saeed, A. T. Ramli, and M. A. Saleh, "Assessment of sustainability in energy of Iraq, and achievable opportunities in the long run," *Renew Sustain Energy Rev,* vol. 58, pp. 1207-1215, 2016, http://doi.org/10.1016/j.rser.2015.12.302

[20] M. G. Prina, D. Mosera, R. Vaccaroa, and W. Sparbera, "EPLANopt optimization model based on EnergyPLAN applied at regional level: the future competition on excess electricity production from renewables," *Int J Sustain Energy Plan Manag,* vol. 27, pp. 35 - 49, 2020, http://doi.org/10.5278/ijsepm.3504

[21] M. G. Prina, M. Lionetti, G. Manzolini, W. Sparber, and D. Moser, "Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning," *Applied Energy,* vol. 235, pp. 356-368, 2019, http://doi.org/10.1016/j.apenergy.2018.10.099

[22] H. Shakouri G, and S. Aliakbarisani, "At what valuation of sustainability can we abandon fossil fuels? A comprehensive multistage decision support model for electricity planning," *Energy,* vol. 107, pp. 60-77, 2016, http://doi.org/10.1016/j.energy.2016.03.124

[23] M. Sharifzadeh, H. Lubiano-Walochik, and N. Shah, "Integrated renewable electricity generation considering uncertainties: The UK roadmap to 50% power generation from wind and solar energies," *Renew Sustain Energy Rev,* vol. 72, pp. 385-398, 2017, http://doi.org/10.1016/j.rser.2017.01.069

[24] H. Tavakoli, and B. D. Barkdoll, "Sustainability-based optimization algorithm," *International Journal of Environmental Science and Technology,* vol. 17, no. 3, pp. 1537-1550, 2019, http://doi.org/10.1007/s13762-019-02535-9

[25] M. G. Prina, V. Casalicchio, C. Kaldemeyer, G. Manzolini, D. Moser, A. Wanitschke, and W. Sparber, "Multi-objective investment optimization for energy system models in high temporal and spatial resolution," *Applied Energy,* vol. 264, 2020, http://doi.org/10.1016/j.apenergy.2020.114728

[26] T. Luz, P. Moura, and A. de Almeida, "Multi-objective power generation expansion planning with high penetration of renewables," *Renew Sustain Energy Rev,* vol. 81, pp. 2637-2643, 2018, http://doi.org/10.1016/j.rser.2017.06.069

[27] R. Chedid, S. Karaki, and A. Rifai, "A multi-objective design methodology for hybrid renewable energy systems," *IEEE Russia Power Tech*, 2005, http://doi.org/10.1109/PTC.2005.4524339

[28] P. S. Moura, and A. T. de Almeida, "Multi-objective optimization of a mixed renewable system with demand-side management," *Renew Sustain Energy Rev,* vol. 14, no. 5, pp. 1461-1468, 2010, http://doi.org/10.1016/j.rser.2010.01.004

[29] N. Zhang, Z. Hu, C. Springer, Y. Li, and B. Shen, "A bi-level integrated generation-transmission planning model incorporating the impacts of demand response by operation simulation," *Energy Conversion and Management,* vol. 123, pp. 84-94, 2016, http://doi.org/10.1016/j.enconman.2016.06.020

[30] A. Moreira, D. Pozo, A. Street, and E. Sauma, "Reliable Renewable Generation and Transmission Expansion Planning: Co-Optimizing System's Resources for Meeting Renewable Targets," *IEEE Power & Energy Society General Meeting (PESGM)*, 2018

[31] S. Fazlollahi, S. L. Bungener, G. Becker, and F. Maréchal, "Multi-Objectives, Multi-Period Optimization of district heating networks Using Evolutionary Algorithms and Mixed Integer Linear Programming (MILP)," *22nd European Symposium on Computer Aided Process Engineering*, Computer Aided Chemical Engineering, pp. 262-266, 2012, http://doi.org/10.1016/b978-0-444-59519-5.50053-8

[32] M. S. Mahbub, M. Cozzini, P. A. Østergaard, and F. Alberti, "Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design," *Applied Energy,* vol. 164, pp. 140-151, 2016, http://doi.org/10.1016/j.apenergy.2015.11.042

[33] M. G. Prina, M. Cozzini, G. Garegnani, G. Manzolini, D. Moser, U. Filippi Oberegger, R. Pernetti, R. Vaccaro, and W. Sparber, "Multi-objective optimization algorithm coupled to EnergyPLAN software: The EPLANopt model," *Energy,* vol. 149, pp. 213-221, 2018, http://doi.org/10.1016/j.energy.2018.02.050

[34] R. A. Al Hasibi, S. P. Hadi, and S. Sarjiya, "Multi-Objective Optimization of Integrated Power System Expansion Planning with Renewable Energy-Based Distributed Generation," *International Review of Electrical Engineering (IREE),* vol. 14, no. 1, 2019, http://doi.org/10.15866/iree.v14i1.16082

[35] IRENA. "Renewable Energy Jobs: Status, Prospects & Policies," https://www.irena.org/publications/2012/Jan/Renewable-Energy-Jobs-Status-Prospects--Policies-2012.

[36] IRENA. "Renewable Energy Jobs & Access," https://www.irena.org/publications/2012/Jun/Renewable-Energy-Jobs--Access-2012.

[37] B. W. Ang, W. L. Choong, and T. S. Ng, "Energy security: Definitions, dimensions and indexes," *Renew Sustain Energy Rev,* vol. 42, pp. 1077-1093, 2015, http://doi.org/10.1016/j.rser.2014.10.064

[38] WEC. "2013 Energy Sustainability Index," https://www.worldenergy.org/assets/images/imported/2013/09/2013-Energy-Sustainability-Index-VOL-2.pdf.

[39] X. Gan, I. C. Fernandez, J. Guo, M. Wilson, Y. Zhao, B. Zhou, and J. Wu, "When to use what: Methods for weighting and aggregating sustainability indicators," *Ecological Indicators,* vol. 81, pp. 491-502, 2017, http://doi.org/10.1016/j.ecolind.2017.05.068

[40] PLN, *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL)*, PLN, 2018. https://web.pln.co.id/statics/uploads/2018/04/RUPTL-PLN-2018-2027.pdf

[41] MEMR, *National Energy Masterplan*, Ministry of Energy and Mineral Resources, 2017. https://www.esdm.go.id/assets/media/content/content-rencana-umum-energi-nasional-ruen.pdf

[42] NREL, *COST AND PERFORMANCE DATA FOR POWER GENERATION TECHNOLOGIES*, National Renewable Energy Laboratory, 2012. https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf

[43] IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change (IPCC), 2018. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

[44] J. Rutovitz, E. Dominish, and J. Downes, *Calculating Global Energy Sector Jobs 2015 Methodology Update 2015. Prepared for Greenpeace International by the Institute for Sustainable Futures*, University of Technology Sydney, 2015. https://opus.lib.uts.edu.au/handle/10453/43718.

[45] Østergaard PA, Johannsen RM, Lund H, and M. BV, "Latest Developments in 4th generation district heating and smart energy systems," *Int J Sustain Energy Plan Manag*, 2021, http://doi.org/10.5278/ijsepm.6432