Flexible hybrid renewable energy system design for a typical remote village located in tropical climate

Laith M. Halabi*, Saad Mekhilef**

Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia

**Corresponding author.
E-mail addresses: L.halabi@outlook.com, Lhalabi@siswa.um.edu.my (L.M. Halabi), saad@um.edu.my (S. Mekhilef).

Abstract
Energy management and sustainable resources are regarded as major concerns when designing hybrid energy systems. Finding an efficient framework that combines reliable design and satisfies continuous operation at minimal cost at all conditions is essential for both customers and investors. In this regard, this paper details the adoption of a creative approach using HOMER software to come up with a flexible design of a hybrid system that includes conventional and renewable energy sources. This study involves a comprehensive survey in this field, detailed techno-economic assessments, analyses of operational performance, and the evaluation of environmental aspects pertaining to the aforementioned system. It investigates all conditions that influence the system for both off-grid and on-grid connections by examining it over a typical remote Malaysian village. A sensitivity analysis was also conducted at all stages to verify the optimum design among all changes of different sell-back, power purchase, fuel prices, load growth, and other variables. Also, this study was proceeded to determine and examine the technical, economical and environmental aspects of the system. The results showed that the optimum system for both off-grid and on-grid connections consists of 300 kWp of photovoltaic (PV) modules, two diesel generators rated at 100 kW and 50 kW, a 150 kW converter and 330 kWh battery banks. The total Net Present Cost (NPC) and Cost of Energy (COE) fell within (1500000.0 e 2450000.0 $) and (0.151 e 0.233 $/kWh), respectively, for different renewable energy fraction (RF) values of (23 e 55.43%) and CO2 emissions of (245284.0 e 570643.0 kg/Yr). Moreover, the results indicated the importance of considering all parameters prior to the implementation of any hybrid system in order to realize the proposed objectives. The study demonstrates the high capability of the proposed flexible design in meeting the loads, support continuous operation, and reduce the harmful emissions towards the environment over all conditions for both off-grid and on-grid connections.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction
Finding sustainable and reliable sources of energy represents a perennial challenge in the current and past decade. Meanwhile, renewable energy resources play an important role in providing clean, reliable, and sustainable energy (Lau et al., 2010). The positive environmental impact of renewable energy resources makes it favored for use as an energy source in power generation (Adaramola, 2015). On the other hand, fossil fuel suffers from several adverse effects brought about by its transportation, storage, and prices. It is also harmful effects towards the environment (Shezan et al., 2016). Besides, its ubiquity and extensive usage have also resulted in its shortage and increased prices over time (Ong et al., 2011). While dispersed populations located far away from the national grid makes the connection to the power grid technically inefficient and economically impossible (Shaahid and Elhadidy, 2007). The aforementioned problems can be mitigated using an alternative solution involving a hybrid system made up of more than one source of energy (Rajkumar et al., 2011). Fig. 1, shows a simplified block diagram of a typical hybrid system.

Nevertheless, using standalone renewable energy sources is considered unreliable due to the random nature of renewable energy resources and the associated high costs (Phuangpornpitak and Kumar, 2007). Specifying the most suitable configuration requires deep analysis of the availability of natural resources at the proposed
location. Using a suitable Load Management (LM) system is especially important from a management standpoint, as it helps reduce peak power loads (Amini et al., 2013). The reported results confirmed the effectiveness of using LM system for large distribution networks with minimum error calculations.

The feasibility of employing hybrid renewable energy systems for electrifying remote locations was widely investigated in different parts of the world (Hurtado et al., 2015; Ataei et al., 2015; Izadyar et al., 2016). In (Hurtado et al., 2015), the hybrid system was designed and built in a laboratory, where it includes Photovoltaic (PV) and biomass energy resources, in addition to a battery storage system. This system operated for a long period of time and was duly tested in order to determine its operational behavior. The stability of the generated energy reaches 98% and it was deemed to be efficient to supply remote areas. Similarly, in (Ataei et al., 2015), the authors examined the feasibility of a hybrid wind/PV/diesel generator system. Three different scenarios working under different conditions were investigated. The results confirmed the high capability of the hybrid system over standalone diesel generator system in reducing the total Net Present Cost (NPC) and Cost of Energy (COE) of the system. It also indicated that the application of a maximum limit on the produced harmful emissions would result in increasing the total cost of the system, but would simultaneously reduce the dependence on the diesel generators. Correspondingly, the authors in (Izadyar et al., 2016) demonstrated the significant potential of using hybrid systems in Malaysia. They reported that Langkawi island is the most suitable location for a hybrid wind/solar system, followed by Tioman island. Hybrid systems assess the continuous supply of the loads, which help enhance the reliability and efficiency of the proposed sites. Similarly, The techno-economic feasibility for on-grid connection was assessed in (Nacer et al., 2016). The results indicated that introducing RE hybrid system to the grid would enhance the reliability of the national grid at peak load period and reduce its harmful emissions.

The current technological developments would reduce the photovoltaic (PV) price, which would significantly support the development of new projects (Adaramola and Vagnes, 2015). Several studies discussed the feed-in tariff (FIT) policies related to hybrid renewable energy systems. The results indicated that finding suitable FIT strategies and appropriate governmental subsidies would promote the establishment hybrid renewable energy systems around the world (Wong et al., 2015; Chua et al., 2011; Mekhilef et al., 2012). A summary of the most common metrics of standalone and hybrid systems are tabulated in Table 1.

Many researchers developed new approaches towards the optimization of hybrid renewable energy systems. Numerous methods were proposed, such as using mathematical models (Kaabeche and Ibitouen, 2014; Caballero et al., 2013), simulation software (Fathima and Palanisamy, 2015; Fadaee and Radzi, 2012), control models (Dreidy et al., 2017) and artificial intelligence (Behzadi and Niasati, 2015; García-Trivino et al., 2014). A review of the usage of different approaches in off-grid and on-grid systems is presented in (Erdinc and Uzunoglu, 2012). In this study, a systematic review has been established, which includes a detailed analysis of the commercial sizing software tools, optimization techniques, and the promising future techniques. It posits that the optimal sizing significantly improves techno-economic performance as well as promote the widespread use of environmentally friendly resources. In addition, it also outlines the advantages of including more than one source of energy (hybrid systems) compared to using one source of energy in the provision of more economical, and reliable energy supply.

