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Optimal Multi-criteria Selection of Hybrid Energy Systems for Off-grid Electrification

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Energy poverty or lack of access to electricity is still a pressing development challenge worldwide particularly in archipelagic countries like the Philippines and Indonesia. As rural electrification in these remote areas through on-grid extension becomes costly, these communities typically resort to diesel-powered off-grid generators, characterized by high operating costs, unstable supply and price of fuel, and environmental issues. The deployment of clean energy alternatives is clearly needed, but these must be selected systematically using multiple but possibly conflicting criteria. Currently, the decision on which technology to use is derived based on the levelized cost of electricity primarily. In this illustrative case study, a novel multi-criteria decision-making methodology is proposed for the selection of the most appropriate energy system for the off-grid electrification of Marinduque Island. Eight technology combination options were evaluated using six criteria covering socio-economic, environmental, and technical aspects. Fuzzy AHP was used to derive weights of the criteria while addressing ambiguity and subjectivity of decision-makers. Performances of the technology options across different criteria were determined quantitatively via techno-economic simulations, or qualitatively via domain expert estimates. Grey Relational Analysis (GRA) was then used to aggregate the entire range of performance attributes of each alternative into a single score. Results indicate that system reliability and social acceptability are the most important criteria in selecting hybrid energy systems for off-grid electrification. Among the eight alternatives, the fuel saver (diesel-solar PV hybrid) and diesel-solar PV-Li-ion hybrid systems yield the highest performance scores. The prioritization was mainly affected by system reliability and social acceptability, indicating that decision making for the attainment of sustainable island energy supply should not be limited to technical and economic considerations only. This is consistent with the current worldwide trend of implementing the diesel-solar PV-Li-ion hybrid systems in off-grid areas, thus, validating the applicability of the facile methodology developed in this work.

1. Introduction

Access to electricity is among the main drivers of human and technological development, economic growth, and environmental sustainability (International Energy Agency, 2017). According to World Bank, in 2014, about 10.87 % of the total population of the Philippines lacks access to electricity, resulting from geographic barriers brought about by its archipelagic structure. This has largely suppressed the socio-economic growth of the marginalized sectors in remote areas. These off-grid sites are mostly located in the bigger islands or small islands where on-grid extension is deemed infeasible due to high costs, high system losses, challenging geography, and possible destruction of local natural resources. Hence, there is a clear need for deploying sustainable off-grid energy systems.
Majority of off-grid energy systems installed in these areas are small, conventional diesel-powered plants providing electricity at limited hours with a high generation cost, and greenhouse gas emissions (Blum et al.,

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2013). Moreover, the increased dependence on non-renewable energy sources lead to energy unsustainability. To combat this, increased penetration of renewable energy sources is considered an important solution for future energy sustainability (Choi et al., 2017). A major drawback on the increased renewables penetration; however, is the power system instability brought about by the intermittency of renewable energy supply. Thus, Hybrid Renewable Energy System (HRES) is proposed for incorporating renewable energy sources, such as but not limited to solar photovoltaics (PV) and wind power generators, supported by a diesel power generator as backup during renewable energy shortage coupled with a battery energy storage system (BESS) for stabilizing off-grid power supply and for storing excess PV power (Chang, 2015). The wide-range of technological options (i.e., many BESS chemistries and renewable energy resource options) necessitates the selection of the most appropriate energy system applicable for any specific location. To this end, multiple and possibly conflicting criteria will have to be balanced according to the priorities of decision-makers, e.g. policy makers, regulatory agencies, electric cooperatives, investors, residents, etc. (Promentilla et al., 2015). The consideration of several dimensions in the decision-making structure gives rise to several complexities requiring systematic decision aids (Munoz et al., 2013). Thus, leading to the use of Multi-Criteria Decision Making (MCDM) tools for a rational approach to the decision-making problem.

Analytic Hierarchy Process (AHP) is a widely utilized decision-making tool originally developed by Saaty (1977) to derive ratio-scale priorities from pairwise comparison judgments. AHP's applicability, however, is limited due to its inability to account for vagueness associated with data gathered from subjective and personal judgments of decision-maker Hence, the use of Fuzzy AHP (FAHP) is imperative to address these limitations (Promentilla et.al, 2015). Additionally, Grey Relation Analysis (GRA) also serves as another methodology to determine the desirability of an alternative through its similarity or closeness to an ideal reference sequence across different criteria (Eusebio et.al, 2016).

