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Economic Assessment of Photovoltaic-Based Microgrid Incorporated with Solar Tracking System

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Solar energy is a major renewable energy source as it is clean and abundant. The solar radiation yield of a PV system can be enhanced by fixing the solar panel at optimal orientation or coupling with a solar tracking system. This study aims to evaluate the cost-effectiveness of incorporating solar trackers into microgrid to improve the energy gain. A mathematical model is formulated for the optimal sizing of microgrid and the model is implemented on a case study with 500 households. The study outcome suggests the feasibility of solar tracking system is greatly dependent on its cost. When the cost of solar tracker is low, east-west single-axis tracking system is the most feasible option, but the fixed-tilt system becomes more feasible when the cost of solar tracker is high. The threshold for east-west single-axis tracking system investment is found to be <240 USD/kWp.

1. Introduction

The concerns on energy security and climate change have been driving the exploration of sustainable energy supply. Solar energy is one of the most important renewable energy sources as it is clean and readily available (Huang et al., 2019). It has the potential to fulfil Malaysia energy requirement with its abundance in Malaysia (Khaliludin et al., 2020). The yield of solar energy is greatly influenced by the tilt and azimuth angle of the solar collector, which is usually oriented towards the equator with an optimal slope (Bahrami et al., 2017). Solar tracker increases the energy harvested by tracking the path of the sun from time to time (Bahrami et al., 2016) to keep the surface of PV module perpendicular to the incoming solar radiation (Alkaff et al., 2019). The solar tracking systems can be classified into single-axis tracking system and dual-axis tracking system depending on their movement degree of freedom (Awasthi et al., 2020). A single-axis system has only one rotation axis, therefore it usually consumes less energy and is less complex compared to a multi-axis system (Sumathi et al., 2017). There are several configurations of single-axis trackers including horizontal, horizontal with tilted modules, vertical, tilted and polar aligned (Nsengiyumva et al., 2018). A dual-axis solar tracking system (DAT) tracks the sun in two different axes using two pivot points to rotate. It is superior in tracking the yearly sun movement such as the altitude of sun from season to season, making it more efficient and has higher solar energy gain (Hafez et al., 2018).

Several studies have been done to evaluate the techno-economic performance of solar trackers. Bahrami et al. (2016) investigated the effect of latitude on the energy yield in Europe and Africa. Alkaff et al. (2019) compared the energy gain of three tracking systems to the fixed south-oriented tracking system at six locations with latitude 0° to 55°. Bahrami et al. (2017) compared the energy gain and levelized cost of electricity (LCOE) resulted from fixed, single and dual-axis solar trackers in low latitude countries using nine selected locations in Nigeria as case study. The work is then extended to evaluate the performance of solar tracking system in northern hemisphere (Bahrami and Okoye, 2018). Although some previous studies have evaluated the LCOE of different PV systems, the intermittency of solar resources has been neglected when determining the energy system cost. For a solar-based renewable energy system, energy storage plays a vital role in balancing the intermittent energy supply and demand profiles by storing the excess energy generated by renewables and discharge at later time to compensate the energy deficits.

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A microgrid is a small-scale power system with local power generation, energy storage and load demands, which can operate as a standalone system or connected to the main grid (Li et al., 2017). Potential energy storage options include batteries, hydrogen, pumped-hydro, flywheel, compressed air storage, supercapacitor, and superconducting magnetic energy storage. The optimization of microgrid capacity is crucial to prevent system oversize and reduce the cost of investment. Jacob et al. (2018) proposed a generic sizing methodology using pinch analysis and design space to optimize the hybrid energy storage in a standalone PV-based power system. Zhang et al. (2018) adopted simulated annealing algorithm for optimizing a wind and solar-based energy system with hybrid battery-hydrogen energy storage. Huang et al. (2019) conducted multi-objective optimization on an isolated PV energy system with hydrogen and retired electric vehicle battery as energy storage.

The use of solar tracking system could reduce the solar panel requirement by increasing the energy gain per unit area. However, the solar tracker installation incurs additional cost despite the reduction of solar panel investment. Up to date, the cost-effectiveness of installing solar tracking system in a microgrid is yet to be explored. This study aims to evaluate the economic performance of PV systems with and without solar trackers in a standalone microgrid, where the PV systems being studied include system with fixed-tilt and optimal slope (FO), north-south single-axis tracking (NSSAT), east-west single-axis tracking (EWSAT), vertical single-axis tracking (VSAT) and dual-axis tracking (DA) as illustrated in Figure 1.

