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Formulating an Optimal Energy Mix for Palawan Island using Multi-Criteria Decision Analysis and Goal Programming

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Abstract

Palawan Island has an energy plan, which is the first ever local energy plan developed in the country. However, the plan ran into difficulties due to the conflicting objectives of various energy stakeholders in the island province. This study aimed to formulate an optimal energy mix that considers the stakeholders' varying objectives. Applying Multi-Criteria Decision Analysis and Goal Programming, the study weighed each of the stakeholders' objectives and factored all of these to generate an optimal energy mix. Results showed that the optimal energy mix for Palawan is about 69% hydropower run of river, 1% hydro dam type, and 30% natural gas. The overall achievement of objectives for the resulting energy mix is shown to be greater than those of the other energy mixes it is compared with. This study demonstrates that an energy plan that takes into account the conflicting objectives among various decision makers can be formulated using Multi-Criteria Decision Analysis and Goal Programming.

Keywords: Philippines, stakeholder conflict in energy planning, energy mix optimization

Introduction

Palawan is an off-grid island whose electricity falls under the Small Power Utilities Group and the Philippine Small Grid Dispatch Protocol. The province is included in the Missionary Electrification under the RA 9136 Electric Power Industry Reform Act (EPIRA) of 2001, with its electricity subsidized under the universal charge of electricity payers. If the subsidy were pulled out suddenly, this can have a direct effect on the energy planning and situation of Palawan. As of 2016, there are seven municipalities being supplied with electricity for 24 hours; one municipality supplied for 16 hours; one municipality supplied for 12 hours; and three municipalities supplied for eight hours (Department of Energy, 2016).

The demand for electricity increased in Palawan province over time especially due to its rapid local economic growth as a popular tourism destination. Energy planning towards a more stable energy supply in the island was conducted from 2013 to 2015, resulting in the Palawan Island Power Development Plan (PIPDP), which is the first local energy plan developed in the country. The plan was prepared by the Joint Energy Development Advisory Group of Palawan (JEDAG, 2014) that was composed of different stakeholders from Palawan and the Department of Energy (DOE). The PIPDP energy plan was based on least cost solution, which includes an energy demand forecast, reserve capacity model, scheduling of power plant construction, and transmission and distribution line development. It also relied on a business-as-usual forecast and aggressive scenario, and solution for aggressive energy mix with coal. However, the PIPDP did not consider the objectives that fall under environmental, social, and technological aspects (JEDAG, 2014). As a consequence, some stakeholders were dissatisfied with the plan, like the local non-government groups who opposed the construction of coal-fired plants in the island and brought the matter to the courts (Ranada, 2013). The conflicting objectives of the various stakeholders posed serious challenges to the plan, resulting in the persistence of power crisis in the island (Anda, 2015; The Manila Times, 2015).

A review of models and actors in energy mix optimization has revealed a gap between the stakeholders and decision makers representing the groups and those who have the knowledge and best practice in energy planning, strategy, and implementation (Weijermars et al., 2012). In addition, Hiremath, Shikha and Ravindranath (2007) pointed out that a bottom-up approach is an appropriate method for energy planning in consideration of the varying objectives at different levels (municipal/local, provincial, and national). To deal with the conflicting objectives of stakeholders, recent studies used the Multi-Criteria Decision Analysis (MCDA) as a valuable tool for planning of combined energy systems, energy planning and selection, energy resource allocation, energy exploitation, energy policy, building energy management, and transportation energy systems, among others (Løken, 2007; Wang et al., 2009). Pohekar & Ramachandran (2004) and Klein & Whalley (2015) also used MCDA in sustainable planning, suggesting that it can provide solutions to problems involving conflicting and multiple objectives as well as in comparing energy technologies.

Other studies also employed Goal Programming (GP) in conjunction with MCDA (Jones & Tamiz, 2010). While MCDA is a widely acceptable tool to evaluate conflicting objectives, GP is an operations research tool that can mathematically calculate the optimization of multiple objectives and convert the weights from MCDA into an energy mix. Jayaraman et al. (2015) used weighted GP to determine the planning for suitable sustainable development goals in Gulf cooperation council countries. GP was used to integrate conflicting criteria on economy, energy, environment and social aspects. Cristobal (2012) also used GP for the decisions of the optimal mix of different plant types and the location of renewable energy in north Spain.

Combining both the MCDA and GP as tools, this study aims to formulate an optimal energy mix for Palawan Island that will address the conflicting preferences, values, and objectives of the energy stakeholders. In contrast to that of the Palawan Island Power Development Plan, the study will come up with a methodology that will consider all the preferences of the various decision makers and propose an energy mix that will be more acceptable to the energy stakeholders in the island.

