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Research Article

Microgrid Hybrid Solar/Wind/Diesel and Battery Energy Storage Power Generation System: Application to Koh Samui, Southern Thailand

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Abstract. This paper presents the optimization of a 10 MW solar/wind/diesel power generation system with a battery energy storage system (BESS) for one feeder of the distribution system in Koh Samui, an island in southern Thailand. The main objectives are to maximize the deployment of renewable energy-based power generation and to minimize the levelized cost of energy (LCOE). A hybrid renewable energy-based power generation system, consisting of solar PV, wind turbine generators, diesel generator (DiG), bi-directional grid-tied charging inverter (CONV) and BESS, was simulated using HOMER Pro®. This study accessed the database of the National Aeronautics and Space Administration (NASA) for the Surface meteorology and Solar Energy (SSE) for the global solar radiation and temperature, along with the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) wind database. The simulations show that Scenario 1 (PV/Wind/DiG/BESS/CONV) and Scenario 3 (PV/DiG/BESS/CONV) are the optimal configurations regarding the economic indicators (i.e. minimum net present costs (NPC) of 438 M$ and LCOE of 0.20$/kWh) and the environmental indicators (i.e. lowest greenhouse gases (GHG) emission avoidances of 6,339 tonnes/year and highest renewable fraction (RF) of 89.4%). Furthermore, the sensitivity analysis illustrates that Scenario 3 offers the optimal system type with the largest annual energy production (AEP). Besides contributing to the body of knowledge of optimization methodologies for microgrid hybrid power systems, the outcome of this work will assist the regional energy practitioners and policy makers regarding optimal configurations of microgrid hybrid systems in the development of a Green Island concept for Koh Samui.

Keywords: Solar PV, Wind Turbine Generator, Optimization, Levelized Cost of Energy, Renewable Fraction, Battery Energy Storage System.

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1. Introduction

Jurisdictions and organizations are vigorously working to extract the energy from eco-friendly energy resources, along with ensuring the sustainable development of their economies, to the benefit of their citizens. Renewable energy resources, particularly solar and wind energy, are inexhaustible in nature and have the potential to meet, at affordable costs, the energy demand of nations. Significant increases have been noticed in the exploitation of solar and wind energies, notably due to the environmental concerns in power generating systems (Argin *et al.*, 2019; Ranthodsang *et al.*, 2020). However, the intermittent nature of these resources often leads to unreliable electricity generation without support of battery energy storage systems (BESS) or/and fossil fuel-based power generating systems. However, the efficiency of renewable-based power systems can be improved by combining various renewable energy technologies. In several aspects, studies have shown the synergy role of hybrid solar photovoltaic (PV) and wind power systems (Al-Ghussain *et al.*, 2021a; Amrollahi and Bathaee, 2017).

The combination of solar PV and wind power enhances the energy efficiency of a system through increasing the demand-supply coordination (Al-Ghussain *et al.*, 2021b; Al-Ghussain *et al.*, 2021c). Nevertheless, hybrid solar PV and wind power have been found less effective without BESS and/or without other power generating systems (Eltamaly and Mohamed, 2014; Eltamaly *et al.*, 2016). Hence, it is essential to provide energy supply that can deliver electric power to load demand without interruption.

The effects of intermittency of solar PV and wind power can be mitigated by incorporating a diesel generator (DiG) and/or BESS (Bouchekara *et al.*, 2021). In this regard, the BESS plays a key role in facilitating the discrepancy between power

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generation and load demand. The design and sizing of hybrid systems is challenging on the economic and technical prospectives (Yang *et al.*, 2009). In general, the undersizing of hybrid systems results in shortages of power supply, whereas oversized systems result in high costs (Bukar *et al.*, 2019). Thus, referring to the aforementioned problems, the optimum design and sizing of hybrid microgrid systems can play a significant role in power system operation and planning.

HOMER Pro® has widely emerged as a convenient simulation tool for several hybrid renewable energy systems, particularly in off-grid applications (Islam *et al.*, 2021; Jahangir *et al.*, 2020; Lian *et al.*, 2019; Rey *et al.*, 2017; Sen and Bhattacharyya, 2014; Sood and Muthusamy, 2020; Tsai *et al.*, 2019; Uwineza *et al.*, 2021; Vendoti *et al.*, 2021). Various researchers focused on studies related to energy systems such as thermal (Das *et al.*, 2021; Xing *et al.*, 2021), desalination (Atallah *et al.*, 2020; Bundschuh *et al.*, 2021; Padrón *et al.*, 2019), rural electrification (Ahmad *et al., 2018;* Harish *et al., 2022;* Li *et al.*, 2020), irrigation (Elkadeem *et al.*, 2019; Haffaf *et al.*, 2021; Rezk *et al.*, 2019), farming (Lukuyu *et al.*, 2019; Teo and Go, 2021), and indigenous communities (Das *et al.*, 2017; Vides-Prado *et al.*, 2018). Furthermore, some recent studies scrutinized hybrid renewable energy systems along with BESS for island applications (Babaei *et al.*, 2022; He *et al.*, 2021; Pascasio *et al.*, 2021; Qi *et al.*, 2022), where the levelized cost of energy (LCOE) and the net present costs (NPC) were calculated and compared for different hybrid configurations (Elkadeem *et al.*, 2020).

Hybrid renewable energy systems have been studied in Thailand (Chaichan *et al.*, 2021; Kohsri *et al.*, 2018; Waewsak *et al., 2020).* Some studies assessed suitable locations for the development of energy facilities using biomass (Waewsak et al., 2020), wind power potential (Kamdar *et al.*, 2021; Kamdar and Taweekun, 2022; Waewsak *et al.*, 2019), and techno-economic assessment of solar PV (Ketjoy *et al.*, 2021; Khamharnphol *et al.*, 2023; Tongsopit *et al.*, 2019).