In this study, a novel methodology for the selection of the most appropriate energy system among eight possible alternatives for off-grid electrification is presented to address the research gap on the systematic selection process among alternative hybrid energy systems, battery energy storage systems, and other similar technologies. Optimized Levelized Cost of Electricity (LCOE), carbon footprint during operation, and system reliability were calculated from the techno-economic calculations using an in-house HOMER®-like and HOMER®-validated program (Island System $LCOE_{min}$ Algorithm or ISLA) capable of simulating the operation of the microgrid and optimizing the sizes of the components to minimize the LCOE. Flexibility for future expansion, ease of installation and operation, and social acceptability were derived from expert interviews. FAHP was used to determine the crisp priority weights of each of the six criteria obtained from expert judgments. By performing Grey Relation Analysis (GRA), a single score is derived through the aggregating of the performance attributes of each technology option. GRA was selected to greatly reduce data inputs and to reduce tedious mathematical processes as this tool is suitable for solving problems with complicated interrelationships among multiple factors and variables (Kuo, et al., 2008).

2. Methodology

The detailed steps of the proposed multi-criteria decision-making framework for microgrid system selection in outlined as follows:

Step 1. Decision problem was organized in a hierarchical structure as shown in Figure 1 starting from first level (blue solid line) with the primary objective of selecting the most appropriate energy system for off-grid electrification. The following level (solid gray line) are sets of criteria used for the selection of alternatives, with each criterion having different local priorities (i.e., numerical representation of the level of importance such that the higher the numerical value, the higher the importance; consequently, the greater local priority in the decision-making process) with respect to the objective, the values of which were elicited from the judgment of decision-makers. Lastly, on each criterion, the performance attribute of each alternative was determined using GRA. The overall methodology layout is shown in Figure 2. It involves independent calculations for performance attributes of alternatives per criterion, and the relative importance of each criterion with respect to the overall objective. The results from each calculation were then processed in a single calculation process to yield the prioritization of alternatives with respect to the overall objective.

$$\widehat{a_{ij}} = \langle l_{ij}, m_{ij}, u_{ij} \rangle;\ m_{ij} = \prod (a_{\mathrm{ij}})^{\frac{1}{\alpha}};\ u_{ij} = \max(a_{ij})\,;\ l_{ij} = \min(a_{ij}) \tag{1}$$

Step 2. Value judgments were elicited from domain experts, stakeholders, and other decision-makers regarding the relative importance of one criterion over another in a pairwise fashion using the 9-point linguistic scale presented in Saaty (1980). The value of the judgments obtained from α experts is represented by a grouped triangular fuzzy number $(\widehat{a_{ij}})$ given by Equation 1. The lower bound of the fuzzy number (l_{ij}) represents the minimum value judgment elicited while the upper bound (u_{ij}) represents the maximum value judgment elicited. The modal value (m_{ij}) is obtained using the geometric mean method.