Methodology

Method

The first step was to identify the energy problem and the stakeholders for the energy planning in Palawan. Then individual interviews were conducted with key decision makers from each stakeholder group in order to gather their objectives on solving the energy problem. Using Keeney's Value Focused Thinking technique and mind mapping to differentiate the fundamental and means objectives, an equivalent attribute for each means objectives was obtained. A second interview was done to obtain the individual preferences of the decision makers representing the stakeholders. The individual preferences were based on the weights of each attribute using Swing Weight method. This was to ensure that each decision maker's preferences were accounted for, from the most to the least important objectives. Goal Programming was then used to calculate the optimal energy mix for Palawan based on the decision maker's weight input and the limitations of each energy technology (see Annex 1). In the end, the resulting optimal energy mix was compared to the energy mix based on the PIPDP energy plan and another energy mix based on the direct preferences of the decision makers on the energy technology.

Respondents

The energy planning stakeholders in the province who were considered in the study include the local government units as representatives of the people of Palawan (particularly the offices of the provincial governor and the city mayor), the environmentalists, the academe, and the research institutions in the province. The players that are directly in the power industry including power generation, distribution and transmission were also included as stakeholders. The institution from the National Government that has a direct influence on energy planning for Palawan was also listed as a stakeholder.

The respondents of the study were chosen from the various stakeholders. These respondents are the decision makers from the stakeholder groups (one to represent each group). They were determined based on their roles, contribution, and influence on the energy plan of Palawan. For the listing of stakeholders and the respective decision makers chosen, see Annex 2.

Data gathering instrument

For data gathering, a questionnaire was used to determine the objectives of the stakeholders. The questionnaire was pre-tested among energy engineering students and faculty for fluency and comprehensiveness. The first set of interviews with the respondents were conducted from September 2 to 9, 2016, with each interview lasting for 30 to 60 minutes. The stakeholders' objectives were organized to form a hierarchy of network objectives, and then each objective was assigned a quantifiable value (attribute) to represent this. The attributes were categorized into four aspects, namely, economic, environmental, social, and technological. The attributes for each aspect are as follows: economic – cost of electricity; environmental – greenhouse gas (GHG) emissions, air pollution, land use, and water consumption; social – job creation, fatality rates, and social acceptability; and, technological – respond time, capacity factor, efficiency, and supply risk (see Annex 3 for details of each attribute).

The second set of interviews was conducted to determine the preferences of each stakeholder based on the weights of each attribute. These were held from March 23 to 29, 2017 at 30 to 60 minutes per interview. For the weighting method, a swing weight method was employed. For each attribute, there was one attribute at best and the others at worst. Then the stakeholders were asked to assign weights to each alternative. Additive utility function was employed.

The data used for the GP were from the PIPDP. Only the conservative or business-as-usual scenario was used (based on the historical electricity consumption); the aggressive scenario (based on the increased entry of businesses and industries) was not included. The data used for the forecasted energy demand (i.e., 258.1 MW) was the computed data of the Joint Energy Development Advisory Group, the energy planning committee for the Palawan Development Plan. Meanwhile, the data for maximum potential resources for each energy technology were from different established studies (JEDAG 2014, JICA, DOE & PGP 2004, DOE 2016, 2015, 2012). The power plant technologies that were considered for the evaluation of the energy mix allocation were biomass, coal, geothermal, large hydropower (dam), small hydropower (run-of-river), natural gas combined cycle, nuclear, offshore wind, onshore wind, concentrated solar power, solar photovoltaic panels, and piston engines (diesel and gas). For the listing of energy technologies, see Annex 4.

Goal Programming was used to compute the optimal energy mix for Palawan in megawatts for each energy technology. The objectives functions were defined by each stakeholder's weights, and formulated mathematically. In this study, the weights for each stakeholder are equal. Then the Goal Programming was a single composite function in order to find the optimum solution (see Annex 1).

For the verification of the proposed methodology, the output energy mix was compared through utility calculation to the energy mix of direct preferred energy mix of decision makers and the energy mix of the PIPDP as seen in the report. The result of the study must be an optimal energy mix that will address the preferred attributes of decision makers. Finally, the optimal energy mix was compared with the energy mix of the PIPDP and the preferred mix by the decision makers through utility calculation.

Results

Objectives and Attributes

Based on the interviews conducted, the different stakeholders from Palawan have varying objectives that are often conflicting with each other. These objectives and their corresponding attributes are summarized in Table 1.

Table 2 shows the key words used by the decision makers in the interviews. The key words were either direct or indirect. Direct words refer to those when the decision maker explicitly defined the objective. Indirect words were those whose context was close to the attribute. Thus, if a decision maker said that one of his objectives is to comply with DENR, this was taken to mean compliance to GHG emission, total air pollution, and water use as mandated by DENR. Zoning usually refers to land use; effectivity of the system means reliability and dependability.