Electric power is crucial for the people's daily life, and for social and economic development. Power systems generally include generation, transmission, distribution and consumption (Katsivelakis *et al.*, 2021). In remote and tourism islands, it is usually difficult to construct centralized conventional power generation, with high investment costs, to serve low demand. The utility authorities solve this type of problem by installing diesel power generation provisions and, when possible, by extending the power system network using submarine cabling for short distance interconnections with the mainland.

At present, due to the cost reduction of renewable power equipments, such as solar PV panels and balance of system (BOS), distributed green power generation has become an interesting alternative for powering remote islands. Apart from the extensive efforts made to increase the applicability of various renewable energy systems to respond the climate change (Kim *et al.*, 2021), green power generation also minimizes the use of fossil fuel in power generation. Hybrid renewable power is of increasing interest for cleaner production in remote islands. However, the nature of renewable energy sources, such as solar PV and wind energy, has the drawbacks of intermittency. Therefore, scenario investigations of hybrid systems usually integrates solar PV and wind turbine generators, along with diesel generators in order to increase the reliability and the efficiency, as well as to minimize the need for large scale energy storage capacity and to reduce the levelized cost of energy (Kavadias and Triantafyllou, 2021). Moreover, fuel cell technology is also of interest as an alternative in hybrid renewable energy power systems; however, there are challenges in terms of cost effectiveness (Akter *et al.*, 2022).

Renewable energy-based distributed power generation is increasingly considered with hybrid systems and microgrids (Bloomberg *et al.*, 2020). However, the microgrids installed in the last five years have prioritized the integration of solar PV and battery energy storage systems, with diesel generators as backup, while small utility scale wind power generation is much less common for microgrids (Arribas *et al.*, 2021).

In this context, the main objective of this paper is to present the optimization of a microgrid hybrid solar PV/wind/DiG power generation, that integrates a battery energy storage system, for Koh Samui, an island in southern Thailand. Koh Samui is a well-known tourist island in the Gulf of Thailand, which is interconnected to the mainland by means of submarine cables under the responsibility of the Provincial Electricity Authority (PEA). The proposed models consider different configurations and scenarios based on techno-enviro-economic perspectives for microgrid hybrid systems. Beyond the contribution to the body of knowledge of optimization methodologies for microgrid hybrid power systems, the outcome of this work will assist the regional energy practitioners and policy makers regarding optimal configurations of microgrid hybrid systems in the development of a Green Island concept for Koh Samui.

2. Materials and Methods

2.1 Study area and renewable energy resources

With an area of 227 km² and a population of over 65,000, Koh Samui is an island situated in Surat Thani province. The island, situated in the Gulf of Thailand at latitude 9°30.7'N and longitude 100°0.8'E, is visited by thousands of tourists every year. The weather is tropical wet and dry climate, with an average monthly temperature of 29°C (Pears *et al.*, 2013).

Koh Samui has a great potential for renewable energy integration in terms of solar PV and wind, as reported by the Asia Pacific Energy Research Centre (APERC). A significant amount of municipal solid waste is also produced, notably due to the large presence of tourists. In addition, the island is currently under several research and development projects to integrate new renewable energy technologies, such as tidal, hydrogen, fuel cell and geo-thermal energy (Sirasoontorn and Koomsup, 2017). The geographical map of Koh Samui, including its three substations (KMA, KMB and KMU) and its 33 kV distribution system, is shown in Figure 1.

This study is based on the solar radiation and the wind speed data of Koh Samui obtained from the Surface meteorology and Solar Energy (SSE) and the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) databases.

On one hand, the solar radiation over the area of interest is estimated to achieve the optimum utilization of the available solar energy (Waewsak *et al.*, 2014). The annual average daily solar radiation is 5.32 kWh/m²/day, which varies from a minimum of 4.16 kWh/m²/day in November, to a maximum of 6.44 kWh/m²/day in March. The annual average clearness index value is approximately 0.5, which is measured by using the annual average daily solar radiation in HOMER Pro®. Figure 2 (a) illustrates the monthly average solar radiation and clearness index on Koh Samui. For its part, the annual average wind speed is 5.17 m/s at an elevation of 50 m above ground level (agl). The maximum average wind speed is 6.53 m/s in August while the minimum average wind speed is 3.56 m/s in April. Figure 2 (b) illustrates the monthly average wind speeds at an elevation of 50 m agl on Koh Samui.

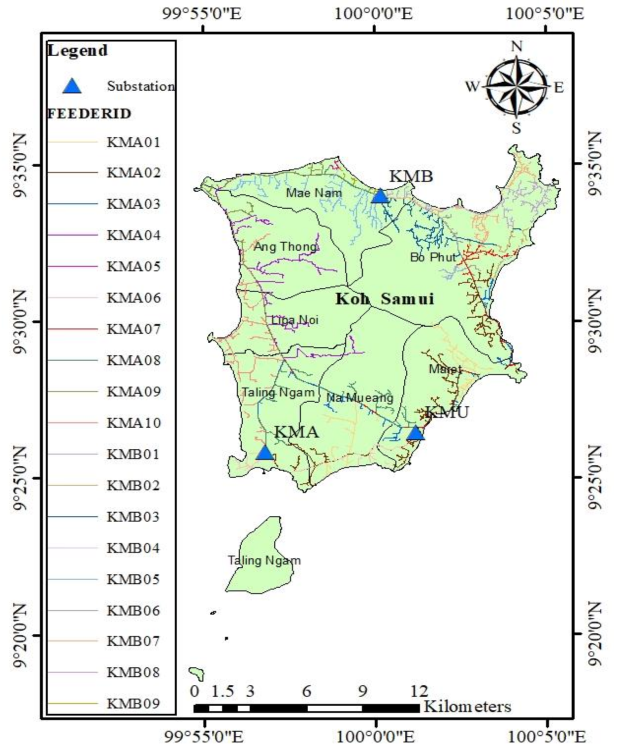


Fig. 1 Geographical position of the three substations (KMA, KMB and KMU) and the 33 kV distribution system in Koh Samui.

