Capture and Storage of PV-Energy for Domestic Consumption

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Abstract—**This paper investigate the capture and storage of photovoltaic (PV) energy for domestic consumption. System sizing and cost – benefit analysis are carried out for the development of a solar powered sustainable energy system. This work also, contains an investigation to examine an advanced low cost energy monitoring system to help lower the overall system cost for consumers.**

Keywords—renewable energy; power management; monitoring; storage ; solar.

I. Introduction

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 the countryside [1 – 3]. Of all the challenges in developing a solar powered sustainable energy systems the most pressing is how to efficiently store and optimise the energy which has been generated [4].

Low cost lead acid batteries are currently most commonly used for remote energy storage, the newer lithium based battery chemistries are also investigated because of their higher energy densities, longer cycle life and greater tolerance to part cycling [5, 6]. Unfortunately, however, the additional cost implications brought about by their complex manufacturing process and relatively expensive monitoring and management systems mean that they are, to date, conspicuously absent in this market [7].

In order to address the energy storage problem, a key part of this research work is focussed on the system sizing and cost – benefit analysis. With the intended application of self-sustainable energy system in the remote areas of the South Wales valleys, the photovoltaic (PV) system has been chosen as being more suitable than alternative renewable energy technologies, although the benefits could equally be applied to wind or other energy recovery systems.

Housing and buildings in countryside consume a significant amount of primary energy for thermal or electrical power [4]. This sector is very important to Wales's economy and its sustainability due to its geographical place in the world. Wales is home to many historical sites, countryside buildings and houses, which are spread throughout the countryside. Powering these sites may prove to be problematic, as power cables will disturb the landscape and prove costly. Using a solar powered self-sustainable energy system may resolve these problems. Furthermore, with the growing demand for energy and the decreasing cost of the PV technology, encourage the implementation of solar powered self-sustainable system in many household in Wales. However, the overall and initial implementation cost of the system is still high. Large amounts of research work have addressed various topics for sustainable energy systems; and includes modelling and simulation to analyse the complex interactions within the system and with exogenous factors. In addition, the application of control, in trying to maintain and evaluate optimal system performance have been of interest [8, 1].

In this work, system sizing and cost – benefit analysis are carried out for the development of a solar powered sustainable energy system. In addition, an advanced low cost energy monitoring system is also investigated to help lower the overall system cost for consumers.

II. Methodology

A. Photovoltaic System

This paper is focused in the PV based energy system in building and housing sector. PV technology has the best characteristics to be integrated in buildings with quite environmental conditions. The presence of PV generation is increasing worldwide, achieving 9.8 GW in Germany and 3.5 GW in Spain of installed power at the end of 2009 [3].

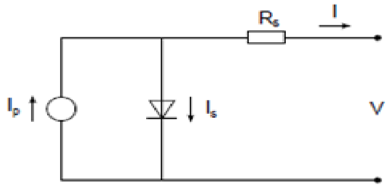

Fig.1. Equivalent circuit for PV array

PV based sustainable energy in buildings studied with reference to a two-story countryside house in Wales. The PV system described in this work consist of PV modules, battery pack, power management system and tasks. Usually the PV-module is modelled as an equivalent circuit, which consists of a current source, a diode and a series resister as shown in Figure 1. The typical current-voltage (I-V) characteristic for PV cell is expressed in equation (1)

$$I = I_p - I_s\left(\exp\left(\frac{V + IR_s}{\varepsilon V_t}\right) - 1\right) \quad (1)$$

where I_p is the photo current, I_s is the reverse saturation current which is affected by the temperature of the PV cell, V is the cell voltage, ε is the ideality factor which is approximately equal to 1, V_t is the thermal voltage.

B. Storage System

It is important to note that the energy sources of renewable energy technologies are unreliable and intermittent a storage component is required to store energy during excess power generation, which can be used during periods when demand exceeds energy production. A comparison of different energy storage technologies conducted by Hadjipaschalis et al. [9] concluded that battery technology systems are preferable for continuous energy storage/use. The conclusion was also reached that although modern flywheel systems and fuel cell systems are promising technologies their prohibitive costs preclude current usage. The super capacitor is another storage device, it has a very quick charge/discharge times but due to its lower specific energy capabilities than batteries, it is not considered in this work.

