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Development of a solar powered self-sustainable energy system

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Abstract. This paper discusses a systematic approach for the development of a solar powered self-sustainable energy system. In remote locations, self-sustainable energy system configurations are of interest, and may prove more cost effective than a grid connected systems. This paper investigates a typical self-sustainable energy system configuration and performance optimization. The potential benefits of such a system design is investigated using data collected at a specific location and the performance of the system under variable conditions determined. This paper also described an optimal design and implementation of an efficient self-sustainable energy system.

Key words

Energy storage, renewable energy, solar, power management, energy system.

1. Introduction

Solar powered self-sustainable energy system could assist for conserving the environment by using solar energy in locations without access to electricity and act as an indispensable electricity source for remote areas. The solar system has been deployed widely and more and more organisations and people are benefiting from installing photovoltaic (PV) panels, which converts the solar energy to electrical energy [1]. The reason for that includes its free access and abundance for most places in the world. The installation of PV system is growing significantly in response to the increasing global energy demand. It is estimated that the PV industry had a global total of 40GW capacity, which is significant compared with other renewable energy sources [2].

Housing and buildings in the countryside consume a significant amount of primary energy for thermal or electrical power [2]. 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.

Sustainable energy system can be either stand-alone or grid connected, or a hybridisation of both. Over the past decade, the development and application of sustainable energy system has increased significantly [3]. A Large amount of research work has addressed various topics for sustainable energy system; 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 has been of interest [3, 4].

2. System structure

The common self-sustainable energy system architecture will have the following subsystems, which are, renewable energy source (PV modules), energy storage subsystem (battery pack), power management system (controllers) and tasks (load). For illustration purpose a structural block diagram for a proposed flexible solar energy system is shown in Fig.1. The solid black arrows represent the electricity flow; the dotted grey arrow represents the control signals.

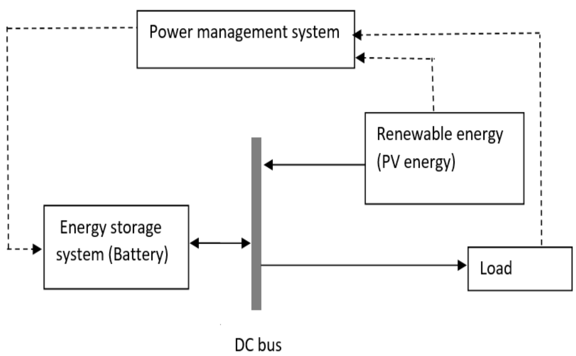

Fig.1. System configuration of the solar powered self-sustainable energy system.

In this study, a two-storey countryside house in Wales 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.

A. System model

Several researchers have addressed the development of an accurate system model, and the design and application of such systems [5, 6]. In this paper, a common but accurate PV model presented in [7] is adopted. The model of the PV system is based on an equivalent circuit, which consists of a current source, a diode and a series resister as shown in Figure 2.

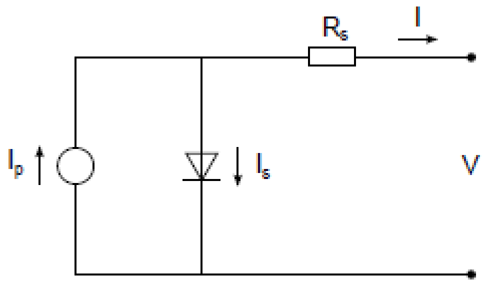

Fig.2. Equivalent circuit for PV array

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 and its given by;

$$V_t = {k_B T}/{q} \quad (2)$$

With the Boltzmann constant $k_B = 1.38 \times 10^{-23} JK^{-1}$; T is the absolute temperature of the diode in Kelvin and $q = 1.6 \times 10^{-19} C$ is the charge represented by an electron. Finally, R_s is the equivalent series resistance of the PV array describing an internal resistance to the current flow.

All the parameters can be determined by equation (3) with the subscript r represents reference. E is irradiation, K_0 is the temperature coefficient of the short circuit current which can be found from the manufacture's data sheet together with T_r , E_r and short circuit current I_{scr} , V_g is the band gap voltage of the semiconductor, finally, term $\frac{dV}{dI_{V_{OC}}}$ can also be generated from manufacturer's data sheet.

$$\left.\begin{aligned}
I_p &= I_{pr} + K_0(T - T_r) \\
I_{pr} &= I_{scr}\frac{E}{E_r} \\
I_s &= I_{sr}\left(\frac{T}{T_r}\right)^{\frac{3}{\varepsilon}}\exp\left(-\frac{qV_g}{\varepsilon k_B}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right) \\
I_{sr} &= \frac{I_{scr}}{\exp\left({qV_{OCr}}/{\varepsilon k_B T_r}\right) - 1} \\
R_s &= -\frac{dV}{dI_{V_{OC}}} - \frac{1}{X_V} \\
X_V &= I_{sr}\frac{q}{\varepsilon k_B T_r}\exp\left(\frac{qV_{OCr}}{\varepsilon k_B T_r}\right)
\end{aligned}\right\} \quad (3)$$