The load demand on Koh Samui is relatively constant throughout the year, with the months of March and August having the highest electrical load consumption, which is highly associated with the utilization of air-conditioners and electrical fans due to the particularly hot weather during these months. Figure 3 illustrates the monthly electrical load demand on Koh Samui (Provincial Electricity Authority).

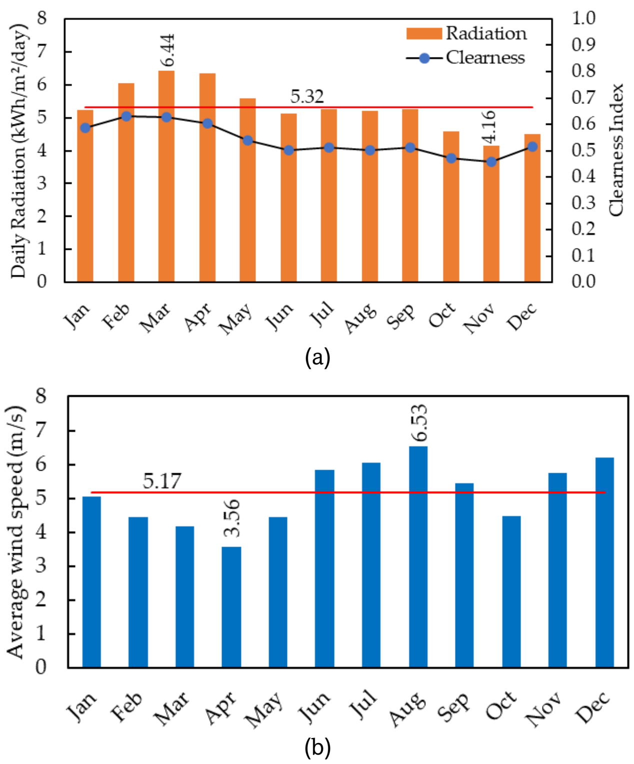


Fig. 2 a) Monthly average solar radiation and clearness index (Source: SSE database), and b) monthly average wind speeds at an elevation of 50 m agl on Koh Samui (Source: MERRA-2 database).

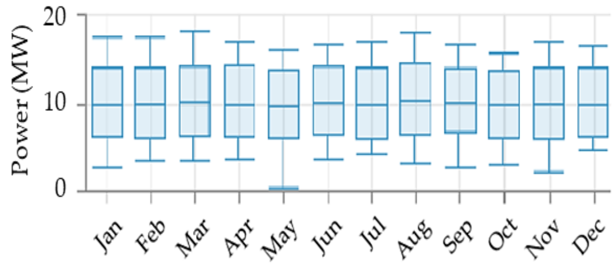


Fig. 3 Profile of the monthly electrical load demand on Koh Samui (Source: Provincial Electricity Authority).

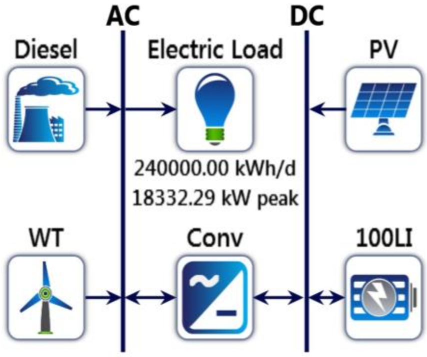


Fig. 4 Schematic diagram of the microgrid hybrid solar PV/Wind/DiG/BESS system.

2.2 System modeling

2.2.1 System configuration

Figure 4 shows the schematic diagram of a microgrid hybrid configuration which includes solar PV panels, wind turbines, a diesel generator (DiG) and a battery energy storage system (BESS). The average electrical load of the island is 240 MWh/day, with a peak demand of 18.33 MW. The alternating current (AC) grid is connected to the wind turbine and the DiG, while the direct current (DC) grid is connected to the solar PV and the BESS. The purpose of the diesel generator is to provide the power for the electrical load in peak load hours. This microgrid hybrid configuration employs a power convertor for DC to AC and AC to DC conversions. Li-Ion batteries of 100 kWh store the electrical energy due to the variable nature of the solar PV and the wind energy production.

Furthermore, the layout of a single line diagram that includes the solar PV modules, the DC combiner box, the solar inverter and the main distribution board (MDB) is shown in Figure 5.

2.2.2 Mathematical model of the microgrid hybrid system components

This study considers a microgrid hybrid system that depends on the accessibility and the availability of renewable energy resources to fulfil the energy demand of Koh Samui. The following subsections present the mathematical models deployed for the components of the microgrid hybrid system. Furthermore, the technical and economic characteristics of the various system components are discussed, which are summarized in Table 1 presented at the end of the subsection.

2.2.2.1. Mathematical model of the photovoltaic panels

The solar radiation activates solar PV panels that convert photon energy directly into electrical energy. This research employs the Canadian made solar PV panel (MaxPower CS6X-

325P). The rated power and derating factor of the solar PV panels are 325 kW and 88%, respectively. The expected capital costs, and the operational and maintenance costs, are respectively 700 US$ and 14 US$/kW/year, with no replacement costs since the solar PV panels have a lifespan of 25 years (Duman and Güler, 2018; Elkadeem *et al.*, 2020).

The mathematical expression used to calculate the solar PV output power is given as (Katsivelakis *et al.*, 2021; Kim *et al.*, 2021):

$$P_{PV}(t) = P_{PV,r} \cdot f_{PV} \cdot \left(\frac{G_T(t)}{G_{T,STC}}\right) \cdot [1 + C_P(T_{cell}(t) - 25)] \qquad (1)$$

where $P_{PV}(t)$ = PV output power (kW), $P_{PV,r}$ = rated capacity of the PV array (kW), f_{PV} = derating factor, $G_T(t)$ = solar radiation on the PV panels (kW/m²), $G_{T,STC}$ = solar radiation on the PV panels under the standard conditions (kW/m²), C_P = power temperature coefficient (% °C⁻¹) and $T_{cell}(t)$ = real-time temperatures of the PV panels (°C).