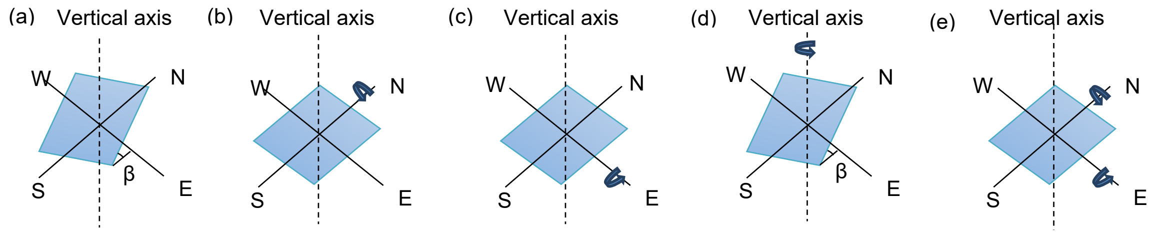

Figure 1: PV system with (a) fixed tilt (b) EWSAT (c) NSSAT (d) VSAT (e) DAT

2. Methodology

This section describes the configuration of microgrid and the mathematical model used for the sizing of microgrid. Figure 2 shows the configuration of a standalone microgrid that uses solar photovoltaic (PV) to convert sunlight into direct current (DC). The DC can be converted to alternating current (AC) through an inverter to satisfy the load demand. When the electricity generated from solar radiation is greater than the load demand, excess electricity will be charged into the battery. The stored electricity will be discharged when the electricity produced from solar PV is unable to satisfy the demand.

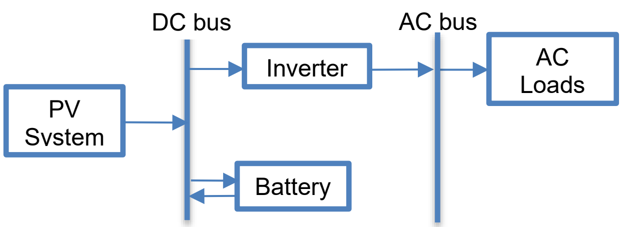

Figure 2: Configuration of microgrid

2.1 Problem statement

Given the annual average hourly solar radiation collected in different types of PV systems, the capacity of the energy system is optimized for minimum operation cost while satisfying the energy demand. In the mathematical model, *t* represents the time in a day on hourly basis.

2.2 Mathematical model

The electricity generated from solar radiation in DC form, $E_t^{\mathrm{PV,DC}}$ is given by Eq(1), where SR_t is the solar radiation at time *t* and PV^{Cap} is the capacity of solar panel.

$$E_t^{\mathrm{PV,DC}} = \mathrm{SR}_t\, PV^{\mathrm{Cap}} \quad \forall t \tag{1}$$

The overall energy balance is shown in Eq(2), where B_t^{Out} is the amount of electricity discharged from battery at time *t*, B_t^{In} is the amount of electricity charged into battery at time *t*, $\mathrm{INV}^{\mathrm{Eff}}$ is inverter efficiency and $\mathrm{E}_t^{\mathrm{Demand}}$ is the electricity demand in AC form at time *t*. The efficiency of inverter represents how much DC is converted to AC power. As the electricity demand is in AC form, the term $\frac{\mathrm{E}_t^{\mathrm{Demand}}}{\mathrm{INV}^{\mathrm{Eff}}}$ in Eq(2) computes the corresponding DC requirement.

$$E_t^{\mathrm{PV,DC}} + B_t^{\mathrm{Out}} = B_t^{\mathrm{In}} - \frac{\mathrm{E}_t^{\mathrm{Demand}}}{\mathrm{INV}^{\mathrm{Eff}}} \quad \forall t \tag{2}$$

