Research Article

Development of solar home system with dual energy storage

Bin-Juine Huang[1] · Po-Chien Hsu[1] · Yi-Hung Wang[1] · Tzu-Chiao Tang[1] · Jia-Wei Wang[1] · Xin-Hong Dong[1] · Ming-Jia Lee[1] · Jen-Fu Yeh[1] · Zi-Ming Dong[1] · Min-Han Wu[1] · Shen-Jie Sia[1] · Kang Li[1] · Kung-Yen Lee[2]

Abstract
Distributed energy generation with energy storage is quite important for high penetration of solar PV energy. A solar home system which generates solar power for self-consumption was studied. The solar home system utilizes a switching-type solar PV (HyPV) which operates in either solar or grid mode automatically without feeding solar power into grid. The solar home system also uses dual energy storage consisting of a battery and an electric water heater which stores PV energy as hot water (thermal storage) when the battery is full. Since thermal storage is much cheaper than battery, the dual energy storage would reduce the total cost of solar home system dramatically. Four HyPV solar home systems were built to run long-term field test. The results show that the specific PV energy generation approximates that of feed-in-tariff PV system. A solar PV energy production cost analysis shows that the HyPV solar home system with dual storage is economic if it was used to replace partial energy demand which is paid at higher grid electricity price. This verifies the possibility of grid parity for a solar PV system with energy storage.

Keywords Solar PV system · Solar home system · Solar PV with storage

1 Introduction

High penetration of solar photovoltaic (PV) energy using grid-tied PV system may cause grid transmission problems. Distributed energy generation with energy storage is a good choice to cope with this problem. However, the cost of energy storage is very high and the solar PV system may not be economic.

Hsu et al. [1, 2] developed a hybrid solar PV system (HyPV) as shown in Fig. 1. HyPV operates in stand-alone PV mode or grid mode automatically using switching technique. No solar power is fed into grid. When solar energy is available, including PV power generation and battery storage, it operates in PV mode and the load is powered completely by solar energy as a stand-alone PV. When PV power generation and battery storage is low, it switches to grid mode through ATS (Automatic Transfer Switch). The load is supplied completely by grid, and the battery is charged again by solar PV. HyPV will switch back to PV mode when the battery is charged certain amount of energy.

Solar home system generating electrical power using HyPV with storage device for self-consumption was further proposed [3]. This kind of PV system is usually in small size (1–3 kWp) and looks like a home appliance. Thus, it can be combined with hot water supply system since there is always a hot water demand in a household. Since the thermal storage is much cheaper than battery, this will reduce the cost of energy storage dramatically.

Since no solar PV power is fed into the grid in HyPV, the energy storage has to be large enough in order to avoid the PV energy generation loss. An electric water heater is used to store PV energy as heat to provide enough storage capacity, called "HyPV solar home system" (Fig. 2). In PV mode, the PV energy will be stored as hot water (thermal storage) by the electric heater through ATS2 when the

✉ Bin-Juine Huang, bjhuang@seed.net.tw | [1]Department of Mechanical Engineering, National Taiwan University, Taipei 106, Taiwan. [2]Department of Engineering Science and Ocean Engineering, National Taiwan University, Taipei 106, Taiwan.

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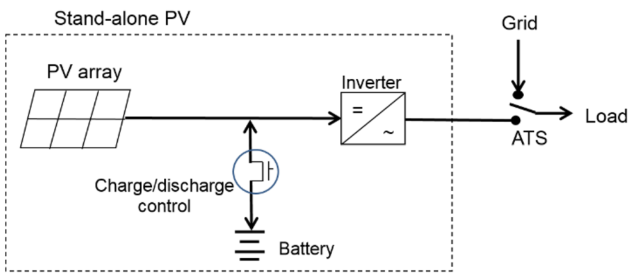

Fig. 1 Schematic diagram of HyPV [1]

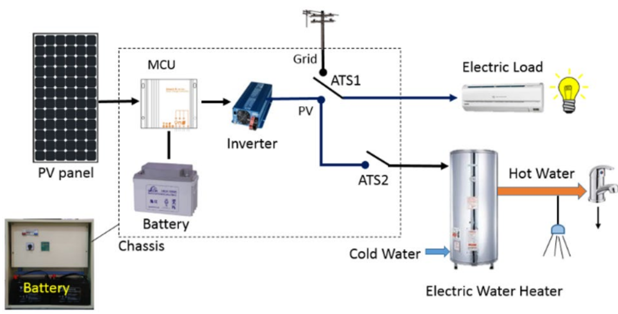

Fig. 2 HyPV solar home system with dual energy storage

battery is full. Since thermal storage is much cheaper than battery, the dual energy storage would reduce the total cost of HyPV solar home system.