Similarly, the formula to calculate the PV cell temperature is written as (Bagheri *et al.*, 2019; HOMER Pro®, 2021):

$$T_{cell}(t) = T_\alpha(t) + (T_{cell,NOTC} - T_{\alpha,NOTC}) \cdot \left(\frac{G_T(t)}{G_{T,NOTC}}\right) \cdot \left[1 - \frac{\eta_c}{\alpha \cdot \tau}\right] \qquad (2)$$

where $T_\alpha(t)$ = temperature of the ambient air (°C), $T_{cell,NOTC}$ = nominal operating temperature of the PV panels (°C), $T_{\alpha,NOTC}$ = temperature of the ambient air (°C), η_c = electrical conversion efficiency of the PV array (%), α = PV solar absorbance (%) and τ = solar transmittance (%).

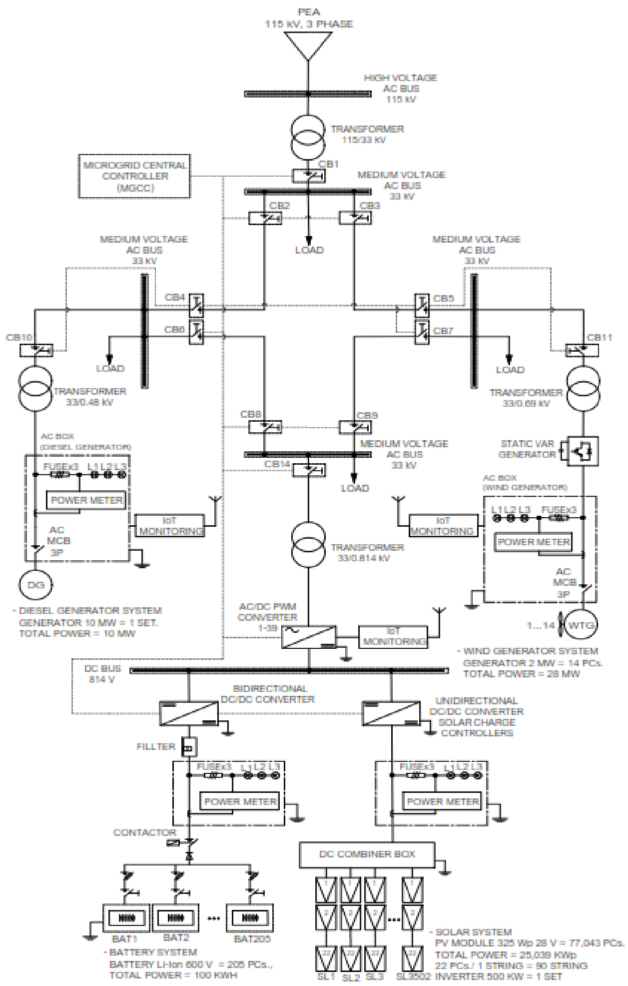


Fig. 5 Single line diagram of the microgrid hybrid system.

To determine the wind speeds at higher elevations, it is significant to calculate the wind shear coefficient as it strongly depends on the atmospheric conditions, the surface roughness, and other local factors (Werapun *et al.*, 2017). The variation of the wind speeds at elevations above the ground level is expressed as (Bagheri *et al.*, 2019; HOMER Pro®, 2021):

$$v_w(t) = v_{anem}(t) \cdot \left[\frac{ln\left(\frac{H_{hub}}{H_0}\right)}{ln\left(\frac{H_{anem}}{H_0}\right)}\right] \qquad (3)$$

where $v_w(t)$ = wind speed at the hub height (m/s), $v_{anem}(t)$ = wind speed at the anemometer height (m/s), H_{hub} = hub heigh (m), H_{anem} = anemometer height (m) and H_0 = surface roughness length (m).

The mathematical expression used to calculate the expected output power of the wind turbine at standard temperature and pressure is computed as (Dahiru and Tan, 2020):

$$P_{w,STP} = \begin{cases} 0 & v_w(t) < v_i \\ P_{w,r} \cdot \left[\frac{v_w^3(t) - v_i^3}{v_r^3 - v_i^3}\right] & v_i \le v_w(t) \le v_r \\ P_{w,r} & v_r < v_w(t) \le v_o \\ 0 & v_w(t) > v_o \end{cases} \qquad (4)$$

where $P_{w,STP}$ = output power at the standard conditions of temperature and pressure (kW), $P_{w,r}$ = rated output power (kW), v_i = cut-in wind speed (m/s), v_o = cut-out wind speed (m/s) and v_r = rated wind speed (m/s).

Ultimately, the formula used for the real air density is expressed as (Bagheri *et al.*, 2019; HOMER Pro®, 2021):

$$P_w(t) = P_{w,STP}(t).\left(\frac{\rho(t)}{\rho_0}\right) \qquad (5)$$

where $P_w(t)$ = output power (kW), $\rho(t)$ = real air density (kg/m³) and ρ_0 = air density at standard pressure and temperature (1.225 kg/m³).

2.2.2.2 Mathematical model of the diesel generator

The integration of a DiG in the microgrid hybrid model provides an uninterruptible power supply, notably in cases of emergency. Hence, this study considers the auto-size genset diesel generator with a rated power of 10 MW. The estimated capital and replacement costs are 500 US$/kW, along with operational and maintenance costs of 0.03 US$/hr/kW. The expected lifespan of the auto-size genset diesel generator is 87,600 hr. Further, the price of diesel fuel, in accordance with the Thailand Oil and Gas Market, is projected at 1 US$/L. The mathematical expression used to determine the diesel fuel consumption is given as (Abo-Elyousr and Elnozahy, 2018; Elkadeem *et al.*, 2020; HOMER Pro®, 2021):

$$F_{DiG}(t) = a_{DiG} \,.\, P_{DiG,g}(t) + b_{DiG}.\, P_{DiG,r} \qquad (6)$$

where $F_{DiG}(t)$ = diesel fuel consumption (L/h), $P_{DiG,g}(t)$ = output power of the DiG (kW), $P_{DiG,r}$ = rated capacity of the DiG (kW), a_{DiG} = fuel curve intercept coefficient (L/hr/kW$_{rated}$) and b_{DiG} = diesel fuel curve slope (L/hr/kW$_{output}$).

