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A multi-objective decision framework for the selection of feasible and viable hybrid renewable energy systems in energy-constrain communities

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Abstract: Choosing the appropriate system configuration that meets the multi-objective of profit-making and environmental protection is always a critical decision for both entrepreneurs and the government. The choice is complicated primarily if several possible alternatives exist. In this paper, a decision framework was developed to select from four configurations the configuration that best fits a decision-makers multi-objective of profit-making and environmental protection. It was found that, overall, the grid-connected PV-battery hybrid configuration, for now, offers the best fit to the desired profitability and CO_2 mitigation effort with a similarity index of 96.10%. Whereas for now, the standalone PV-batt configuration is only about 29.93% close to this desired objective. It is inferred, therefore, that the complete exclusion of conventional energy from the concept of sustainable energy, for now, leads to an unequivocal increase in installation costs, preventing investments in green technology, particularly in developing countries.

Keywords: hybrid energy system; techno-economic; multi-objective; CO_2 emission.

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1 Introduction

The building energy system must swiftly transform from the conventional energy system to zero or low carbon energy systems to stay within the scope of the Paris Convention, particularly the goal of reducing CO_2 emissions in the residential building sector by 28% by the end of 2025 (Goldstein et al., 2020). Consequently, the modern-day energy demand requires that power systems meet demand with high reliability in the most economical way and require that energy systems meet the multi-objective of resilience and environmental protection (Braun et al., 2020). These objectives are conflicting since renewable power technology, which forms the evolutionary backbone, is not fully developed, is randomly fluctuating in nature, and has not reached cost parity with the grid. This development has created an enormous challenge that has received considerable attention from policymakers and researchers alike. In line with cost reduction and safety objectives, energy systems gradually evolve from a comprehensive passive system generated over a long distance to independent and small smart grid systems closer to consumers (Das et al., 2016). The UK Government's blueprint, for instance, has shown its commitment to reducing the carbon content of its energy to at least 80% of its 1990 level by 2050 (NECP, 2019). This evolutionary change and transition witnessed in the power sector are mainly driven by the adverse effect of climate change due to the long-term impact of fossil-based energy activities (Gielen et al., 2019; Gu et al., 2018; Martins et al., 2018). Besides, recent indications have also shown global awareness created by the apparent effect of climate change resulting in huge losses arising from flooding in almost all major cities worldwide. This glaring effect of climate change has led to the need to reduce our over-dependence on fossil fuel technologies globally and accept renewables, particularly wind and solar, as alternatives for energy, despite the substantial initial investment in this option. The sudden realisation of the finite nature of even the fossil fuel reserve is also a significant factor in shaping the transition to alternative energy sources (Aziz et al., 2019; Ghenai and Bettayeb, 2019). As of 2017, the share of renewable in global power production has already risen to 26.5%.

There are currently different roadmaps and technical solutions to tackle the effects of increased demand for energy. In this respect, addressing building energy demand holds a critical and vital role in reducing the damages caused to our environment due to the increase in energy demand. Due to covid 19, the need for building energy has increased significantly, accounting for the global rise in the demand for power in the residential sector (Rouleau and Gosselin, 2021). As a result, the building's global carbon dioxide energy-related emission contribution may exceed its contribution of about 28%, as reported in 2019 (IEA, 2019). Furthermore, more than 65% of the carbon dioxide from the building sector is related to power consumption (IEA, 2019). For example, in the USA, the building energy requirement represents about 40% of its total energy requirement accounting for more than one-third of energy-related emissions (Ghenai and Bettayeb, 2019). For most developing countries, including Nigeria, the building energy demand represents more than 55% of the total power consumption (Olaniyan et al., 2018). Therefore, replacing buildings with renewable energy technologies will reduce carbon emissions in the global effort to produce cleaner, affordable and accessible energy for all in the future. In recent times, the use of the micro and intelligent grid for power use in different facilities is increasingly examined (Wu and Ren, 2017; Liu et al., 2018). Even old buildings that have already integrated into the grid power as the principal energy source are integrated with renewable energy sources to provide low-carbon energy and cost-effective solution that increases renewables in the building industry. Consequently, sustainable and environmentally friendly technologies, especially renewables and energy efficiencies, are expected in the transition roadmap to unleash a massive decline of about 500 million tonnes per year of energy-related emissions from the building sector between now and 2050 (IEA, 2019).

For now, electricity from the grid seems to be the cheapest energy source to satisfy energy demand. However, grid power is exceptionally unreliable and unsustainable in most developing countries, including Nigeria. Therefore, the hybrid energy system, which combines conventional and renewable energy systems, is unarguably the option that offers the best compromise between the economic and environmental protection in building energy systems (Aziz et al., 2019). Interestingly, the hybrid energy system also provides a better option to address the intermittent grid power fluctuations in energy-constrained communities. Even though hybrid renewable energy systems seem to offer a cost-effective alternative solution in energy-constrained and developing nations, several factors must be considered in deciding the most appropriate alternative technologies for applicability in these locations. The most beneficial energy technology with optimum energy and economic profitability is a good option in most cases. For example, good solar and wind resource areas may attract investment in solar and wind energy technologies. The social and environmental impact also determine the acceptability of decision-makers and the general public (Sliogeriene et al., 2013).

The size and nature of the load are another consideration in selecting the appropriate energy technology. For a small load, choosing technology with a low initial investment will be more appropriate than an investment with substantial initial capital. Undoubtedly, renewable energy technologies are yet to be at parity with grid power in most locations. Invariably, this assertion could be the cause of the slow pace at which renewable technologies are used to replace fossil energy technologies in most areas (Aly et al., 2019; Herrando et al., 2018; Okoye and Oranekwu-Okoye, 2018; Rodriguez-Hernandez et al., 2019). Besides, the low efficiency and high initial investment combined with little public awareness of the renewable energy system, especially wind and solar photovoltaics, remain a significant challenge (World Energy Council, 2016). Therefore, perhaps the solution is finding a reliable, viable, and environmentally friendly hybrid energy system to meet the building energy consumption of urban or rural facilities connected to the grid power characterised by frequent haphazard outages (Rodriguez-Hernandez et al., 2019). Therefore, considerable studies have tried to establish different techniques to determine the feasibility and viability of hybrid renewable energy systems compared to the conventional energy source in most locations.

