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Feasibility Study on Building Energy System with PVB, EV and PHS: A Case in Hong Kong

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ABSTRACT

A future building energy system is established with photovoltaic (PV) generation and hybrid storage system in a case in Hong Kong. The battery, electric vehicle (EV) and pump-hydro storage (PHS) system are considered. A technical feasibility study is conducted to assess the influence of different storage priorities. The PHS is shown to reduces the total energy efficiency by 7.16% at user side. The low self-sufficiency rate, 16.29% to 17.77% recommends the addition of remote renewable generation. The low usage rate of storage system, 31 to 58, annual equivalent battery cycle number emphasizes the need of grid charging.

Keywords: renewable energy resources, hybrid energy system, operation strategy, battery, electric vehicle, pump hydro storage

INTRODUCTION

Photovoltaic (PV) is one of the most promising renewable technology with the proportion of 9.75% in global total renewable energy production in 2019 [1]. Also, the distributed PV system, especially rooftop system is emphasized in China with good economic revenue under the carbon neutrality targets [2, 3].

The mismatch of PV generation curve and residential load demand curve, as well as the fluctuation and intermittency of the PV generation both require the energy storage system in the distributed PV system [4]. Besides the battery storage [5], the electric vehicle (EV) could also be a good choice with the novel concept, vehicle to home [6]. The EV is promising in Hong Kong (HK) as planned by the transport department to achieve zero carbon emission for vehicles before 2050 [7]. Also, the pump-hydro storage (PHS) system with large storage capacity and long lifetime is a good choice for renewable energy storage and onsite consumption [8]. Thus, this study focuses on a future building energy system with onsite PV and hybrid storage system (battery, EV and PHS) and varied operation strategies.

1. METHODLOGY

1.1 System description

The grid-connected hybrid building energy system is shown in Fig. 1 with onsite PV, PHS, battery and EV. The building is set as the public residential building in HK with 30 floors and 14407 m^2 area totally. The floor plan could be get from HK housing department for Standard block, New harmony 1 (Option2) [9]. 16 families/floor are assumed and the height of each story is assumed 2.5m as required by the government [10].

The rooftop PV system includes 385Wp mono-silicon panel and the façade PV system contains 460Wp thin-film panel on the south side. Thus, the PV installation is 157.465kWp on rooftop and 151.8kWp on the façade. Battery is set 4.8 kWh for 480 families each.

As stated in the roadmap for popularization of EV in HK, about 90% people in HK use public transportation and EV takes up about 12.4% in private vehicle usage [7]. Thus, the EV number in the group is estimated to be 6 and could be extended to 48 in the future. Tesla Model Y is selected with 60 kWh battery and 390 km travel distance at most [11]. The cycle number ranges 3,500 to 4,000 and SOH will be 90% after 8 years [12].

The PHS system is set via the building roof plan, with 830m^3 reservoir volume and 50 m total water head. The pump and turbine powers are set as 40 kW and 80 kW with 80% total energy efficiency [13]. The self-discharge is neglected and minimum SOC_{phs} is assumed as 5% [14].

