NSGA-II and MOPSO based optimization for sizing of hybrid PV/wind/battery energy storage system

Mohamad Izdin Hlal[1], Vigna K. Ramachandaramurthya[2], Sanjeevikumar Padmanaban[3], Hamid Reza Kaboli[4], Aref Pouryekta[5], Tuan Ab Rashid bin Tuan Abdullah[6]

[1, 2, 5]Institute of Power Engineering, Department of Electrical Power Engineering, College of Engineering ,
Universiti Tenaga Nasional, Malaysia
[3]Department of Energy Technology, Aalborg University, Denmark
[4]UM Power Energy Dedicated Advanced Centre (UMPEDAC), Wisma R&D, University of Malaya (UM), Malaysia
[6]Institute of Energy Policy and Research (IEPRe), Universiti Tenaga Nasional, Malaysia

Article Info

ABSTRACT

This paper presents a Stand-alone Hybrid Renewable Energy System (SHRES) as an alternative to fossil fuel based generators. The Photovoltaic (PV) panels and wind turbines (WT) are designed for the Malaysian low wind speed conditions with battery Energy Storage (BES) to provide electric power to the load. The appropriate sizing of each component was accomplished using Non-dominated Sorting Genetic Algorithm (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) techniques. The optimized hybrid system was examined in MATLAB using two case studies to find the optimum number of PV panels, wind turbines system and BES that minimizes the Loss of Power Supply Probability (LPSP) and Cost of Energy (COE). The hybrid power system was connected to the AC bus to investigate the system performance in supplying a rural settlement. Real weather data at the location of interest was utilized in this paper. The results obtained from the two scenarios were used to compare the suitability of the NSGA-II and MOPSO methods. The NSGA-II method is shown to be more accurate whereas the MOPSO method is faster in executing the optimization. Hence, both these methods can be used for techno-economic optimization of SHRES.

Corresponding Author:

Mohamad Izdin Hlal,
Institute of Power Engineering, Department of Electrical Power Engineering,
College of Engineering ,Universiti Tenaga Nasional,
Jalan IKRAM-UNITEN, 43000 Kajang, Malaysia.
Email: mohamadizdinhlal@yahoo.com

1. INTRODUCTION

In recent years, the increasing concern on the depletion of fossil fuel and global warming has catalyzed the growth of renewable energy sources due to their promising economic and environmental benefits [1], [2]. Wind turbines and solar photovoltaic are commonly used in the renewable energy system to supply power to consumers in the remote regions because there is no fuel cost involved, easy to install and are also non-polluting. Nevertheless, designing a renewable energy system can be a challenge. Thus, knowledge of all aspects that influences system performance and component sizing is a precondition for an accurate SHRES design. Large fluctuations in climatic and meteorological conditions cause intermittency of renewable energy sources. Malaysia which lies close to the equator has seasonal wind speed and does not have a comprehensive wind assessment [3]. This problem can practically be overcome by using battery energy storage system [4]. They design and optimization methods are important aspects for SHRES to

guarantee supply reliability and security, and also to ensure maximum utilization of PV panels, wind turbines and battery energy storage, based on the load profile [5], [6].

There are several methodologies that utilize traditional optimization methods to design a techno-economic hybrid energy system based on the Loss of Power Supply Probability (LPSP) [7]-[9]. A common drawback of these optimization methods is the low calculation efficiency, therefore consuming excessive central processing unit time. In addition, the optimization methods cannot find the best compromise point between the objective functions. On the other hand, Artificial Intelligence (AI) methods are able to achieve all the conditions, such as LPSP and COE. Authors in [10]-[12] presented a methodology to calculate the optimal number of PV panels, wind generation, and battery using genetic algorithm approach by calculating LPSP and system cost. In [13], AI methods such as the Non-dominated Sorting Genetic Algorithm (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) were used to produce a Pareto-optimal solution in a single simulation run. Several authors have studied the hybrid optimization system using NSGA-II. In 2017, Moslem Yousefi et al. [14] used NSGA-II algorithm and HOMER software to find the robust project design of SHRES by the varying engine loads with optimal Annual Energy Recovery (AER) and total cost of the system. Much attention was paid to discuss SHRES and Battery Energy Storage (BES) sizing. Reference [15] discussed the economic approach of multi-optimization of a standalone hybrid PV-Wind – Battery and diesel generator system through the application of multi-objective using NSGA_II method. The economic benefits include the minimization of power generation cost and maximizing the useful life of the battery, including the life loss, fuel, environmental, and maintenance cost. In addition, it has considered the lifetime characteristics of lead-acid batteries.

Ce Shang et al. [16] focused on the battery energy storage system sizing in stand-alone hybrid power system to guarantee reliability and minimize the levelized cost of energy using NSGA_II method. In reference [17], techno-economical optimization for HRES was applied using NSGAII method to analyze the trade-off between three conflicting objectives: total cost, autonomy level, and wasted energy rate. However, the optimal sizing of the system components was not considered. The hybrid solar/wind system with the traditional fossil fuel-fired generators was described in [18]. While two objectives that controlled the NSGA-II procedure was proposed to minimize the cost and emission. To achieve the best compromise solution, the Fuzzy priority ranking has used. The paper presented effectuality of the algorithm for evaluating through solving cost and emission dispatch issue without considering the power generation, for comparison reasons and results were compared with methods contained in the literature. Reference [19] presented small hybrid renewable system depends on the cost and environmental criteria using NSGA_II technique, with two integrated energy storage units from battery banks and hydrogen storage system combined. Hence, minimized the COE and greenhouse gas emission (CO_2).The main contribution of this work was that the computing of total greenhouse gas emissions according to life cycle analysis of each system's component.

Many researchers have investigated the hybrid system using MOPSO method. Authors in [20] presented the optimization of an off-grid hybrid micro-grid system to determine the optimal sizing in twelve Swedish regions. The optimal design was selected after running the multi-objective optimization method to determine the trade-off between the three objectives: LPSP, COE, and the environmental impact (CO_2). A hybrid renewable energy system with multi-storage system configuration for buildings in Canada that adopts the MOPSO method was proposed in [21] for optimal economic operation in order to minimize the total Net Present Cost (NPC) and CO_2. Reference [22] proposed the design of a stand-alone hybrid generating system to determine the optimum sizing of the number and type of PV panels, wind turbines, battery bank, as well as diesel generators location using MOPSO method. The sizing was done based on a one-year data to minimize the cost and emission.