As Kaiser [10] shows in his research, the lead acid battery has, until now, been favoured by the renewable energy sector with research carried out by Kaiser to increase the lifetime of the battery system [11]. This is achieved using deep cycle lead acid batteries and a split string technique to allow certain batteries to charge/discharge depending on state of charge (SoC). Therefore, in this work lead acid battery is used as the energy storage mechanism.

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 [12], but they are unparalleled in their tolerance for abusive conditions and are low cost [13]. 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 or too cold 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]. 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.

The battery state of charge S is the only state variable within the battery system model and is defined as;

$$S = \frac{Q_{\max} - \int_0^t I_b dt}{Q_{\max}} \quad (2)$$

where $Q_{\max}$ is the battery's maximum capacity. The battery current I_b is defined by;

$$I_b = -(I_{PV} - I_{Load}) \quad (3)$$

where I_{PV} is the PV array's current and I_{Load} is the load current. When charging the battery, the current is positive and a negative current would indicate that the battery is discharging. It is typically found that the length of a battery's life maybe extended by avoiding overcharging and deep discharging. Knowing the $Q_{\max}$ is important to determine the size of the battery pack, which can support the load demand of a given period.

C. 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 midpoint, 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 maximise the usage and minimise the operating cost.

III. Consumption Analysis

A. Demand

To determine the best possible PV-system, data analysis is carried out by using the data's obtained from PVGIS – CMSAF, solar radiation database for the location of $51^{\circ}23'59''$ North, $33^{\circ}24'36''$ West, inclination of plane 35° with zero orientation. Daily average energy demand for each month of a year is obtained (see, Fig.1.). For the calculation of the data profile, the days are separately, grouped as weekdays (W/D) and weekends (W/E). Energy demand for the WE and WD is shown by (red) solid and (blue) dashed lines respectively. Form the figure, it can be seen that the daily average demand for WE and WD is 11.16kWh and 10.4kWh respectively.

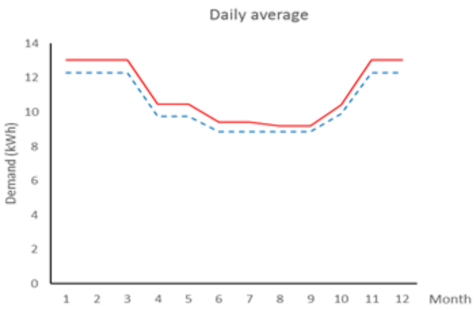

Fig.1. Daily average energy demand (for different month)

To satisfy this demand with the use of a PV based energy system, different installation size of PV energy generation options are considered. Nominal power of the considered crystalline silicon PV system is 1 kW. For this system, the combined PV system losses accounted as 23.2%, which included the 6.9% of estimated losses due to temperature and low irradiance (using ambient temperature), 2.9% of losses due to angular reflectance effects and 13.4% of other losses, such as cable etc. The data for per square meter (m^2) of solar panel is presented in Table 1. Where, E_d and E_m represent the average daily and monthly electricity production for the given system. Similarly, G_{i_d} and G_{i_m} represent the daily and monthly average sum of global irradiation per square meter (m^2) by the modules of the given system. Yearly average and total for the year are denoted by Y_A and Y_T .

Table 1: Data for per square meter of solar panel

	Fixed system: Inclination 35° (0°)			
	E_d	E_m	G_{i_d}	G_{i_m}
Jan	1.14	35.4	1.4	43.2
Feb	1.87	52.4	2.31	64.7
Mar	3.31	102	4.17	129
Apr	4.12	124	5.36	161
May	4.42	137	5.83	181
Jun	4.49	135	5.99	180
Jul	4.25	132	5.72	177
Aug	3.77	117	5.05	157
Sep	3.33	99.9	4.39	132
Oct	2.23	69.1	2.87	89
Nov	1.43	43	1.79	53.6
Dec	1.05	32.5	1.28	39.8
Y_A	**2.96**	**89.9**	**3.85**	**117**
Y_T	**1080**		**1410**	

With this demand and generation data information, it is identified that a PV panel capable of producing 4kWh energy may satisfy the system requirement.