2.2.2.4 Mathematical model of the power converter

In microgrid hybrid systems, power converters are used to manage the power flow, and it acts as an interface between the AC and DC sides (Li *et al.*, 2018). This research has utilized a generic, large, free converter model. The capital and replacement costs of the model are 750 US$/kW, while the operational and maintenance costs are 15 US$/year/kW. The expected lifespan is 15 years. The formulas used for the energy conversion from DC to AC and from AC to DC are given as (Dahiru and Tan, 2020):

$$\eta_{DC/AC}^{Con}.[P_{BAT}(t) + P_{PV}(t)] \leq N_{conv} \quad (7)$$

$$\eta_{AC/DC}^{Con}.[P_{WT}(t) + P_{DiG}(t)] \leq N_{conv} \quad (8)$$

where $\eta_{DC/AC}^{Con}$= energy conversion efficiency from DC to AC, $\eta_{AC/DC}^{Con}$= energy conversion efficiency from AC to DC, and N_{conv}= converter capacity (kW).

2.2.2.3 Mathematical model of the battery energy storage system

The solar radiations and the wind kinetic energy are intermittent and variable sources of renewable energy. On the other hand, batteries can act as energy storage systems, while maintaining constant voltage and efficiently re-distributing the stored energy (Farret and Simões, 2006). This work utilizes a Li-Ion battery with a capacity of 100 kWh and a nominal voltage of 600 V. The lifespan of a battery is 8 years, and it has a maximum charging current of 167 A. The estimated capital and replacement costs are 45,166 US$, while the operational and maintenance costs are 200 US$/year. The equation for the storage capacity of a battery is written as (Bagheri *et al*., 2019):

$$C_{wh} = E_L.AD.\eta_{Conv}.\eta_{BAT}.DOD \quad (9)$$

where C_{wh}= battery capacity (kW), E_L= total load demand (kWh/day), AD = daily autonomy, DOD = depth of discharge and η_{BAT}= battery efficiencies.

2.3. Objective function formulation

The total net present costs (NPC) or the life cycle costs have been applied as an economic tool to evaluate the feasibility of this work. The NPC is used to equate the total costs, including the capital costs, the replacement costs, the operational and maintenance costs of the project over its lifespan, minus the present value of all revenues it generates (Bagheri et al., 2019; Elkadeem *et al.,* 2020). In order to minimize the NPC of the microgrid hybrid system, the objective function can be computed as (Acuña *et al*., 2018; HOMER Pro®, 2021):

$$Objective\ function = min(NPC) = min\left(\frac{TAC}{DF(i, n_{proj})}\right) \quad (10)$$

where TAC = total annualized costs (US$/year) and $DF(i, n_{proj})$ = discount factor based on the interest rate.

Table 1
Technical and economic characteristics of the various system components of the hybrid microgrid system.

Component/Model	Parameter	Value	Unit
Solar PV CanadianSolar MaxPower CS6X-325P	Rated power	0.325	kW
	Derating factor	88	%
	Capital costs (per kW)	700	$
	Replacement costs (per kW)	0	$
	O&M costs (per kW)	14	$/yr.
	Life time	25	years
Wind turbine Enercon E-82 E2	Rated power	2	MW
	Cut-in speed	2	m/s
	Cut-out speed	34	m/s
	Rated wind speed	12.5	m/s
	Capital costs (per unit)	2,202,880	$
	Replacement costs (per unit)	0	$
	O&M costs (per unit)	110,144	$/yr.
	Hub height	85	m
	Life time	25	years
Battery/Generic 100kWh Li-Ion	Nominal capacity	167	Ah
	Nominal voltage	600	V
	Maximum charging current	167	A
	Minimum state of charge	20	%
	Round trip efficiency	90	%
	Capital costs (per unit)	45,166	$
	Replacement costs (per unit)	45,166	$
	O&M costs (per unit)	200	$/yr.
	Life time	8	years
Diesel generator/Autosize Genset	Rated power	10	MW
	Capital costs (per kW)	500	$
	Replacement costs (per kW)	500	$
	O&M costs (per kW)	0.03	$/op.hr.
	Life time	87,600	hr.
	Diesel fuel price	1	$/L
Converter/Generic large, free converter	Capital costs (per kW)	750	$
	Replacement costs (per kW)	750	$
	O&M costs (per kW)	15	$/yr.
	Life time	15	year
Other	Interest rate	6	%
	Discount rate	6	%
	Loss of Load Expectation	0.7	day/yr.
	Project life	25	years

Similarly, the levelized cost of energy (LCOE) is a measure of the sum of the annual costs (US$/year) of the project to the total electrical load (kWh/year) generated by the energy system. It can be calculated as (Acuña *et al.*, 2018; HOMER Pro, 2021):

$$LCOE = \frac{TAC}{E_{load}} \tag{11}$$

where E_{load} indicates the total electrical load in kWh/year.

The renewable fraction (RF) is basically the amount of energy delivered compared to the load developed from the renewable resources (solar and wind). It is measured in percentage and is computed as (HOMER Pro®, 2021):

$$RF = 1 - \left(\frac{E_{g,non-ren}}{E_{load}}\right) \tag{12}$$

where $E_{g,non-ren}$ signifies the non-renewable electrical production (kWh/year).

2.4 System simulation and optimization algorithm

Optimization and sensitivity algorithms were used to evaluate the economic and technical feasibility of several technology options and to account for the variations in technology costs and energy resource availability.

The operation of the system was simulated by making energy balance calculations in each time step (interval) of the year. For each time step, the electric demand in that time step compared to the energy that the system can supply in that time step was computed, and the flow of energy to and from each component of the system was calculated. For the system designed, which included the BESS and the diesel generator, the operation of the diesel generator and the charge or discharge of the BESS are determined in each time step.