The NSGA-II and MOPSO are the modern random optimization methods that are able to find Pareto. Hence, both these methods are applied to design the SHRES and to minimize the multi-objectives such as LPSP and COE. This paper presents a comparative evaluation of the performance of NSGA-II and MOPSO to determine the optimal sizing of SHRES using Pareto optimization. In order to determine the best combination of energy sources and to ensure their seamless integration into the distribution system to be at the optimal size, the numbers of PV panels, WT system, and batteries are used as the decision variables to minimize the LPSP and COE. The rest of the paper is organized as follows. A brief overview of hybrid WT/PV models and BES is presented in Section 2. The optimal configuration of the stand-alone hybrid system is explained in Section 3. The comparative analyses of the simulation are discussed in Section 4, followed by the conclusion in Section 5.

2.   POWER CIRCUIT OF THE (SHRES)

In order to predict the SHRES performance, the energy sources need to be practically designed to meet the load demand. At the same time, the power obtainable from a hybrid renewable system has

significant fluctuations due to weather conditions and hence, the constant load demand may not be met. To mitigate this issue, a battery bank can be integrated to the hybrid system. However, the high cost of batteries is an issue in renewable energy systems. Thus, optimizing the size of the PV-WT-BES system becomes essential. These contributions reduce the capital cost and increase the chances of investment in renewable energy plant installation. Therefore, the optimal combination of renewable power resources with appropriate storage sizing, as proposed in this work, will give a vital contribution for the future economic feasibility of such plants, thus making the design more attractive for investors.

2.1. Wind turbine modeling

The wind is characterized by its speed and direction and is affected by factors, such as geographic position, meteorological factors and height above ground level. Wind turbine reacts to the wind, capturing a part of its kinetic energy and switching it into usable energy. The output power of wind turbine is determined as a function of the rated wind speed (V_r), the cut-in wind speed (V_{ci}) and the cut-out wind speed (V_{co}) according to the following (1):

$$P_{WT} = \begin{cases} 0 & V < V_{ci} \ or \ V > V_{co} \\ V^3 \left(\frac{P_r}{V_r^3 - V_{ci}^3}\right) - P_r \left(\frac{V_{ci}^3}{Vr^3 - V_{ci}^3}\right) & V_{ci} \leq V \leq V_r \\ P_r & Vr \leq V \leq V_{co} \end{cases} \quad (1)$$

Where, P_{WT} is the output power by wind turbine, P_r is the rated wind power, V is the wind speed, $V_{ci,}$ V_r and V_{co} represent the cut-in wind speed, nominal wind speed, and cut-out wind speed respectively. The turbine cut-in speed is small, which enhances the effective operation of the system even under low wind speed [20]-[23].

2.2. Solar PV array modeling

Solar panels are defined as a group of cells connected in parallel and series to generate the required electrical power based on meteorological factors such as solar radiation and temperature. The current model used to predict the output power of a PV module can be expressed through the following (2) and (3) [24]:

$$P_{PV} = PV_{STC} \left(\frac{G}{G_{ref}}\right) \left(1 + K_T(T_C - T_{ref})\right). \quad (2)$$

$$T_C = T_a + (0.0256 * G). \quad (3)$$

Where, PV_{STC} is the nominal power in (kW), G is the global solar radiation (kW/m2), G_{ref} is the solar radiation under STC (1000/m²), T_C is the temperature of PV cell, $T_{ref} = 25$ C°, K_T is the PV temperature coefficient, $3.7*10^{-3}$ (1/Ċ) and T_a is the surrounding temperature.

2.3. Battery storage modeling

The typical batteries that are used for hybrid energy system in areas of low wind speed and intermittent solar radiation conditions are the lead-acid and lithium-based batteries[25]. Commonly, both these batteries are employed in most large-scale energy storage projects because of their low cost, long life span, and durability, in addition to their commercial availability [26]. Membrane based lead acid batteries are also available in the market presently. Battery storage is sized to meet the load demand during a shortage or interruption of renewable energy source, usually referred to as Autonomous Days (AD). Regularly, AD is taken to be one to three days according to (4). Typically battery capacity design depends on the load and AD. Thus, battery capacity can be calculated using the following equation:

$$C_B = (E_L * AD) / (DOD * \mu_{bat} * \mu_{inv}) \quad 4)$$

Where, C_B is the battery capacity, E_L is the load demand, DOD is the depth of discharge, μ_{bat} is the efficiency of battery and μ_{inv} is the inverter efficiency. It is noteworthy that, the preceding expression is only used when the hybrid PV/WT system is unable to supply the required energy [20]. The hybrid PV/WT and battery system is formulated as a multi-objective optimization problem to improve the techno-economic performance simultaneously.

2.4. Hybrid energy management system

The uncertainty of renewable energy supplies (E_{RE}) is the main limitation of hybrid renewable energy plants. Therefore, an energy management strategy is required to complement the exchange of power from the generating sources and the load under variable weather conditions. It is calculated using the following (5) and (6):

$$\Delta_{Enet} (t) = E_{RE} (t) - E_L (t) \tag{5}$$

$$E_{RE} (t) = N_{WT}* E_{WT} (t) + N_{PV} * E_{PV} (t) \tag{6}$$

Where, Δ_{Enet} is the net energy of SHRES, N_{WT} is the number of wind turbines, N_{PV} is the number of PV panel, E_{WT} is the energy generated by the wind turbines, E_{PV} is the energy generated from the PV panels, and E_L (t) is the load demand at hour (t) where (t) equals one hour.

The following cases are taken into account in this article, to simulate an energy management strategy, as depicted in Figure. 1:

a. When the generated power is higher than the load demand, the surplus power is employed to charge the battery bank.
b. When the generated power is higher than the load demand and the state of charge of the battery bank is full, the surplus energy is consumed in a dump load.
c. When the generated energy is lower than the load demand, the battery bank is discharged to sufficiently supply the load demand.
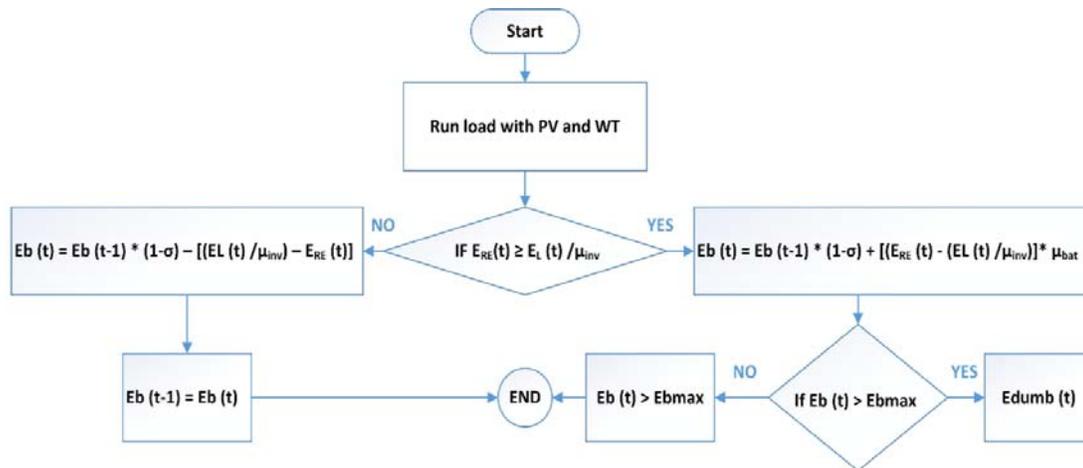