Table 1. Decision Makers' Objectives and their Corresponding Attributes

Lowest Level Means Objectives	Attributes
Lower electricity rates/affordable electricity	LCOE
Comply with DENR/ Minimize carbon footprint	GHG Emission
Comply with DENR/Minimize air pollution	Air Pollution
Comply with ECAN zoning	Land Use
Comply with DENR	Water Consumption
Create additional employment	Job Creation
Ensure safety of technologies	Fatality Rates
Social acceptance on technologies	Social Acceptability
Reliability of electric supply/24 hours supply	Respond Time
Dependable electricity	Capacity Factor
Power generation to run at optimal MW	Efficiency
Use indigenous resources/Availability of energy technology	Supply Risk

Table 2. Summary of Objectives Included in the Interview of Each Decision Maker

Attribute\Decision Maker	Energy Planning	City Mayor	Distribution	Generation	Research &Regulatory	Environ-mentalist	Academe	Private generation and consumer	NEA	DOE
Cost of Electricity	***	***	*	***	***	***		*	*	*
GHG Emission	***	*	*	***	***	*	*	***	*	*
Air Pollution	*	*	*	*	***	***	*	***	*	*
Land Use	*	*	*	*	***	*	*	*	*	*
Water Consumption	*	***	*		*	*		*		
Job Creation	***	***	***				*			***
Fatality Rates		***			***	***		***		*
Social Acceptability		*			***				***	
Respond Time	*	*	*	***	***					*
Capacity Factor	*	*	*	*			***			***
Efficiency			***	***					***	***
Supply Risk	***	***						*		***

Legend: *** Direct words used in the interview
* Indirect, but contextual

Weight Assignment per Attribute by Decision Makers

The preferred attributes of the decision makers were determined using the swing weight method. The twelve (12) attributes have numerical values that are most preferred and least preferred. For example, the most preferred value for the cost of electricity is the smallest value because it reflects the objective of minimizing the cost of electricity. Then the least preferred values were benchmarked as the worst attribute, which would also be the last alternative. Then, the decision makers were asked to rank their preferred attributes, from the highest priority to the lowest. The decision makers rated each ranked attribute based on the difference of the values from best to worst. Table 3 summarizes the rate of the attributes of the decision-makers, where 100 is the most preferred and the next weight is based on the importance of the attribute on the swing or change of the value from best to worst.

Calculation of Processed Weight Preferences to be used in Goal Programming

Using calculation from MCDA to determine the distance of the weights for each decision maker and assuming a linear utility function, utility values were calculated using the following formula:

$$u(x_i) = (x_i - x_{min})/(x_{max-}x_{min})$$

This formula makes the lowest value as zero and the highest value as one. Table 3 shows the transformed utility weights.

Table 3. Rate of the Attributes for Each Decision Makers

Attribute\Decision Maker	City Mayor	Distribution	Energy Planning	Environ-mentalist	Academe	Provincial Government	Research &Regulatory	NEA	Generation	DOE
Cost of Electricity	78	100	78	92	100	87	93	82	88	75
GHG Emission	80	80	100	100	85	78	85	96	96	78
Air Pollution	85	80	90	93	60	80	90	98	94	70
Land Use	84	65	75	95	50	83	75	90	98	80
Water Consumption	73	65	70	94	70	84	70	92	100	85
Job Creation	75	70	74	70	20	88	70	88	92	88
Fatality Rates	77	75	50	73	40	85	65	100	90	65
Social Acceptability	83	75	88	75	40	89	95	94	86	90
Respond Time	100	95	85	79	90	95	95	86	80	100
Capacity Factor	95	78	83	80	70	93	85	84	82	95
Efficiency	90	78	82.5	85	60	90	90	78	78	94
Supply Risk	70	60	79	74	50	86	95	80	84	68

Table 4. Preferred Weights of Decision Makers transformed into Utility Value

Attribute\Decision Maker	City Mayor	Distribution	Energy Planning	Environ-mentalist	Academe	Provincial Government	Research &Regulatory	NEA	Generation	DOE
Cost of Electricity	0.27	1.00	0.56	0.73	1.00	0.53	0.93	0.18	0.45	0.29
GHG Emission	0.33	0.50	1.00	1.00	0.81	0.00	0.67	0.82	0.82	0.37
Air Pollution	0.50	0.50	0.80	0.77	0.50	0.12	0.83	0.91	0.73	0.14
Land Use	0.47	0.13	0.50	0.83	0.38	0.29	0.33	0.55	0.91	0.43
Water Consumption	0.10	0.13	0.40	0.80	0.63	0.35	0.17	0.64	1.00	0.57
Job Creation	0.17	0.25	0.48	0.00	0.00	0.59	0.17	0.45	0.64	0.66
Fatality Rates	0.23	0.38	0.00	0.10	0.25	0.41	0.00	1.00	0.55	0.00
Social Acceptability	0.43	0.38	0.76	0.17	0.25	0.65	1.00	0.73	0.36	0.71
Respond Time	1.00	0.88	0.70	0.30	0.88	1.00	1.00	0.36	0.09	1.00
Capacity Factor	0.83	0.45	0.66	0.33	0.63	0.88	0.67	0.27	0.18	0.86
Efficiency	0.67	0.45	0.65	0.50	0.50	0.71	0.83	0.00	0.00	0.83
Supply Risk	0.00	0.00	0.58	0.13	0.38	0.47	1.00	0.09	0.27	0.09

Energy Mix Output of Goal Programming

The target goals used for this scenario are the most preferred value for each energy mix. This means that each objective is optimized. Table 5 shows the attributes and the numerical value used as target goals in goal programming.

