Optimal Energy Storage Evaluation of a Solar Powered Sustainable Energy System

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Abstract: This paper provides an advanced optimal energy storage evaluation of a solar powered sustainable energy system. This work contains an investigation to examine the Li-ion and lead-acid batteries capabilities with reference to cost – benefit analysis. The results indicate that the lead-acid battery is the best option for the solar powered sustainable energy system for buildings and Li-ion battery is suitable for the mobile stand-alone PV system described in this paper.

Keywords: Energy storage, solar energy, performance optimization, power management, batteries.

1. INTRODUCTION

The building and housing sector has growing demand for energy, yet it is currently mainly dependent on the grid system. The combination of renewable energy sources with high standard energy storage option carries great promise for a cleaner, more efficient energy future, particularly for the housing and buildings sector in countryside. A self-sustainable approach to cope with the energy demand in housing and buildings sector is continue to grow significantly. While predictions vary, this trend is likely to continue for the foreseeable future. The historic energy consumption data shows that there is a significant increase in energy consumption in the housing and buildings sector. Research and developments have a fundamental role to play in addressing issues of (solar powered) sustainable energy system, such as public acceptance, whilst proving the technologies to be widely employed. To this end, research and development is being carried out to investigate and improve the performance, stability and reliability of the system, see for example [1]. The nature of the system requires elaborate and innovative studies for proper configuration, component sizing and control system development to fully explore the potential of this technology [2, 3].

2. PV-SYSTEM STRUCTURE

The common photovoltaic (PV) – battery system architecture will have the following subsystems, which are, PV modules, battery pack, power management system and tasks (see, Figure 1).

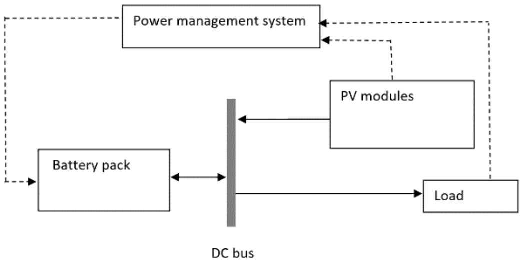

Fig.1. Solar powered energy and storage system

In this paper two type of PV – battery based system is studied. 1) A mobile stand-alone PV system, 2) PV based sustainable energy in buildings studied.

2.1 Mobile stand-alone PV system

The mobile stand-alone PV system studied in this work, consists of a 70 W PV module, a four pack 40 Ah Li-Ion battery pack with nominal voltage of 3.7 V each, a buck DC/DC converter and a controller. The controller incorporated in this particular system is the Morningstar's SunSaver MPPT™ solar controller with TrakStar™ Technology; it is an advanced maximum power point tracking (MPPT) battery charger for off-grid PV systems. The entire system was tested in various conditions to verify its performance while experimental data was collected from the PV system components. To conduct system monitoring analysis, and demonstrate the mobile stand-alone PV system concept, researchers at the Faculty of Engineering, Computing and Science in the University of South Wales used a laboratory setup, which is illustrated by Figure 2.

Fig.2. Laboratory setup and testing of PV module

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Figure 2 shows the general laboratory setup of the PV system and the PV system testing in the laboratory condition, in that the PV module is glide over a test-bed with $1000\,Wm^{-2}$ which represents an average mid-day sun light acting perpendicular to the cells of the PV panel.

System monitoring can provide useful information about their operation and what should be done to improve performance. Temperature is identified as a key parameter and monitored for system behavior and performance analysis. The battery pack used in this system is the four pack 40 Ah Li-ion battery with nominal voltage of 3.7 V. Its operational temperature range has been testified and verified. It has been observed that the storage range is -30℃<T<60℃, whereas, the charge temperature range is 0℃<T<45℃ and the discharge temperature range is -30℃<T<60℃ which is the same as the standard operational range specified by the manufacture. Further observation, shows that the temperature on the back of the PV panel is evenly distributed and in general, many repeated tests it was found below 70°C. Therefore, it is possible that an efficient mobile stand-alone PV system can be implemented with the use of Li-ion battery that has a storage range of temperature -30°C<T<60°C. Using this information, a simple but an efficient mobile stand-alone PV system has been designed (see Figure 3). The system is able to power up a 12 V DC lamp, which may be used to light up a signboard in the night or other electrical equipment such as TV, fan and radio etc.