B. Supply

General supply for the South Wales is determined by obtaining irradiation date for Cardiff (St. Athan) during the period of January 2002 to December 2011. Table 2 and 3 shows the daily and monthly average irradiation respectively. Using the data, mean irradiation (Wh/m^2) for stated inclination from horizontal is calculated and included in the tables.

Table 2: Daily average irradiation

	Inclination				
	0	**30**	**45**	**60**	**90**
Jan	25.00	42.84	48.68	51.87	49.52
Feb	52.61	77.21	84.07	86.54	77.64
Mar	86.97	112.26	117.00	115.74	95.61
Apr	145.67	165.77	164.37	154.97	114.67
May	168.06	173.90	165.87	150.42	101.87
Jun	195.93	196.40	184.27	164.43	106.70
Jul	165.26	168.16	158.71	142.61	94.16
Aug	141.55	153.39	149.16	138.16	98.32
Sep	108.70	132.43	135.03	130.93	103.50
Oct	57.48	79.45	84.87	85.87	74.55
Nov	29.70	47.77	53.37	56.10	52.30
Dec	19.35	34.68	39.84	42.81	41.45
Mean	**99.69**	**115.35**	**115.44**	**110.04**	**84.19**

Table 3: Monthly average irradiation

	Inclination				
	0	**30**	**45**	**60**	**90**
Jan	775	1328	1509	1608	1535
Feb	1473	2162	2354	2423	2174
Mar	2696	3480	3627	3588	2964
Apr	4370	4973	4931	4649	3440
May	5210	5391	5142	4663	3158
Jun	5878	5892	5528	4933	3201
Jul	5123	5213	4920	4421	2919
Aug	4388	4755	4624	4283	3048
Sep	3261	3973	4051	3928	3105
Oct	1782	2463	2631	2662	2311
Nov	891	1433	1601	1683	1569
Dec	600	1075	1235	1327	1285
Mean	**3037**	**3512**	**3513**	**3347**	**2559**

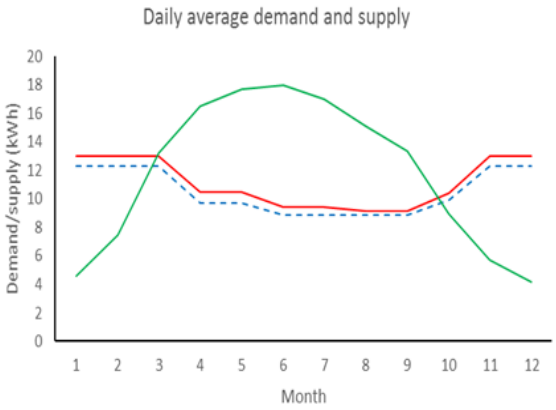

Fig.2. Daily average demand and supply

Daily demand and supply energy data for the 4kWh system is shown in Table 4.

Table 4: Daily average surplus/deficit of the 4kWh system

	Demand		Generation		4kWh system Surplus/Deficit (kWh)	
	W/D	W/E	1kWp	4kWh	W/D	W/E
Jan	12.29	13.025	1.14	4.56	-7.73	-8.47
Feb	12.29	13.025	1.87	7.48	-4.81	-5.55
Mar	12.29	13.025	3.31	13.24	0.95	0.22
Apr	9.735	10.453	4.12	16.48	6.75	6.03
May	9.735	10.453	4.42	17.68	7.95	7.23
Jun	8.87	9.423	4.49	17.96	9.09	8.54
Jul	8.87	9.423	4.25	17.00	8.13	7.58
Aug	8.865	9.18	3.77	15.08	6.22	5.90
Sep	8.865	9.18	3.33	13.32	4.46	4.14
Oct	9.895	10.418	2.23	8.92	-0.98	-1.50
Nov	12.29	13.025	1.43	5.72	-6.57	-7.31
Dec	12.29	13.025	10.5	4.20	-8.09	-8.83

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 (Fig.2). 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.