Based on Goal Programming, the resulting optimal energy mix for Palawan is as follows: 69% hydropower run of river, 1% hydro dam type, and 30% natural gas (see Figure 1).

The assumption used is that the weighting of each decision maker is of equal weights. For the equal weights of decision makers, the highest weight of rating of attribute comes from the ability to respond to demand (0.72), GHG emission (0.632), LCOE (0.594), air pollution (0.58), and capacity factor (0.576). For the energy technology, hydropower run-of-river has four best attributes, the lowest GHG emission, and the lowest air pollution. Moreover, it has a high ability to respond to demand, high efficiency, and low supply risk.

Table 5. Numerical Value of each Attribute used as Target Goals in the Goal Programming

Attribute	Unit	Objective	Goals
Electricity Cost	(dollars/MWh)	Minimize	37.9
Greenhouse Gas Emission	(gCO_2eq/kWh)	Minimize	2.75
Air Pollution	(mg/kWh)	Minimize	21
Direct Land Use	(m^2/GWH)	Minimize	0.0527
Water Consumption	(L/MWh)	Minimize	0.14
Job Creation	(Job years/ GWh)	Maximize	0.87
Accident-related Fatality	(rates/TWh)	Minimize	0.13
Social Acceptability	(%)	Maximize	1
Ability to Respond	(%)	Maximize	1
Capacity Factor	(%)	Maximize	85
Efficiency	(%)	Maximize	88
Supply Risk	(%)	Minimize	0

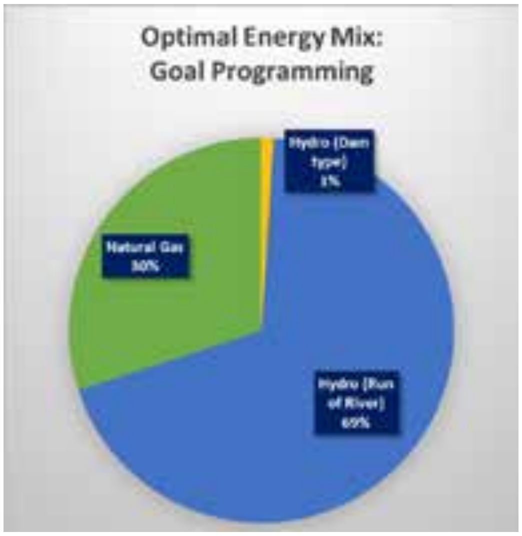

Figure 1. Optimal Energy Mix Output from Goal Programming using Optimized Objectives

When comparing the optimal energy mix with the preferred energy mix of decision-makers and the PIPDP's, there is a large difference in the resulting energy mix. Only few energy technologies are included in the optimal energy mix and that of the PIPDP, while in the decision-makers' preferred energy mix, all energy technologies have values. This was because in the decision-makers' energy mix, the decision-makers based their preference solely on the energy technology. In the optimal energy mix using MCDA and GP, the individual decision makers based the energy mix on the weights of each objective represented in the attributes (Figure 2).

resulting optimal energy mix computed for the island is 69% hydropower run-of-river, 1% hydro dam type, and 30% natural gas.

To validate the optimal energy mix computed through Goal Programming, the utility value of each attribute was calculated and compared. Utility value reflects how well the objectives for each energy mix are satisfied overall. In terms of utility calculation, the optimal energy mix is 4.491, which is better than the decision-makers' preferred energy mix value of 3.755, and that of the Palawan Island Power Development Plan which has a value of 4.178 (see Annex 5). This means that the overall achievement of objectives for the energy mix resulting from this study is greater than those of the other energy mixes formulated from the two other methods mentioned. The results showed a lesser value in cost, greenhouse gas, air pollution, land use, water consumption and accident-related fatalities; and higher value in social acceptability, capacity factor and efficiency as compared to the decision-makers' preferred energy mix. However, there is a lesser value in job creation, response time, and a higher value in supply risk. As compared to the PIPDP energy mix, the optimal energy mix also showed advantages in terms of electricity cost, air pollution, accident-related fatality, and social acceptability, ability to respond to demand, capacity factor and efficiency. Its disadvantages,