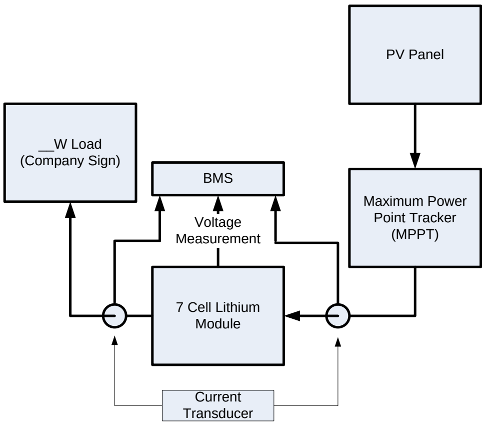

Fig.3. Mobile stand-alone PV system application [4]

2.2 Solar powered sustainable energy system

PV based sustainable energy in buildings (see Figure 4) studied with reference to a two-story countryside house in Wales. Therefore it is assumed to be as a reference load profile. A photovoltaic array is considered as the main power source to a system which enables to meet a predefined load demand. Due to the inherent intermittency of solar irradiation, a battery pack is included, but not only to smooth the fluctuation of the solar power generated, when such smoothing is necessary, it is also act as a primary energy storage when excess power is available. Furthermore, when there is a shortage of direct solar power, the battery pack will feed back the stored energy into the system.

Fig. 4. Example of sustainable energy in buildings [5]

According to the common photovoltaic (PV) – battery system architecture (see Figure 1), the other subsystem is the power management system. The key role of the power management system is to make full use of the power generated from solar irradiation and minimizing the use of stored energy in the battery pack, i.e., to keep the battery state of charge (SoC) at around 50%, which will extend its lifespan and increase the overall system efficiency. Therefore, with carefully selected system components, all the power generated by the solar PV array will be used either to support the load demand or to charge the battery pack, alternatively feedback to the sustainable system environment, which maximize the usage and minimize the operating cost.

The remaining sections of the paper, investigate the sustainable energy in buildings with reference to system sizing and energy storage options.

3. SYSTEM ANALYSIS

An economically viable way to start using the solar energy is in the production of electricity. The cost of electricity produced by PV modules maybe calculated by the following equation [2].

$$C_e = (C_{i_{PV}} \times C_r)\tau . C_{PV}^{-1} + (C_0 + C_m) \quad \textbf{(1)}$$

where C_e is the cost of electricity generated $(£/kWh)$, $C_{i_{PV}}$ is the cost of installed capacity for PV modules, C_r is the capital recovery factor. τ is the operational time, C_{PV} is the capacity factor for PV cells is generally defined as the ratio of the annual average power output to the peak power output. C_0 is the operational cost and C_m is the maintenance cost. Determining the final cost of PV energy composed of three functional steps; production, storage and usage (consumer), therefore it is important to consider the costs of the entire cycle. Date analysis indicated that the payback period is approximately seven (7) years. This payback period could be reduced or at least maintained while system-sizing operation are carried out to determine the size of an energy (storage) system to minimize the energy bill of the household.

To determine the best option, system sizing and cost analyses is carried out using the data obtained from Rhoose area, near Cardiff airport (UK) with latitude: $51^{\circ}30'0''$ North, longitude: $3^{\circ}12'0''$ West, inclination of plane $35\deg$ with zero orientation. Therefore, global irradiance (G) on a fixed plane (supply) is obtained (see, Table 1). Similarly, electricity user demand profile date is obtained for the same area and analysed.

Table 1: Global irradiance (G) on a fixed plane

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
G(Wm^2)	2751	4610	8348	10724	11649	11982	11428	10105	8773	5743	3578	2574

For the data analysis, firstly, the daily energy user demand profile data was determined. For the calculation of the data profile, the days are separately grouped as weekdays (W/D) and weekends (W/E). The year is broken down into the following five (5) seasons; spring (*Spr*), summer (*Smr*), high summer (*Hsr*), autumn (*Aut*) and winter (*Wtr*). For the data analysis the seasons defined as follows; *Spring (Spr)* – defined as the period from the day of clock change from Greenwich Mean Time (*GMT*) to British Summer Time (*BST*) in March, up to and including the Friday preceding the start of the summer period. *Summer (Smr)* – defined as the ten-week (10) period, preceding high summer, starting on the sixteenth (16) Saturday before the August bank holiday. *High summer (Hsr)* – the period of six weeks (6) and two days (2) from the sixth (6) Saturday before August bank holiday up to and including the Sunday following August bank holiday. *Autumn (Aut)* – is the period from the Monday following the August bank holiday, up to and including the day preceding the clock change from *BST* to *GMT* in October. *Winter (Wtr)* – defined as the period from the day of clock change from *BST* to *GMT* in October, up to and including the day preceding the clock change from *GMT* to *BST* in March.