Satisfying high reliability, overcoming standalone system’s deficiencies, and reducing the dependence on fossil fuels are the main reasons for selecting a suitable optimization tool. For example, HOMER software was used to examine the potential of using PV and wind turbines to meet load demands of onshore locations in Temaju, Indonesia (Hidro et al., 2013). The results indicate that HOMER software offers optimal sizing and reports a comprehensive techno-economic analysis. More optimized studies using different methods are found in (Wang et al., 2015; Alsayed et al., 2013; Kazem et al., 2013). Table 2, summarizes optimization techniques commonly used in finding the optimal system.

1.1. Literature review over off/on grid connections

There are some studies that are particularly informative, discussing different off-grid and on-grid topologies and detailed as follows:

1.1.1. Off-grid systems (standalone system)

Standalone hybrid renewable energy systems have been widely developed all around the world for different purposes. A study in Iran involved finding the optimal design for a hybrid PV-wind-fuel cell system (Maleki et al., 2016). The general aim of this study was to minimize the life-cycle cost at maximum allowable losses of power supply probability. The results confirmed that the most cost-effective system among all the configurations is the PV-wind-fuel cell, where it is the most cost-effective system in supplying electrical energy at the proposed location. Similarly, MATLAB Simulink was used to develop an optimum standalone system. The authors implemented an illustrated techno-economic analysis to determine the optimal solution. The optimum system was determined to be PV-wind combination system. This study specified that all capital,
maintenance, operation, and the lifetime of the project should be considered to find the optimum design (Belmili et al., 2014). Accordingly, a study detailed two methods for optimizing hybrid renewable energy systems. The proposed systems included a combination of PV, wind, and micro-hydro generators for two village renewable hybrid energy systems for electrifying remote areas. The proposed method results in improved the economic aspects while it enhanced the technical performance of the system.

The majority of studies reported in literature involved developing various hybrid system configurations based on a stable power supply, minimum Cost of Energy (COE) and lower CO₂ emissions over off-grid conditions.

### 1.1.2. On-grid systems (grid-connected systems)

This section details grid-connected hybrid systems. Some studies involved determining an optimal system based on different operating conditions over off-grid and on-grid connections, separately as shown in (Asrari et al., 2012) and (Hafez and Bhattacharya, 2012). In (Asrari et al., 2012), the authors used HOMER software to evaluate the feasibility of various combinations of diesel generators and renewable energy sources (on-grid). The results demonstrated the advantage of adding renewable energy sources to the off-grid connection towards reducing operational costs and generating cleaner energy. However, including the grid in the system would enhance the technical performance of the system.

#### Table 1
Comparison between standalone and hybrid systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standalone (Conventional source)</th>
<th>Standalone (Renewable energy source)</th>
<th>Hybrid system (Conventional and renewable energy source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependency on natural resources</td>
<td>Independent</td>
<td>Highly dependent</td>
<td>Partially dependent</td>
</tr>
<tr>
<td>Dependency on fossil fuel</td>
<td>Highly dependent</td>
<td>Independent</td>
<td>Partially dependent</td>
</tr>
<tr>
<td>The need for maintenance and repair</td>
<td>Frequent</td>
<td>Low</td>
<td>Less frequent</td>
</tr>
<tr>
<td>Capital cost per kW</td>
<td>Low</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Availability</td>
<td>Limited available due to dependent on the need for maintenance experts (technicians) and fossil fuels</td>
<td>Limited available due to dependent on the accessibility of natural resources</td>
<td>Highly available due to complementary nature of resources</td>
</tr>
<tr>
<td>Harmful environmental impact</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

#### Table 2
Commonly used techniques in optimizing hybrid renewable energy systems.

<table>
<thead>
<tr>
<th>No.</th>
<th>Optimization technique</th>
<th>Approach</th>
<th>System configuration</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deterministic approach</td>
<td>• By determining specific values using constant factors.</td>
<td>PV/wind/diesel/battery</td>
<td>(Mahmoud and Ibrik, 2006)</td>
</tr>
<tr>
<td>2</td>
<td>Iterative approach</td>
<td>• Using loss of power supply probability (LPSP) with the lowest cost.</td>
<td>PV/battery</td>
<td>(Shen, 2009)</td>
</tr>
<tr>
<td>3</td>
<td>MATLAB SIMULINK</td>
<td>• Based on an evaluation technique to find the optimum system over various combinations.</td>
<td>PV/diesel/battery</td>
<td>(Wies et al., 2005)</td>
</tr>
<tr>
<td>4</td>
<td>Artificial intelligence</td>
<td>• Using long-term PSO evaluation algorithm, training the system, learning from previous states to find the optimum component size.</td>
<td>PV/wind/fuel-cell/electrolyzer/battery/hydrogen tank/grid connected</td>
<td>(García-Triviño et al., 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Using multi-objective evolutionary algorithm (MOEA) and a genetic algorithm (GA) to design the optimum system.</td>
<td>PV/wind/diesel/hydrogen/battery</td>
<td>(Dufo-López and Bernal-Agustín, 2008)</td>
</tr>
</tbody>
</table>
| 5   | Optimization software  | • Using HOMER software, by comparing the technical, economical and environmental performance of different combinations. | PV/wind/diesel/battery/grid connected
PV/wind/battery | (Asrari et al., 2012)
(Ma et al., 2014) |
|     |                        | • Using other software tools (HYBRID2, etc.) to classify the most optimum solution with the lowest cost based on economic analysis. | PV/wind/hydro/fuel-cell etc. | (Erdinc and Uzunoglu, 2012) |
result in lower Cost of Energy (COE) compared to an off-grid system. Correspondingly, in (Hafez and Bhattacharya, 2012), the authors presented four different topologies that included standalone diesel generators, standalone renewable energy, hybrid diesel generators-renewable energy, and hybrid grid-connected systems. Optimal sizing and planning were carried out for each scenario to determine the best design. The results showed different configurations for each scenario, where hybrid diesel generators-renewable energy exhibits the lowest NPC. Contrarily, standalone renewable energy system emitted zero CO2 emissions at a higher NPC.