After the energy balance calculations for the designed system configuration, the model then determines a configuration which is feasible and which can meet the electric load demand under the specified conditions, while estimating the costs of installing and operating the system over its operational lifetime. The system cost calculations account for all the costs, notably the capital, replacement, operation and maintenance, fuel, and interest costs.

Two optimization algorithms were applied. The original grid search algorithm simulates all of the feasible system configurations defined by the Search Space. The proprietary derivative-free algorithm to search for the least-costly system was then applied. A list of configurations, sorted by net present costs (life-cycle costs) was performed, which will be used to compare and select the design options for the system.

The proposed model considers different configurations and scenarios based on techno-enviro-economic perspectives for microgrid hybrid systems. The details of each configuration and scenario are as follows:

Scenario 1 (PV/Wind/DiG/BESS/CONV),
Scenario 2 (Wind/DiG/BESS/CONV) and
Scenario 3 (PV/DiG/BESS/CONV).

3. Results and Discussion

3.1 Analysis of the microgrid hybrid system

In this study, various scenarios based on techno-enviro-economic perspectives for hybrid microgrid system were analysed. The optimization of the hybrid microgrid system illustrates the outcomes of various scenarios ranked from the utmost feasible to the least interesting. Table 2 displays the results associated with the NPC, LCOE, RF and GHG in terms of Scenarios 1, 2 and 3, whereas Table 3 presents the capacity and costs of each component used in the hybrid microgrid configuration.

The main results and outcomes from the simulation models are as follows:

- For the sake of comparison, Scenario 1 (PV/Wind/DiG/BESS/CONV) ranks as the utmost feasible configuration in terms of NPC and LCOE for the island to fulfill its power consumption, as can be seen in Table 2. The NPC and the LCOE are estimated as the minimum values of 438 M$ and 0.20 $/kWh, respectively.
- Scenario 3 (PV/DiG/BESS/CONV) is the optimum configuration in regards to the environmental perspective, with the lowest GHG emissions of 6,339 tonnes/year and the highest RF of 89.4%.
- The least interesting configuration from environmental and financial perspectives is Scenario 2 (Wind/DiG/BESS/CONV). In this scenario, the NPC and the LCOE have the maximum values of 515 M$ and 0.236 $/kWh, respectively. Additionally, this scenario has the highest GHG emissions of 30,349 tonnes/year.
- As indicated in Table 3, the components of the microgrid hybrid system for Scenario 2 include 27 wind turbines with a 2 MW rating, a 10 MW DiG, 205 battery units with 100 kWh rating, and 8,336 kW power converters present the highest O&M cost of 4.78 M$/year.
- In terms of O&M costs, Scenario 3 has the lowest costs at 2.40 M$/year, but with the highest capital costs of 181.0 M$.

Table 2
Model optimization results of the hybrid renewable energy power generation ranked by LCOE.

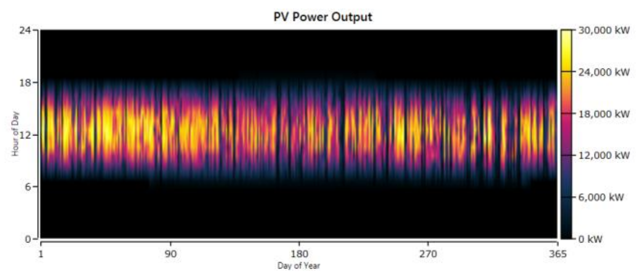
Rank	Sr.	Hybrid renewable energy configuration	NPC (M$)	LCOE ($/kWh)	R.F. (%)	GHG (tonnes/yr)
1	1	PV/WT/DiG/BAT/ CONV	438	0.200	60.0	23,954
2	3	PV/DiG/ BAT/CONV	503	0.230	89.4	6,339
3	2	WT/DiG/BAT/CONV	515	0.236	49.4	30,349

Note: Sr. = Scenario, NPC = Net Present Cost, LCOE = Levelized Cost of Energy, RF = Renewable Fraction, GHG = Greenhouse Gases.

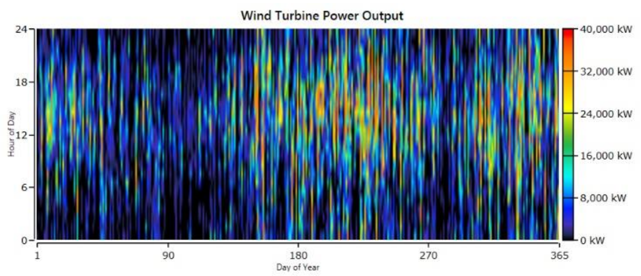
Table 3
Optimized system component sizing and associated costs for each hybrid renewable energy configuration.

Sr.	Equipment Size					Costs	
	PV (MW)	WTG (Units)	DiG (MW)	BAT (Units)	Conv (MW)	O&M (M$/yr)	Capital (M$)
1	32.139	18	10	174	14.204	3.95	85.7
2	-	27	10	205	8.336	4.78	80.0
3	99.558	-	10	2,048	18.154	2.40	181.0

The power generation of the microgrid hybrid configurations for Scenario 1, Scenario 2 and Scenario 3 are shown in Figure 6, Figure 7 and Figure 8, respectively. In the case of Scenario 1, the peak power output for the solar PV and the wind turbine is in the order of 30,0000 kW and 40,000 kW, respectively. Similarly, the peak power output is in the order of 60,000 kW for the wind turbine in Scenario 2, whereas the peak solar PV power output is in the order of 100,000 kW in Scenario 3. The solar PV produces the maximum output power in March and April, which mostly occurs during midday in Scenario 1 and Scenario 3. Besides, the wind turbines in Scenario 1 and Scenario 2 produce the maximum output power in the evening, particularly in August.