Bocklisch [4] discussed hybrid energy storage (HESS) for power flow control for peak shaving. Lee [5] theoretically studied solar lighting system with battery and heater which stores PV energy at daytime when the battery is full.

Akbaria et al. [6] reviewed all types of energy storage systems that can be integrated with PV system consisting of electrical and thermal energy storage. The integration of PV energy storage in smart buildings is discussed together with the role of energy storage for PV in the context of future energy storage developments. The future energy storage development was summarized, and even demand-side energy management was discussed. It is shown that thermal storage will satisfy thermal comfort needs of buildings when operating with heat pumps while battery deployment may operate with electric vehicles and/or electric heat pumps at times of local grid congestion.

Faccia et al. [7] analyzed the transition from natural gas to electricity-based heating for residential applications, considering the interplay between grid-tied solar PV electricity generation on site and the thermal energy storage to optimize the heating devices. The analysis found that if heat pumps are used instead of natural gas boilers, energy costs are reduced up to 41%. The simultaneous utilization of heat pumps (as substitutes of boilers) and PV panels is shown to be economic and yields grid parity.

The studies of [3–9] are all related to grid-tied solar PV system with energy storage, and no experimental data were reported. The present HyPV solar home system is basically a stand-alone PV combined with grid power through a switching device. No PV power is fed into grid to cause possible grid congestion. Hence, the solar system requires a larger energy storage to obtain high PV generation efficiency. This may lead to high cost.

The present study focuses on the technical feasibility of non-grid-tied solar home system with dual energy storage. Four HyPV solar home systems with dual energy storage were built for field test to collect the long-term performance data. Solar energy production cost was also analyzed.

2 Installation of HyPV system

2.1 Design of HyPV systems

Four HyPV systems were built in the present study. The system design specification is shown in Table 1. Three of them (D3, D5, and D11) were installed in household to collect data in real application as a home appliance. The PV power is used to drive 2 or 3 air conditioners and LED lighting in the house. The city water is preheated by solar PV power when the battery is full. The 120L water heater with electric heating element provides 4.2 kWh thermal storage capacity (E_w) for water temperature rise $\Delta T = 30$ °C which is larger than the usable battery capacity (E_{bat}).

As shown in Table 1, the ratio of battery storage to maximum PV energy generation (E_{bat}/E_{pv}) for the four HyPVs is all less than 1.0. This will cause solar PV energy generation loss if only battery storage is used. In the present study, the total usual energy storage capacity (E_{tot}) including battery and hot water storage ranges from 5.35 to 7.08 kWh. With this combination, the ratio of total energy storage to expected solar PV energy generation (E_{tot}/E_{pv}) ranges from 1.36 to 2.11. It is known that the FIT solar PV systems generate maximum solar power which is directly fed into grid at optimal energy conversion efficiency since the MPPT (maximum power point tracking) was always used. This means that the designed total energy storage capacity (E_{tot}) including battery and hot water storage is large enough to store the daily solar PV energy generation, if the daily hot water load is larger than 4.2 kWh.

2.2 Installation of HyPV systems

Figures 3, 4, 5 and 6 show the installation of four HyPVs in Taipei and Chia-Yi (southern Taiwan). D3 was installed in a resident house surrounded by apartment buildings. D5 was installed at the top of an 7-floor apartment building.

Table 1 System design specification of four HyPVs

HyPV	D3	D5	D8	D11
Installation location	Taipei	Taipei	Taipei	Chia-Yi
Specific energy generation of FIT PV system (S_{pv}) (kWh/kWp per day)	2.47	2.47	2.47	3.84
PV Module				
Size (P_{pv})(kWp)	1.47	1.47	1.08	1.08
Expected PV energy generation (E_{pv}) (kWh/day)	3.63	3.63	2.67	4.15
Battery				
Type	LA	Li	LA	LA
Voltage (V)	48	48	24	24
Capacity(E_{bat0}) (kWh)	4.8	1.44	2.4	2.4
Usable capacity (E_{bat}) [kWh @DOD60% (LA) or 80% (Li)]	2.88	1.15	1.44	1.44
Cost of battery (TWD)	19,200	28,800	9600	9600
Water heater				
Tank volume (L)	120	120	120	120
Power input (kW)	1.0	1.0	0.7	0.7
Heat storage capacity(E_w) (kWh @ΔT = 30 °C)	4.2	4.2	4.2	4.2
Cost of water heater (TWD)	8400	8400	8400	8400
Total usable energy storage capacity ($E_{tot} = E_{bat} + E_w$) (kWh)	7.08	5.35	5.64	5.64
Inverter (kW @220 V)	1.5	1.5	1.5	1.5
Load				
Type	Cooling, lighting	Cooling, lighting	Cooling	Cooling
Load power (kW)	0.2–1.4	0.2–1.2	0.2–1.2	0.2–1.2
Load pattern	24 h a day	Night	24 h a day	Night
Ratio of usable battery storage to max PV energy generation E_{bat}/E_{pv}	0.79	0.32	0.54	0.35
Ratio of total usable energy storage to max (FIT) PV energy generation E_{tot}/E_{pv}	1.95	1.47	2.11	1.36
Total cost of dual energy storage (TWD)	27,600	37,100	18,000	18,400
Total cost of energy storage using Li battery only (TWD)	177,000	133,750	141,000	141,000