The state of charge of the battery, SOC_t^{Bat} can be determined using Eq(3), where σ is the hourly self-discharge rate, $\mathrm{BC}^{\mathrm{Eff}}$ is battery charging efficiency and $\mathrm{BD}^{\mathrm{Eff}}$ is the discharging efficiency of battery. As some electricity would be lost during charging and discharging of battery, the battery charging efficiency represents the net amount of electricity charged into the battery divided by the total amount of electricity input to the battery. The discharging efficiency is the ratio of net amount of electricity discharged from the battery to the total amount of electricity withdrawn from the battery.

$$SOC_t^{\mathrm{Bat}} = SOC_{t-1}^{\mathrm{Bat}}(1-\sigma) + B_t^{\mathrm{In}}\mathrm{BC}^{\mathrm{Eff}} - B_t^{\mathrm{Out}}/\mathrm{BD}^{\mathrm{Eff}} \quad \forall t \tag{3}$$

The amount of battery required, N^{Bat} can be estimated using Eqs (4) and (5), where $\mathrm{BAT}^{\mathrm{Rating}}$ is the capacity of a single battery, BAT^{Cap} is the total battery capacity required and DOD is the maximum depth of discharge.

$$N^{\mathrm{Bat}} = \frac{BAT^{\mathrm{Cap}}}{\mathrm{BAT}^{\mathrm{Rating}}} \tag{4}$$

$$BAT^{\mathrm{Cap}} \geq \frac{SOC_t^{\mathrm{Bat}}}{\mathrm{DOD}} \quad \forall t \tag{5}$$

The number of inverter required, N^{Inv} can be calculated via Eqs (6) and (7), where $\mathrm{INV}^{\mathrm{Rating}}$ is the capacity of a single inverter and INV^{Cap} is the total inverter capacity required.

$$N^{\mathrm{Inv}} = \frac{INV^{\mathrm{Cap}}}{\mathrm{INV}^{\mathrm{Rating}}} \tag{6}$$

$$INV^{\mathrm{Cap}} \geq \frac{\mathrm{E}_t^{\mathrm{Demand}}}{\mathrm{INV}^{\mathrm{Eff}}} \quad \forall t \tag{7}$$

The objective function of this model is to minimize the annualized cost of PV-based standalone energy system (C^{annual}), which comprises annualized capital cost (C^{acapex}), operating cost (C^{opex}), and annualized replacement cost (C^{arep}) as illustrated in Eq(8).

$$C^{\mathrm{annual}} = C^{\mathrm{acapex}} + C^{\mathrm{opex}} + C^{\mathrm{arep}} \tag{8}$$

The general formulas for annualized capital and replacement cost are extracted from Huang et al. (2019). The annualized capital cost can be calculated using Eq(9), where C^{capex} is the total capital cost, i is the interest rate, and Y^{SL} is the system life. Eq(10) shows the annualised replacement cost calculation, where C^{rep} is the total replacement cost and Y^{CL} is the lifespan of system components.

$$C^{\mathrm{acapex}} = C^{\mathrm{capex}} \frac{\mathrm{i}(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{SL}}}}{(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{SL}}}-1} \tag{9}$$

$$C^{\mathrm{arep}} = C^{\mathrm{rep}} \frac{\mathrm{i}}{(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{CL}}}-1} \tag{10}$$

For this study, the capital investment includes solar panel, inverter, solar tracking system and battery, therefore Eq(9) is extended to Eq(11), where $\mathrm{PV}^{\mathrm{Capex}}$ is the unit capital cost of solar panel, $\mathrm{ST}^{\mathrm{Capex}}$ is the unit capital cost of solar tracker, $\mathrm{INV}^{\mathrm{Capex}}$ is the unit capital cost of inverter, and $\mathrm{BAT}^{\mathrm{Capex}}$ is the unit capital cost of battery.

$$C^{\mathrm{acapex}} = \left[PV^{\mathrm{Cap}}\mathrm{PV}^{\mathrm{Capex}} + PV^{\mathrm{Cap}}\mathrm{ST}^{\mathrm{Capex}} + N^{\mathrm{Inv}}\mathrm{INV}^{\mathrm{Capex}} + N^{\mathrm{Bat}}\mathrm{BAT}^{\mathrm{Capex}}\right] \frac{\mathrm{i}(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{SL}}}}{(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{SL}}}-1} \tag{11}$$