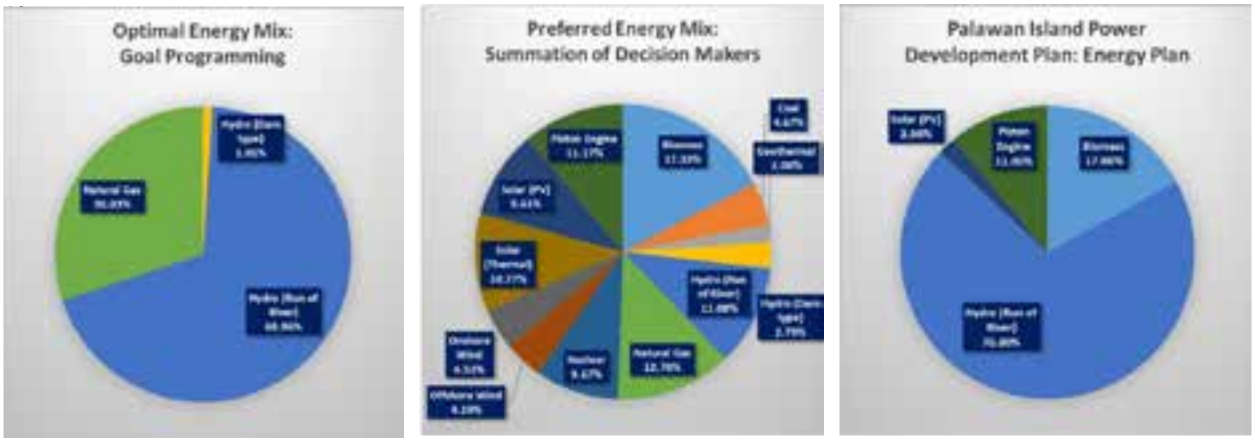

Figure 2. Comparison of Optimal Energy Mix generated through GP, Decision-makers' Preferred Energy Mix and PIPDP Energy Mix for Power Generation

Discussion

Energy planning is often done with one or two objectives, and the popular objective is usually the least cost solution. However, Løken (2007) and Malkawi et al., (2017) show that decision-makers often have a list of objectives that are quite often conflicting. This was revealed to be true in this study, as indeed the decision-makers in Palawan also have conflicting objectives. In any case, as these objectives all need to be considered in the energy planning, the conflicting objectives were integrated using Multi Criteria Decision Analysis and Goal Programming for mathematical computations. From this, the again as compared to the PIPDP's energy mix, include increased greenhouse gas emission, land use, water use, low job creation and high supply risk.

These results show that different energy mix results in different calculations of the utility value of the attributes. It is in the decision-maker's capacity to include a target or goal which is acceptable to the stakeholders. The stakeholders must have a very good knowledge of each attribute and to understand that there is always a compromise between the attributes. Since the GP maximizes or minimizes the attribute, it calculates the highest utility of the entire list of attributes. This means that the GP does not have any preference for one attribute over another but instead processes these as a whole. However, it will be limited by the energy resource availability.

This study has several limitations. First, equal weights were given to each of the decision makers. In real-world situations, decision makers often do not have equal capabilities to influence or implement decisions. Though decisions do not necessarily depend on one decision maker alone, certain decision makers may have more power to influence the outcome of decisions. Thus, different weights must be considered for different decision makers. Second, the study used numerical values (for each energy technology) based on US and European studies and other data available from literatures. It is advisable that data for the Philippine setting must be established and used to calculate the optimal energy mix accurately. Third, this study focused only on energy technology for electricity generation; it did not calculate the forecasted energy demand, potential energy resources and values of each attribute for the energy technologies, schedule, nameplate rating, and location of building an electricity generation. Finally, the study did not include the transmission and distribution plan for the energy grid; separate studies must be done to acquire accurate data for these.

Conclusion

Traditional energy planning focused on delivering the demands at the lowest cost; but as sustainability becomes a global mission, energy planning must also include environmental, social, and economic considerations, as voiced out by the different decision makers. This study's proposed method for energy planning in Palawan using MCDA and GP factored the different and conflicting objectives of the various decision makers. Moreover, by using Goal Programming, the method came up with an optimal energy mix that is able to meet the set objectives in such a way that maximizes utility value, as compared to both the PIPDP's energy mix and the preferred energy mix by the decision makers.