Over the past decade, many research works have attempted to provide different solutions based on other objectives and applications. To solve the mismatch between building load and the energy supply from the hybrid energy system, Xu, Yan, and Jin (Murugaperumal and Raj, 2019) used the matrix approach to normalise the mathematical model that integrates the building energy utilisation processes with multiple renewable energy systems models. The unified and normalised system model was the basis for multi-objective optimisation of the building energy system that minimises the operating cost and initial investment. To validate the method, the author used the proposed approach to redesign the photovoltaic solar thermal hybrid energy system initially designed and installed in a small energy building in Beijing based on the conventional design method. The results revealed that the total life cycle investment of the original building energy system (BHS) was reduced by 14.9%.

In addition, there are many studies carried out in the literature that integrates different renewable energy technologies for separate applications. Murugaperumal and Raj (2019) used HOMER software to assess the feasibility and viability of an independent hybrid renewable energy system comprising a PV, wind turbine, and biomass array for applications in the remote village of Korkadu in India. In their approach, the developed hybrid power system was optimally dimensioned to meet load reliably based on the village's power demand of 179.23 kWh/day predicted utilising an artificial neural feedback network and Levenberg-Marquardtdata analysis. An economic study of the proposed hybrid energy system has shown that the system is viable with a net present cost of INR 1.21 million, translating to a one-unit energy generation cost of INR 13.71. Consequently, the authors concluded that the proposed optimal hybrid energy system is cost-effective based on the weather condition of the study location. Wang et al. (2019) used a two-stage decision-making framework for evaluating wind turbine-based hybrid energy system output for seaport use. In the two-stage decision framework, the various components of the hybrid subsystem were optimally tailored to an objective that minimises investment costs. The authors also used a simulation strategy to evaluate the seaport power requirement, as data are unavailable. Their report submitted that the methods could be employed to maximise the output of an onshore wind power system for application in the port.

Based on simulated performance employing HOMER software, Salisu et al. (2019) reported that a standalone hybrid PV-wind-diesel combined with the battery storage system as a backup is a viable energy alternative for Giri village of central Nigeria. From their results, an optimal hybrid system consisting of 160 kW of the entire PV array, a diesel generator of 50 kW capacity, and 320 units of 1 kWh battery is capable of meeting Agiri's village total power requirement of about 474.36 kWh/day with a peak of about 66.63 kWh/day and unit cost of energy (COE) of about 0.11 USD/kWh. Notably, in comparison, the COE of 0.11 USD/kWh is far less than the unit COE in some countries (Gbadegesin et al., 2019; Galvez et al., 2019; Dahmouni et al., 2011; Olatayo et al., 2018).

Hartner et al. (2017) studied the profit maximising of a rooftop grid-connected photovoltaic (PV) for more than 800 households in Austria based on different subsidy regimes, electric tariffs, and the benefits of investment in PV size within the size range of 1–20 kW. In their methodology, the researchers collected the load demand of 821 households within a 100 Km radius from the centre of Linz at a time step of 15 minutes of the load demand. The researchers implemented the model in a simulation tool to optimise the PV size. Each household was simulated separately under six different cost and three price scenarios. The objective was to maximise the PV system's internal return (IRR) rate based on individual household load profiles under subsidy and no subsidy assumptions. The authors argued that many factors ranging from simple load consumption style and electric tariff influence the required system size alongside the installation cost from the results obtained.

Several studies attempted to evaluate the economic viability of hybrid renewable energy systems under different climate conditions. For example, Krishan and Suhag (2019) evaluated the technical performance of a P.V./wind/battery hybrid energy system to find the most economically viable system architecture that meets the Yamunanagar district's agricultural and residential electric load demand in India using HOMER software. Also, the study implemented a MATLAB/Simulink model of the optimal system configuration to actualise the power balance of the various elements of the hybrid system. In one study, Kumar et al. (2019) used HOMER to find the optimal component sizes of a solar P.V./battery system integrated into a grid with a limited but scheduled power outage. The study opines that flexible load shifting based on demand response management effectively reduces system size and overall levelised cost of energy (LCOE).

Despite these efforts, the commercially available photovoltaic module technology can only convert about 20% of the incident irradiance to electricity, and the remaining absorbed radiation is turned into heat, increasing the cell temperature. The increase in solar cell temperature decreases the power output of the PV module (Soliman et al., 2019; Diwania et al., 2020). Photovoltaic panel temperature in areas with a very high irradiance can rise to 90°C (Brahim and Jemni, 2017). The rise in module temperature could have profound power implications for a module with an operating temperature between 25 to 40°C. Interestingly, the use of thermo-electric-generators (TEG), as demonstrated in a study conducted by Kolambekar and Bhole (2015), can be a good concept that can increase the energy harvesting from the waste heat of the module and hence increase system economic viability when integrated on the back surface of the PV module. Similarly, Abdul and Bhole (2021) studied the effect of wind load on a solar PV utility power plant with the PV module tilt adjusted based on different seasons.

Undoubtedly, extensive research has been carried out to assess the potential of the renewable hybrid energy system for residential building applications. Nonetheless, in most studies, the selection of the optimal hybrid system configuration selected from all the feasible solutions found from the optimisation results using HOMER is, in all cases, based on the intuitive decision of the decision-maker. Moreover, only a few studies have analytically investigated the techno-economic photovoltaic-battery-based hybrid energy system in north-central Nigeria (Salisu et al., 2019; Adaramola, 2014; Ohijeagbon et al., 2019).

Therefore, the contribution of this study is to develop a multiple-objective decision framework that forms the basis for selecting optimal hybrid solutions from all feasible solutions obtained from HOMER optimisation search results using the weather data and load scenario in Heipang village Nigeria. The goal is to select an energy system that matches policymakers economic and pollution mitigation multi-objectives in an intermittent grid power failure community using HOMER software.

Based on a multi-objective decision framework, this study determines the most viable photovoltaic battery (PV-batt)/grid-connected hybrid power system based on a random grid outages scenario closest to the multi-objective of satisfying system reliability while simultaneously maximising the economic viability and minimising the emission of CO_2 to the environment. The baseline energy system, which consists of a generator set coupled with grid power, serves as the reference system for the performance analysis of hybrid energy systems conducted in this study. The primary aim is to compare each hybrid energy system's techno-economic and environmental benefits under the same weather and load scenario. Second, a proposed decision framework is used to evaluate the benefit of each hybrid system based on the designer's multi-objective. The result should be the basis for a quick, informed decision on the most beneficial hybrid energy system in communities with poor grid access.