The components to be replaced at regular interval are battery and inverter, thus the annualized replacement cost is computed using Eq(12), where $\mathrm{Y}^{\mathrm{INV}}$ is the lifespan of inverter and $\mathrm{Y}^{\mathrm{BAT}}$ is the lifespan of battery.

$$C^{\mathrm{arep}} = N^{\mathrm{Inv}}\mathrm{INV}^{\mathrm{Capex}}\frac{\mathrm{i}}{(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{INV}}}-1} + N^{\mathrm{Bat}}\mathrm{BAT}^{\mathrm{Capex}}\frac{\mathrm{i}}{(\mathrm{i}+1)^{\mathrm{Y}^{\mathrm{BAT}}}-1} \quad (12)$$

The operating cost is given by Eq(13), where $\mathrm{PV}^{\mathrm{Opex}}$ is the unit operating cost of solar panel, $\mathrm{ST}^{\mathrm{Opex}}$ is the unit operating cost of solar tracker, $\mathrm{INV}^{\mathrm{Opex}}$ is the unit operating cost of inverter, and $\mathrm{BAT}^{\mathrm{Opex}}$ is the unit operating cost of battery.

$$C^{\mathrm{opex}} = PV^{\mathrm{Cap}}\mathrm{PV}^{\mathrm{Opex}} + PV^{\mathrm{Cap}}\mathrm{ST}^{\mathrm{Opex}} + N^{\mathrm{Inv}}\mathrm{INV}^{\mathrm{Opex}} + N^{\mathrm{Bat}}\mathrm{BAT}^{\mathrm{Opex}} \quad (13)$$

3. Case study

Figure 3 shows the annual average hourly solar radiation of the PV systems. It is observed that the solar radiation yield is higher when a solar tracking system is used. With the solar trackers, the energy harvested improves significantly in the morning and evening. In this study, the mathematical model discussed in section 2 will be employed to analyze whether the solar tracking system is worth investing despite the yield improvement. Figure 4 presents the electricity demand for a community with 500 households, where the domestic load profile is extracted from Ponniran et al. (2012). This data will be used in the optimization model for the targeting of microgrid capacity.

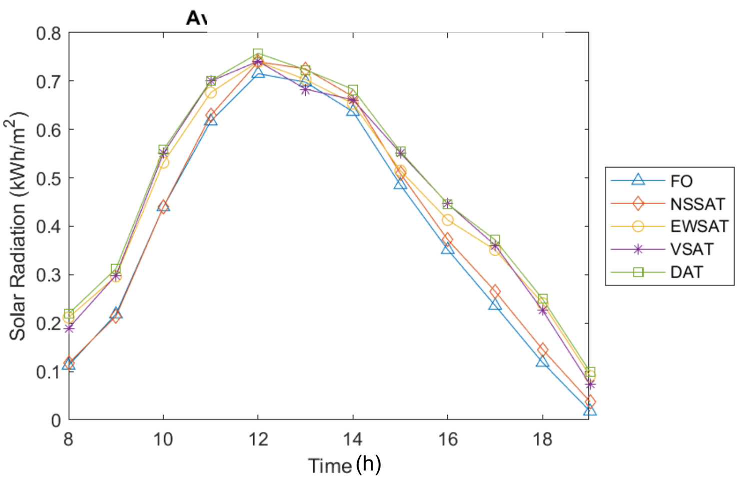

Figure 3: Average hourly solar radiation collected in each PV system

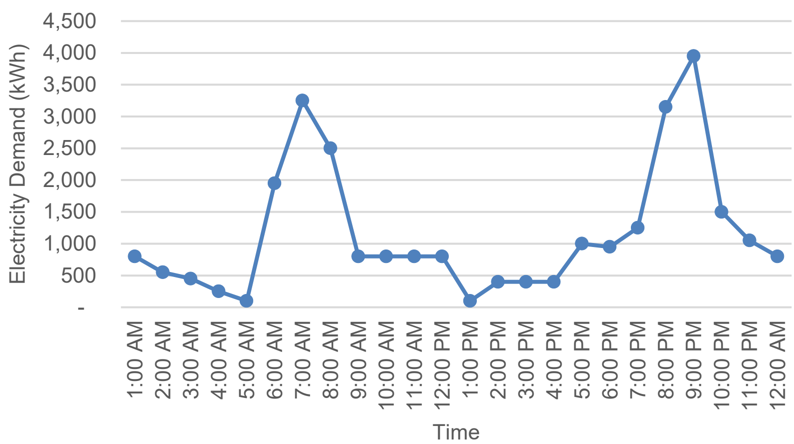

Figure 4: Electricity load profile

Table 1 summarizes the parameters used in the case study. As the cost of solar trackers is given as a range, several scenarios will be studied to evaluate the least-cost PV system when the price of solar tracker is at (i) lower end (ii) middle point and (iii) higher end.