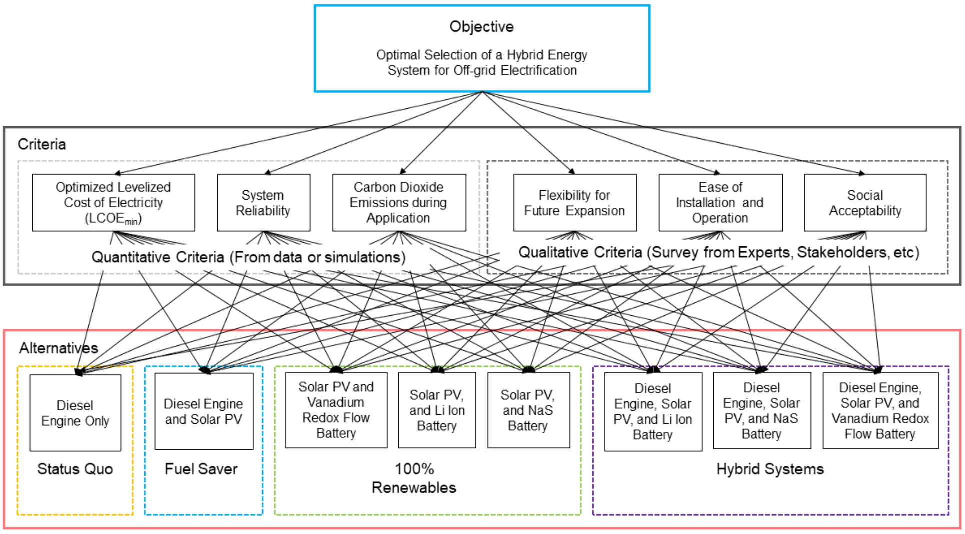

Figure 1: Hierarchical Decision Structure

Step 3. FAHP was applied to determine the crisp priority weights of each criterion with respect to the goal through a non-linear fuzzy preference programming approach discussed thoroughly in Promentilla et al. (2015). Step 4. Performance attributes of alternatives were evaluated depending on the nature of the criterion. Qualitative criterion scores, elicited from domain experts, reflect the desirability of an alternative in comparison to the ideal alternative using a 5-point scale system (1 being the least desired and 5 being the ideal alternative). Quantitative criteria, $LCOE_{min}$ and system reliability, were obtained by performing techno-economic calculations in ISLA based on the actual power demand of Marinduque Island yielding results such as optimized sizing of the hybrid configuration generating the $LCOE_{min}$, percentage renewables penetration, and energy flows, and the corresponding system reliabilities associated with the energy system configuration. Fuel requirement for the operation for the microgrid operation in ISLA were then used to estimate the carbon dioxide emissions.

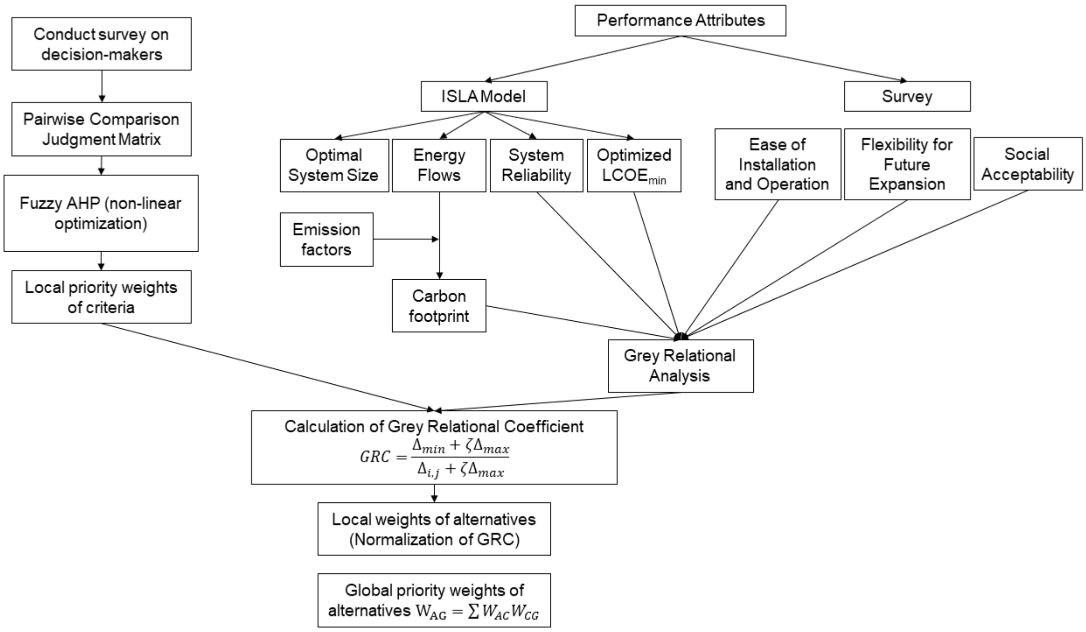

Figure 2: Overall methodological structure.

Step 5. GRA was applied to derive the grey relational coefficient (GRC) i.e., the closeness of the alternative to the ideal alternative, a detailed procedure of which can be found in Kuo et al. (2008). A distinguishing coefficient (ζ) of 0.5 is used in this study as the distinguishing coefficient only determines the range of the resulting GRC and the use of any value does not affect the final ranking output (Kuo et al., 2008). Normalization of the resulting GRC yields the local weights of alternatives with respect to the goal. A summation of all the products of the local weight of a criterion and the local weight of an alternative on that criterion over the entire range of criteria results to the global priority weight of an alternative, allowing the ranking of different microgrids.