To determine the best possible option for this system requirement, investigation of system sizing and cost analysis is conducted. Table 5 shows the surplus energy for the different size of PV panel system.

Table 5: 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**	

The total surplus energy for standard 14-panel PV system is 6040.60kW, but for the 10-panel PV system is 3059.05kW and the annual cost with solar is about £295, which is almost the same as the standard 14-panel PV system (see Fig.3.).

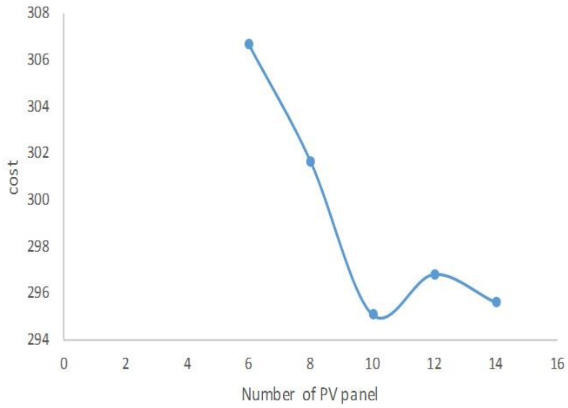

Fig.3. Cost against size of PV system

However, further reduction of the panel size, increase the annual cost. Therefore, the sustainability of the system becomes vulnerable. From the above analyses, it is concluded that the 10-panel system producing 2.5kW and an energy storage system that can store 4.8kWh is the best option for the given PV based energy system in building and housing sector.

Now, for the energy storage, a suitable lead-acid battery pack need to be identify and constructed. Through the system analysis, it has been identified that the 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. This may be the best possible energy storage option for the 3059.05 kW total surplus energy of 10-panel system.

IV. Monitoring System

The UK has set itself the world's first legally binding target of reducing carbon emissions by 80% compared to the 1990 emissions level by the year 2050 [15]. One of the ways in which it proposes to meet this target is by reducing energy consumption through the universal usage of smart meters by businesses, consumers and the public sector. The aim is to provide every house and small business in the UK with a smart energy meter by 2020 [15]. A smart meter is a device that can monitor the consumption of utilities: electricity, gas and water. Although this is possible with traditional analogue energy meters, the smart meter is equipped with a communication device, which enables the system to remotely upload meter readings at regular and frequent intervals (Fig. 4). The advantage of frequent meter readings is that real time energy consumption information is available for both energy providers and consumers. This equips the consumer with the means of being able to observe when an application is consuming power unnecessarily, and, therefore, turn it off, giving them more effective control over their energy consumption. Even if energy saving is not of interest to the consumer, accurate billing allows them to see how much money they are wasting by not being more energy efficient. Using the energy data and cost saving to educate the customer in energy conservation is known as behavioural energy saving [16, 17].

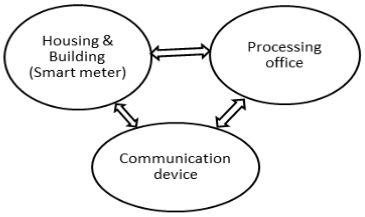

Fig.4. Smart meter (energy monitoring system)

Smart meters help to balance demand for energy with interrupt supply. Therefore, an advanced function low cost smart meter could act as an energy monitoring system. With the inclusion of the smart meter (energy monitoring system), the self- sustainable energy system become more stable and acceptable.

It is important to ensure that this energy monitoring system can easily keep a record of how the battery bank is used, recording parameters such as temperature, voltage and current. There is also an added level of monitoring as the system can record when the voltage or SoC is out of the safe battery limits. Data from the load and energy sources can be used to discover why the problem occurred. This feature will not just serve as a battery protection procedure, but will also be a good method of data collection to further improve PV-based energy system design in the future.

V. Conclusion

In this paper, an investigation of capture and storage of PV- energy for domestic consumption is carried out. This work also, contains an investigation to examine an advanced low cost energy monitoring system to help lower the overall system cost for consumers.