2 Materials and method

2.1 Description of system

This study determines whether a photovoltaic battery (PV-batt)/grid-connected hybrid power system based on a random grid outages scenario is viable for intermittent grid power societies. Furthermore, the study also determines which configuration of the PV-batt-based system fits most with the ideal solution in a given community. In most energy-constrained communities, four PV-batt-based system configurations are typical. These are:

1 PV-batt/grid/gen configuration, mostly a choice perceived to increase the system reliability since the grid failure is highly random

2 PV-batt/gen, hybrid architecture, for most communities with no access to the national grid

3 PV-batt/grid configuration in which the battery storage is large enough to cater for just a period of insufficient radiation and grid outage

4 PV-batt only; this is the case in most typical and remote locations.

Table 1 summarises the PV-batt-based system configurations standard scenarios in most developing countries considered for this study. Since the Paris Agreement requires that the modern-day energy system meet load requirements with good reliability and minimal impact on the environment in the most economical way possible, the system configuration closest to this multi-objective for a given location craves innovative ideas and solutions. The primary aim of this study is to assess the techno-economic and environmental benefits of each hybrid energy system based on the desired multi-objective. These hybrid energy systems were modelled, evaluated, and analysed using HOMER software. A baseline energy system consisting of a generator set coupled with grid power is the reference system for this study's hybrid energy systems performance analysis.

Table 1 Hybrid system configuration considered for the preliminary study

Hybrid system	*System configuration/architecture*				
Hybrid A	PV module	Battery storage	Inverter	Grid	Gen. set
Hybrid B	PV module	Battery storage	Inverter	-	Gen. set
Hybrid C	PV module	Battery storage	Inverter	Grid	-
Hybrid D	PV module	Battery storage	Inverter	-	-
Base-case	-	-	-	Grid	Gen. set

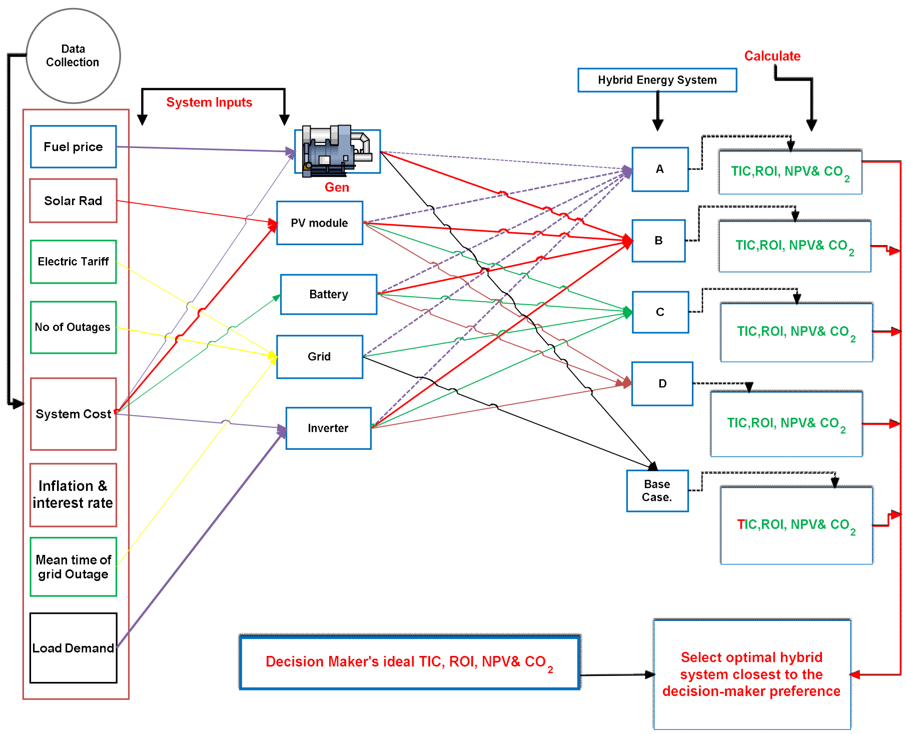
2.2 Description of approach

The economic viability of a renewable energy project for a specific location is usually the first and the most critical assessment of the system's productivity and profitability compared to other available green energy systems. This study used a multi-energy hybrid optimisation tool (HOMER) to assess the lifetime performance of four photovoltaic hybrid energy systems, as described in Table 1. The aim here is to develop an approach that identifies the hybrid system that meets the multi-objective of maximising economic benefits and minimising the negative environmental impact of the hybrid energy system while meeting the energy requirement of residential buildings.

First, the chosen hybrid energy systems model is formulated using HOMER software. After that, the case study's load characteristics, renewable energy resources, and economic variables are used as inputs to optimise selected hybrid energy systems, as shown in Table 2. Therefore, every optimally sized hybrid system's techno-economic is evaluated.

Second, the techno-economic performance indicators as measured using HOMER form the inputs for the decision framework to select the most appropriate system based on the designer's choice. For this study, each hybrid system's initial expenditure, payback period (PBP), return on investment (ROI), and CO_2 emissions were used as standard indicators of the hybrid system's profitability and conservation impact, as accepted in several research works (Kumar et al., 2019; Soliman et al., 2019; Diwania et al., 2020). Figure 1 illustrates the method showing both inputs and expected results in each analysis step. Interestingly, when modelling the grid-connected hybrid system, excess power generated by the renewable system is not sold to the grid but dumped, as this is the right scenario for most developing countries. In this case, the economic analysis does not consider carbon dioxide mitigation benefits or penalties, even though there is an assumption that carbon dioxide mitigation costs per ton will rise to about USD 43.00 in 2020 (Brahim and Jemni, 2017).

Figure 1 A schematic of the approach for the optimisation and selection of optimum configuration (see online version for colours)



2.3 *Description of study location and case study*

The proposed methodology in this study is demonstrated by utilising the Plateau State Polytechnic (PSP) health centre load demand data. The polytechnic health centre is located at Heipang, a rural settlement under Barkin Ladi district located about 20 km away from Jos's city centre in Nigeria. Heipang has an annual average solar radiation of 5.6 KWh/m^2/day (Aghenta and Iqbal, 2019). It is located at latitude 9.93 N and long 8.7 E with an altitude of 1,200 m above sea level. On the other hand, wind speed in Jos in most locations is 63% of the time during the year, between 3–5 m/s and predominantly in the north-east south-west direction (Meteoblue, 2022). Even though wind energy, when harnessed, will be a viable option, this technology's high initial cost (Galvez et al., 2019) is a crucial barrier to its wide adoption in rural settlements compared to the simple photovoltaic energy system, especially in developing countries.