Fig. 3 HyPV D3 installed in a house (Taipei)

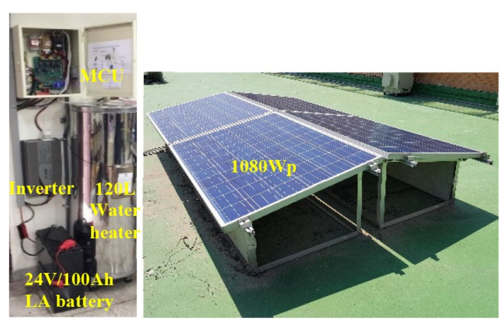

Fig. 5 HyPV D8 installed in laboratory (Taipei)

Fig. 4 HyPV D5 installed in an apartment (Taipei)

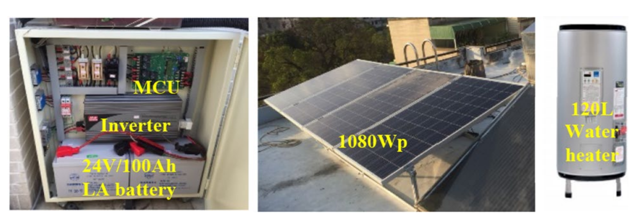

Fig. 6 HyPV D11 installed in a house (Chia-Yi)

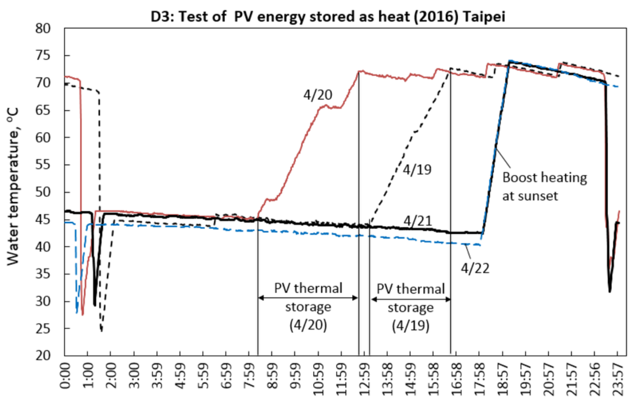

Fig. 7 Performance of solar PV thermal storage in D3

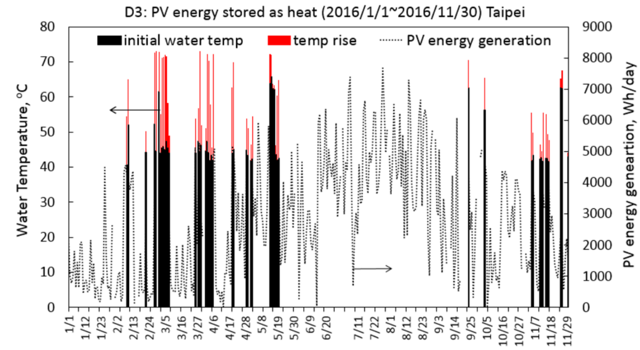

Fig. 8 Performance of D3 with PV thermal storage

D8 was installed at the solar energy laboratory, National Taiwan University, on the rooftop of a building. D11 was installed in Chia-Yi, southern part of Taiwan, in a residential house. Only D5 utilizes Li battery in the dual energy storage. D3, D8, and D11 utilize lead-acid (LA) battery.

The microprocessor-based power control unit (MCU) monitors the instantaneous performance of HyPV. All the data are remotely transmitted to a PC in the laboratory at National Taiwan University, except D5 without internet.