Figure 1. Flowchart of the hybrid energy system

3. OPTIMAL CONFIGURATION OF THE STAND-ALONE HYBRID SYSTEM

Once the hybrid component specifications have been determined, two cases will be investigated based on multi-objective optimization using NSGA-II and MOPSO methods. In the first case, the hybrid system will consist of PV panels, WT, and battery bank, while the second case consists of PV panels and battery bank only. The following two sub-sections illustrate the definitions of the objective functions in detail.

3.1. Reliability analysis

There are two approaches to determine the long-term performance of LPSP in a stand-alone hybrid system, namely, chronological method and probabilistic techniques [27]. The chronological method is more common and accurate, especially to determine the energy produced from the battery and the computational time is typically larger than that of probabilistic models. It is common in the chronological models to perform a one-year simulation with a one-hour time step. Computation time is especially necessary because this kind of model is generally used for component size optimization that requires several iterations. Hence, the chronological method is utilized in this paper. The LPSP is defined as the probability of unmet load over the

total energy produced [26], as mentioned in the first objective. The unmet load can be calculated by utilizing the deficit power between the load and sources in SHRES through the following (7) [3] :

$$LPSP = \frac{\sum_{t=1}^{T} E_L(t) - E_{RE}(t) + (Eb(t) - Ebmin(t)) * \mu_{inv}}{\sum_{t=1}^{T} E_L(t)} \tag{7}$$

3.2. Economic analysis

COE is defined as the average cost per kilowatt-hour ($/kWh) of electrical energy produced by the hybrid energy system [24], which can be achieved via the following equations:

$$COE = (CRF * TAC) / E_L \tag{8}$$

$$CRF = \frac{d\,(1+i)^T}{(1+i)^T - 1} \tag{9}$$

Where, CRF is the capital recovery factor, which calculates the present value of system components by considering the interest rates (i = approximated as 6%) and project life span (T= 20 years in our case). TAC is the total annualized cost in $. The total annualized cost is the sum of the annualized capital cost (CC), operation and maintenance cost ($C_{O\&M}$) and replacement cost (CR).

$$TAC = C_C + C_{O\&M} + C_R \tag{10}$$

$$C_C = (N_{PV}*P_{PV}*C_{PV}) + ((N_{WT}*P_{WT}*C_{WT}) + (C_{WT}*N_{WT}*20/100)) + (N_B*C_b*C_B) + (N_{INV}*C_{INV}) + (C_{REG\_PV} + C_{REG\_WT}). \tag{11}$$

Where, C_{PV}, C_{WT}, and C_b, are PV panel unit-price, WT unit- price, and battery unit-price respectively. Also, C_{INV}, C_{REG_PV}, and C_{REG_WT} are inverter unit price, regulator of PV price, and regulator of WT price respectively. In addition, N_{INV} is the number of inverters and equal 2 as well as the cost of the wind tower estimated as 20% of the system capital cost. The $C_{O\&M}$ taken as 1% of the total cost as earlier supported [28]. For the Replacement Cost, expressed in (16) and (17).

$$C_R = C_{REP} * SFF\,(i, P_{R\_LF}) \tag{12}$$

$$C_{REP} = i_r * ((N_B * C_{RB}) + (N_{INV} * C_{R.INV}) + (N_{REG\_PV} * C_{R\_REG\_PV}) + (N_{REG\_WT} * C_{R\_REG\_WT})) \tag{13}$$

Where SFF expressed as the sinking fund factor, P_{R_LF} is lifespan of components (battery, inverter, and regulators). C_{RB}, C_{RINV}, $C_{R\_REG\_PV}$, and $C_{R\_REG\text{-}WT}$ are the replacement cost of the battery, inverter, PV regulator and WT regulator respectively.

While N_{REG_PV} is the number of voltage regulator and equal 1, N_{REG_WT} is the number of WT regulator and equal 1. Whereas the sinking fund factor is clarified by the following equation:
Therefore, the sinking fund factor is clarified by the following equation:

$$SFF\,(i, P_{R\_LF}) = \frac{i}{(1+i)^{P_{R\_LF}} - 1} \tag{14}$$

3.3. Solution methodology

MOPSO and NSGA-II algorithms work by creating new reliable solutions. However, their working mechanism differs. Table1 shows the differences between the two algorithms.

Table 1. Difference between NSGA-II and MOPSO algorithms

NSGA_II	MOPSO
Selection, crossover, and mutation are used during each generation. Those individuals or chromosomes are combined to create children model.	Particle positions are affected by their self-data and information sharing among swarm member. It uses two equations: velocity and position.
Great at finding the global optimum solution.	Capable of finding the local optimum
More complex due to mutation and crossover; takes extra time compared to MOPSO.	Fast and easy to implement as only a few parameters need adjustment.

In recent years, the implementation of NSGA-II and MOPSO algorithms based on GA and PSO are the foremost techniques adopted for global optimization in various fields, such as business, engineering, and in stochastic nature of renewable energy applications [1]. In this study, the NSGA-II and MOPSO methods are utilized to size the stand-alone hybrid PV/wind systems and these methods are shown to be better than the single-objective methods such as hybrid genetic algorithm (GA) or particle swarm optimization (PSO).