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Annex I. Goal programming method

The general form of goal programming is:

Minimize $\sum_i(d_i^+ + d_i^-)$
Such that $\sum_{j=1}^{n}(a_{ij}x_j)d_i^+ +$
And $x_j + d_i^+, d_i^- \geq 0$
Where:

d_i^-	amount by which goal i is underachieved
d_i^+	amount by which goal i is overachieved
x_j (j=1,2,.....,n)	variables in goal equation
b_i (i=1,2,.....,m)	targets or goals
a_{ij}	coefficients of variables

Decision Variables:
Let
x_i = Total amount of energy (in MWh) produced by energy technology where is from 1 to 12, and each corresponds to a technology
N_i = Minimum amount of electricity (in MW) produced by energy technology where is from 1 to 12, and each corresponds to a technology
M_i = Maximum amount of electricity (in MW) produced by energy technology where is from 1 to 12, and each corresponds to a technology

Objective Functions:
g_1 = Minimize total levelized cost of electricity (in $)
d_1^+ = Positive deviation (in $) from the targeted total levelized cost of electricity
d_1^- = Negative deviation (in $) from the targeted total levelized cost of electricity
g_2 = Minimize total life cycle greenhouse gas emissions (in g)
d_2^+ = Positive deviation (in g) from the targeted total life cycle greenhouse gas emissions
d_2^- = Negative deviation (in g) from the targeted total life cycle greenhouse gas emissions
g_3 = Minimize total air pollution (in mg)
d_3^+ = Positive deviation (in mg) from the targeted total air pollution
d_3^- = Negative deviation (in mg) from the targeted total air pollution
g_4 = Minimize direct operational land use (in m2)
d_4^+ = Positive deviation (in mg) from the targeted direct operational land use
d_4^- = Negative deviation (in mg) from the targeted direct operational land use
g_5 = Minimize on site direct operational water consumption (in L)
d_5^+ = Positive deviation (in $) from the targeted on-site direct operational water consumption
d_5^- = Negative deviation (in $) from the targeted on-site direct operational water consumption
g_6 = Maximize number of employees per unit of electricity produced (in job years)
d_6^+ = Positive deviation (in %) from the targeted employees per unit of electricity produced
d_6^- = Negative deviation (in %) from the targeted employees per unit of electricity produced
g_7 = Minimize accident-related fatality (in rates)
d_7^+ = Positive deviation (in %) from the targeted accident-related fatality
d_7^- = Negative deviation (in %) from the targeted accident-related fatality
g_8 = Maximize social acceptability level
d_8^+ = Positive deviation (in %) from the targeted social acceptability level
d_8^- = Negative deviation (in %) from the targeted social acceptability level
g_9 = Maximize ability to respond to demand
d_9^+ = Positive deviation (in %) from the targeted ability to respond to demand

d_9^- = Negative deviation (in %) from the targeted ability to respond to demand
g_{10} = Maximize capacity factor (in %)
d_{10}^+ = Positive deviation (in g) from the targeted capacity factor
d_{10}^- = Negative deviation (in g) from the targeted capacity factor
g_{11} = Maximize efficiency (in %)
d_{11}^+ = Positive deviation (in mg) from the targeted efficiency
d_{11}^- = Negative deviation (in mg) from the targeted efficiency
g_{12} = Minimize external supply risk
d_{12}^+ = Positive deviation (in mg) from the targeted external supply risk
d_{12}^- = Negative deviation (in mg) from the targeted external supply risk

Constraints:

a_{1j} = Levelized cost of electricity (in $/MWh) produced by energy technology where is from 1 to 12, and each corresponds to a technology
a_{2j} = Life cycle greenhouse gas emissions (in g/MWh) produced by energy technology where is from 1 to 12, and each corresponds to a technology
a_{3j} = Air pollution (in mg/MWh) produced by energy technology where is from 1 to 12, and each corresponds to a technology
a_{4j} = Direct operational land use (in m²/MWh) of energy technology where is from 1 to 12, and each corresponds to a technology
a_{5j} = Direct operational water consumption (in L/MWh) of energy technology where is from 1 to 12, and each corresponds to a technology
a_{6j} = Number of employees (in job years/MWh) required for energy technology where is from 1 to 12, and each corresponds to a technology
a_{7j} = Accident-related fatalities (in rates/MWh) that occur for energy technology where is from 1 to 12, and each corresponds to a technology
a_{8j} = Social acceptability level of energy technology where is from 1 to 12, and each corresponds to a technology
a_{9j} = Ability to respond to demand (in %) of energy technology where is from 1 to 12, and each corresponds to a technology
a_{10j} = Capacity factor (in %) of energy technology where is from 1 to 12, and each corresponds to a technology
a_{11j} = Efficiency (in %) of energy technology where is from 1 to 12, and each corresponds to a technology
a_{12j} = External supply risk (in %) of energy technology where is from 1 to 12, and each corresponds to a technology
g = Forecasted energy demand

Objective Functions:

$$\text{Min } z = W_1\left(d_1^+ + d_1^-\right) + W_2(d_2^+ + d_2^-) + W_3\,(d_3^+ + d_3^-) + W_4(d_4^+ + d_4^-) + W_5\left(d_5^+ + d_5^-\right) + W_6(d_6^+ + d_6^-) + W_7\,(d_7^+ + d_7^-) + W_8(d_8^+ + d_8^-) + W_9\left(d_9^+ + d_9^-\right) + W_{10}(d_{10}^+ + d_{10}^-) + W_{11}\,(d_{11}^+ + d_{11}^-) + W_{12}(d_{12}^+ + d_{12}^-)$$