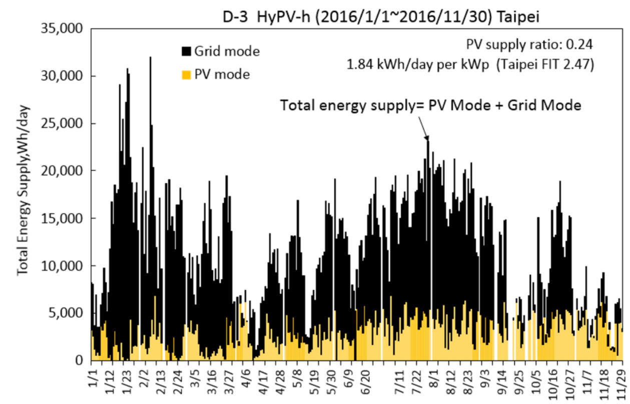

Fig. 9 Energy supply of D3

3 Field test results

The four HyPV systems are run continuously on side.

3.1 HyPV-D3

Figure 7 shows the performance of thermal storage in D3. On 2016/4/19 and 2016/4/20, the PV power drives the water heater to store PV energy as heat since there is no electric load in daytime. The hot water heater stores PV energy from 42 to 72 °C, about 4.2 kWh. The water heater is boosted to 70 °C (set temperature) at sunset if the PV energy is insufficient for hot water supply at night.

Figure 8 shows the long-term performance of D3 with PV energy storage as heat. The hot water temperature reaches 70 °C in winter, spring, and fall when the air conditioners are not used. Figure 9 shows the daily energy supply from solar PV and grid. It shows that the solar PV supplies 24% of the total load. The long-term average specific PV energy generation of D3 in 2016 (Fig. 10) is 1.84 kWh/kWp per day (Fig. 9) which is about 20% lower than that of FIT solar PV system (2.47) in Taipei. This is due to the shadow effect caused by surrounding buildings which is quite serious in afternoon between October and March.

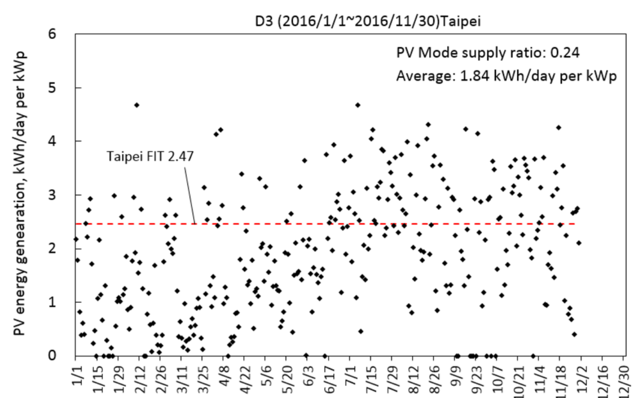

Fig. 10 Daily specific PV energy generation of D3 in 2016

3.2 HyPV-D5

D5 was installed on the rooftop of an apartment building. No remote monitoring system was installed. The performance was monitored through regular metering. Table 2 shows the average performance of D5 in about a year. The average specific PV energy generation of D5 in 2016

Table 2 Average performance of D5 (2015/5/21-2016/5/31)

PV generation (kWh/day)	3.80
Energy consumption of air conditioners (kWh/day)	5.40
Energy consumption of water heater (kWh/day)	1.00
Total load (kWh/day)	6.40
Specific PV energy generation (kWh/kWp per day) (grid-tied FIT PV in Taipei: 2.47)	2.59

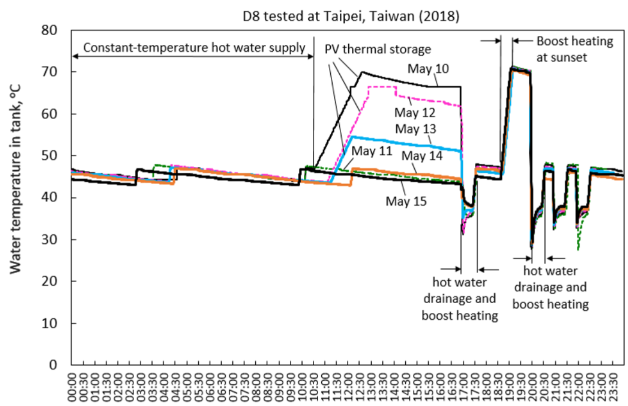

Fig. 11 PV thermal storage of D8

is 2.59 kWh/kWp per day which is about 5% higher than that of FIT solar PV system (2.47) in Taipei.

3.3 HyPV-D8

D8 was installed in the laboratory with regular hot water drainage control to simulate real application in home. Figure 11 shows the water temperature variation during PV thermal storage. It is seen that solar PV energy was stored as heat when the battery is fully charged and the load is not in use. D8 also performed boost heating at sunset if the water temperature is below 70 °C. Table 3 is the daily performance of D8 in May 2018. Figure 12 shows the average specific PV energy generation of D8 in May 2018 is 4.05 kWh/kWp per day which is about 64% higher than that of FIT solar PV system (2.47) in Taipei. This is due to the good weather in May which is better than the whole year average.