In Fig.5, the individual seasons, daily energy usage is shown and the *Dashed* lines indicate the weekday's energy consumption and *solid* lines indicate the weekend day's energy consumption. Blue, black, grey, purple and brown dashed lines and red, green, light-green, orange, dark-red indicates the weekday's and weekend day's energy consumption of spring, summer, high summer, autumn, and winter respectively.

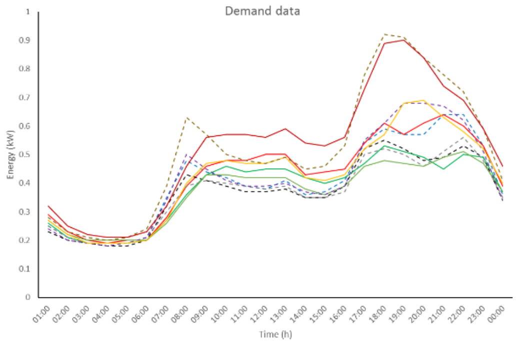

Fig.5. Daily energy usage

It is important to note that the definitions of day types and seasons are similar to those followed by the UK electricity associations. The energy user demand profile date is calculated for this particular year is 3952.14 kWh^{-1}. However, it is should be noted that form the recent historic date (20 years period), the yearly average usage is estimated as 3000 kWh^{-1}, but it is depend on many factors, such as the type of the high summer and heavy winter etc.

Further data analysis are carried out by assuming eight (8) weekend days per month with cost of electricity $14.17\,p/kWh$ and sale price of $5\,p/kWh$. The standard 250W panel with average panel size $1.44m^2$ is used for this analysis, and for the calculations 25% losses are assumed. Firstly, the daily surplus (or deficit) energy for different configuration of solar panels is obtained. Using these data, the monthly surplus energy for different size of PV panel is calculated and presented in Table 1. This information is then used for the cost/benefit analysis.

Table 1: Surplus energy (kW)

	8-Panel		10-Panel		12-Panel		14-Panel	
	W/D	W/E	W/D	W/E	W/D	W/E	W/D	W/E
Jan	-57.07	-25.55	-0.67	-5.93	55.73	13.68	112.12	33.30
Feb	4.89	-3.74	67.57	21.33	130.24	46.40	192.92	71.47
Mar	75.42	20.53	164.95	51.67	254.47	82.81	343.99	113.95
Apr	177.09	58.66	274.91	94.23	372.73	129.80	470.54	165.37
May	243.25	79.04	355.07	117.93	466.89	156.82	578.70	195.72
Jun	251.17	85.77	362.75	126.34	474.33	166.91	585.91	207.49
Jul	249.71	81.29	363.14	120.74	476.57	160.19	590.00	199.65
Aug	214.99	72.26	319.71	108.68	424.43	145.11	529.15	181.53
Sep	139.72	46.63	229.07	79.12	318.42	111.61	407.77	144.10
Oct	89.29	26.88	168.51	54.43	247.73	81.99	326.95	109.54
Nov	-28.43	-16.04	32.05	5.96	92.54	27.95	153.02	49.95
Dec	-66.97	-28.99	-13.05	-10.24	40.88	8.52	94.80	27.28
	1916.60		**3059.05**		**4549.83**		**6040.60**	

With reference to equation (1) and using above date, energy cost for different size of PV panel system is calculated and presented in Tables 2 – 5.