3.3.1. Optimal configuration based on NSGA_II algorithm

In 2002, Deb proposed the use of NSGA-II algorithm[29], in which the population is distributed into several non-domination levels and each solution is assigned a fitness equal to its non-domination level. The algorithm can be summarized as follows [19]:

a. In the first step, the requested input data are provided. This data involves the specifications of the hybrid system (hourly radiation, temperature and wind speed) and also load demand, data to compute the technical and economic functions and data to assess the constraint situations.
b. Upper and lower bound of the number of PV-WT and BES
c. The energy output of PV and wind turbine are calculated through the PV and wind models by using (1-3). The model of energy storage battery by using (4) with the total capacity (CB) is allowed to charge and discharge up to a limit defined by the maximum depth of discharge (DOD), by using (5, 6) and Figure 1.
d. A random parent population (Pi) is created with size N. Then, the population of children (Qi) including N solutions is produced through genetic manipulation (crossover and mutation).
e. Calculate the objective functions for each individual of Pi population (LPSP and COE) using (7-14).
f. The two populations are combined to form the (Ri) population with size 2N.
g. Classification of the Ri population is made in accordance with the Pareto front on the bases of fitness (non-dominated sorting is performed to determine the rank (front) of each population member).
h. The next population of one of the fronts is built according to priorities by performing a general comparison of the members of the Ri population.
i. Since the size of Ri is equal to 2N, the remaining solutions can simply be ignored because it is impossible to place all members in the new population (Pi+1).
j. The end, if the maximum number of iterations referred in Step 3 is reached, the non-dominated sorting resolution at the last iteration was achieved as the optimal sizing and design for the SHRES. Otherwise go back to number 2.

Figure 2 displays the NSGA-II algorithm application approach. This approach is aimed at finding the numbers of variables that depend on the state of N_{PV}, N_{WT}, and N_{BES} in order to meet the minimized system LPSP and COE. This is executed by using NSGA-II optimization toolbox in MATLAB, with a selected population size of 200, the crossover value of 0.8, and the maximum simulation generation number set at 500.
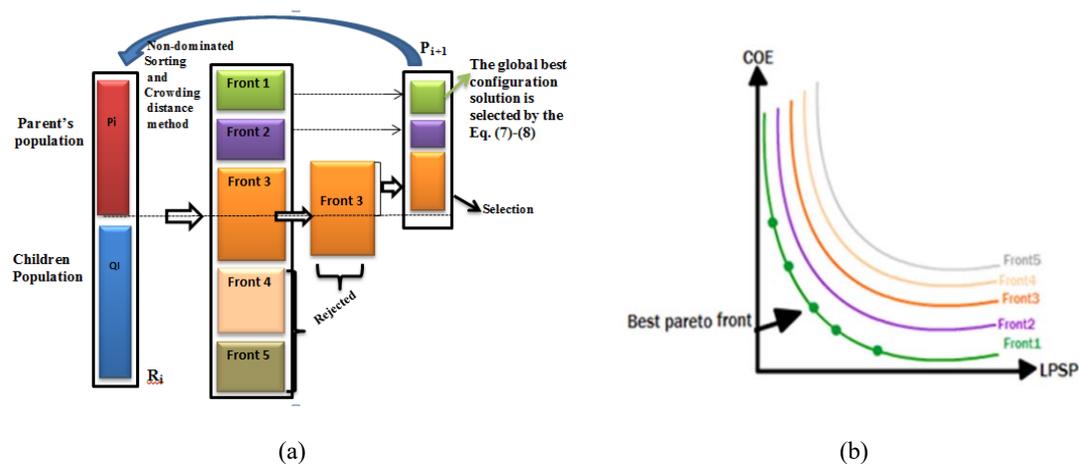

(a) (b)

Figure 2. (a) and (b) NSGA-II procedure [27]

3.3.2. Optimal configuration based on MOPSO algorithm

In 1995, Kenney and Eberhart showed that the Particle Swarm Optimization (PSO) has two separate concepts: a) social interaction which is exhibited by swarming and b) field of evolutionary calculation. In PSO, the two best values will determine the position of each particle.

PSO is an AI approach which is based on the swarm social interaction within a field of evolutionary calculation, as proposed [30]-[32]. The algorithm determines the two best positions for each particle. Initially, the best value is obtained, called the individual best (p_{best}), and is retained by the particle, while the next value is determined by the PSO optimization algorithm within a global best populations. Individual particle position defines the particles variable target values and velocity that is applied to monitor the overall global best value (g_{best}). The fitness equation of this algorithm is to search the best solution from amongst all possible available options, with additional constraints added. The algorithm is based on each particle fitness appraisal, individual and global best fitness update, alongside with particle position and velocity.

During the operation of the algorithm, each particle keeps the best fitness value that it has achieved. The particle with the best fitness value is calculated and updated during iterations. In this case, each particle represents a potential configuration of the PV-wind turbine and battery hybrid system: N_{PV}, N_{WT} and N_{BES}, and the search space dimension are three. Then, the objective function of each particle is computed, corresponding to each scenario configuration (LPSP and COE). The following steps illustrate utilized this method for HRES as the following:-

a. In the first step: Initialization, the requested input data are provided. This data involves the specifications of the hybrid system (hourly radiation, temperature and wind speed) and also load demand, data to compute the technical and economic functions and data to assess the constraint situations.
b. Upper and lower bound of the number of PV-WT and BES
c. The energy output of PV and wind turbine are calculated through the PV and wind models by using (1-3). The model of energy storage battery by using (4) with the total capacity (CB) is allowed to charge and discharge up to a limit defined by the maximum depth of discharge (DOD), by using (5, 6) and Figure 1.
d. Constants :
   - Personal and global coefficients, C1 = C2 =2.
   - Inertia weight, w = 0.9.
e. The position and velocity of particles are randomly selected in order to generate the initial population and then applied to the objective functions to find the optimum fitness value, by using (7-14).
f. Evaluate the fitness value, with minimum LPSP and COE
g. Calculate and update (Pbest and gbest)
h. Calculate and update velocity and position of each particle
i. Apply the updated value to find optimum value of LPSP and COE
j. The end, if the maximum number of iterations referred in Step 3 is reached, the non-dominated sorting resolution at the last iteration was achieved as the optimal sizing and design for the SHRES. Otherwise go back to number 2.

The sizing model of the hybrid PV/wind energy systems is more complex than the single-source generation systems. This is because the variables must be considered for system optimization. Moreover, system performance over a long-term, economic parameters, and reliability objectives should be well thought-out in order to achieve a suitable compromise between COE and LPSP. NSGA-II and MOPSO are the appropriate methods with regards to global optimization and the random nature of renewable power sources. These methods have been used in many hybrid applications in recent years [4], [33], [34]

In this paper, the NSGA-II and MOPSO algorithms were applied to size the stand-alone hybrid PV/WT and battery system. In principle, these algorithms aim to find the optimum number of PV panels, wind generation, and batteries to minimize the LPSP and COE. The optimization method was done using MATLAB software by executing the same number of iterations and population in both algorithms. Finally, the results were compared and the algorithm with the best result was identified.