3. Illustrative case study: Off-grid electrification of Marinduque Island

Marinduque Island (13 °N 121 °E), which is located on the southern coast of Luzon, was selected because it is relatively huge off-grid island in the Philippines, experiencing frequent power interruptions brought about by the inadequacy of energy supply from four diesel power plants and one power barge. Moreover, the use of diesel-engine powerplants alone results to expensive costs, and high carbon emissions, thus penetration of renewable energy sources was seen to be among the possible solutions resolving the aforementioned issues. Due to the climate and year-round availability of sunlight in the Philippines, decreasing cost of solar PV panels, and scalability of solar PV plants, solar energy was chosen as the renewable energy source for off-grid electrification. Solar energy, however, is intermittent in nature thus battery energy storage systems were introduced. Eight alternatives were considered, namely: 1) Diesel Engine only (Status Quo); 2) Diesel Engine, and Solar PV (Fuel Saver); 3) Diesel Engine, Solar PV, and Li Ion; 4) Diesel Engine, Solar PV, and Na-S; 5) Diesel Engine, Solar PV, and VRF; 6) Solar PV, and Li Ion; 7) Solar PV, and Na-S; and 8) Solar PV, and VRF. These alternatives were scored based on six criteria, namely 1) Optimized Levelized Cost of Electricity ($LCOE_{min}$), 2) System Reliability, 3) Carbon Footprint during operation, 4) Flexibility for Future Expansion, 5) Ease of Installation and Operations, and 6) Social Acceptability.

Table 1: Optimal local priorities of each criterion with respect to the main objective

Ranking	Local Priority	Criteria
1	0.2423	System Reliability
2	0.2376	Social Acceptability
3	0.1536	Optimized Levelized Cost of Electricity ($LCOE_{min}$)
4	0.1404	Carbon Footprint during Operation
5	0.1323	Flexibility for Future Expansion
6	0.0938	Ease of Installation and Operation

Table 2: Performance attributes of alternatives

Criterion\Alternative	Diesel Engine	Diesel Engine and Solar PV	Diesel Engine, Solar PV, and LiIon	Diesel Engine, Solar PV, and NaS	Diesel Engine, Solar PV, and VRF	Solar PV, and Li Ion	Solar PV, and NaS	Solar PV, and VRF
$LCOE_{min}$ (USD/kWh)	0.365	0.357	0.350	0.344	0.350	0.430	0.377	0.420
System reliability	0.956	0.999	0.999	0.999	0.999	0.992	0.992	0.992
Carbon footprint during operation (kg CO_2/kWh)	0.264	0.175	0.168	0.149	0.169	0.030	0.061	0.031
Flexibility for future expansion	3.500	4.167	4.833	3.500	3.333	4.167	2.667	3.167
Ease of installation and operation	4.833	4.167	3.333	2.333	3.000	3.833	3.333	3.667
Social acceptability	3.667	3.833	3.500	2.333	3.167	3.667	2.833	3.500

FAHP was applied to the pairwise comparison judgment matrix elicited from decision-makers using MATLAB R2017b resulting to an overall consistency index of $\lambda = 0.688$ with the corresponding local priorities listed in Table 1. Results indicate that System Reliability and Social Acceptability are the two criteria greatly affecting the decision-making process. This reflects the importance of a reliable off-grid energy system, which are based on technologies that are locally understood and accepted. Knowledge of the locals on the technology greatly affects lifetime of the installed technology through its efficient operation and maintenance. Familiarity of the technology could be a key factor in the technology's social acceptance. System Reliability and Social

Acceptability are followed by $LCOE_{min}$, Carbon Footprint, Flexibility for Future Expansion, and Ease of Installation and Operation.

Values of each alternative under each criterion were then determined and listed in Table 2. ISLA was used to generate the optimal renewables mix (percentage renewables penetration) yielding the minimum costs associated with an energy system throughout the project lifetime, $LCOE_{min}$. ISLA model was also used to calculate the amount of electricity supplied from solar PV and diesel engine, and the amount of excess energy stored in the battery systems. Emission factors obtained from different studies (EPA, NREL, Hiremath 2015, etc.) were applied to the corresponding energy source from ISLA. These emissions were divided by the total energy output from the energy system to allow comparability. System reliability was calculated from the individual probabilities of failure of energy generating sources as reliability depends on the ability of the system to satisfy energy demand. And the last three criteria scores were elicited from domain experts using a 5-point scoring system determining the desirability of the alternatives.

Using GRA on the performance attributes of alternatives, the ranking of the alternatives was obtained and listed in Table 3. The impact of each performance attribute on the global ranking, which is the product of the local weight of the criterion and local weight of an alternative in that criterion, is depicted in the radar chart (Figure 3).