Currently, the electric power from the grid in Heipang is characterised by random and frequent outages averaging 33 times power outages per month, lasting a minimum duration of about eight hours (Gielen et al., 2019). During prolonged outages, the standby generator provides the energy requirement of the health facility. Furthermore, the total power demand of the health centre was obtained based on the direct measurement method as adopted in Ghaib and Ben-Fares (2017) and Llanos et al. (2017); by this method, the rating of each appliance acquired from the datasheet of the survey form is multiplied by the number of hours per day of use of each appliance to obtained the kWh/day demand of each appliance. The kWh/day of each appliance is summed to arrive at the centre's total demand of 48.2 kWh/day; the hourly distribution of the power of the healthcare facility is as indicated in Figure 2.

Furthermore, the typical meteorological year (TMY) data of the study location available at the National Renewable Energy Laboratory (NREL) database was the driving function in the simulation. The TMY data represents weather and solar data of any location because it is an average collected over not less than 20 years (Huld et al., 2018; Ernst and Gooday, 2019). Figure 3 is the monthly average solar radiation on a horizontal surface obtained by processing the TMY data using the TYPE 15 weather processor of TRNSYS 18 software. The solar data is one of the primary input data for the optimisation using HOMER software. Additionally, Table 2 is technical data used as input in the system optimisation and economic evaluation of the hybrid systems formulated using HOMER software based on the scenario of the study location.

Table 2 Power elements and economic inputs for the optimisation in HOMER

S/N	*Component*	*Parameter*	*Value*	*Unit*	*Ref*
1	PV module	Installation cost	857	USD/kW	Krishan and Suhag (2019)
		Replacement cost	857	USD/kW	Krishan and Suhag (2019)
		O&M cost	10	USD/kW/year	Krishan and Suhag (2019)
		Degrading factor	0.5	%	
		Lifetime	25	Years	Nyeche and Diemuodeke (2020)
		Conversion efficiency	20	%	
2	Battery	Installation cost	210	USD/kW	Ohijeagbon et al. (2019)
		Replacement cost	210	USD/kW	Ohijeagbon et al. (2019)
		O&M cost	0	USD/year	
		Lifetime	10	Years	Ohijeagbon et al. (2019)
		Minimum state of charge	30	%	
		Round trip efficiency	95	%	
3	Inverter	Installation cost	310	USD/kW	Nyeche and Diemuodeke (2020)
		Replacement cost	310	USD/kW	Nyeche and Diemuodeke (2020)
		O&M cost	50	USD/year	
		Lifetime	15	Years	
		Conversion efficiency	90	%	

Table 2 Power elements and economic inputs for the optimisation in HOMER (continued)

S/N	*Component*	*Parameter*	*Value*	*Unit*	*Ref*
4	Generator	Installation cost	500	USD/kW	Adesanya and Schelly (2019)
		Replacement cost	500	USD/kW	Adesanya and Schelly (2019)
		O&M cost	0.03	USD/op.hr	
		Lifetime	15	Years	Adesanya and Schelly (2019)
		Conversion efficiency	95	%	
		Fuel price	0.75	USD/L	Adesanya and Schelly (2019)
5	Grid	Demand rate	0.07	USD/kWh	
		No. of failure	33	Per month	
		Meantime of repair	12	Hour/failure	
		Variability	10	%	
6	Economics	Inflation rate	11	%	Krishan and Suhag (2019)
		Discount rate	8	%	

Figure 2 Hourly load profile of the case study health centre (see online version for colours)

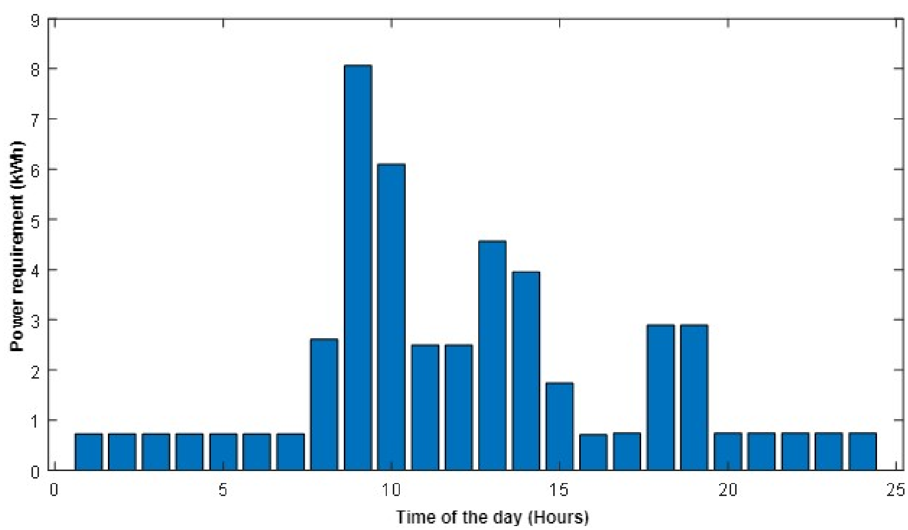
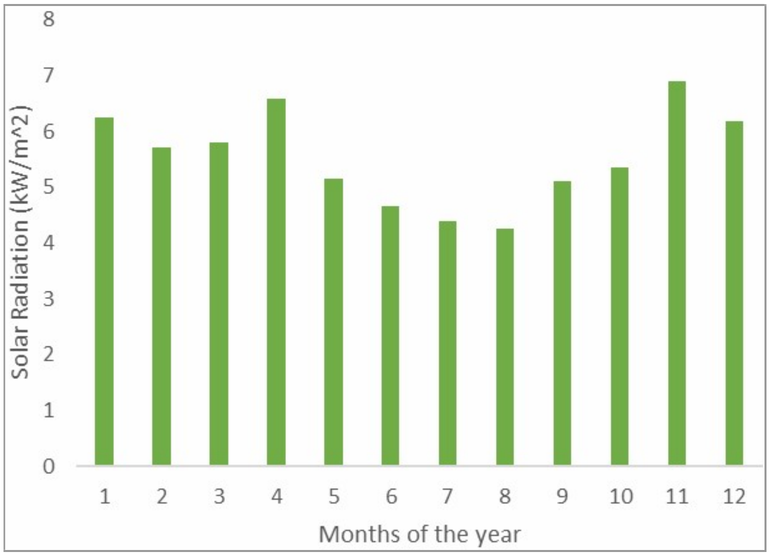