The optimization method starts with the following input values: hourly output power for PV, WT and load profile. Then, the loop iterates the NSGA-II or MOPSO algorithms. The optimum results generated by the two algorithms are converted to the nearest integer values. This gives the sizing of the generating source. The optimum sizing along with COE and LPSP values are recorded for each run and stored in an array for each iteration. Finally, all appropriate solutions are obtained through non-dominated optimal called Pareto front [35]. The number of each generating units are provided. Flow charts of the NSGA-II and MOPSO algorithms are shown in Figure. 3.
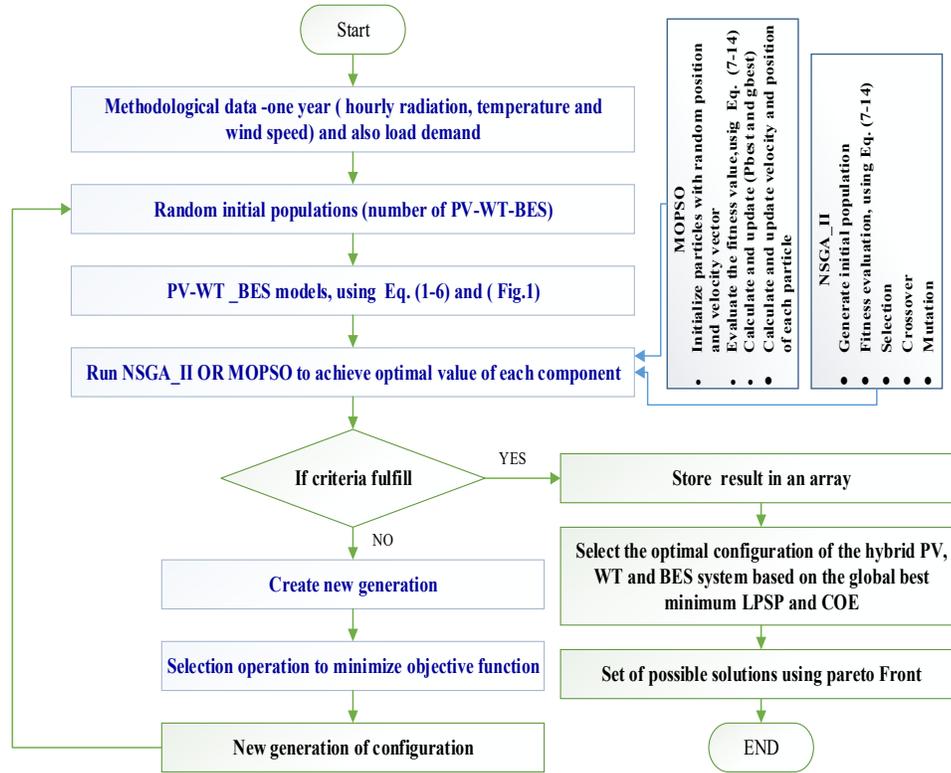
Figure 3. NSGAII or MOPSO optimization flow chart for stand-alone hybrid energy system

4.   RESULT AND DISCUSSION

The methodology was applied to find the optimal size for SHRES. The load profile for a typical rural village in Malaysia consisting of 20 households is shown in Figure 4 and the total energy consumption per day is 138.4 kWh [36]. The maximum solar radiation was approximately 1050 W/m^2 and the maximum wind speed was recorded at 5m/sec. The annual meteorological conditions in Malaysia, and solar radiation and wind speed are illustrated in Figure 5a and 5b, respectively. The data was obtained from the Malaysian Meteorological Department. Table 2 indicates the parameters of PV panels, wind, battery and inverters.
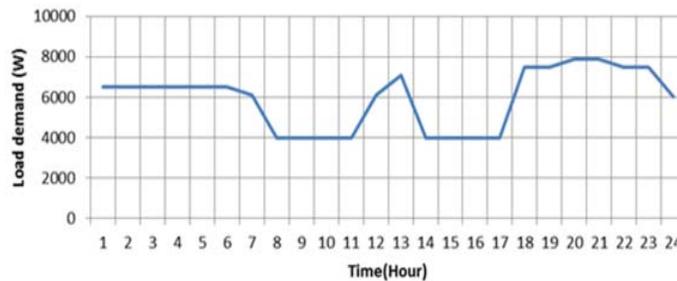

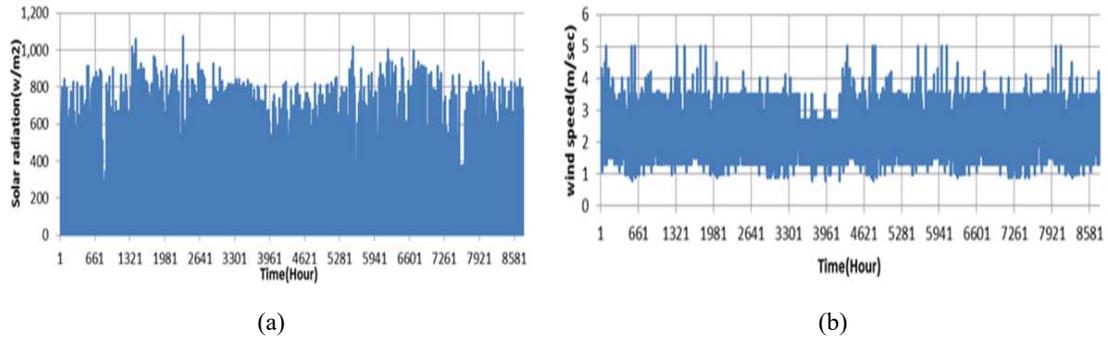
Figure 4. Hourly load profile for rural area in malaysia

(a)   (b)

Figure 5. Annual meteorological conditions for rural area in malaysia,
(a) Solar radiation and (b) wind speed

Table2. Parameters of PV, wind turbine, battery and inverter

PV modules Specifications	Wind turbine specifications	Battery specifications	Inverter specifications
Power max = 320W	Rated output power = 3 kW	Rated capacity = 1000Ah	Rated output power 6500 W
Rated voltage = Vmpp 54.7v	Generator voltage = 230 V-ac	Rated voltage =2V	Input Voltage 12V_{DC} / 24V_{DC}
Rated current = Impp 5.49A	Cut-in wind speed = 2 m/s	Efficiency = 85%	Frequency 50 HZ
Initial cost = $ 290 [37, 38]	Rated wind speed = 12 m/s	DOD = 70%	Efficiency = 90%
PV regulator cost =$ 750 [39]	Initial cost =$ 2800 [40]	Initial cost =$ 230 [42]	Initial cost = $ 2528 [43]
Life time = 20 years	Wind regulator cost = $ 750 [41]	Life Time = 10 Years	Life time = 12 years
	Life time = 20 years		