Similarly, a study investigated multiple combinations of hybrid PV-wind-battery systems over off-grid and on-grid systems (Baneshi and Hadianfard, 2016). A range of PV and wind turbines were reported in a range of (0–1000) kW and (0–600) kW for PV modules and wind turbines, respectively. Different Renewable Fraction (RF) values of (0–43.9) % and COE of (9.3–12.6) ¢/kWh for off-grid connection, alongside (0–53) % of RF and (5.7–8.4) ¢/kWh of COE for on-grid connection were considered. The results reported a range of possible scenarios for off-grid and on-grid systems based on different combinations for each scenario. Another study detailed obtaining the optimal design in terms of energy efficiency, while establishing an eco-worthy feasibility using three different scenarios in both off-grid and on-grid connections (Prodromidis and Coutelieris, 2011). The results showed that using an off-grid system for the designated location is not economically feasible, and the need of using on-grid system comes only to sell excess energy. Also, the benefits associated with the hybrid wind-PV combination in terms of supplying larger loads than typical house loads make it more economically feasible. Moreover, the abbreviation of the system was crucial in terms of capital investment, while smaller hybrid system configurations would result in smaller years of abbreviation.

Based on the above literature, it can be seen that most studies have been prepared to examine the feasibility of establishing or optimizing hybrid renewable energy systems for a specific system in a certain location. Generally, most studies that involve the determination of the optimal design at on-grid connection analyzed multiple configurations for each scenario. This involves changing the entire topology without including a common design to operate at both off-grid and on-grid systems. The literature discussed multiple combinations of the off-grid and on-grid connections separately. Where HOMER software and the other approaches were widely used in designing and optimizing typical hybrid renewable energy systems. Meanwhile, such studies are more limited to the specific system (off-grid or on-grid) at each location. Besides, being unable to be applied at different sites with diverse conditions. However, this work developed a detailed framework of a flexible hybrid power station design which includes all associated operational performance parameters in both off-grid and on-grid connections. Furthermore, it demonstrates a comprehensive approach to design/analyze a flexible hybrid renewable energy systems performance using HOMER software. According to literature, the present study is implemented for the first time in Malaysian's tropical climate areas. Besides, this study includes a method of improving and developing the operational performance of existing systems as well as designing new systems.

A simulation for all possible scenarios that contain different combinations of photovoltaics (PV), diesel generator, batteries, power converters, and grid connection. All possible scenarios were subsequently modeled and discussed. Each system includes two main parts: the first contains a renewable energy source, and the second contains a conventional energy source (i.e., diesel generators). The proposed hybrid system is expected to correctly combine the best utilization of all parts of the system to realize all possible benefits. HOMER software is used throughout this work to model, optimize, and conduct sensitivity analysis alongside the economic and environmental calculations (Lambert et al., 2006). Fig. 2 presents a general description of the proposed models.

2. Methodology

In this study, the hybrid energy system contains PV, diesel generator (DG), batteries, power converters, and grid connection. All possible scenarios were subsequently modeled and discussed. Each system includes two main parts: the first contains a renewable energy source, and the second contains a conventional energy source (i.e., diesel generators). The proposed hybrid system is expected to correctly combine the best utilization of all parts of the system to realize all possible benefits. HOMER software is used throughout this work to model, optimize, and conduct sensitivity analysis alongside the economic and environmental calculations (Lambert et al., 2006). Fig. 2 presents a general description of the proposed models.

2.1. Fundamental principle and evaluation criteria

The modeling concepts that are used by HOMER mainly depend on minimizing the costs. Each dispatchable energy source in HOMER are economically represented by two main values; fixed cost in ($/hour), and a marginal cost of energy in ($/kWh). These values represent all costs associated with producing energy with that power source that hour. Based on these values, HOMER searches for the best solution which can cover electrical/thermal loads as well as the operating reserve at the lowest cost. Satisfying the loads’ demand and operating reserve is regarded as critical roles for HOMER, meaning that any cost will be accepted to avoid capacity shortage. On the other hand, if the proposed combinations of the dispatchable sources can equally supply the loads demand, then HOMER will choose the lowest cost combination (Lambert et al., 2006). Furthermore, HOMER uses different algorithms to calculates the environmental impact as well as the technical evaluation process. Meanwhile, the economic, environmental, and technical evaluation criteria are deeply clarified and explained in
the following sections.

2.1. Economic evaluation

HOMER evaluates the economics for different combinations of renewable and nonrenewable energy resources using the following parameters:

I. Net Present Cost (NPC): In HOMER, the life-cycle cost is represented by the total NPC which includes capital, replacement, operating and maintenance (O&M), and fuel costs (Olatomiwa et al., 2015). NPC is expressed in Equation (1) (Lambert et al., 2006):

\[
CNPC = \frac{C_{ann\;tot}}{CRF(i, R_{proj})}\;
\]

where, \(C_{ann\;tot}\), CRF, \(i\), and \(R_{proj}\) are the total annualized cost, capital recovery factor, annual real interest rate, and project lifetime respectively. Meanwhile, CRF can be calculated using Equation (2) (Lambert et al., 2006):

\[
CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}
\]

where \(N\) is the total number of years.

II. The cost of energy (COE): Represents the average cost per kilowatt-hour of the produced energy. COE is expressed in Equation (3) (Lambert et al., 2006):

\[
COE = \frac{C_{ann\;tot}}{E_{served}}
\]

where \(E\) is the total produced energy which include the total served loads, and the amount of energy sold to the grid annually. In this study, the interest rate and the project lifetime is considered to be 6% and 25 Yr, receptively. The prices used in the simulation are in US dollars ($) at a rate of 1$ = 4.26 Malaysian Ringgit (RM).

2.1.2. Environmental evaluation

Any hybrid system that includes non-renewable energy sources would generate an amount of CO2 emissions. Equation (4) is used to calculate this amount (Shezan et al., 2016):

\[
tCO_2 = 3.667 \times m_f \times HV_F \times CEF_f \times X_c
\]

where, \(tCO_2\) is the total amount of CO2 emissions, \(m_f\) is the fuel quantity in (liter), \(HV_F\) is the fuel heating value in (MJ/L), \(CEF_f\) is the carbon emission factor in (ton carbon/TJ), and \(X_c\) is the oxidized carbon fraction. 3.667 g of CO2 includes 1 g of carbon.

2.2. Site specifications

The work examines a typical Malaysian village that is remotely located on the eastern side of Malaysia (5.10° N/119.13° E) at Tanjung Labian, Sabah. A characteristic tropical (hot and humid) climate is evident at all months of the year. The average temperature is \(-26.34\; ^\circ C\), ranging between 25.64 and 26.77°C. All meteorological parameters, including relative humidity, wind speed, and solar irradiation data were obtained from NASA website (NASA) (i.e. solar radiation, wind speed, ambient temperature, etc.).