3.4 HyPV-D11

D11 was installed in early 2018 in a resident house in Chia-Yi (southern part of Taiwan). It is clearly seen from battery voltage variation that PV power was converted into heat storage when the battery is fully charged as shown in Figs. 13 and 14. Table 4 shows that the average specific PV energy generation of D11 is 4.35 kWh/kWp per day which is about 13% higher than that of FIT solar PV system (3.84) in Chia-Yi. This is because the data collected are not long enough to cover the whole year.

3.5 Overall performance comparison

The performance of four HyPVs (D3, D5, D8, and D11) can be compared. It is seen from Table 5 that the average specific PV energy generation is all near that of FIT solar PV system installed locally, except D3 which has serious shadow effect between October and March. This verifies that the dual energy storage in HyPV can eliminate solar PV generation loss due to system mismatch. By using thermal storage, the cost of energy storage can be reduced.

Table 3 Daily performance of D8 in 2018

Date	Solar irradiation (Wh/m^2)	PV generation (Wh)	Energy supplied by PV (Wh)	Thermal storage (Wh)	Total PV energy supply (Wh)	Specific PV generation (kWh/kWp per day)	PV system efficiency
5/12	6423	4690	2328	1588	3916	4.69	0.114
5/13	4543	3460	2801	783	3584	3.46	0.119
5/14	5068	3740	3428	0	3428	3.74	0.115
5/15	3470	2530	2542	0	2542	2.53	0.114
5/17	5142	4220	3542	0	3542	4.22	0.128
5/18	6210	4870	4672	0	4672	4.87	0.123
5/20	5787	4910	4851	0	4851	4.91	0.133
5/21	4396	3750	3476	0	3476	3.75	0.133
5/23	3518	2920	2778	0	2778	2.92	0.130
5/24	5749	4660	4490	0	4490	4.66	0.127
5/25	4688	3840	3757	0	3757	3.84	0.128
5/26	5741	4750	4610	0	4610	4.75	0.129
5/27	6336	4970	4819	0	4819	4.97	0.123
5/28	4472	3690	3565	0	3565	3.69	0.129
5/29	4557	3780	3654	0	3654	3.78	0.130
Average	5073	4052	3688	0	3846	4.05	0.125

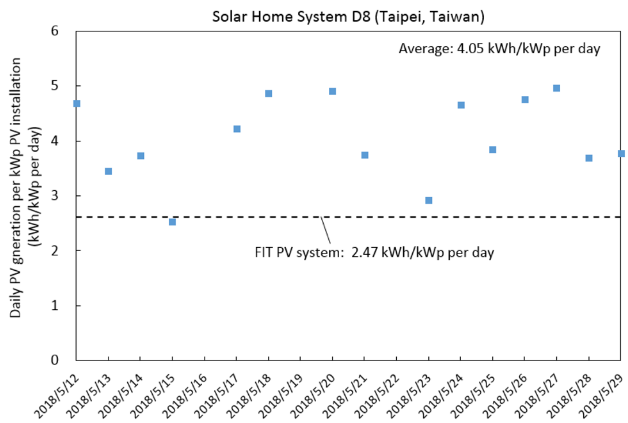

Fig. 12 Daily specific PV energy generation of D8 in May

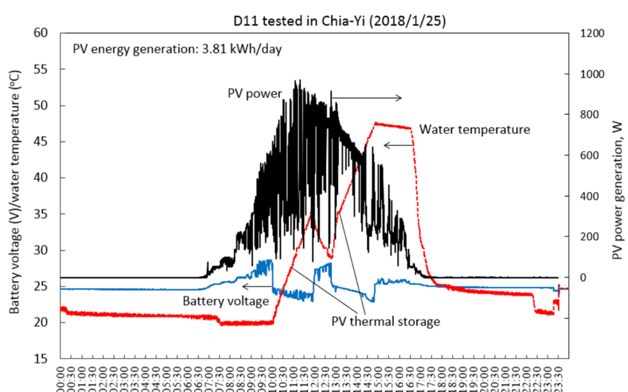

Fig. 13 Performance of solar PV thermal storage (1/25)

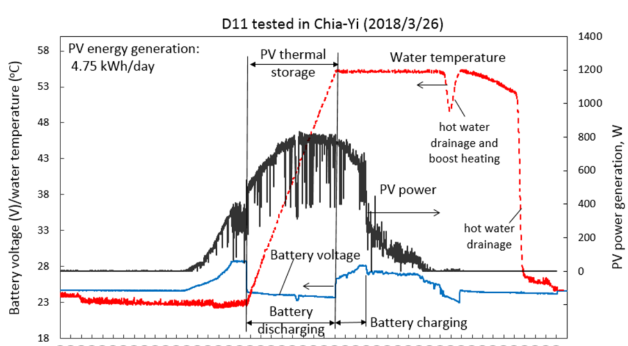

Fig. 14 Performance of solar PV thermal storage (3/26)

4 PV production cost analysis

To analyze the PV production cost, a long-term system analysis is carried out using the performance model of HyPV and meteorological data with different system design parameters and load pattern.