Table 2: Cost of energy (£) – 8 Panel PV system

	No Solar		With Solar		Excess Solar	
	W/D	W/E	W/D	W/E	W/D	W/E
Jan	41.58	15.30	29.08	9.94	7.03	2.10
Feb	36.16	15.30	22.31	8.93	7.83	2.85
Mar	41.58	15.30	22.14	7.78	11.30	3.67
Apr	31.50	12.30	14.23	5.29	13.69	4.73
May	30.01	11.26	10.85	3.87	15.85	5.27
Jun	28.71	11.26	9.38	3.51	15.75	5.48
Jul	30.01	11.26	10.63	3.79	16.10	5.35
Aug	29.99	10.80	12.35	4.29	14.95	5.07
Sep	32.02	12.26	16.21	5.92	12.50	4.35
Oct	33.48	12.26	19.32	6.70	11.03	3.62
Nov	39.77	15.30	26.33	9.48	7.53	2.42
Dec	41.58	15.30	29.29	10.05	6.61	1.97
	574.30		**301.66**		**187.02**	

Table 3: Cost of energy (£) – 10 Panel PV system

	No Solar		With Solar		Excess Solar	
	W/D	W/E	W/D	W/E	W/D	W/E
Jan	41.58	15.30	26.24	9.13	9.85	3.08
Feb	36.16	15.30	22.18	8.87	10.92	4.08
Mar	41.58	15.30	22.01	7.74	15.73	5.21
Apr	31.50	12.30	13.94	5.18	18.49	6.47
May	30.01	11.26	10.63	3.79	21.37	7.18
Jun	28.71	11.26	9.21	3.44	21.27	7.49
Jul	30.01	11.26	10.39	3.71	21.69	7.30
Aug	29.99	10.80	12.16	4.22	20.12	6.87
Sep	32.02	12.26	15.96	5.86	16.88	5.95
Oct	33.48	12.26	19.21	6.66	14.96	4.98
Nov	39.77	15.30	26.08	9.43	10.47	3.50
Dec	41.58	15.30	29.08	10.00	9.23	2.89
	574.30		**295.10**		**255.96**	

Table 4: Cost of energy (£) – 12 Panel PV system

	No Solar		With Solar		Excess Solar	
	W/D	W/E	W/D	W/E	W/D	W/E
Jan	41.58	15.30	29.08	9.94	12.67	4.06
Feb	36.16	15.30	22.05	8.82	14.01	5.32
Mar	41.58	15.30	21.88	7.69	20.16	6.76
Apr	31.50	12.30	13.85	5.08	23.34	8.22
May	30.01	11.26	10.40	3.71	26.88	9.10
Jun	28.71	11.26	9.03	3.38	26.78	9.49
Jul	30.01	11.26	10.29	3.68	27.33	9.26
Aug	29.99	10.80	11.97	4.17	25.29	8.67
Sep	32.02	12.26	15.89	5.84	21.32	7.56
Oct	33.48	12.26	19.11	6.62	18.88	6.35
Nov	39.77	15.30	25.94	9.38	13.44	4.59
Dec	41.58	15.30	29.08	9.94	11.93	3.80
	574.30		**296.81**		**325.22**	

Table 5: Cost of energy (£) – 14 Panel PV system

	No Solar		With Solar		Excess Solar	
	W/D	W/E	W/D	W/E	W/D	W/E
Jan	41.58	15.30	29.08	9.94	15.49	5.04
Feb	36.16	15.30	21.93	8.77	17.10	6.56
Mar	41.58	15.30	21.76	7.65	24.59	8.30
Apr	31.50	12.30	13.75	4.96	28.20	9.96
May	30.01	11.26	10.40	3.72	32.47	11.05
Jun	28.71	11.26	8.95	3.35	32.34	11.51
Jul	30.01	11.26	10.20	3.64	32.97	11.22
Aug	29.99	10.80	11.92	4.15	30.51	10.49
Sep	32.02	12.26	15.83	5.82	25.77	9.18
Oct	33.48	12.26	19.00	6.59	22.81	7.72
Nov	39.77	15.30	25.94	9.33	16.47	5.67
Dec	41.58	15.30	29.08	9.88	14.62	4.72
	574.30		**295.62**		**394.75**	

From the data analysis, it is evident that the total surplus energy for standard 14-panel PV-system is 6040.60 kW, but for the 10-panel PV-system is 3059.05 kW and the annual cost with solar is about £295, which is almost the same as the standard 14-panel PV system. However, the further reduction of the panel size, increase the annual cost (see Tables 2 – 5). Therefore, the sustainability of the system become vulnerable. To determine the best possible PV-system, further analysis is carried out by using the daily average data. Firstly, daily average energy demand for each month of the year is obtained for WD and WE (see, Figure 6).