Table 1: Case study parameters

Parameter	Value	Unit	Ref
Project lifetime	20	y	
Interest rate	5	%	
Solar Panel			
Capital cost of solar panel	1806	USD/kWp	(Maleki, 2018)
Operating cost of solar panel	54	USD/kWp/y	(Maleki, 2018)
Solar panel lifespan	20	y	(Maleki, 2018)
Inverter			
Nominal inverter power	3	kW	(Maleki, 2018)
Efficiency of inverter	95	%	(Maleki, 2018)
Capital cost of inverter	1583	USD/kWp	(Maleki, 2018)
Operating cost inverter	15	USD/kWp/y	(Maleki, 2018)
Inverter lifespan	10	y	(Maleki, 2018)
Solar Tracker			
EWSAT/NSSAT capital cost	135-700	USD/kWp	(Bahrami et al., 2017)
EWSAT/NSSAT operating cost	13.5-70	USD/kWp	(Bahrami et al., 2017)
VSAT capital cost	350-930	USD/kWp	(Bahrami et al., 2017)
VSAT operating cost	35-93	USD/kWp	(Bahrami et al., 2017)
DAT capital cost	600-1900	USD/kWp	(Bahrami et al., 2017)
DAT operating cost	60-190	USD/kWp	(Bahrami et al., 2017)
Solar tracker lifespan	20	y	(Bahrami et al., 2017)
Battery			
Nominal capacity of battery bank	2.1	kWh	(Maleki, 2018)
Capital cost of battery	310	USD	(Maleki, 2018)
Operating cost of battery	10	USD/y	(Maleki, 2018)
Battery lifespan	5	y	(Maleki, 2018)
Hourly self-discharged rate	0.02	%	(Maleki, 2018)
Charging efficiency	85	%	(Maleki, 2018)
Discharging efficiency	100	%	(Maleki, 2018)
Maximum depth of discharge	80	%	(Maleki, 2018)

4. Result and discussion

The mixed-integer linear programming (MILP) model is solved using the commercial optimization software GAMS, in HP Elitebook 850 G5 with Intel Core i5-8250U (1.60 GHz) processor and 8 GB RAM. The average Central Processing Unit (CPU) time for solution generation is 0.06 s with zero optimality gap. Table 2 shows the optimization results where the PV system capacity decreases with increasing solar radiation yield. The inverter capacity remains the same regardless of the type of PV system. With higher energy gain in the PV system, the required battery capacity is reduced. In scenario 1 where the cost of solar tracking system is low, EWSAT is found to be more economical than FO system. However, with increasing solar tracker cost EWSAT becomes less economical than FO (scenario 2 and 3).

Table 2: Case study results

	FO	NSSAT	EWSAT	VSAT	DAT
Solar panel capacity (kWp)	7,187	6,859	6,122	6,065	5,850
Inverter capacity (kW)	4,158	4,158	4,158	4,158	4,158
Battery capacity (kWh)	27,413	27,077	26,077	26,400	26,060
Annualized cost (USD/y)					
Scenario 1	2,988,462	3,075,639	2,867,668	3,104,100	3,296,683
Scenario 2	2,988,462	3,424,897	3,179,380	3,421,132	3,982,087
Scenario 3	2,988,462	3,774,156	3,491,092	3,738,164	4,667,491

To identify the minimum cost of EWSAT to be economically more feasible than the fixed-tilt system, a sensitivity analysis is conducted by interpolating the solar tracker cost within the range of 135 USD/kWp (scenario 1) and 417.5 USD/kWp (scenario 2). Figure 5 illustrates the sensitivity result, where 240 USD/kWp is identified as the threshold for EWSAT to be worth the investment.