Table 4 Test results of D11

Date	PV generation (kWh/day)	Specific PV generation (kWh/kWp per day)
2018/1/25	3.81	3.53
2018/2/25	4.20	3.89
2018/3/22	5.68	5.26
2018/3/24	5.45	5.05
2018/3/26	4.75	4.40
2018/3/31	4.27	3.95
Average	4.69	4.35

3.84 kWh/kWp per day for FIT grid-tied PV systems in the same location

4.1 System simulation model

In the HyPV, the incident solar radiation (I_T) is absorbed and converted into electricity P_{pv} which drives the load (P_L) and charges the battery (P_{bat}), as shown in Fig. 15. The energy balance equation, Eq. (1), is derived [1].

$$P_{\mathrm{bat}} = P_{\mathrm{pv}} - P_{\mathrm{L}} \quad (1)$$

The battery charging will be cut off and the PV power generation approximates the load power, if it is fully charged. This will results in a PV generation loss. That is, there are two operating states in PV power generation as described in Eq. (2).

$$\frac{\mathrm{d}E_{\mathrm{b}}(t)}{\mathrm{d}t} \approx \begin{cases} P_{\mathrm{pv}} - P_{\mathrm{L}}, & \text{battery not fully charged} \\ 0, & \text{battery fully charged} \end{cases} \quad (2)$$

where E_b is the battery storage level (i.e., state of charge—SOC).

4.2 System analysis

The long-term system simulation for different design parameters was carried out using the local meteorological data. Four load patterns are used in the present study: load pattern A (100% energy used in daytime 6:00–18:00), load pattern B (75%), load pattern C (50%), and load pattern D (25%). Total PV energy generation over 20 years was calculated. The total investment cost includes initial and maintenance costs. Table 6 is the cost structure of HyPV solar home system used in the economic analysis.

Three parameters are defined, Eq. (3), to correlate the long-term system performance results:

$$R_{pL} = \frac{P_{pv}}{P_L}; \quad R_{hb} = \frac{E_h}{E_{bat}}; \quad t_{bp} = \frac{E_{bat}}{P_{pv}} \quad (3)$$

R_{pL} is defined as the ratio of maximum PV power generation (P_{pv}) to load power (P_L); R_{hb} is the ratio of thermal

Table 5 Overall performance comparison of D3, D5, D8, and D11

HyPV	D3	D5	D8	D11
Test period	2016/1/1–2016/11/30	2015/5/21–2016/5/31	2018/5/12–2018/5/29	2018/1/25–2018/3/31
Specific PV generation (kWh/kWp per day)	1.84	2.59	4.05	4.35
FIT PV system	2.47	2.47	2.47	3.84

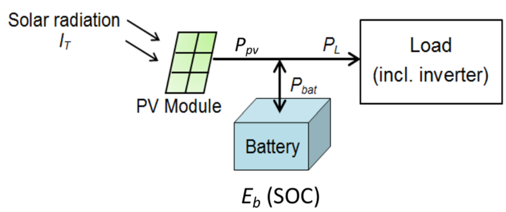

Fig. 15 Energy balance of HyPV in PV mode

Table 6 Cost of HyPV components used in economic analysis

Item	Unit price (1 USD = 31 TWD)
Solar PV system	24 TWD/Wp
Li battery storage	20 TWD/Wh
Thermal storage	2 TWD/Wh
Inverter	10 TWD/W
System Installation	15 TWD/Wp
BOS	10 TWD/Wp
Tax and gross profit	25%
Maintenance	2% initial cost per year
Cycle life of Li battery	4000 cycles @80%DOD