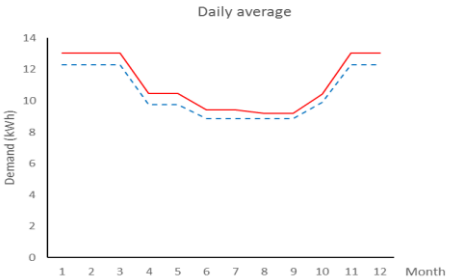

Fig.6. Daily average energy demand (for different month)

To satisfy this demand with the use of a PV based energy system, different installation size of PV energy generation options are considered. Table 6, shows the three (3) possible installation sizes capabilities, such as 4kWh, 6kWh, and 8kWh.

Table 6: Daily average PV energy generation for different installation size

	Demand		Generation	Installation size		
	W/D	W/E	1kWp	4kWh	6kWh	8kWh
Jan	12.29	13.025	1.14	4.56	6.84	9.12
Feb	12.29	13.025	1.87	7.48	11.22	14.96
Mar	12.29	13.025	3.31	13.24	19.86	26.48
Apr	9.735	10.453	4.12	16.48	24.72	32.96
May	9.735	10.453	4.42	17.68	26.52	35.36
Jun	8.87	9.423	4.49	17.96	29.94	35.92
Jul	8.87	9.423	4.25	17.00	25.50	34.00
Aug	8.865	9.18	3.77	15.08	22.62	30.16
Sep	8.865	9.18	3.33	13.32	19.98	26.64
Oct	9.895	10.418	2.23	8.92	13.38	17.84
Nov	12.29	13.025	1.43	5.72	8.58	11.44
Dec	12.29	13.025	10.5	4.20	6.30	8.40

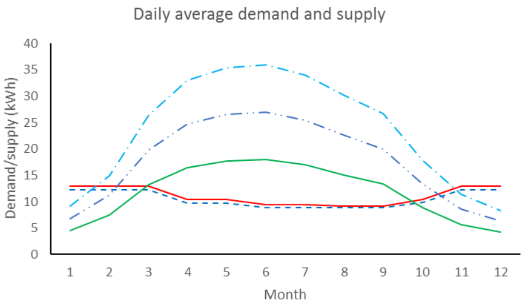

Fig.7. Daily average demand and supply for different installation size

Daily average demand and supply energy requirements for this type of systems is plotted in Figure 7. The blue and light-blue dashed lines indicates the supply capability of 6kWh and 8kWh system respectively. Green solid line indicate the 4kWh system's supply capability. Energy demand for the WE and WD is shown by (red) solid and (blue) dashed lines respectively. Furthermore, daily average surplus/deficit of supply is calculated and presented in Table 7. From the results, it is clear that the 4kWh system is the better match to cope with the requirement (see Figure 8).

Table 7: Daily average surplus/deficit of supply

	Demand		4kWh		6kWh		8kWh	
	W/D	W/E	W/D	W/E	W/D	W/E	W/D	W/E
Jan	12.29	13.025	-7.73	-8.47	-5.45	-6.19	-3.17	-3.91
Feb	12.29	13.025	-4.81	-5.55	-1.07	-1.81	2.67	1.91
Mar	12.29	13.025	0.95	0.22	7.57	6.84	14.19	13.46
Apr	9.735	10.453	6.75	6.03	14.99	14.27	23.23	22.51
May	9.735	10.453	7.95	7.23	16.79	16.07	25.63	24.91
Jun	8.87	9.423	9.09	8.54	18.07	17.52	27.05	26.50
Jul	8.87	9.423	8.13	7.58	16.63	16.08	25.13	24.58
Aug	8.865	9.18	6.22	5.90	13.76	13.44	21.30	20.98
Sep	8.865	9.18	4.46	4.14	11.12	10.08	17.78	17.46
Oct	9.895	10.418	-0.98	-1.50	3.49	2.96	7.95	7.42
Nov	12.29	13.025	-6.57	-7.31	-3.71	-4.45	-0.85	-1.59
Dec	12.29	13.025	-8.09	-8.83	-5.99	-6.73	-3.89	-4.63