Figure 3 Monthly average solar radiation on the horizontal surface of Heipang (see online version for colours)



2.4 Optimal system performance evaluation and the multi-objective decision framework

After the inputs and optimisation constraints were established, the system was simulated. The techno economics of the hybrid energy systems was also assessed. Based on the formulated hybrid model in HOMER software, a search technique using the HOMER algorithm and energy dispatch strategy was used to search and return optimal components size and the techno-economics of each hybrid energy system, as seen in Table 3 and Table 4. Furthermore, a methodology to select the hybrid energy system that matches a decision-maker ideal system multi-objective techno-economic performance indicator is further formulated, as demonstrated in Figure 4. For this study, the ideal system is defined based on a tri-objective performance indicator as a system with the least initial investment, maximum ROI, and minimal CO_2 in its energy mix. These performance indicators are represented as a position $i(x, y, z)$ on a three-axis plot of the tri-indicators.

Similarly, the non-ideal system is defined as a system with the highest initial investment, least ROI, and maximum CO_2 in its energy blend and plotted as $n(x, y, z)$ on a three-axis plot tri-indicators. Similarly, the tri-performance indicator of each optimal hybrid energy system is also plotted relative to the positions of the ideal and non-ideal indicators. Finally, the Euclidean distance between the position of each hybrid from the ideal and non-ideal is evaluated (Lee, 2019). Consequently, the similarity evaluator matrix E_m as defined in equation (1) is used to compute the fitness of each hybrid to the ideal solution (Li et al., 2019).

$$E_m = \frac{E_{Dn}}{E_{Di} + E_{Dn}} \tag{1}$$

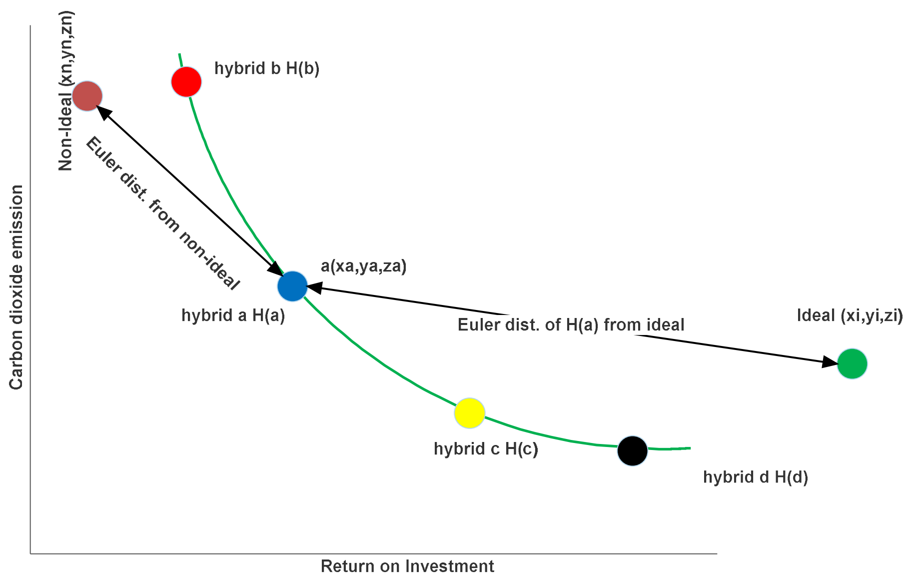
where

E_m is the similarity evaluation matrix of each hybrid solution

E_{Dn} is the Euler distance of each optimal indicator from the non-ideal user-defined indicator

E_{Di} is the Euler distance of each optimal indicator from the ideal user-defined indicator.

Figure 4 Illustration of Euler's distances of optimal feasible solutions from the user-defined solution (see online version for colours)



A schematic representation of the evaluation of the similarity of each feasible Paretor solution from the user-defined ideal and non-ideal solutions is illustrated in Figure 4. For example, assuming that the user-defined ideal and non-ideal indicators are defined as $i(x_i, y_i, z_i)$ and $n(x_n, y_n, z_n)$ respectively, then the Euler distance of the optimal hybrid energy system with performance indicators $a(x_a, y_a, z_a)$ from the ideal multi-indicators $i(x_i, y_i, z_i)$ and non-ideal indicators $n(x_n, y_n, z_n)$ is expressed as:

$$E_{Di} = \sqrt{(x_a - x_i)^2 + (y_a - y_i)^2 + (z_a - z_i)^2} \tag{2}$$

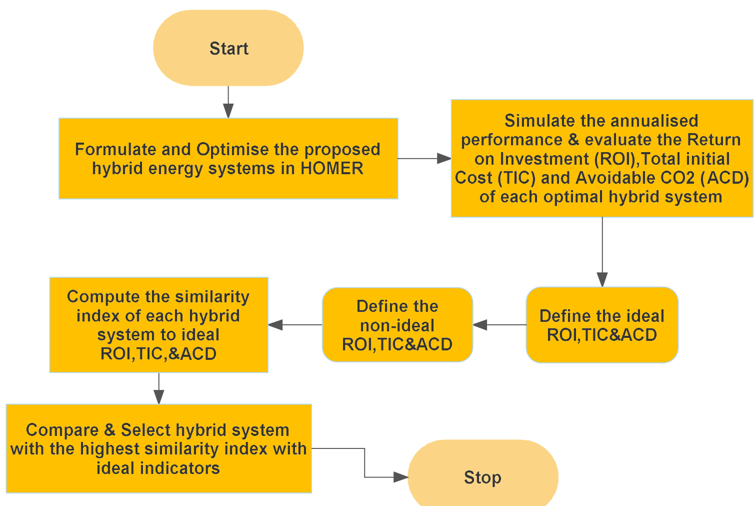
$$E_{Dn} = \sqrt{(x_a - x_n)^2 + (y_a - y_n)^2 + (z_a - z_n)^2} \tag{3}$$

where E_{Di} and E_{Dn} are the Euler distances of the hybrid system from the ideal and the non-ideal decision-maker ideal and non-ideal solution, respectively, similarly, the similarity of the hybrid system to a user-defined non-ideal system predictor is expressed as:

$$E_m = \frac{\sqrt{(x_a - x_n)^2 + (y_a - y_n)^2 + (z_a - z_n)^2}}{\sqrt{(x_a - x_n)^2 + (y_a - y_n)^2 + (z_a - z_n)^2} + \sqrt{(x_a - x_i)^2 + (y_a - y_i)^2 + (z_a - z_i)^2}} \quad (4)$$