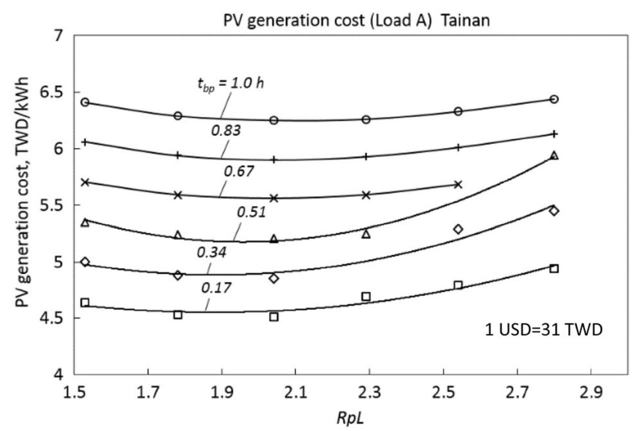

Fig. 16 Variation of PV generation cost with R_{pL}

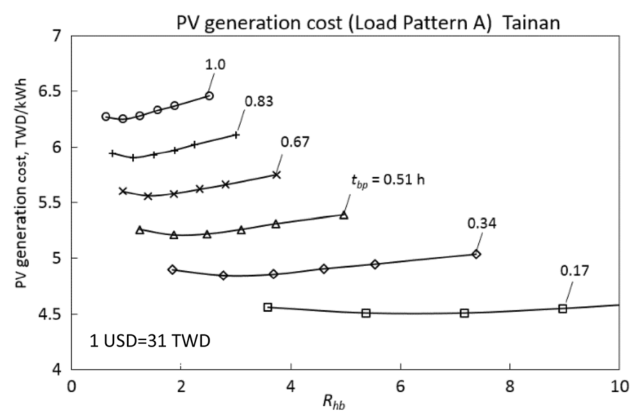

Fig. 17 Variation of PV generation cost with R_{hb}

storage (E_h) to battery storage (E_{bat}); and t_{bp} is the charge time for solar PV to fully charge the battery.

4.3 PV energy production cost

Figure 16 is the variation of PV energy generation cost with R_{pL}. It shows that there is an optimal design for PV generation cost. The optimal ratio of maximum PV generation P_{pv} to load power P_L (R_{pL}) is between 1.7 and 2.2.

Figure 17 is the variation of PV generation cost with R_{hb}. An optimal design for PV generation cost can be found. The optimal ratio of thermal to battery storage capacity (R_{hb}) is between 1 and 6, depending on t_{bp} (ratio of battery size to PV module installed). It is seen from Figs. 16 and 17 that the PV energy production cost decreases with decreasing t_{bp}. That is, smaller battery is more economic.

The grid electricity price in Taiwan is categorized in staircase structure (higher electricity consumption paying higher unit price). The grid electricity price forecast for the next 20 years is shown in Fig. 18, according to the government policy. The PV generation cost from system simulation for 20 years at different designs is then compared with the average grid electricity price. Table 7 shows the optimal design for four kinds of load patterns in three cities of Taiwan. It is seen that the PV energy production cost is among 4.66–7.24 TWD/kWh (1 USD = 31 TWD). For load pattern A–C, the present HyPV

	Present price, TWD/kWh	Monthly consumption, kWh/mon	Yearly price increase, %/y	Price after 20 years, TWD/kWh	Average price, TWD/kWh
Category 6	6.12	>1000	4.6	15.04	10.58
Category 5	5.42	701-1000	4	11.88	8.65
Category 4	4.64	501-700	3.4	9.06	6.85
Category 3	3.52	331-500	2.8	6.12	4.82
Category 2	2.38	121-330	2.2	3.68	3.03
Category 1	1.63	<121	1.6	2.24	1.93

Fig. 18 Grid electricity price in Taiwan (1 USD = 31 TWD)

solar home system with dual energy storage is economic if it was used to substitute partial energy demand (29–59%) which is paid at higher grid electricity price (Category 3 or 4). For load pattern D (worst case), the solar home system is economic if it is used to substitute 17–20% of daily energy demand which is paid at higher grid electricity price (Category 4 or 5). This is the partial grid parity.

4.4 Cost reduction of dual energy storage

The above economic analysis is for HyPV solar home systems with Li battery and hot water storage. For the four HyPV solar home systems built and tested as described in Sects. 2 and 3, only D5 utilizes Li battery. We can compare the total energy storage cost at various combinations. Using the same design of HyPV D3, D5, D8, and D11, we can calculate the total energy storage cost at various combinations as shown in Table 8.

It is seen that the dual energy storage would reduce the energy storage cost by 72–87% if using Li battery only and 41–52% if using LA battery only except D5. D5 utilizes a rather large heat storage (about 78% of total energy storage capacity), and this causes no cost reduction even using all LA battery to replace it. That is, using LA battery only to replace Li battery and the cheaper and larger thermal storage (4.2 kWh) in D5 will increase the total energy storage cost because the heat storage used is relatively large. This can explain the existence of optimal R_{pL} (ratio of maximum PV generation P_{pv} to load power P_L) and R_{hb} (ratio of thermal storage E_h to battery storage E_{bat}) in Figs. 16 and 17.