Solar irradiation data is shown in Fig. 3. The average solar irradiation is 5.57 kWh/m\(^2\)/day, ranging between 4.87 and 6.44 kWh/m\(^2\)/day. Once the monthly solar radiation values are entered, HOMER builds a set of 8760 solar radiation values, i.e. for each hour of the year. HOMER uses Graham's algorithm (Graham and Hollands, 1990) to create the required values for each hour in the year. The results create a sequence of data that has realistic day-to-day and hour-to-hour variability and autocorrelation (Lambert et al., 2006), as shown in Section (2.4). However, wind speed is regarded to have low potential in Malaysia and unsuitable for running wind turbine in, as per (Ngan and Tan, 2012). It seems that solar energy provides the most suitable solution for obtaining hybrid renewable energy systems in tropical areas.

2.3. Dispatch strategy

HOMER software offers two main dispatch strategies; Load Following (LF) and Cycle Charging (CC) strategies. In CC strategy, the system uses diesel generators to charge batteries and supply the loads when renewable energy sources are unavailable. The LF strategy uses diesel generators to supply loads only when renewable energy sources are unavailable. The LF strategy is more trends
to be dependent mainly on the renewable energy sources, and generates a lower amount of CO₂ emissions. LF seems to be the optimal strategy, as it helps reducing the excess energy and total NPC (Ngan and Tan, 2012). Therefore, the LF dispatch strategy is used to design and analyze the data collected during this study. More information could be found in (Lambert et al., 2006). In the meantime, the energy delivered to the load by renewable resources is expressed as a renewable fraction (RF). HOMER calculates the renewable fraction as shown in Equation (5) (Halabi et al., 2017):

$$ RF = \left( 1 - \frac{E_{\text{non-renew}} + H_{\text{non-renew}}}{E_{\text{served}} + H_{\text{served}}} \right) \times 100\% $$

where \( E_{\text{non-renew}} \) and \( E_{\text{served}} \) are the electrical energy produced by nonrenewable energy sources and total served electrical loads in (kWh/yr), respectively, and \( H_{\text{non-renew}} \) and \( H_{\text{served}} \) are the thermal energy produced by nonrenewable energy sources and total served thermal loads in (kWh/yr), respectively.

### 2.4. Load data

The load profile was calculated based on a previous study that determined the hourly load profile for a typical remote Malaysian village household in a tropical area. It took into account the consumer’s behavior on a weekly basis (Ismail et al., 2013). The loads used in such households usually contain lights, fan, TV, refrigerator, and another mini appliance. In this study, a small village comprising of 35 households is considered, and the hourly and yearly load profiles are shown in Fig. 4 (a) and (b), respectively. In the morning, there are some small loads, which peaked at noon (213.60 kWh), then the loads decrease simultaneously. However, the total annual average load was 2138.50 kWh/day. In the meantime, the day-to-day variability and time-step variability were assumed to be at low variation values of 5%, due to its equatorial location, since seasonal variations are almost non-existent. The operating reserve is defined by HOMER as the reliable amount of power that should be supplied if the RE supply suddenly decreased or the load demand suddenly increased (Halabi et al., 2017). Some studies obtained the optimal value of operating reserves of 10% of hourly loads and 25% solar energy output as shown in (Halabi et al., 2017) Hence, these values are used in this study.

### 2.5. Components data

HOMER assumes a certain step size for each system component when considering sizing. In this work, the technical properties of all the components are listed in Table 3.

In remote locations, the DGs quote a higher maintenance price compared to non-remote locations, due to increased transportation costs pertaining to replacement tools and technical experts into such locations. Lead Acid batteries are the most commonly used type in remote areas, as per literature. The capacity curve of the batteries is shown in Fig. 5, where the minimum state of charge (SOC) of the batteries is 40%.

Multiple step sizes are considered to determine the optimum solution. Meanwhile, each part of the system' components has its own distinguished configurations, as well as capital, replacement, and maintenance prices. All prices that quoted in this work are summarized in Table 4. However, no solar charge regulator is considered as an individual component in this study.

All parts of the hybrid system include diesel generators, PV, battery banks, and power converters, all of which are necessary to ensure a continuous supply to the load. In the off-grid scenario, the PV arrays supply the necessary energy requested by the loads at the day-time under normal conditions. Excess energy is stored in the battery banks, which is used when the PV arrays are inefficient in supply the loads. The diesel generators work as a backup system when the PV arrays or battery banks are inefficient in meeting the load demand. However, in the on-grid scenario, the grid does the role when the PV arrays are unable to supply the loads in addition to utilizing the excess energy. The diesel generators are used to supply the loads whenever the minimum load factor is equal to or more than 25%; This ratio is recommended by most generators’ manufacturers to reduce the wear/tear of the generators, which increases the life-cycle as well as reduce the fuel consumption, which is needed to supply the loads at low demand ratio (Hossain et al., 2016). This ratio would not prevent the generators from being switched off, but it would prevent it from working at low loads (Lambert et al., 2006).

The system is designed for continuous operation (i.e., 24 h/day)

---

**Table 3**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV modules</td>
<td>Efficiency (%)</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Derating factor (%)</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Operation temperature (°C)</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Temperature co-efficient (°C)</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>Lifetime (Years)</td>
<td>25</td>
</tr>
<tr>
<td>Electrical generator</td>
<td>Minimum load ratio (%)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Minimum running hours (h)</td>
<td>15000</td>
</tr>
<tr>
<td></td>
<td>Fuel type</td>
<td>Diesel</td>
</tr>
<tr>
<td>Battery banks</td>
<td>Battery type</td>
<td>Lead Acid batteries</td>
</tr>
<tr>
<td></td>
<td>Round trip efficiency (%)</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Nominal capacity (kW h/Cell)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Nominal voltage (V/Cell)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Lifetime per battery (Years)</td>
<td>7</td>
</tr>
<tr>
<td>System converter</td>
<td>Rectifier efficiency (%)</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>Inverter efficiency (%)</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Lifetime (Years)</td>
<td>15</td>
</tr>
</tbody>
</table>
with no interruption. The system is subjected to several changes to ensure meeting the proposed criteria for finding the flexible design and evaluating the operational performance of the system. The optimal design is expected to be able to withstand against all changes over the project’s lifetime. In this work, two different schemes are examined, which include off-grid and on-grid systems. A detailed sensitivity analysis is also conducted to ensure that it meets the flexibility requirement of the optimum design of major changes that the system may face at disparate periods. The procedure is detailed in Fig. 6.