Subject to:

$$\left(\sum_{j=1}^{12} a_{1j}x_j\right) + d_1^+ + d_1^- = g_1$$

$$\left(\sum_{j=1}^{12} a_{2j}x_j\right) + d_2^+ + d_2^- = g_2$$

$$\left(\sum_{j=1}^{12} a_{3j}x_j\right) + d_3^+ + d_3^- = g_3$$

$$\left(\sum_{i=1}^{12} a_{4j}x_i\right) + d_4^+ + d_4^- = g_4$$

$$\left(\sum_{j=1}^{12} a_{5j}x_j\right) + d_5^+ + d_5^- = g_5$$

$$\left(\sum_{i=1}^{12} a_{6j}x_i\right) + d_6^+ + d_6^- = G_6$$

$$\left(\sum_{j=1}^{12} a_{7j}x_j\right) + d_7^+ + d_7^- = G_7$$

$$\left(\sum_{j=1}^{12} a_{8j}x_j\right) + d_8^+ + d_8^- = g_8$$

$$\left(\sum_{j=1}^{12} a_{9j}x_j\right) + d_9^+ + d_9^- = g_9$$

$$\left(\sum_{i=1}^{12} a_{10j}x_i\right) + d_{10}^+ + d_{10}^- = g_{10}$$

$$\left(\sum_{j=1}^{12} a_{11j}x_j\right) + d_{11}^+ + d_{11}^- = g_{11}$$

$$\left(\sum_{i=1}^{12} a_{12j}x_i\right) + d_{12}^+ + d_{12}^- = g_{12}$$

Constraints:

$$\left(\sum_{j=1}^{12} x_j\right) = g$$

$$x_i \geq N_i\,, x_i \leq M_i;\ \forall\, i = 1,\ 2, \dots,\ 12$$

$$x_i \leq x_i\ \ \forall\, i = 1,\ 2, \dots,\ 12$$

Annex 2. Stakeholders, and key decision makers and their roles in energy planning in Palawan

Stakeholders	Key decision makers	Functions in relation with energy planning
Provincial LGU	Office of the Provincial Governor	Prioritizes and plans projects within the province (including energy)
PIPDP - JEDAG	Energy Advisor	Gives advice on energy plan and forms a Technical Working Group (TWG) under the PIPDP
City LGU	Office of the City Mayor	Approves the business permits for power sector in the city; Prioritizes and plans projects within the city (including energy)
Environmentalists	Executive Director	An NGO concerned with the environmental policies mandated by law (applies for energy)
Academe	Dean	Conducts independent research on energy
Research	Director	Conducts independent research on energy; Regulatory body for environment/ welfare of Palawan
Power Generation	Division Manager	Oversees the operation and maintenance of electricity generation
Power Distribution	General Manager	Oversees the operation and maintenance of the electricity distribution
Energy Planning for Palawan	Deputy Administrator, Director	Oversees the energy plan for the region of Palawan
Private Industrial Company (with own power generation)	Engineer	Independent power consumer and producer

Annex 3. Identified aspects, attributes, and sources of secondary data used for calculations

Aspects	**Attribute/s**	**Sources of secondary data used for calculations**
Economic	Cost of Electricity	Levelized cost of electricity from (IEA & NEA, 2015)
Environmental	Greenhouse Gas (GHG) Emissions	All the life cycle greenhouse gas emission data came from (Klein & Whalley, 2015) except for the piston engine which came from (Gomelsky & Figueroa, 2012). Klein & Whalley used the data from NREL LCA Harmonization Project, except for binary geothermal and CSP technology.
	Air Pollution	The air pollution emission data came from Klein & Whalley (2015) and EEA (2008). Klein & Whalley used (Masanet et al., 2013) for the non-harmonized air pollution values across technologies that are based on IPCC 2011 Intergovernmental Panel on Climate Change. The total air pollution data for piston engine came from (Sims et al., 2007).
	Land Use	Land use data came from (Klein & Whalley, 2015). The direct land uses occupied by the power plant done by Klein & Whalley are estimates from different sources. Klein & Whalley used the formula for direct land use as equal to land area in meter square divided by the product of net rated capacity and the operating hours and the capacity factor of the plant. The run-of-river land use estimate came from (Flury & Frischknecht, 2012). For the land use of piston engines, the estimate was calculated using the formula: $Land\ Use = \frac{Land\ Area}{(Installed\ capacity\ x\ 365\ days\ x\ 24\frac{hours}{day}\ x\ Capacity\ factor)}$
	Water Consumption	The direct water consumption data came from (Klein & Whalley, 2015). For the hydropower dam type, the calculation was based on the operational water with a reservoir or dam while the run-of-river water consumption is based on the evaporation of the water in a run-of-river with a reservoir. This data was used for the comparison of water consumption only. The data used from Klein & Whalley was the median data from different plants in the US. The run-of-river water use estimate came from Flury & Frischknecht (2012). The diesel engine water use came from Gomelsky & Figueroa (2012), and used radiator cooling, closed system for light fuel oil.