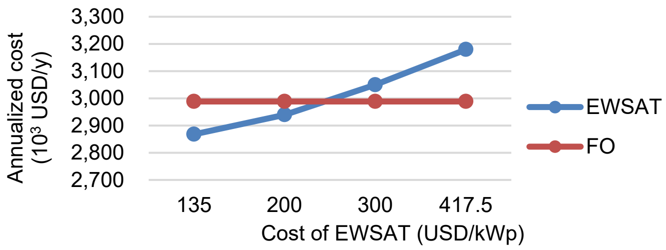

Figure 5: Sensitivity result on the cost of EWSAT

5. Conclusions

In this study, a MILP model has been formulated for the sizing of PV-based microgrid with battery as energy storage. The optimization result shows that the feasibility of solar tracking system installation is highly dependent on its cost. The cost of east-west tracking system should be below 240 USD/kWp to be more feasible than the fixed-tilt system. In future studies, other load profiles such as commercial and industrial electricity demands should be considered to evaluate the cost-effectiveness of solar tracker under different demand profiles.

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References

Alkaff S.A., Shamdasania N.H., Go Y.L., Venkiteswaran V.K., 2019, A Study on Implementation of PV Tracking for Sites Proximate and Away from the Equator, Process Integration and Optimization for Sustainability, 3(3), 375-382.
Awasthi A., Shukla A.K., S.R M.M., Dondariya C., Shukla K.N., Porwal D., Richhariya G., 2020, Review on sun tracking technology in solar PV system, Energy Reports, 6, 392-405.
Bahrami A., Okoye C.O., 2018, The performance and ranking pattern of PV systems incorporated with solar trackers in the northern hemisphere, Renewable and Sustainable Energy Reviews, 97, 138-151.
Bahrami A., Okoye C.O., Atikol U., 2016, The effect of latitude on the performance of different solar trackers in Europe and Africa, Applied Energy, 177, 896-906.
Bahrami A., Okoye C.O., Atikol U., 2017, Technical and economic assessment of fixed, single and dual-axis tracking PV panels in low latitude countries, Renewable Energy, 113, 563-579.
Hafez A.Z., Yousef A.M., Harag N.M., 2018, Solar tracking systems: Technologies and trackers drive types – A review, Renewable and Sustainable Energy Reviews, 91, 754-782.
Huang Z., Xie Z., Zhang C., Chan S.H., Milewski J., Xie Y., Yang Y., Hu X., 2019, Modeling and multi-objective optimization of a stand-alone PV-hydrogen-retired EV battery hybrid energy system, Energy conversion and management, 181, 80-92.
Jacob A.S., Banerjee R., Ghosh P.C., 2018, Sizing of hybrid energy storage system for a PV based microgrid through design space approach, Applied energy, 212, 640-653.
Khaliludin N.I.A., Hasim N.I.A., Hashim H., Ab Muis Z., Yunus N.A., Ismail M.I., 2020, A Framework of Solar Thermal Performance Study for Poultry Industry, Chemical Engineering Transactions, 78, 589-594.
Li B., Roche R., Miraoui A., 2017, Microgrid sizing with combined evolutionary algorithm and MILP unit commitment, Applied energy, 188, 547-562.
Maleki A., 2018, Design and optimization of autonomous solar-wind-reverse osmosis desalination systems coupling battery and hydrogen energy storage by an improved bee algorithm, Desalination, 435, 221-234.
Nsengiyumva W., Chen S.G., Hu L., Chen X., 2018, Recent advancements and challenges in Solar Tracking Systems (STS): A review, Renewable and Sustainable Energy Reviews, 81, 250-279.
Ponniran A., Mamat N.A., Joret A., 2012, Electricity profile study for domestic and commercial sectors, International Journal of Integrated Engineering, 4(3), 8-12.
Sumathi V., Jayapragash R., Bakshi A., Kumar Akella P., 2017, Solar tracking methods to maximize PV system output – A review of the methods adopted in recent decade, Renewable and Sustainable Energy Reviews, 74, 130-138.
Zhang W., Maleki A., Rosen M.A., Liu J., 2018, Optimization with a simulated annealing algorithm of a hybrid system for renewable energy including battery and hydrogen storage, Energy, 163, 191-207.