Note: $1.0 = RM 3.90

In this paper, two scenarios are investigated to determine the optimal sizing of SHRES. In the first case, the hybrid system consists of PV panels, wind turbines, and battery bank, while the second case comprised of PV panels and battery bank only. The output power curve generated by the first and second case of SHRES and the state of charge and discharge of the battery on an hourly basis under the best configuration are represented in Figure 6a and 6b, respectively. Even though the total energy generated was sufficient to cover the peak load in the evening, the surplus power was employed to charge the battery bank. These figures clearly indicated that the battery, in the period from 7 PM to 7 AM, was state of discharge and it satisfied the load demand, while the period from 7 AM to 7 PM was state of charge. In consonance with the two case studies, the contributions of output PV, wind turbine and battery bank through a one-year period are shown in Figure 7a and 7b. Based on Figure 6, it can be seen that the area had low wind speed and high solar radiation. Further, it was evident that the use of PV panels has a great advantage because the renewable energy for this location will enable the communities to access energy for their daily living.
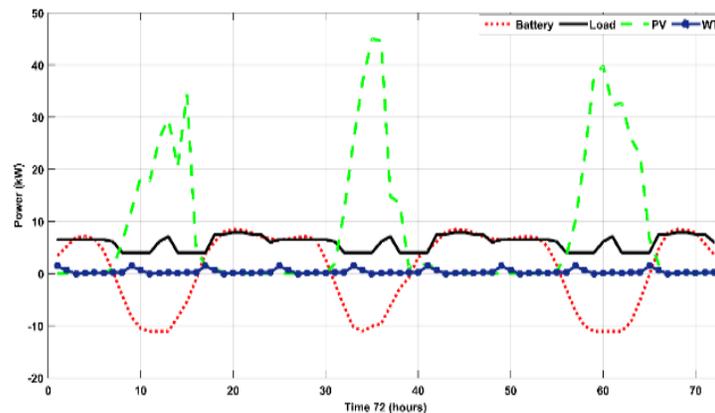

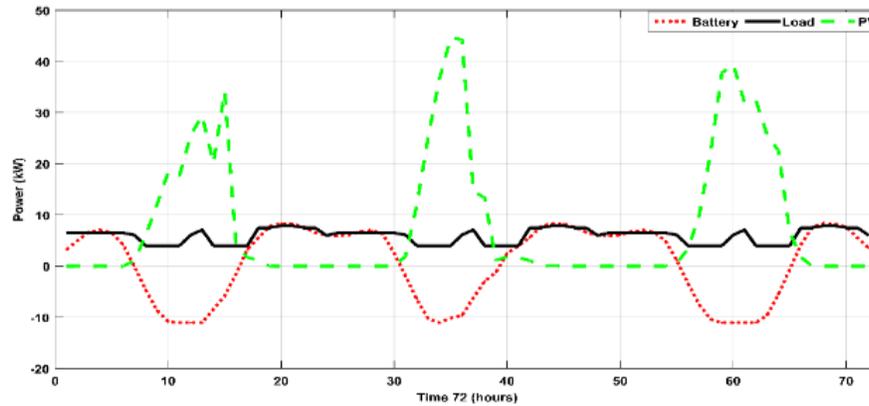Figure 6 (a). Output of PV-WT and charge-discharge curve of the batteries

Figure 6 (b). Output of PV and charge-discharge curve of the batteries

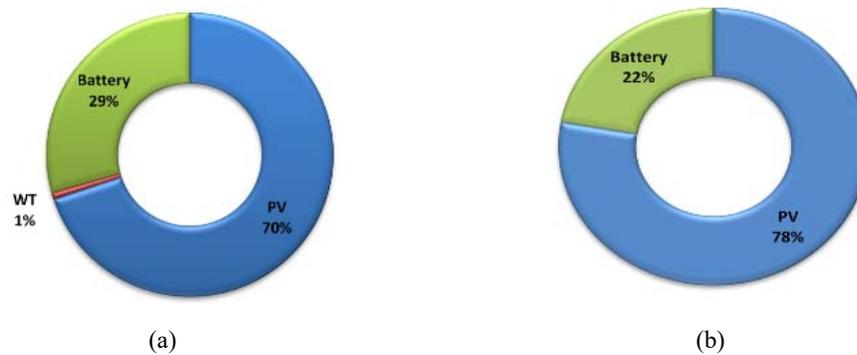| (a) | (b) |

Figure 7. (a) Contribution of energy using first case study (PV, wind and battery during one year) and
Figure. 7(b) Contribution of energy using second case study (PV and battery during one year)

For the first case study, the set of solutions obtained from the NSGA-II and MOPSO approaches for one year are shown in Figure 7a and Figure 7b, respectively. Each solution represents the LPSP and COE that demonstrate the minimum value of the multi-objective optimization set of solutions known as a Pareto-optimal set or Pareto front. This technique selects one of the different solutions and makes decision on LPSP against COE based on the number of PV (NPV), wind turbine (NWT) and battery energy storage (NBES). Any of the solutions can be considered optimum, which means that no improvement can be achieved on one of the objective functions without aggravating the other objective function. In order to make the best decision, a number of points on the Pareto front was selected, and then the optimal solutions were chosen based on the tradeoff between cost and reliability.

Figure 8c shows the comparison of space of operating points (non-dominated); the matching between two methods of optimization results was quite close. The NSGA-II algorithm had good global search ability but a slower convergence speed than MOPSO.