The performance indicator (x, y, z) is the techno-economic indicator defined as ROI, total initial cost (TIC), and avoidable carbon dioxide (ACO_2), respectively. E_{ma} is defined as the similarity evaluation matrix of the hybrid energy system to the ideal predictors. Similarly, the similarity index of all other feasible hybrid systems is evaluated. Accordingly, the hybrid system with the highest similarity matrix index is selected as the solution that matches the user-defined post-optimality reference. Figure 4 illustrates the distance of the hybrid A (blue ball) performance indicators from a decision-maker ideal and non-ideal techno-economic indicator represented on an emission versus ROI Paretor curve. Figure 5 illustrates the stages that are involved in the decision framework for the selection of the optimal.

Figure 5 Decision framework for the selection of optimal system configuration (see online version for colours)



3 Results and discussion

The optimum component sizes of the power element needed to satisfy energy demand efficiently for each hybrid system configuration considered for this study are shown in Table 3. This table shows that for system architecture in which the grid and the genset are combined as part of the power elements of a PV-battery-based hybrid system configuration, the size of the PV module and the battery storage is significantly different and reduced. This reduction in the size of the PV and battery has a remarkable advantage in lowering the cost of the project's initial investment, as seen in Table 4. In hybrid B, the grid source power is excluded from the system configuration, and as a result, the size of the PV module required to meet the load satisfactorily is increased from 16 kW to 22 kW compared with hybrid A. The change in the size of the PV module represents an increase of 32%.

Consequently, the system's initial cost increases from 42,805 USD to 54,030 USD, representing a significant increase of 87.3%. For hybrid C system architecture in which the grid power replaces the genset, the size of the battery storage is increased from 43 number of 1 kWh to 69 number of 1 kWh battery. This change again shows a significant increase of 60.4% in the size of the battery storage. Interestingly despite the increase in the size of the battery storage, the initial investment declined by 5.1%. Considering a standalone PV-battery hybrid configuration, as in the case of hybrid D, the size of the PV and the battery storage required to optimally meet load significantly increased by 172% and 32.5%, respectively, compared to hybrid B. Again, this sharp increase resulted in a massive increase in the initial investment; it is observed that in comparison to hybrid B, the use of hybrid C consequentially lowers the share of the renewables in the energy mix from 96.5% to 89.3%. Therefore, hybrid C over hybrid B in meeting the energy requirement has considerably increased the negative impact of the energy system on the environment. Accordingly, a CO_2 rise from 566 kg/yr to 1,080 kg/yr corresponds to an over 90% increase in greenhouse emissions in the energy mix. Notably, replacing the generator set in hybrid B with the grid power, as seen in hybrid C, is the primary reason for a significant increase in CO_2 emission of the energy mix by about 90.9%. The substantial increase in CO_2 results from an emphasis on the grid power in meeting energy demand due to its lower price than diesel fuel. Even though replacing the generator with the grid led to a significant CO_2 increase. However, the positive thing about this is that the initial investment has dropped by around 5.1%.

On the contrary, hybrid C, which has a higher CO_2 than that hybrid B, has a higher ROI of 21.4% than hybrid B of 19.9%. This cost reduction results from the low cost of purchasing power from the grid compared to diesel fuel. Therefore, considering the business sense of investment in renewable energy systems, potential investors may be more interested in hybrid C than hybrid B. Likewise replacing the generator set with the grid source of power resulted in the load met more from the grid. Notably, the battery size increased from 43 to 69 of 1 kWh battery when the generator set in the hybrid was replaced with the grid power source. In contrast, hybrid D has the highest initial investment yet is 100% free from CO_2, making it the most promising option for reducing the CO_2 content of the energy mix.

Nonetheless, a substantive amount of its power generated (about 82% over what is required to meet load) is dumped with no use. Thus, for developing countries with no regulation to sell excess power from renewables to the grid, the excess power is considered a waste. Furthermore, there will be no justification for selecting this hybrid system for developing countries since it is the most expensive option. Interestingly, hybrid A has the lowest total cost over the system's entire lifetime compared to the other hybrid options. On the contrary, hybrid A has the highest CO_2 emission of 1,959 kg/yr second after the baseline case. Furthermore, the similarity index of hybrid C is about 44% better in greenhouse gas mitigation compared to hybrid A. On the contrary, hybrid A has lower initial capital and a 6% higher ROI than hybrid C.

In general, as seen from the results, a hybrid energy system that combines fossil fuel energy sources with renewable energy sources offers good energy decarbonisation options, reducing the carbon content of the energy supplied by a minimum of 92.7%

compared to the emission level of the baseline system. Overall, it could be concluded that each hybrid solution is optimal depending on which performance measure is the objective. Therefore, it is difficult to decide which hybrid system is better than others in meeting a multi-objective of minimising the negative impact of power generation and, at the same time, maximising the various economic benefits. The following section, thus, exposes the compromise between the different economic objectives and the greenhouse mitigating capacity of each feasible configuration. Equally, the approach and method used to decide which hybrid designs best fit the multi-objective of minimising initial investment while maximising the ROI and CO_2 mitigation.

Table 3 Optimal components sizes for each configuration and the base case

	Optimal component sizes		*Inverter (kW)*	*Genset (12 kW)*	*Grid power (33 kVA)*
	PV (KW)	*Battery (number of 1 kWh)*			
Hybrid A	16	43	13	Yes	Yes
Hybrid B	22	43	11	Yes	No
Hybrid C	22	69	13	No	Yes
Hybrid D	60	57	14	No	No
Baseline	-	-	-	Yes	Yes

Table 4 Techno-economic analysis of each optimal solution

S/N	*System architecture*	*Initial cost (USD)*	*Excess power produced (%)*	*Renewable fraction (%)*	*Return on investment (ROI) (%)*	*Simple payback period (yrs)*	*Kg CO_2/yr*
1	Hybrid A	42,805.2	40.0	81.8	27.6	3.15	1,959
2	Hybrid B	54,030.5	51.5	96.5	19.9	4.18	566
3	Hybrid C	51,237.4	52.7	89.3	21.4	4.02	1,081
4	Hybrid D	111,573.2	82.0	100.0	6.5	9.3	0
5	Base-case	6,100	38.0	0	0	NA	26,810