The seconder energy source is the battery pack which creates a DC connection between all components in the solar powered self-sustainable energy system. It is used as an energy store and buffers fluctuations in storage and compensates for fluctuation in power generation by the PV cells. The battery state of charge S is the only state variable within the battery system model and is defined as;

$$S = \frac{Q_{\max} - \int_0^t I_b dt}{Q_{\max}} \quad (4)$$

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

$$I_b = -(I_{PV} - I_{Load}) \quad (5)$$

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 negative current indicates 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.

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.

3. System sizing and cost analysis

Investing in Solar powered self-sustainable energy system could lead to economic growth and may ensure energy security. System sizing in such system play a key role in reducing energy cost. Energy cost in any given renewable energy source depends on the system design and operation characteristics and the quantity and type of losses encountered during production and delivery to the end user. An economically viable way to start using the renewable energy is in the production of electricity. The cost of electricity produced by PV modules can be calculated by the following equation [2].

$$C_e = (C_{i_{PV}} \times C_r)\tau . C_{PV}^{-1} + (C_0 + C_m) \qquad (6)$$

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 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 $35\,\mathrm{deg}$ 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.

During the individual seasons, daily energy usage is recorded and plotted against time (see, Figures 3 – 7). In Figure 3, spring season daily energy consumption is shown, where, dashed (blue) line indicates the weekday's energy consumption and solid (red) line indicates the weekend day's energy consumption. Similarly, for the other seasons dashed and solid lines indicate the weekday and weekend days' energy consumption respectively.

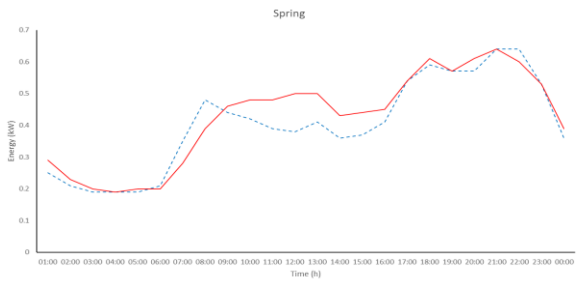

Fig.3. Energy against time (Spring)

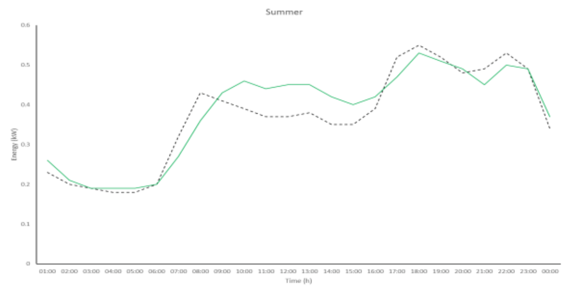

Fig.4. Energy against time (Summer)

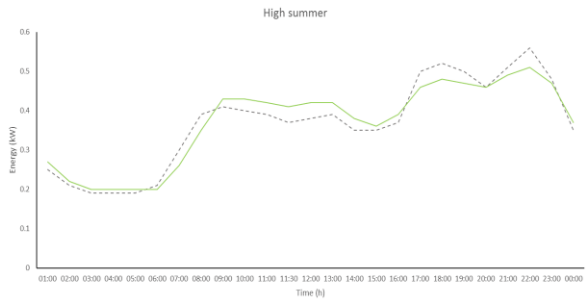

Fig.5. Energy against time (High summer)

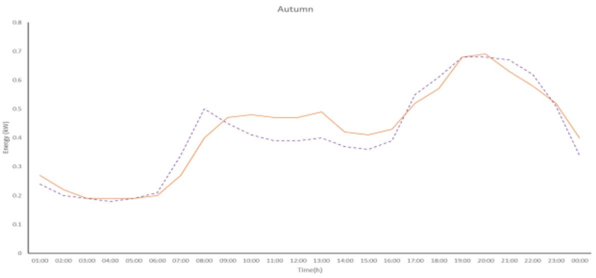

Fig.6. Energy against time (Autumn)

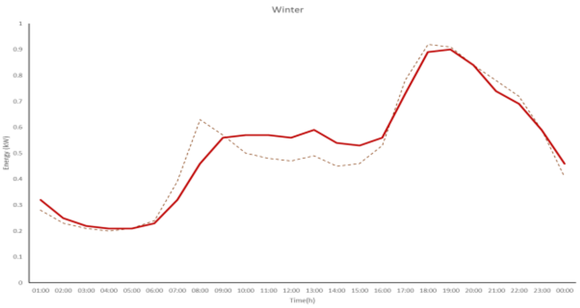

Fig.7. Energy against time (Winter)