Social	Job Creation	The job creation data came from (Maxim, 2014). The computation only included direct hire which was the number of people hired during the implementation and operation of the plant over the unit life cycle of the technology and did not include indirect and induced hires. Maxim (2014) used the data from Wei et al. (2010) for the technologies except for large hydro, which came from Navigant Consulting for the US National Hydropower Association.
	Fatality Rates	Fatality rates are deaths from accidents in the life cycle of an energy technology from manufacturing to decommissioning and the extraction of fuel. Klein & Whalley (2015) calculated the fatality rates data for the technologies which was sourced from (IPCC, 2011). The data for fatality rates for run-of-river and diesel engine were from Hirschberg et al. (2004).
	Social Acceptability	Seranilla (2017) has conducted a survey in Puerto Princesa regarding the acceptance of energy technologies in Palawan. Maxim (2014) has the data for social acceptability of each energy technology. The data came from different surveys of the public regarding the favorability of an energy technology. The social acceptability parameters are high, medium, and low, which were translated in 1, 0.5 and 0, for the numerical equivalent. It can be noted that, the two studies are different in Natural Gas and Piston Engine.
Technological	Respond Time	The data for the ability of each energy technology to respond to the given demand came from Maxim (2014). There are three parameters used: the "yes, rapid" which means that the energy technology can supply the demand immediately; the "yes, slow" which means that the technology can supply the demand but needed a certain time; and the "no" which means the technology cannot supply electricity on demand. This translates to numerical value as 1, 0.5 and 0.
	Capacity Factor	The data for capacity factors of energy technologies also came from Maxim (2014). Capacity factor is the ratio of actual energy produced during a period over the maximum theoretical technical nameplate capacity at full load during the entire period. Maxim (2014) gathered this data from IEA 2011a, IEA, NEA, OECD 2010. The capacity factor data (Department of Energy – Electric Power Industry Management Bureau, 2015) was computed using the: $Capacity\ factor = \frac{Gross\ Generation}{Installed\ capacity\ x\ 365\ days\ x\ 24\ hours/day}$
	Efficiency	Efficiency data values came from Raj Thangavelu (2015). Efficiency is defined as how well the energy input usually in the form of fuel and other energy technologies, can be transformed into the electricity output of the energy technology.
	Supply Risk	Maxim's (2014) data for supply risk was based on Le Coq & Paltserva (2009) and the risk assessment included import dependence, supplier diversification, transit risk, fungibility of supply, etc. External supply risk means the percentage of an energy technologies availability and prices of fuel supply to be affected heavily by imports, thus risking the operation of a power plant. Lower external supply risk entails greater energy security while higher supply risks impose low energy security.

Annex 4. Energy technology considered in energy planning and their references

Energy technology	**MW**	**Sources**
Biomass Plant	50	Palawan Island Power Development Plan FY 2014-2035
Coal Plant	Max	Technology can match the demand.
Geothermal Plant	1	Matias, 2011
Large Hydropower Plant (Dam)	2.609	JICA, DOE, and PGP, Final Report of "The Master Plan Study of Power Development in Palawan Province," Sept. 2004
Small Hydropower Plant (Run of River)	182.47	Palawan Island Power Development Plan FY 2014-2035 (Sourced at: JICA, DOE, and PGP, Final Report of "The Master Plan Study of Power Development in Palawan Province," Sept. 2004)
NGCC Natural Gas Combined Cycle	Max	Technology can match the demand.
Nuclear Power Plant	Max	Technology can match the demand.
Offshore Wind Plant	10	Department of Energy: Philippine Energy Plan
Onshore Wind Plant	10	Department of Energy: Philippine Energy Plan
Concentrated Solar Power	13	Palawan Island Power Development Plan FY 2014-2035 (Sourced at: Department of Energy)
Solar Photovoltaic Panels	13	Palawan Island Power Development Plan FY 2014-2035 (Sourced at: Department of Energy)
Piston Engines (Diesel, Gas)	Max	Technology can match the demand.

Annex 5. Multi-attribute Utility Value Computation

The utility functions for each attribute are scaled from 0 (worst value) to 1 (best value) Clemen & Reilly (2014). Using utility calculation from MCDA to determine the utility function, the following formula was used:

$U_i(x_i) = (x_i - x_{min})/(x_{max-}x_{min})$ for maximizing the attribute

$U_i(x_i) = (x_{max} - x_i)/(x_{max-}x_{min})$ for minimizing the attribute

The Utility Value is computed as:

$$U_T(x_i \ldots . x_n) = w_1U_1(x_1) + \ldots + w_nU_n(x_n)$$

Where: $U_i(x)$ is the utility value of an attribute
w is the weight of the decision makers