3.1 Economic and emission trade-off in hybrid system selection

The study utilises the position of the four optimised hybrid energy systems on the optimality curve to determine the compromise or trade-off between the economic and environmental impact of the energy system in selecting a given hybrid energy system. Figure 6 shows the position of the four-hybrid system on the TIC versus CO_2 emission optimality curve. Similarly, Figure 7 shows the position of the four optimal hybrid energy systems on the ROI versus CO_2 emission optimality curve. Furthermore, Figure 8 shows the PBP versus CO_2 emission relationship on the optimality curve for all hybrids studied. The dark blue ball represents the position of hybrid system A; the light blue ball indicates the location of hybrid system B, and the green and yellow ball represents the position of hybrid C and D, respectively. A critical evaluation of Figure 6 to Figure 8 shows that hybrid D has the most CO_2 emission mitigation benefit. However, this benefit is being traded off with a high initial cost and low ROI. Likewise, hybrid A has the worst CO_2 emission mitigation benefit but is the least expensive to start.

Figure 6 Relationship between initial capital and CO_2 emission for the four optimal hybrid energy systems (see online version for colours)

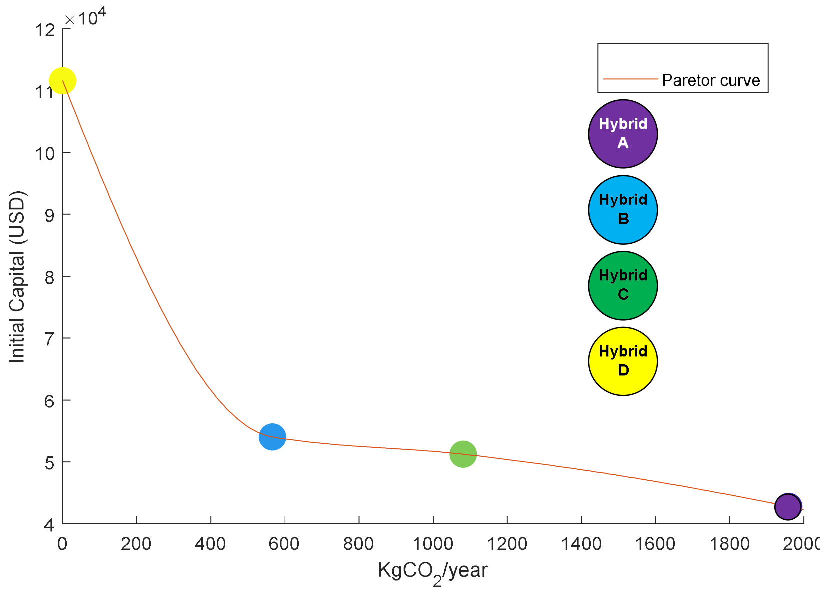
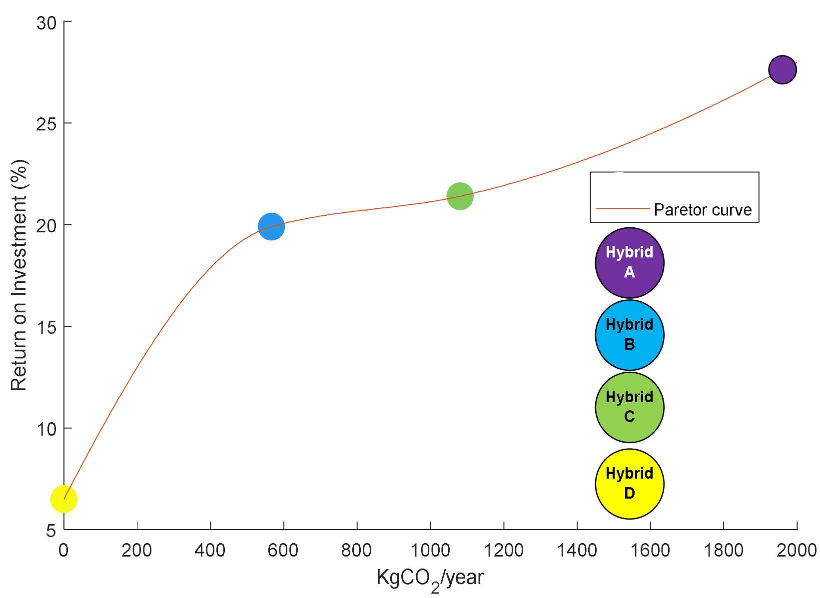


Figure 7 Relationship between ROI and CO_2 for the four optimal hybrid energy systems (see online version for colours)



Similarly, the economic benefits of each hybrid differ with different economic indicators, as can be seen in Figure 7 and Figure 8. The goal of this research, as stated earlier, is to design an energy system that meets the load requirement of a building most reliably and economically while minimising the environmental impact of the energy. The choice of a hybrid system with the most benefit and highest trade-off will be against the targeted multi-objective of maximising profit and minimising the environmental impact of the energy system. The relevant contribution drawn from this analysis is the need to develop further a decision framework that decides which hybrid satisfies the ideal multi-objective as desired by the decision-maker. Consequently, a multi-objective decision framework is required to select a solution closest to the ideal multi-objective desires of the decision-maker.

3.2 Decision framework for the selection of an optimal hybrid system

In this work, three performance indicators are employed to formulate a framework utilised by a decision-maker in selecting the optimal hybrid energy solution among all feasible hybrid options. For this study, the decision-maker's ideal solution is considered an option with zero-emission, maximum ROI, and minimum initial investment represented as $i(x_i, y_i, z_i)$ on the Cartesian coordinate as illustrated in Figure 4. The study also defines the non-ideal solution as the design with the maximum carbon dioxide, the least ROI, and the highest initial investment represented as $n(x_n, y_n, z_n)$ on the Cartesian coordinate. The Euler's distance of each feasible solution from the ideal and non-ideal triple-objective, as seen in Figure 4, is calculated from equations (2) to (4). The Euler's distance of each viable solution is evaluated to determine the similarity and closeness of each optimal solution to the decision-maker preference. The similarity index of each solution is evaluated from equation (1). For this research, the ideal solution is to meet the tri-objective of zero kilograms of CO_2 emission, maximum ROI of 33%, and an initial investment with a renewable energy fraction of 85%. The research equally defines the non-ideal solution as a solution with emissions of 1,959 kg/yr. CO_2, with a 0% ROI and a maximum initial investment of 111,573 USD. These formulated objectives are based on results obtained, and they are represented as $i\begin{pmatrix} x & y & z \\ 0 & 33 & 48{,}805 \end{pmatrix}$ and $n\begin{pmatrix} x & y & z \\ 1{,}959 & 0 & 111{,}573 \end{pmatrix}$ for the ideal solution and non-ideal solution, respectively. The result from the evaluation is shown in Table 5.