Figure 9a and Figure 9b show the Pareto optimum final value for the second case study. Once again, it proved that, compared to MOPSO, the NSGA-II algorithm had a robust search capability but a slower convergence speed.
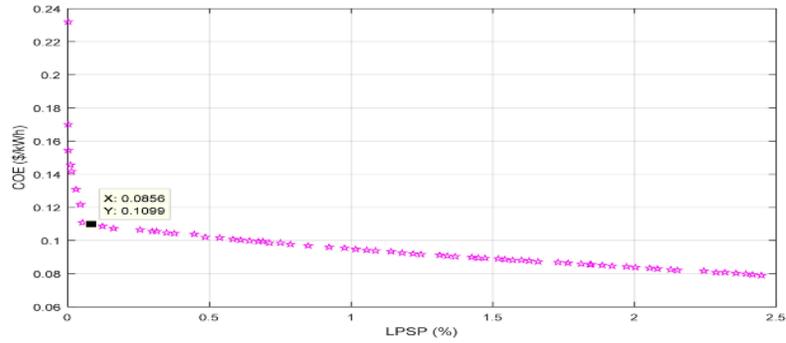
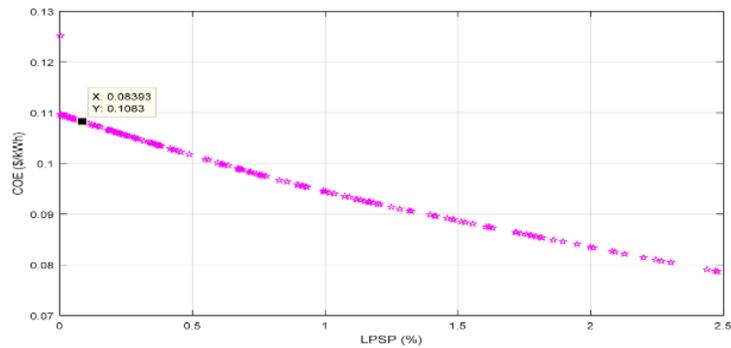Figure. 8 (a) Pareto front for first case study using NSGA-II

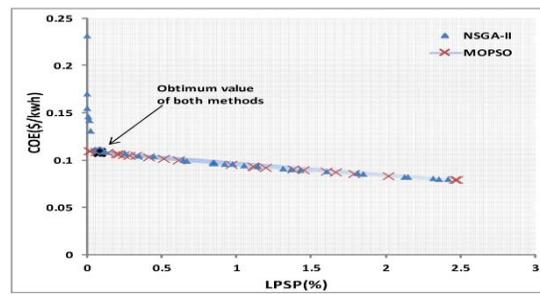Figure. 8 (b) Pareto front for first case study using MOPSO

Figure 8 (c). The matching between the NSGA-II and MOPSO for the first case study
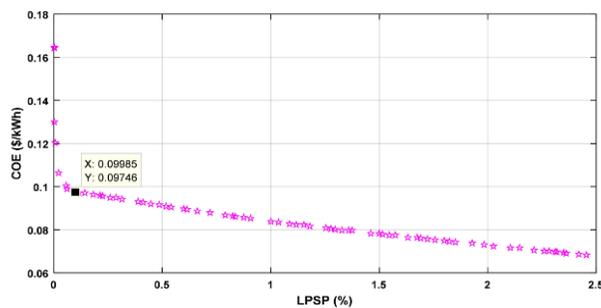according to pareto optimum

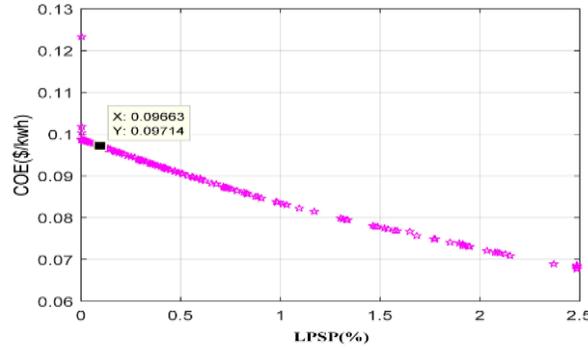Figure 9 (a). Pareto front second case study using NSGA-II

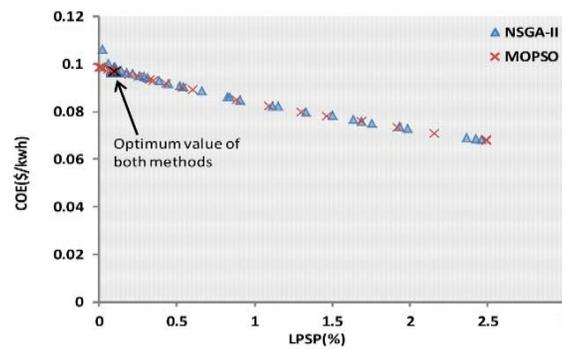Figure 9 (b). Pareto front second scenario using MOPSO

Figure 9 (c). The matching between the NSGA-II and MOPSO for the second case study
according to pareto optimum

The optimal sizing solution obtained by the multi-objective NSGA-II and MOPSO algorithms for the first and second case study is illustrated in Table 3; the two case studies were compared according to the two algorithms, in terms of LPSP, COE and the total cost (C_{TOTAL}). When the two hybrid system designs with minimum LPSP and COE were considered, it was clear that the contribution from PV energy was high. However, the energy mix in the first case study was quite low for wind turbine compared to PV.

Table 3. Optimal sizing result for two case studies

Case Study	Method	NPV	NWT	NBES	LPSP (%)	COE ($/kWh)	Total cost ($)
First	NSGA_II	178	1	1	0.0856	0.1099	66590
	MOPSO	178	1	1	0.084	0.1083	65212
Second	NSGA-II	177	-	1	0.0998	0.0974	60042
	MOPSO	178	-	1	0.0966	0.0971	58993

5. CONCLUSION

This paper presented the optimal sizing of SHRES for a rural area settlement in Malaysia under the prevalent solar and wind conditions. The NSGA-II and MOPSO optimization techniques were used to optimize the sizing. The hybrid power system modeling was conducted in MATLAB using two case studies to select the best configuration in order to find the optimum number of variables; the first case study consisted of PV/WT and BES, while the second case study consisted of PV/BES to minimize LPSP and COE.

The results showed that the comparison between the two algorithms was successful in supplying household load with two operation scenarios, and in varying the availability of solar and wind power during the entire one-year period. Also, the proposed performance model for the two modes were presented, where the NSGA-II method has more robust performance, while the MOPSO was faster in implementing the

optimization. The difference between these two methods in terms of number of variables, as well as LPSP and COE is not significant. Thus both these methods can be used for techno-economic optimization of SHRES. The second case study has proved to be a more efficient solution to meet the energy demand of the remote areas in this location. For the wind turbines have proved to be ineffective and it's not reliable due to low wind speed and also high installation and operational cost, but its utilization may be highly expanded in the future. As conclusion, the proposed system can fulfill the targeted constraints for rural electrification and ensure that the load demand is met.