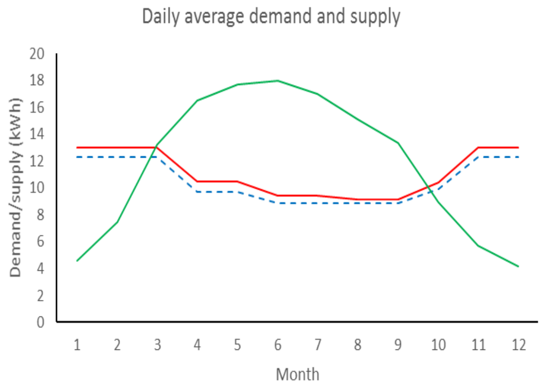

Fig.7. Daily average demand and supply of 4kWh system

For better visualization, in Fig.7, 4kWh PV system's energy generation capability is shown together with daily average demand of WE and WD. From the results and analysis, it has concluded that the 10-panel system that produce 4kWh is the best option.

Now, in-order to determine the best possible energy storage option for the 3059.05 kW total surplus energy, two different type of battery systems, such as Lead-acid and Li-ion batteries are investigated. The reliance that the world's consumer markets have placed on battery technologies can be seen in the vast amount of applications required today. Typically used in portable electronic devices such as cell phones and small items of equipment [6], lithium battery technologies are now becoming more common in many sectors [7]. However, a less obvious application is their integration into many stationary applications. The industrial applications include backup power systems for industry [8, 9] and energy storage for renewable energy systems [10, 11].

There are several large battery technologies being used in today's industry. The following advantages are gained through using lithium technologies over other cell chemistries: (i) a higher cell voltage, which is key to the high energy density; (ii) greatly improved cycle count, with typical figures of 300 – 400 cycles; (iii) a more consistent manufacturing process between cells of the same type, resulting in more balanced battery modules and (iv) an improved specific energy and energy density. However, the benefits of lithium batteries are counterbalanced by several drawbacks: (i) high initial cost – although prices are reducing with increased high volume production; (ii) costly electronics for the battery management system (BMS) to protect the cells; (iii) increased risk of overheating and fire due to the high energy, albeit this is mitigated by the use of a BMS or the consequences of error can results in overheating, fire or explosion such as the well-published incidents in 2006 [12].

Although there have been many battery chemistry implementations, to meet the specific needs listed above, the oldest battery chemistries still command a large market share. The lead acid battery may not have the high energy density or fast cycle rates that the Li-ion technologies possess [13], but they are unparalleled in their tolerance for abusive conditions and are low cost [14]. This is most notable in uninterruptible power supply (UPS) systems where a battery bank can be stored in a remote area, usually an attic or a basement, where conditions can swing between too hot $(+40^{0}C)$ or too cold $(-20^{0}C)$ on a daily basis. The preferred use of lead acid batteries in UPS systems also reflects their low price, with lead acid batteries on average 8.5 times cheaper than lithium technologies (£/kWh) [14, 15]. In a system where the batteries are going to be used only in an emergency, low purchase price is essential. As the batteries are only required in case of an emergency, it is of the utmost importance to ensure that, when called upon, the batteries are in an operational state. Therefore, for the PV based sustainable energy system in buildings, it is obvious that the best option for energy storage is the use of lead-acid battery pack [15].

From the demand /supply energy data analysis, it is evident that for a year (365 days), 210 days produces surplus energy and 155 days left with deficit. Within the profit period 150 WD and 60 WE. Similarly, for the 155 deficit days 110 WD and 45WE. Average demand for WD is 10.4kWh, therefore the total WD energy demand is 2704kWh and average energy demand for WE is 11.158kWh and total WE energy demand is 1171.6 kWh.

Therefore, 4.8kWh battery pack is capable enough to satisfy the system requirement. 4.8kWh battery pack can be developed by connecting 4 lead-acid batteries of 12V with 100Ah and such a battery pack with 1500 cycle is currently produced by Germen battery manufacturer of OPzV. This may be used for this particular solar powered sustainable energy system in buildings.

4. CONCLUSION

From the results and analysis presented in the paper, in particular in section 3, the cost – benefit analysis is a viable technique for the estimation of the total cost of the solar powered sustainable energy system. Furthermore, the impact of PV energy technologies penetration on energy price has been presented.

System sizing and cost analysis are carried out with reference to a specific location and the best configuration for the case has been identified. To store the surplus energy of 3059.05kW (for the 10-panel system) per year, lead-acid batteries likely to be a suitable energy storage option.

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