System sizing and cost analysis with reference to a specific location indicated that the best configuration for the given case is a 10-panel PV- system that can produce 2.5kW of energy is the best option. To store the surplus energy, a 4.8kWh lead-acid battery pack is identified as a suitable energy storage option.

References

[1] G. Bopp, H. Gabler, K. Preiser, D. U. Sauer, H. Schmidt, ‘Energy storage in photovoltaic stand-alone energy supply systems’, Progress in Photovoltaics: Research and Applications, vol. 6, no. 4, pp. 271–291, 1998.

[2] J.P. Dunlop, 'Batteries and charge control in stand-alone photovoltaic systems'. Fundamentals and Application, Sandia National Laboratories, 1997.

[3] K. Thanapalan, S. Carr, F. Zhang, G. Premier, A. Guwy. Renewable Hydrogen Vehicles and Infrastructure Development in the UK. International Journal of Energy Engineering., Vol. 3, no. 1, pp. 27–32, 2013.

[4] F. Zhang, K. Thanapalan, A. Procter, S. Carr, J. Maddy, G. Premier, ‘Power management control for off-grid solar hydrogen production and utilisation system’, International Journal of Hydrogen Energy, vol. 38, no. 11, pp. 4334–4341, Apr. 2013.

[5] S. Barsali, M. Ceraolo. ‘Dynamical models of lead-acid batteries: implementation issues’, IEEE Transaction on Energy Conversion vol 17, no. 1, pp.16-23, 2002.

[6] B. Schweighofer, K. M. Raab, G. Brasseur, ‘Modeling of high power automotive batteries by the use of an automated test system’, IEEE Transactions on Instrumentation and Measurement 52 (4):1087-1091, 2003.

[7] T. Stockley, K. Thanapalan, M. Bowkett, J. Williams, 'Design and implementation of OCV prediction mechanism for PV-Li-ion battery system', in 20th International Conference on Automation and Computing (ICAC), pp. 49–54, 2014

[8] V. Salas, E. Olías, A. Barrado, A. Lázaro, ‘Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems’, Solar Energy Materials and Solar Cells, vol. 90, no. 11, pp. 1555–1578, Jul. 2006. Energy Storage in photovoltaic stand-alone energy

[9] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou. Overview of current and future energy storage technologies for electric power applications. Renewable and Sustainable Energy Reviews, 13(6–7), pp.1513–1522, 2009

[10] R. Kaiser. Optimized battery-management system to improve storage lifetime in renewable energy systems. Journal of Power Sources, 168(1), pp.58–65, 2007.

[11] A. Mariani, K. Thanapalan, P. Stevenson, J. Williams. An advanced prediction mechanism to analyse pore geometry shapes and identification of blocking effect in VRLA battery system. International Journal of Automation and Computing, vol 14, no. 1, pp. 21-32, 2017.

[12] P. F. Ribeiro et al. Energy Storage Systems for Advanced Power Applications. “Proceedings of the IEEE,” vol.89, issue 12, pp. 1744-1746, 2001.

[13] K. C. Divya and J. Ostergaard (2009). Battery energy storage technology for power systems—An overview. “Electric Power Systems Research,” vol. 79, issues 4, pp.511-520.

[14] A. Mariani, T. Stockley, K. Thanapalan, J. Williams, P. Stevenson. Simple and Effective OCV Prediction Mechanism for VRLA Battery Systems. In Proceedings of the 3rd International Conference on Mechanical Engineering and Mechatronics, Prague, Czech Republic, pp.1-10, 2014

[15] Great Britain. Climate Change Act 2008. Chapter 27, London, 2008.

[16] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter. A review of intervention studies aimed at household energy conservation', Journal of Environmental Psychology, 25(3), pp.273–291, 2005

[17] W. Abrahamse, L. Steg, C. Vlek, T. Rothengatter. The effect of tailored information, goal setting, and tailored feedback on household energy use, energyrelated behaviors, and behavioral antecedents', Journal of Environmental Psychology, 27(4), pp.265–276, 2007