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Nomenclature

AD	autonomy days
C1	cognitive parameter
C2	social parameter
C_B	battery capacity
DOD	depth of discharge and equal
Eb	state of battery (charge and discharge)
Ebmax	battery maximum charge quantity
Ebmin	battery minimum charge quantity
E_L	hourly load demand (KWh)
G	global solar radiation (Kw/m^2)
ir number of times replacement of battery, inverters, and regulators during the lifespan of the system	
g_{best}	global best position
K_T	temperature coefficient of the PV panel and equal $3.7*10^{-3}$ (1/Ċ)
N	size of population
Pi	parent population
p_{best}	global best position
P_{PV}	output power of solar PV
PV_{STC}	nominal power under reference conditions
P_r	rated wind power
P_{WT}	output power of wind turbine
Qi	population of children
r1 and r2	represent random numbers distributed uniformly between (0 and 1)
Ri	populations combined (parents and children)
Ta	surrounding temperature
T_C	temperature coefficient of the PV panel
T_{ref}	cell temperature and equal 25
v	particle velocity
V	wind speed
V_{ci}	cut in speed
V_{CO}	cut out speed
V_r	nominal wind speed
x	particle position in iteration t
μ_{bat}	efficiency of battery
μ_{inv}	inverter efficiency
Δ_{Enet}	net energy of SHRES
σ	self-discharge rate

BIOGRAPHIES OF AUTHORS

Mohamad Izdin Hlal received Higher Technical Diploma in electrical engineering from High Institute of Industrial Technology (HIIT), Tripoli, Libya, in 1994, and MSc degree in electrical power from Newcastle University, UK, in 2003, and is currently pursuing the Ph.D. degree in electrical engineering at the University Tenaga National (UNITEN) Malaysia. His research interests include optimization for hybrid renewable energy system.

Vigna K. Ramachandaramurthy (SM'12) received his Ph.D. degree in Electrical Engineering from the University of Manchester Institute of Science and Technology (UMIST) in 2001. He is presently a Professor in the Institute of Power Engineering, UNITEN. In 2008, he received the IET Mike Sargeant Awad for career achievement. In 2009, he received the Institution of Engineers Malaysia (IEM) Young Engineers Award. Prof Vigna has served as the IET Malaysia Chairman, IET Council Member, Institution of Engineers Malaysia (IEM) Council Member, IET Younger Member Board representing West Asia, International Professional Registration Advisor, Interviewer and Convenor for Chartered Engineering (UK) in Malaysia. Prof Vigna is also a Chartered Engineer registered with the Engineering Council of UK and a Professional Engineer registered with the Board of Engineers Malaysia. To date, he has successfully supervised and graduated more than 100 postgraduate students, with many receiving distinctions. His area of interest includes power systems related studies, renewable energy, energy storage, power quality, electric vehicle and rural electrification. Prof Vigna is the principal consultant for Malaysia's biggest electrical utility, Tenaga Nasional Berhad and

Sanjeevikumar Padmanaban (M'12– SM'15) received the bachelor's degree in electrical engineering from the University of Madras, India, in 2002, the master's degree (Hons.) in electrical engineering from Pondicherry University, India, in 2006, the Ph.D. degree in electrical engineering from the University of Bologna, Italy, in 2012, and the Ph.D. degree. He was an Associate Professor with VIT University from 2012 to 2013. In 2013, he joined as the Faculty with the National Institute of Technology, Pondicherry. In 2014, he was invited as a Visiting Researcher at the Department of Electrical Engineering, Qatar University, Qatar, funded by Qatar National Research Foundation (Government of Qatar). He continued his research activities with Dublin Institute of Technology, Ireland, in 2014. He is an Associate Professor with the Department of Electrical and Electronics Engineering, University of Johannesburg, South Africa, from 2016. He has authored 200 plus scientific papers and has received the Best Paper cum Most Excellence Research Paper Award of IET-SEISCON'13, IET-CEAT'16 and five best paper award from ETAEERE'16 sponsored Lecture note in Electrical Engineering, Springer book series. He serves as an Editor/Associate Editor/Editorial Board many refereed journal in particular the IEEE Transaction on Power Electronics, the IET Power Electronics, the IET Renewable Power Generation, the IET Generation, Transmission and Distribution, the IEEE Access, etc. He was involved member on invitation with various capacities in the committee for more than 4500 plus various international conferences include the IEEE and IET.

S. Hr. Aghay Kaboli received the B.Eng degree in electrical engineering from IAU, Esfahan, Iran, in 2009 and the M.Eng. degree from University Malaya (UM), Kuala Lumpur, Malaysia, in 2012. Since 2011, he has been a High Impact Research Assistant for Campus Network Smart Grid for Energy Security project with University Malaya, in the UM Power Energy Dedicated Advanced Center (UMPEDAC). He is a reviewer for IEEE Transactions, Elsevier and Springer journals. He also has been serving as an editor for American Journal of Electrical Power & Energy Systems, International Journal of Computer Systems (IJCS), and a guest editor for the special issue "Some Novel Algorithms for Global Optimization & Relevant Subjects" under the journal "Applied and Computational Mathematics (ACM)". His research interests include Artificial Intelligence (AI), smart grid, and power electronic.

Aref Pouryekta received his Ph.D. degree in electrical engineering from Tenaga National University, Malaysia, in 2017. He is currently a Postdoctoral Research Fellow with Tenaga National University. He is actively involved in several consultancy projects for Malaysian national utility company. His research interests include renewable energy integration, microgrid stability and control, and power system modeling.

Tuan Ab Rashid bin Tuan Abdullah is a registered professional engineer in electrical engineering. He has served the Tenaga National Berhad (TNB) for more than 33 years. He has practical experience in the electrical network planning, construction, maintenance, customer services and electricity tariff formulation. His special contribution to the engineering process and system improvement include the power system automation for medium voltage network, the use of spatial & temporal database for network and operation planning. While in electricity business, his special contribution include the tariff formulation, the second generation customer billing system and optimization of power system asset based on Life-Cycle Cost-Analysis. In the University Tenaga National (UNITEN) he is a research consultant and has served as Manager for power system laboratory, Deputy Dean, Director of UNITEN Consulting Unit, the university's representative for IP Protection at My IPO and Director of the Institute of Energy Policy & Research (IEPRe). His interests since joining TNB was power system asset management and random event analytics in power system. His work has contributed to knowledge in engineering, economic and management, which include the reduction of power system outages based on large data analytics, design of special purpose very low frequency magnetic generator, electricity blueprint for Iskandar Malaysia, greenhouse gas inventory for Malaysia, mitigate harmonics in the Malaysian railroad double tracking, modelling of transient in transmission line, impact of electricity price increase to the Malaysian economic sectors, investment decision system based on life-cycle cost-analysis and warehousing & spare part optimization algorithms for risk-based asset management. He has taught electric machine & drive, energy conversions and electrical installation. His current research area is in energy & electricity industry and market study.