Table 5 Evaluated similarities of hybrid energy systems to the ideal energy system

System configuration	*Ideal Euler distance (m)*	*Non-ideal Euler distance (m)*	*Evaluation matrix (%)*
Hybrid A	6,311.7	73,120.5	92.05
Hybrid B	5,255.9	63,244.8	92.36
Hybrid C	2,661.6	65,592.6	96.10
Hybrid D	62,768.0	26,810.1	29.93

Figure 8 Relationship between PBP and CO_2 emission for the four optimal hybrid energy systems (see online version for colours)

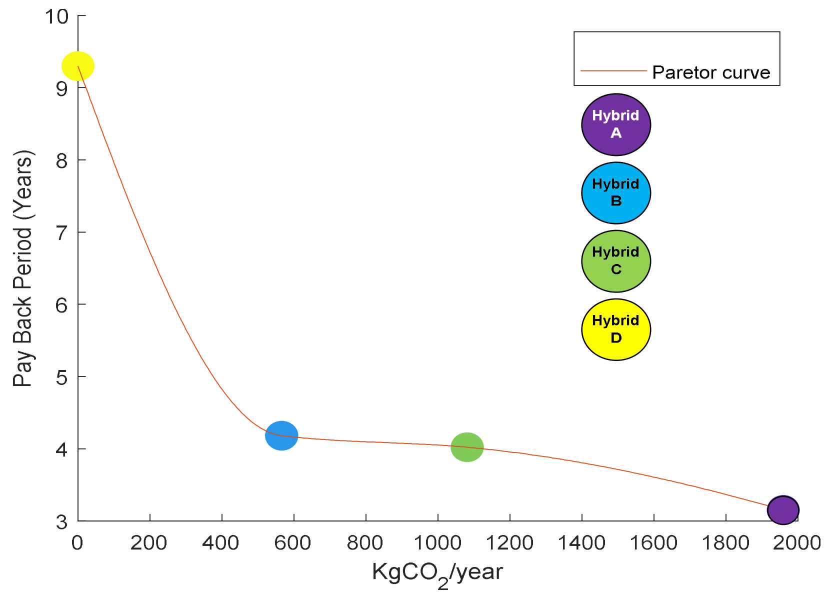
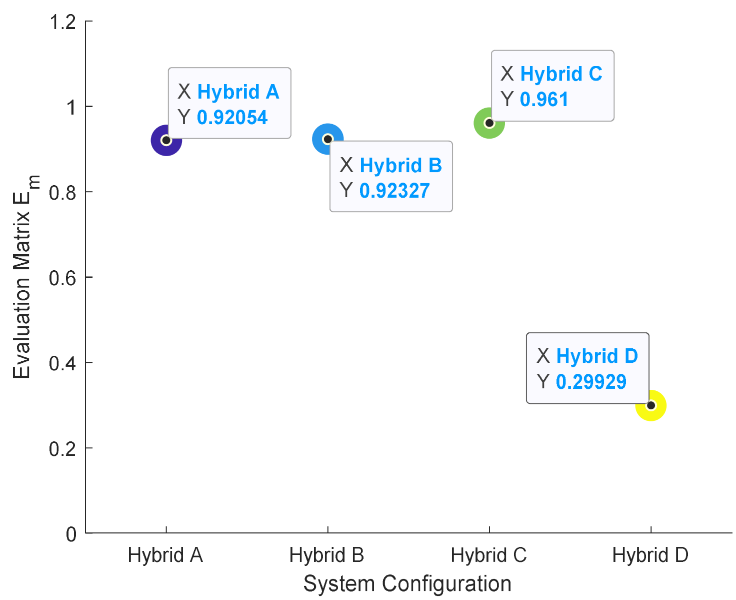


Figure 9 The similarity index of the hybrid energy systems (see online version for colours)



From the result analysis, hybrid C has the lowest Euler's distance from the non-ideal predictors. As a result, the closest to the ideal solution with a similarity index of 96.1% is shown in Figure 9. It is, therefore, the most recommended design and configuration that meets the preference goal of this research. Interestingly, the contribution of this work is that the policymaker's desired objective can be changed, and a hybrid system that matches that objective is correspondingly selected.

4 Summary and conclusions

This study proposes a methodology to establish the most economically viable and environmentally friendly alternative to the photovoltaic battery-based system configuration common in most energy-constrained and developing countries. In most energy-constrained communities, grid power is characterised by frequent intermittent grid power outages. Therefore, the most common solution is an energy technology that integrates the grid power source with the diesel generator. In this study, we developed a quick decision framework as a guide for policymakers and potential investors to appropriately decide from a set of possible viable and environmentally friendly alternatives for the photovoltaic battery-based hybrid energy system the closest to the multi-objective of maximum profitability and minimum impact to the environment. To achieve the goal of this study, four types of photovoltaic-battery-based options were used to demonstrate the methodology. These options include the PV-batt/grid/genset, PV-batt/grid, PV-batt/genset, and the standalone PV-batt configuration. The grid/genset energy technology was the basis for our comparison. The goal was to determine the economic viability of each hybrid energy system based on the weather and scenarios peculiar to the study site. Accordingly, an approach that compares the hybrid systems' performance index with the desired multi-objective of maximising the ROI and minimising both the initial investment and the CO_2 content of the energy mix was successfully implemented to select the preferred hybrid. Hence the following conclusions were drawn from the outcome of this study. The complete removal of fossil-based energy systems from the energy mix leads to huge capital investments, thereby increasing PBPs for renewable energy projects for now. As a result, the business value of renewable energy projects is decreased.

A photovoltaic hybrid energy system combined with the grid offers the closest (about 96.1%) energy solution to the desired multi-objective of minimising the initial investment while maximising the ROI and minimising the negative impact of the energy system on the environment. The elimination of the traditional energy source from the energy mix resulted in a hybrid energy system that only achieves the desired multi-objective fitness of 29.93%. Overall, the choice of the project objective determines which system is optimal for meeting the set objective.

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