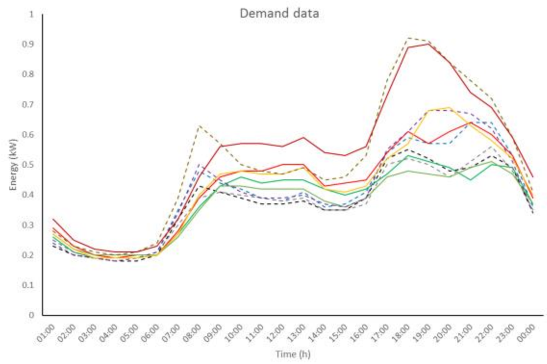

Fig.8. Comparative demand

Figure. 8, shows the comparative demand data for the different seasons. 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 (see Table 2) 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.

Table 2: Demand profile date

	Week days	Weekend days	Number of days	Seasonal average	Seasonal total
Spr	9.735	10.452	48	10.094	484.51
Smr	8.87	9.423	70	9.146	640.22
Hsr	8.865	9.180	44	9.023	397.01
Aut	9.895	10.418	55	10.157	558.64
Wtr	12.29	13.003	148	12.647	1871.76
Tol			365		**3952.14**

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. The table below (Table 3) shows the daily surplus (or deficit) energy for different configuration of solar panels. Using these data, the monthly surplus energy for different size of PV panel is calculated and presented in Table 4. This information is used for the cost/benefit analysis.

Table 3: Daily Surplus (or deficit) 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	-2.48	-3.19	-0.03	-0.74	2.42	1.71	4.87	4.16
Feb	0.24	-0.47	3.38	2.67	6.51	5.80	9.65	8.93
Mar	3.28	2.57	7.17	6.46	11.06	10.35	14.96	14.24
Apr	8.05	7.33	12.50	11.78	16.94	16.22	21.39	20.67
May	10.58	9.88	15.44	14.74	20.30	19.60	25.16	24.46
Jun	11.42	10.72	16.49	15.79	21.56	20.86	26.63	25.94
Jul	10.86	10.16	15.79	15.09	20.72	20.02	25.65	24.96
Aug	9.35	9.03	13.90	13.59	18.45	18.14	23.01	22.69
Sep	6.35	5.83	10.41	9.89	14.47	13.95	18.54	18.01
Oct	3.88	3.36	7.33	6.80	10.77	10.25	14.22	13.69
Nov	-1.29	-2.00	1.46	0.74	4.21	3.49	6.96	6.24
Dec	-2.91	-3.62	-0.57	-1.28	1.78	1.06	4.12	3.41

Table 4: 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 (6) and using above date, energy cost for different size of PV panel system can be calculated, see Tables 5 - 8.

Table 5: 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 6: 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 7: 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 8: 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**	

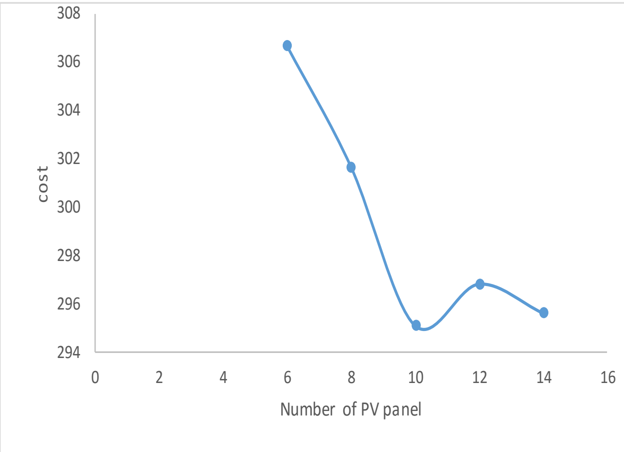

Fig.3. Cost against size of PV system

From the above data analysis, it can be seen, that 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.). However, the further reduction of the panel size, increase the annual cost (see Table 5-8). Therefore, the sustainability of the system become vulnerable. From the above analyses, it can be concluded that the 10-panel system is the best option.

4. Discussion and Concluding remarks

In this paper, Solar powered self-sustainable energy system with efficient energy usage is investigated. 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. These analyses may be generalised to determine the best option for a given location.

Future work includes the development of a complete simulation model of the system and it will be used for the power management controller design to optimize the system performance. Furthermore, to store the surplus energy of 3059kW (for the 10-panel system) per year a viable energy storage system need to be identified, for this case, Li-ion and lead acid battery technologies will be investigated with reference to system sizing and cost.

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