3. Results and discussion

Several scenarios were carried out, with each containing different technical and economic configurations. Fig. 6 details the procedure for finding the optimum system for Off/On-grid connections. The proposed system is designed to serve the whole period project of 25 Yr over numerous changes, such as components’ prices and load demand. Meanwhile, the system should be flexible so that it can serve under almost all conditions, including changes to the main variables that directly affect the hybrid renewable energy systems. The system is tested over the off-grid connection to find the optimum solution. Then, the technical, economic, and environmental performance are all analyzed. Also, the system in off-grid connection is examined during the sensitivity analysis to quantify the impact of changing fuel prices and load demand on the optimal design. Correspondingly, the optimum design is also investigated over the on-grid connection, where the effects of the addition of this connection on the component combination and operational performance are elucidated and explained. Furthermore, the optimum design is examined over sensitivity analysis by changing certain - main - variables at the on-grid connection such as; power purchase, sell-back, fuel prices, and load demand (load growth). As a result, the final system obtains an optimum system that is capable to supply a continuous operation in both off and on grid connections, without any need of replacing/

Table 4
System component prices (Hossain et al., 2016).

| Component | Prices | | |
|-----------|--------|------------------------------------------------|
|           | Capital ($/kW) | Replacement ($/kW) | Maintenance |
| DG        | 220    | 200 | 0.030 $/h |
| PV        | 2000   | 2000 | 10 $/kW/Yr |
| Battery   | 1200   | 1170 | 10 $/kW/Yr |
| Convertor | 890    | 800 | 10 $/kW/Yr |

Fig. 5. Batteries’ capacity curve Capacity (Ah) VS discharge current (A).

Fig. 6. System procedure flowchart.
making major changes to the system design. Accordingly, HOMER classifies the results into two main classifications: (Overall) and (Categorized) categories. In the overall choice, HOMER shows the top-ranked system configurations according to NPC, which does not always reflect the optimal solution of different system combinations. In contrast, the categorized choice shows the lowest-cost system of each type, which includes the optimum solution for each system topology. The simulation results show different combinations of the optimal scenarios that include different RF, COE, and NPC values. While, each system is designed to supply the load profile with a continuous power supply.

3.1. Off-grid hybrid system

No grid connection is obtained in this section. A standalone system includes DG, batteries, converters, and PV, all of which are proposed to meet the load demand without any technical interruption. Fig. 2. (a) shows the proposed system topology. In this case, the system is designed to rely mainly on PV arrays to generate adequate power, while DGs are used as a backup system when the PV and/or battery are unable to meet load requirements, according to the LF dispatch strategy as shown in Section (2.3). Table 5 tabulates the specific step sizes, which have been selected by HOMER as the best configuration in terms of RF, COE, and NPC.

The optimum system includes two DGs with capacities of 100 kW and 50 kW. The best choice of the converter, PV, and batteries are 150 kW, 300 kWp, and 330 kWh, respectively. Table 6, shows the produced energy by each component, where HOMER calculates the renewable energy production by dividing the annual amount of produced electrical energy by the renewable energy components to the total production of all components in the system (Lambert et al., 2006).

In this scenario, a small portion of excess energy is found. It forms 5.4% from of the total production, reporting 47254.0 kWh/Yr. Excess energy is always regarded as one of the main drawbacks of the off-grid systems, where using dumb loads or connecting the system to a national electrical network are regarded as the most effective solutions for totally consuming the excess energy. However, it could also be reduced by adding more batteries to the system, but this would increase the total NPC of the system. Furthermore, the excess energy could also be reduced by decreasing the minimum load ratio for the diesel generators, but this would affect the system’s performance by increasing the operating and maintenance costs, and decreasing the generator’s lifetime. On the other hand, increasing the renewable energy generation would result in increasing the amount of the excess energy, which is classified as system loss. Fig. 7 shows the energy share from each source based on the monthly basis for a year.

In this case, the optimum system includes 300 kW of PV modules, two DGs of 100 kW and 50 kW, 150 kW power converter, and one string batteries of 330 kWh, as per Table 6. The total NPC of the system is $2802919.0, while the COE is 0.281 $/kWh. The total operating and salvage costs of the system are $148976.0 and $28109.0, respectively. The NPC, COE, and operating costs are considered high values, but this due to the remote locations of this site, which increased transportation, storing expenses of the fuels, in addition to the system’s maintenance costs. Generally, in remote areas, fuel prices reached 1.5 times the normal price in other locations (Anwari et al., 2012).

3.1.1. System generators — diesel generators

In order to describe the operational performance of the diesel generator, this section details its performance by elucidating the working hours and generated energy, fuel consumption, and generated harmful emissions towards the environment.

I. Working hours and generated energy

Fig. 8 (a) and (b) describes the DGs work procedure based its monthly routine. DG1 and DG2 are working for 4213.0 h/Yr and 4445.0 h/Yr, with a maximum rated power of 100 kW and 50 kW, respectively. The 100 kW generator works mostly at higher load demands earlier at the evening when the PV and/or batteries are unavailable to produce sufficient power to the loads. While, 50 kW generator works at lower load demands late at the night and early at the morning, besides at different period during the day when the loads have lower values. The monthly generated energy of the DGs is shown in Fig. 8 (b).

II. Fuel consumption

The fuel consumption of the diesel generators is directly related to the working hours and load ratio. These two factors directly