Table 7 Optimal design and economic feasibility

	R_{hb}	R_{pL}	t_{bp} (h)	Battery capacity (Wh)	Solar PV panel (Wp)	20-Year energy saving (TWD)	20-Year total investment (TWD)	PV energy generation cost (TWD/kWh)	Return on investment (%/year)	PV generation loss (%)	Ratio of PV energy supply (%)	Lowest electricity price category for PV to be economical
Load pattern A												
Taipei	2.77	2.04	0.34	1360	4000	595,627	425,322	6.65	2.00	0.67	44	4
Taichung	3.69	2.04	0.34	1360	4000	834,713	429,172	4.65	4.72	1.66	59	3
Tainan	2.77	2.04	0.34	1360	4000	802,813	425,322	4.85	4.44	1.79	58	4
Load pattern B												
Taipei	3.16	2.38	0.34	1190	3500	517,232	371,538	6.68	1.96	1.21	36	4
Taichung	3.69	2.04	0.34	1020	3000	629,168	326,004	4.66	4.65	0.81	44	3
Tainan	3.69	2.04	0.34	1020	3000	606,425	326,004	4.9	4.30	0.61	44	4
Load pattern C												
Taipei	4.92	3.05	0.34	1020	3000	447,375	321,604	6.74	1.96	1.07	28	4
Taichung	3.69	2.03	0.34	680	2000	416,473	222,836	4.78	4.34	0.77	30	3
Tainan	3.69	2.03	0.34	680	2000	415,211	222,836	5.03	4.32	0.58	29	4
Load pattern D												
Taipei	5.9	5.09	0.34	850	2500	369,075	283,120	7.24	1.52	2.84	17	5
Taichung	7.38	5.09	0.34	850	2500	504,338	286,970	5.09	3.79	4.07	20	4
Tainan	5.90	5.09	0.34	850	2500	493,874	283,120	5.35	3.72	5.14	20	4

Table 8 Energy storage cost comparison

HyPV	D3	D5	D8	D11
Battery type	LA	Li	LA	LA
Nominal capacity (E_{bat0}) (kWh)	4.8	1.44	2.4	2.4
Usable storage capacity (E_{bat}) [kWh @DOD60% (LA) or 80% (Li)]	2.88	1.15	1.44	1.44
Unit cost of battery [TWD/Wh (nominal)]	4	20	4	4
Cost of battery @E_{bat0} (TWD)	19,200	28,800	9600	9600
Water heater				
Tank volume (L)	120	120	120	120
Heat storage capacity (E_h) (kWh)	4.2	4.2	4.2	4.2
Cost of water heater @2 TWD/Wh (TWD)	8400	8400	8400	8400
Total cost of dual energy storage (TWD)	27,600	37,200	18,000	18,000
Total usable energy storage capacity ($E_{tot}=E_{bat}+E_h$) (kWh)	7.08	5.35	5.64	5.64
Fraction of heat storage (E_h/E_{tot})	0.59	0.78	0.74	0.74
Nominal capacity of Li battery required for total energy storage E_{tot}/0.8 (DOD) (kWh)	8.85	6.69	7.05	7.05
Nominal capacity of LA battery required for total energy storage E_{tot}/0.6 (DOD) (kWh)	11.8	8.92	9.40	9.40
Total cost of energy storage E_{tot} using Li battery only (TWD)	177,000	133,750	141,000	141,000
Cost reduction by dual energy storage (TWD)	149,400	96,550	123,000	123,000
%	84.4	72.2	87.2	87.2
Total cost of energy storage E_{tot} using LA battery only (TWD)	47,200	35,680	37,600	37,600
Cost reduction by dual energy storage (TWD)	19,600	−1520	19,600	19,600
%	41.5	−4.3	52.1	52.1

5 Conclusion

In the present study, we developed a HyPV solar home system which generates solar power for self-consumption and utilizes dual energy storage. The solar home system utilizes a switching-type solar PV system (HyPV) which operates in either solar or grid mode automatically. No solar power is fed into grid. The combined battery and thermal storage can reduce the system cost since thermal storage is much cheaper than battery. An electric water heater is used to store solar PV energy when the battery is full. Four HyPV solar home systems were built for long-term field test. The test results show that the specific PV energy generation approximates that of FIT PV system.

An economic analysis was also carried out. The cost of dual energy storage as well as the system cost is reduced since thermal storage is much cheaper. It shows that the PV energy generation cost is lower than the electricity price from grid if the system is properly designed. That is, HyPV solar home system with dual storage is economic if it was used to substitute partial energy demand which is paid at higher grid electricity price. This verifies the possibility of grid parity for a solar PV system with energy storage.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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