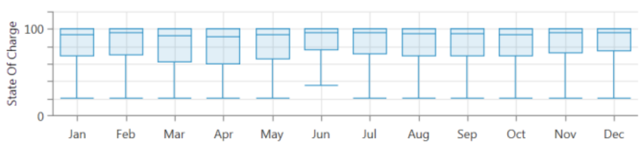


(a)



(b)

(c)



(d)

Fig. 6 Power generation of Scenario 1: (a) Solar PV power output of each day throughout the year; (b) Wind turbine power output of each day throughout the year; (c) Battery SOC of each day throughout the year; and (d) Variation of the monthly battery SOC throughout the year.

The SOC of the battery in all scenarios is within the specific range of 20 – 100%. However, the system utilizes the maximum battery storage from midnight until the early morning in Scenario 1 and Scenario 2 in March and April, while it utilizes the maximum battery storage in Scenario 3 throughout the year. This might be due to the higher demand for electricity during these hours.

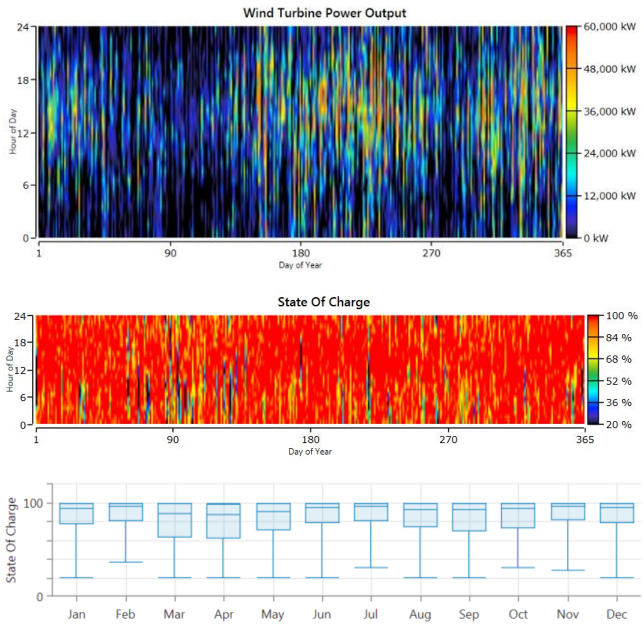


Fig. 7 Power generation of Scenario 2: (a) Wind turbine power output of each day throughout the year; (b) Battery SOC of each day throughout the year; and (c) Variation of the monthly average battery SOC throughout the year.

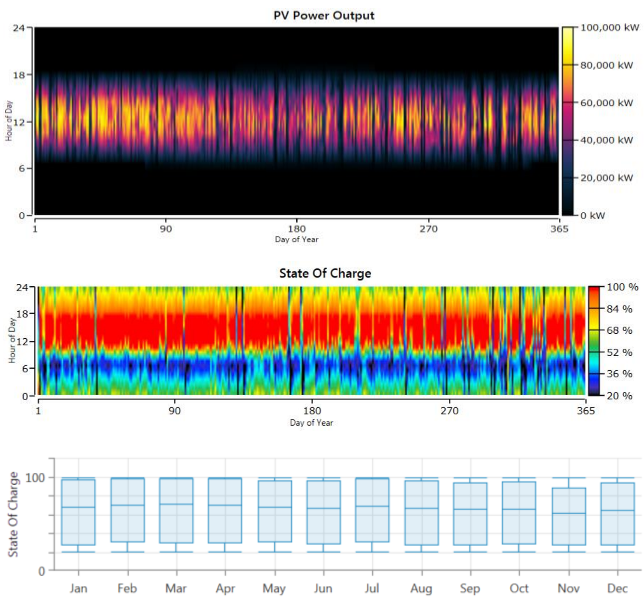


Fig. 8 Power generation of Scenario 3: (a) Solar PV power output of each day throughout the year; (b) Battery SOC of each day throughout the year (c) Variation of the monthly battery SOC throughout the year.

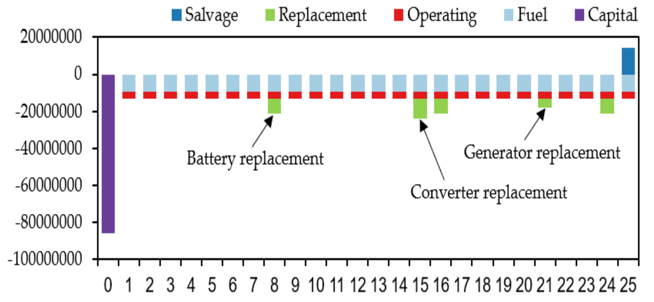


Fig. 9 Annual nominal cash flow of the optimal hybrid microgrid system.

Scenario 1 (PV/Wind/DiG/BESS/CONV) is the optimal model for the hybrid microgrid system, with Figure 9 depicting its annual nominal cash flow. The figure indicates the highest initial costs, which are due to the high costs of the wind turbines, followed by the costs of the battery energy storage system. The battery replacement would be required after each 8 years. Similarly, the replacement periods for the converter and the generator are 15 years and 21 years, respectively. This hybrid microgrid system has a 25-year financial viability.

3.2 Analysis of the electrical power production

It is significant to determine the energy performance analysis during planning of the hybrid microgrid system. Figure 10 depicts the monthly electricity production of the various components of the hybrid microgrid system. It is noticeable from the figure that both the wind turbines and the solar PV produce much higher energy in comparison with the DiG throughout the entire year. The wind turbines harvest the maximum energy in August, which is associated with the higher wind speeds in that month. Furthermore, the energy production from the solar PV is maximum in March, which is due to the increment in sunshine duration. However, the share of energy production from the DiG increases in April, notably due to the minimum wind power generation in that month.

3.3 Simulation results of the various components of the hybrid microgrid system

The power generation for the microgrid components, along with the SOC of the battery for the energy load demand for 8 days in April, July and December are presented in Figure 11, for the hybrid microgrid system. These figures validate the successful operation of the system over a one-year period. It is noticeable from the figures that the power generation from the solar PV and the wind turbines keep the SOC of the battery within the specified limits. For its part, the DiG only operates when the solar PV and the wind power are insufficient. Thus, the optimal hybrid model based on the solar PV, the wind turbines, the DiG and the BESS offers adequate power and can fulfil the electrical load demand of the island.