### Table 5
Multiple ranges of component’s combinations.

<table>
<thead>
<tr>
<th>System</th>
<th>PV (kWp)</th>
<th>DG1 (kW)</th>
<th>DG2 (kW)</th>
<th>Battery (kWh)</th>
<th>Converter (kW)</th>
<th>RF (%)</th>
<th>COE ($/kWh)</th>
<th>NPC ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>300</td>
<td>100</td>
<td>50</td>
<td>330</td>
<td>150</td>
<td>50</td>
<td>0.281</td>
<td>2.80 M</td>
</tr>
<tr>
<td>System 2</td>
<td>350</td>
<td>100</td>
<td>50</td>
<td>330</td>
<td>150</td>
<td>52</td>
<td>0.283</td>
<td>2.82 M</td>
</tr>
<tr>
<td>System 3</td>
<td>350</td>
<td>110</td>
<td>40</td>
<td>330</td>
<td>150</td>
<td>52</td>
<td>0.285</td>
<td>2.84 M</td>
</tr>
<tr>
<td>System 4</td>
<td>400</td>
<td>100</td>
<td>50</td>
<td>330</td>
<td>200</td>
<td>54</td>
<td>0.287</td>
<td>2.87 M</td>
</tr>
<tr>
<td>System 5</td>
<td>250</td>
<td>100</td>
<td>60</td>
<td>330</td>
<td>150</td>
<td>45</td>
<td>0.288</td>
<td>2.88 M</td>
</tr>
<tr>
<td>System 6</td>
<td>300</td>
<td>130</td>
<td>40</td>
<td>330</td>
<td>150</td>
<td>50</td>
<td>0.290</td>
<td>2.89 M</td>
</tr>
<tr>
<td>System 7</td>
<td>350</td>
<td>100</td>
<td>60</td>
<td>660</td>
<td>150</td>
<td>57</td>
<td>0.302</td>
<td>3.01 M</td>
</tr>
<tr>
<td>System 8</td>
<td>400</td>
<td>130</td>
<td>80</td>
<td>990</td>
<td>300</td>
<td>63</td>
<td>0.329</td>
<td>3.28 M</td>
</tr>
<tr>
<td>System 9</td>
<td>350</td>
<td>120</td>
<td>80</td>
<td>990</td>
<td>300</td>
<td>60</td>
<td>0.330</td>
<td>3.29 M</td>
</tr>
<tr>
<td>System 10</td>
<td>450</td>
<td>100</td>
<td>40</td>
<td>1320</td>
<td>300</td>
<td>71</td>
<td>0.341</td>
<td>3.40 M</td>
</tr>
<tr>
<td>System 11</td>
<td>400</td>
<td>110</td>
<td>60</td>
<td>1320</td>
<td>350</td>
<td>67</td>
<td>0.345</td>
<td>3.44 M</td>
</tr>
<tr>
<td>System 12</td>
<td>500</td>
<td>110</td>
<td>70</td>
<td>1320</td>
<td>350</td>
<td>73</td>
<td>0.349</td>
<td>3.49 M</td>
</tr>
<tr>
<td>System 13</td>
<td>500</td>
<td>140</td>
<td>50</td>
<td>1320</td>
<td>400</td>
<td>74</td>
<td>0.351</td>
<td>3.50 M</td>
</tr>
</tbody>
</table>
influence the performance of the diesel generator, the consumed amounts of fuel by both diesel generators are shown in Fig. 9 (a) and (b). It shows the average monthly fuel consumption by DG1 and DG2 for one year, respectively. It is clear from Fig. 9 (a) and (b) that DG1 consumes more fuel than DG2 due to generating more electrical energy at different times of the day. Where, DG1 has higher rated power of 100 kW, and mostly works when higher load demands are found. Although
DG2 works for more hours in the year, DG1 generates higher amounts of the electrical power. The total fuel consumption of DG1 and DG2 is 107680.0 L/Yr and 35681.0 L/Yr, respectively, where DG2 consumes 67% fuel more than DG1.

III. Harmful emissions towards the environment

In this study, no penalties over CO2 emissions was considered. The total produced harmful emissions are shown in Table 7, where Carbon dioxide forms the majority of the produced harmful emissions. While, the Particular matters form the lowest amount of the produced harmful emissions. This difference is due to the types of fossil fuels being used, where the generated harmful emissions would be different in the case of using different types of fuel.

3.1.2. Storage system

The presence of the batteries in the system supports its performance and reduces the uncertainty problems that are associated with renewable energy resources. Hours of autonomy, represent the maximum number of hours that the storage system can continuously supply to the loads. In this study, one string of batteries rated by 330 kWh form 2.22 h of autonomy as the optimal size of the storage system. Fig. 10 shows the monthly SOC of the battery banks. It indicates that months from June to August reported the lowest charging cycles, which reveal the high demand of the stored energy. These months are the hottest months in the year at the proposed site, with lowest rains among the year, thus more energy is needed for cooling purposes. In contrast, months from March to May reported the highest charging cycles, where the system trends to depend more on the other components to meet the load demands.

3.1.3. Sensitivity analysis

Sensitivity analysis is performed to examine the system

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Kg/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>377517.0</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>931.83</td>
</tr>
<tr>
<td>Unburned hydrocarbons</td>
<td>103.22</td>
</tr>
<tr>
<td>Particular matters</td>
<td>70.25</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>758.12</td>
</tr>
<tr>
<td>Nitrogen oxide</td>
<td>8315.0</td>
</tr>
</tbody>
</table>
behavior when changing the main parameters in any standalone system that directly affect its performance. Fig. 11 shows the result of the sensitivity analysis over changing the diesel price from the current price (0.7 $/L) in Fig. 11 (a), to more than (1.5 $/L) in Fig. 11 (b), along with increasing the average load demand (+5% per year) vs. the average monthly solar radiation changes over a 25 Yr period.

The sensitivity analysis creates different combinations of the proposed system equipment according to the available parameters of scaled loads, fuel price, and etc. Once the system meets the required criteria, HOMER chooses the system as the optimum design for the specific conditions. For this purpose, the sensitivity analysis test’s results shown in Fig. 11 demonstrate the wide capability of the designed hybrid system in meeting the load demands at different changes in the metrological data, diesel fuels prices, and average load demands. Based on these results, it is clear that HOMER software selects the optimum combination which illustrated in Table 6. The results also demonstrate the high flexibility of the optimum design over changing the diesel price, increasing the scaled average loads (load growth), and the average solar radiation. The design shows a high capability to serve these changes (which are regarded as major variables) under off-grid connection (standalone conditions). From Fig. 11 (a), there are two main combinations of the generation systems which seems to be the best choices by HOMER; The first includes two diesel generators and battery banks. This combination is preferred only when the average loads increased to more than 2138 kWh/d and the average solar radiation reported low values of less than 1.6 kWh/m²/d. Otherwise, the designed hybrid combination of two DGs, PV arrays, and batteries (which represent the proposed optimum solution) are preferred over the standalone DGs system and all other combinations during the project’s lifetime. In the meantime, the effects of using the on-grid connection and different parameters are presented and explained in the following Section (3.2).