Table 3: Calculated global priority and ranking of energy systems

Ranking	Alternative	Global priority
1	Diesel and Solar PV	0.1500
2	Diesel, Solar PV, and Li Ion	0.1458
3	Solar PV, and Li Ion	0.1302
4	Diesel, Solar PV, and VRF	0.1233
5	Solar PV, and VRF	0.1188
6	Diesel, Solar PV, and NaS	0.1186
7	Diesel engine only	0.1080
8	Solar PV, and NaS	0.1053

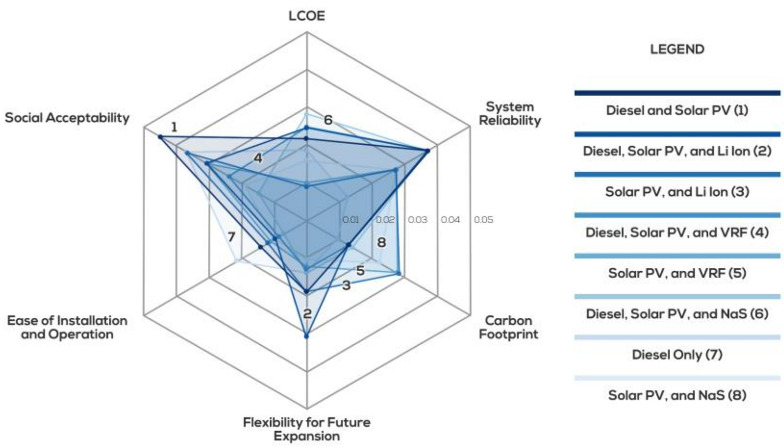

Figure 3: Radar chart on the performance attributes of alternatives

Diesel Engine installed with a solar photovoltaic (fuel saver) was determined to be the most applicable energy system for deployment in Marinduque Island with a global priority of 0.1500, closely followed by diesel-solar PV-battery hybrid system with a global priority of 0.1458. A major impact on the results is the high system reliability associated with systems involving parallel energy sources. This can be explained the ability of the system to still provide energy despite failure of one of the energy sources unlike single source systems. The diesel-solar PV system scored high in Social Acceptability due to the familiarity of the expert respondents on the technology components. It is because of this criterion that the fuel saver system gained a greater priority compared to the diesel-solar PV-battery hybrid system despite hybrid's lower costs and lower carbon emissions. There are distinct disadvantages on social acceptability of hybrid energy systems as the inclusion of developing technologies such as sodium sulfur and vanadium redox flow batteries introduce complexities thus lowering their preference despite promising features.

4. Conclusion

In this work, a novel methodology on the selection of the most appropriate technology option for off-grid electrification is presented. The overall decision-making structure is composed of two sections, namely: Fuzzy Analytic Hierarchy Process, and Grey Relational Analysis. The former was used to derive the crisp local priority weights of every criteria with respect to the goal through the application of a non-linear fuzzy preference programming on judgments elicited from domain experts and other decision-makers, and the latter to aggregate individual performance attributes of alternatives across different criteria into a single score. The results elicited from decision-makers yielded an overall consistency index of 0.688 with system reliability and social acceptability dominating all the other criteria followed by $LCOE_{min}$, carbon footprint, flexibility for future expansion, and lastly ease of installation and operation. Application of GRA on the performance attributes indicates fuel saver (diesel engine and solar PV) system to be the most appropriate energy system for off-grid electrification closely followed by a hybrid energy system (diesel engine, solar PV, and Li Ion). The selection of these alternatives was greatly influenced by the high system reliabilities, and high social acceptability rate despite having relatively high carbon emissions, and costs. Technologies accompanied by complexities and unfamiliarity to the general public greatly impacted the ranking of energy systems with battery energy storage systems despite promising features. The case study on Marinduque island exhibited the utility of the proposed methodology in ranking many technology options. These results are consistent with majority of new off-grid installations based on the solar saver configuration or the diesel-solar PV-Li-ion hybrid system configuration. Further, actions geared towards future sustainability should not be limited to developing and improving technology but also by minimizing the knowledge gap of the general public with technological advancements. Finally, the present multi-criteria approach for technology selection can be applied to other off-grid locations as well and could be improved by refining the problem structure and including interdependencies and performing sensitivity and uncertainty analyses.

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