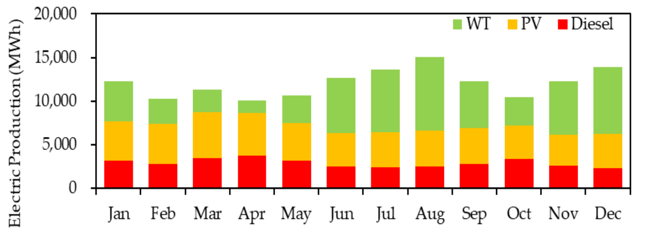


Fig. 10 Power production of each component in the hybrid microgrid system.

3.4 State of charge of the battery energy storage system

The purpose of the battery units in the microgrid is to store the energy due to the intermittent nature of the renewable energy sources (solar PV and wind), while ensuring the availability of energy to satisfy the load demand. The SOC for the Li-Ion battery system, in terms of hours and day of year, is given in Figure 12. The range of SOC for the Li-Ion battery is kept between 20 and 100%, with the SOC achieving maximum values during the daytime, when the solar radiation is at its maximum.

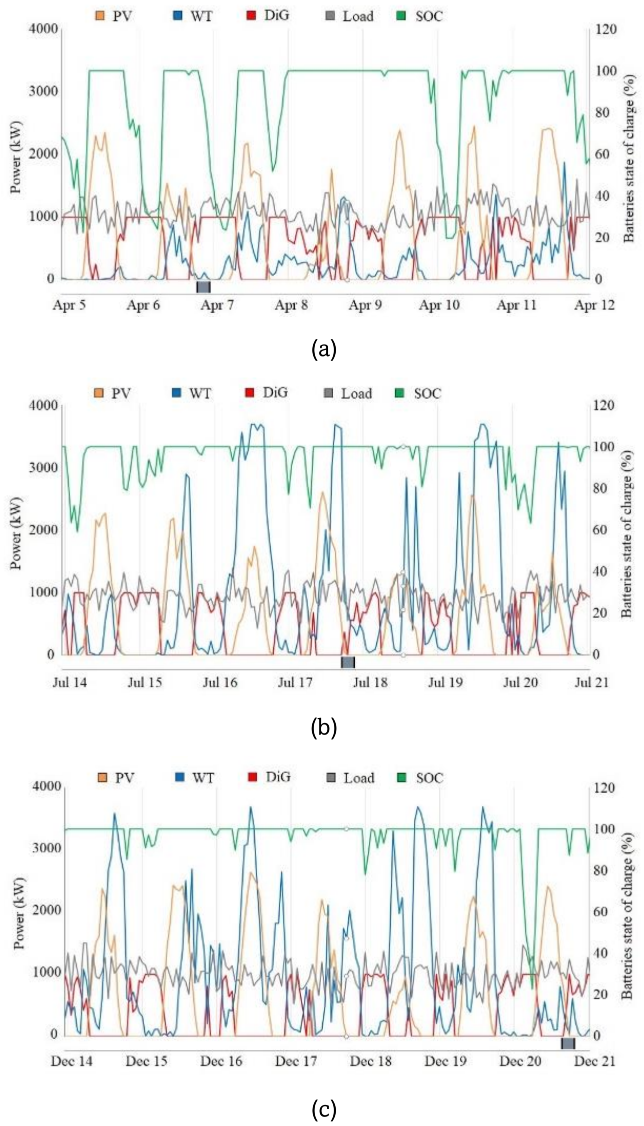


Fig. 11 Power generation from the microgrid components, along with the SOC of the battery for the energy load demand for 8 days of (a) April, (b) July, and (c) December.

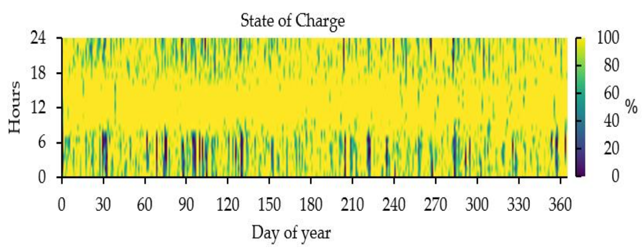


Fig. 12 Battery SOC of the optimal hybrid microgrid system throughout the year.

4. Conclusions

This work studied hybrid microgrid systems based on solar PV, wind, and diesel power generation, along with a battery energy storage system for Koh Samui, an island in the Gulf of Thailand.

Three scenarios of hybrid microgrid systems were developed on the basis of technical, environmental, and economic perspectives. The results show that Scenario 1 (PV/Wind/DiG/BAT/CONV) ranks as the best configuration regarding NPC and LCOE. The NPC and LCOE values are 438 M$ and 0.200 $/kWh, respectively. From an environmental perspective, Scenario 3 (PV/DiG/BAT/CONV) is the best configuration with the lowest GHG emissions of 6,339 tonnes/year and the highest RF of 89.4%. In terms of O&M costs, Scenario 3 has the lowest costs at 2.40 M$/year, but with the highest capital costs of 181.0 M$.

Despite the high costs related to the wind turbines and the BESS, the optimal hybrid microgrid system ensures a financial viability over a 25 years lifespan. The simulation shows that both the wind turbines and the solar PV produce higher energy in comparison to the DiG throughout the year. It has been noticed that the months of February, April, May and October utilize the maximum capacity of the battery energy storage system. The hybrid solar PV, wind turbines, DiG and BESS optimal configuration can sufficiently fulfil the electricity demand of Koh Samui.

The proposed hybrid microgrid methodology can be replicated for similar studies in remote areas or isolated islands. Future work may include the integration of biomass and hydroelectric energy, where available, to exploit the best optimal hybrid microgrid system in isolated islands.

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