3.2. On-grid hybrid system

This section discusses the optimal design assigned to a grid connection. Therefore, the system should be flexible to include this addition without making any change to the system configuration as shown in Fig. 2 (b). Usually, inserting a grid connection after running a standalone system requires some critical changes on top of re-designing the whole system due to possible incompatibility between the system components, as shown in the literature. Consequently, finding the flexible design would reduce the investment cost, which eliminates the need for any modifications. This would promote the development of rural electrification projects without fearing form future changes.

In this case, two main parameters have a direct impact on any on-grid connection, which are the power purchase and sell-back prices. Currently, the national grid is unavailable at the proposed location. Therefore, there are no specific values that could be considered for setting the sell-back and power purchase prices. It is therefore assumed that the power purchase price should be higher than the nearest location with a grid connection due to the far
distance of the proposed site. Meanwhile, the sell-back price should be higher than the power purchase prices as well as the off-grid system’s COE. This increase is due to the feed-in tariff policies and governmental subsidies, which is usually offered by the government for such projects, as per literature. However, in order to study the operational performance under grid connection conditions, the system should be assigned to a detailed sensitivity analysis, which allows elucidating the impact of all parameters on the system, the result of which are detailed in the following section (3.2.1).

3.2.1. Sensitivity analysis

This section performs a detailed sensitivity analysis comprising all changes to the on-grid system’s operation. The applied changes include the load demand (load growth), power purchase, sell-back, and fuel prices. Fig. 12 shows the effects of changing the load demand against power purchase and sell-back prices.

In Fig. 12 (a) - (d), a fixed diesel price of (0.7 $/L) is used; it shows the effects of changing the sell-back price simultaneously with the power purchase prices at different rates, on top of increasing the load demands by 5% of load growth on the optimal system configurations. The results confirmed the direct impact of these parameters on choosing the optimal system’s configuration.

As per Fig. 12, the system’s configuration found in Section (3.1) is still preferred, which contains two DGs, PV, and Grid with the same components’ configurations but without the storage system (battery banks). The elimination of the battery banks appears due to:

I. Backup system: The grid connection provides a reliable backup system, thus there is no need to add batteries, which would increase the total NPC and COE.

II. Excess energy: Excess energy is sold back to the grid, which would add a source of income for the system, thus reducing the COE while consuming the excess energy.

In this case, it is clear that including storage system would result in adding more costs to the system as the capital and replacement prices that are associated with the batteries are considered as expensive factors. The battery storage system does not only request higher capital cost but also high frequent replacement times because of the low battery lifetime compared to the whole project lifetime. The reason as specified by most manufacturers is due to frequent off/on operation that reduces the proposed lifetime of the batteries. On the other hand, due to the current development in the field of energy storage, it is expected to achieve lower costs in the future which may support using the storage systems in all topologies without any fear form higher prices.

Furthermore, if the value of the sell-back price is lower than the COE of the off-grid system (0.281 $/kWh) and power purchase price, the system tends to depend more on the DG2/PV/Grid choice while the load keeps increasing. However, increasing the sell-back price to exceed the COE of the off-grid system (0.281 $/kWh) in addition to the power purchase will cause the system tends to depend more on the optimum design (DG1/DG2/PV/Grid) configuration. Therefore, the system demonstrates the high flexibility of the optimal design in the case of fixed fuel price.

To validate the results, the effects of changing diesel price on the system in terms of load demands, power purchase, and sell-back prices needs to be elucidated. In this context, diesel price varies within the range of (0.7—2.0 $/L), power purchase in a range of (0.15—0.55 $/kWh), and sell-back prices in a range of (0.15—1.00 $/kWh). This would alleviate quantifying the influences of

![Fig. 12. On-grid hybrid system sensitivity analysis showing power price VS average loads at different sell-back prices in ($/kWh) (a) 0.15 (b) 0.25 (c) 0.30 and (d) 0.35 and above.](image-url)
adjusting these main parameters on the operational performance of the system.

The results presented in Fig. 13 (a) - (f), shows that two topologies are preferred, DG2/PV/Grid and DG1/DG2/PV/Grid. These hybrid combination scenarios are still selected as the best scenarios despite high diesel prices. But, the optimum system found in Section (3.1) (i.e. DG1/DG2/PV/Grid) shows higher ability to serve through different conditions, mainly when the price of diesel fuel, power purchase are increased. Meanwhile, higher values of sell-back prices would result in increasing the dependence on the hybrid systems due to selling the excess energy back to the grid. Therefore, the hybrid system would earn increased income, which helps reduce the total COE. Contrarily, another choice of a hybrid system that contains only one DG (DG2/PV/Grid) reported decreased in the reliability, as the system is preferred mainly at higher load demands, lower diesel, and power purchase prices.

As a result, the optimum system is regarded as the best option at all cases, which confirms the high flexibility of the proposed design over the off-grid and on-grid connections.

RF changes based on different power purchase and sell-back prices, as per Fig. 14. The highest RF was found at the off-grid system at 55.43%. Accordingly, RF is inversely proportional to the power purchase prices, while higher sell-back prices are accompanied with higher dependence on the hybrid system. The results indicate that the operational performance of the system is directly affected by both power purchase and sell-back prices. In this study, the RF varies within (23–55.43) %. The analysis of the system indicates that lower power purchase, as well as higher sell-back prices, are preferred in any hybrid system under grid connection conditions.

3.2.2. Economic impact

The effects of varying the sell-back and power purchase prices on the COE, NPC, and operating cost are shown in Fig. 15. Different power prices for both power purchase and sell-back prices of 0.15, 0.25, 0.35, 0.45 and 0.55 $/kWh are considered in Fig. 15 (a–e), respectively.

From the results, it is clear that COE, NPC, and the operating cost increased when the power purchase price increased, for example, when the power purchase is 0.15, 0.25, 0.35, 0.45, and 0.55 $/kWh. The fixed sell-back price is of 0.15 $/kWh. The impact on COE is obvious, as COE values increased by 0.151, 0.203, 0.227, 0.232, and 0.233 $/kWh. On the other hand, increasing the sell-back prices would lead to decreased COE, NPC, and operating costs. The results demonstrate the direct impact of these two parameters on the overall system’s performance. Understanding the performance of
any hybrid system based on these variables in remote areas is important and would influence the whole system, mainly when it comes to updating standalone systems with grid connections.

3.2.3. Environmental impact

The environmental impact of each system is also studied in this work. The result of exhausting different power purchase and sell-back prices is shown in Fig. 16. Higher power purchase prices lead to decreasing the dependence on the grid to meet the load demand and increase the usage of the hybrid system — which includes diesel generators and renewable energy components — in this case; the diesel generators would work more mainly when the renewable energy sources are unavailable. Thus, higher amount of the CO2 emissions is found. While, considering higher sell-back prices (for the same power price), in this case; the system would depend more on the grid as the main source of energy thus, higher amount of CO2 emissions towards the surrounding environment would be generated. HOMER software calculates CO2 emissions in the grid connection by multiplying it with a special factor reported in (Lambert et al., 2006).

3.3. General remarks

3.3.1. Technical remark

Among the different configurations of off-grid and on-grid connections, each scenario has distinct properties. These differences affect the operational behavior and the economic factors of the system. The results show that the off-grid system depends on the storage system (battery banks) as its main backup system and to store excess energy for further use. However, the on-grid system replaces the battery role with the grid connection. In this case, battery banks seem to be economically inefficient in the on-grid connection as the excess energy is sold back to the grid. The system depends mainly on the DGs and PV models to supply the load. In this case, the grid is operated to perform two main tasks:
I. Backup system in case the DGs and PV are inefficient in supplying useful energy to the loads.
II. Consuming excess energy generated by the system, which adds another source of income.

3.3.2. Economical remarks

The costs of the system are directly related to the operation procedure and system configuration. Fig. 17 shows the different costs to the system which includes capital, replacement, Operating and Maintenance (O&M), fuel, operating and salvage costs. Both off-grid and on-grid systems are considered, and the results indicate that the fuel cost performs a huge impact on the system, followed by the capital, O&M, and the replacement costs. Meanwhile, the off-grid system shown in Fig. 17 (a) reported higher costs than the on-grid system which is shown in Fig. 17 (b) - (c), mainly due to the high fuel cost. Furthermore, using different power purchase and sell-back prices led to dissimilar system costs. It also excludes the use of certain components, such as DGs, as shown in Fig. 17 (c) in the case of higher sell-back prices.

4. Conclusions

In this research, the optimum hybrid renewable energy system was designed to meet the load demand of a typical remote Malaysian village located Sabah, Malaysia. Several scenarios for off-grid and on grid connections were performed using HOMER software. The operational behaviors for all of the configurations were investigated and quantified to demonstrate the benefits/risks associated with each system and determine viable flexible design. The main conclusions and limitations found in this study are elucidated as follows:

- To ensure establishing a flexible hybrid system in both Off and On grid connections, the effects of some major factors should be investigated due to their direct impact on the system design and performance. These factors include the fuel’s price, average solar radiation, load demand, fuel consumption, power purchase, and sell-back prices.
- The optimal system includes, two DGs of 100 kW and 50 kW, PV modules of 300 kWp, battery banks of 330 kWh, and a 150 kW converter.
- The important role of battery banks in the off-grid system is highlighted mainly as a backup system. It supports a continuous energy supply, but it directly influences the system by increasing the NPC and COE.
- In on-grid system, the grid seems to be capable to replace the function of battery banks. Therefore, the battery banks are excluded from this system. Also, sold back the excess energy would add another source of income to the grid operator.
- The power purchase and sell-back prices were confirmed to be the main factors that directly affect the on-grid system performance. Where, the results showed that the effects of increasing diesel fuel prices would rend the system to depend on the optimal solution. Inserting a grid connection would reduce the COE, NPC, and the operating cost of the system.
- The sensitivity analysis showed that the COE normally falls within a range of (0.151e0.281 $/kWh), while the NPC of (1500000.0e2802919.0 $) for both off and on grid systems. These ranges are subjected to the availability of battery banks, DGs’ work procedure, fuel consumption, power purchase, and sell-back prices.
- The influence of considering different power purchase and sell-back prices on the total different renewable energy penetration levels were showed and discussed.
- The CO2 emissions generated by the system depends on the working hours of DGs, fuel price, load demands, renewable energy penetration, power purchase, and sell-back prices. The system emits a range of (245284.0e570643.0 kg/Yr) of CO2 emissions, in both off and on grids systems based on the aforementioned parameters.
- In general, the proposed method in this study is limited to the availability of efficient data for load profile and natural resources. In addition, the economical details regarding different grid power prices; power purchased and sell-back prices, forms a major obstacle mainly if there are no records available for the proposed site or any near location.

As a result, the proposed hybrid DGs/PV/Storage system design demonstrated its high capability of operating over different conditions that could affect the system at any stage of the project’s lifetime. Furthermore, studying the performance over unreliable grid connection using hybrid renewable energy power systems could be proposed as a future work. While, it is recommended

Fig. 17. Details cost analysis of (a) off-grid system and on grid system with different power purchase and sell-back prices of (b) 0.350 $/kWh and 0.150 $/kWh (c) 0.250 $/kWh and 0.350 $/kWh (d) 0.550 $/kWh and 0.150 $/kWh respectively.
Initially, to find a suitable model of the unreliable grid, then designing an optimum hybrid system using the proposed approaches in this study. Finally, describe the advantages and the mitigated disadvantages that are associated with the system.

Acknowledgements

The authors would like to acknowledge the financial support received from the University of Malaya, Malaysia, through Frontier Research Grant No. FG007–17AFR and Innovative Technology Grant No. RP043B–17AEI.

Glossary

**Word:** Definition

- **NPC:** Net Present Cost, it represents the life-cycle cost which includes capital, replacement, operating and maintenance (O&M), and fuel costs.
- **COE:** Cost of Energy, it is the average cost of the produced energy per kilowatt-hour.
- **RF:** Renewable fraction, it is the energy delivered to the load which is generated by the renewable resources.
- **SOC:** The State of Charge, it is the current charging level in the battery banks, where the minimum state of charge represents the allowable charging level that the storage system should include to safely maintain.
- **CRF:** Capital Recovery Factor, it is a ratio used to determine the future cash flow with respect to time of the system.
- **CEF:** Carbon Emission Factor, it represents the emitted amount of hydrocarbons which is produced by the generators per unit of the consumed fuels.
- **E_{\text{nom.-rem.}}:** Is the total production of electrical energy by non-renewable energy sources.
- **E_{\text{served}}:** Is the total served electrical loads by the system in a year.
- **H_{\text{nom.-rem.}}:** Is the total produced thermal energy by non-renewable energy sources.
- **H_{\text{served}}:** Is the total served thermal loads by the system in a year.

**References**


Tomos, M.H., Sihnahd, M., 2007. Technical and economic assessment of grid-