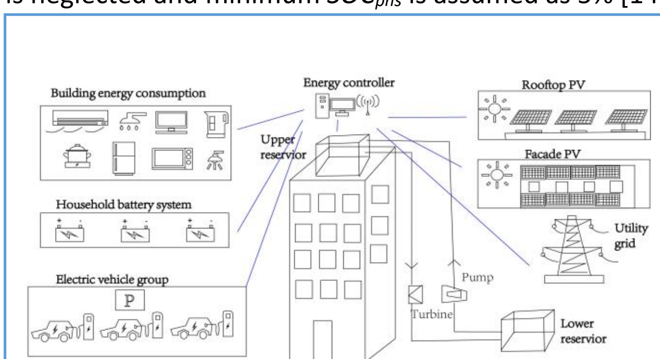

Fig. 1 Systematic diagram of hybrid system

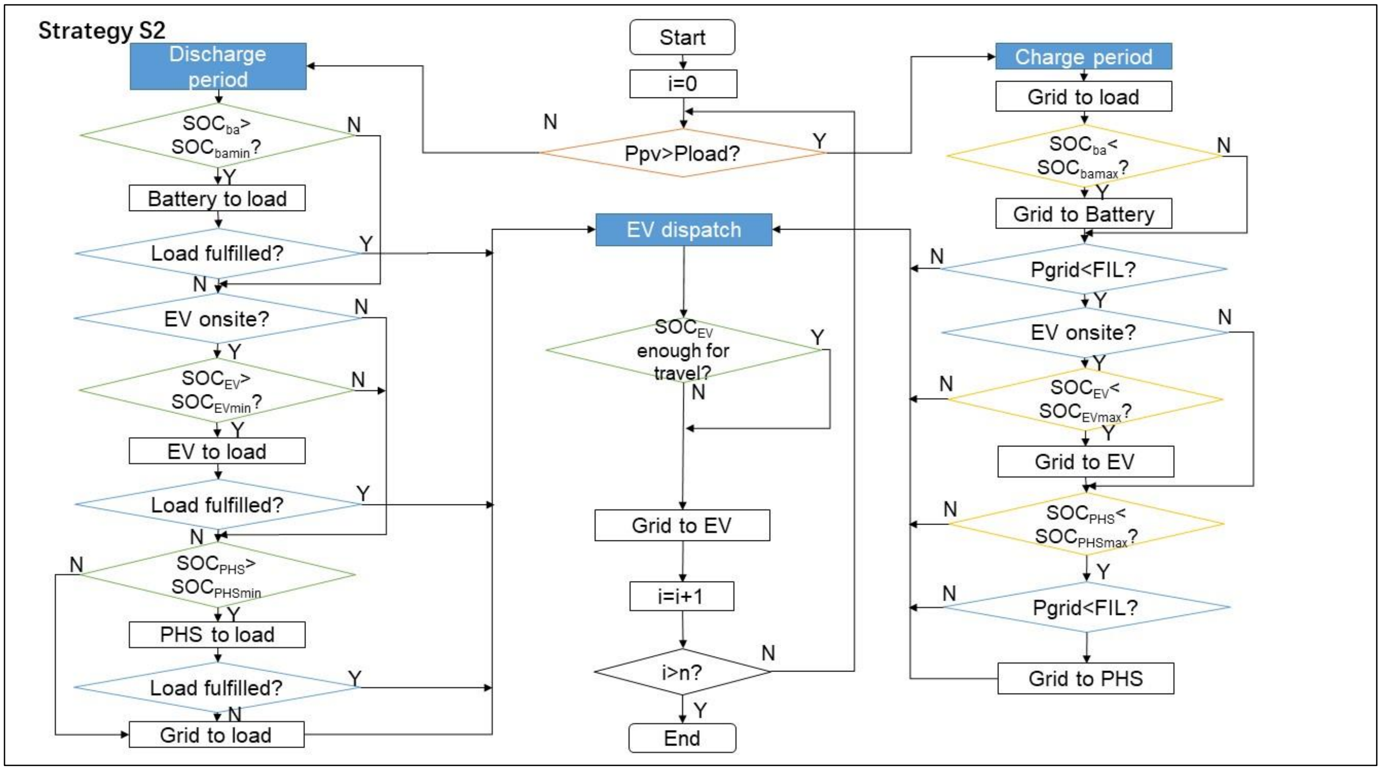

Fig. 3 Strategy flow chart of Strategy S2

1.2 Mathematical models

The energy balance of the hybrid system is the core to the system simulation, as shown below:

$$E_{pv} + E_{evd} + E_{bd} + E_{tur} + E_{gb} = E_{loa} + E_{evc} + E_{pum} + E_{bc} + E_{gs} + E_{los}$$

where E_{pv} is the PV generation (kWh), E_{evd} and E_{bd} are the discharge electricity of EV (kWh) and battery (kWh), E_{tur} and E_{pum} are turbine and pump power consumption of PHS (kWh), E_{gb} and E_{gs} are the grid injection (kWh) and sold electricity (kWh), E_{evc} and E_{bc} are the charge electricity of EV (kWh) and battery (kWh), E_{load} is the load consumption (kWh) and E_{los} is the energy loss (kWh).

The solar irradiance from the horizontal data to the data on the plane with slope I_t is converted based on the model by Liu and Jordan [15], as presented:

$$I_t = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho\left(\frac{1-\cos\beta}{2}\right)$$

where I_b and I_d are the horizontal direct and diffuse solar radiation (W/m^2), I is the horizontal global solar radiation (W/m^2), R_b is the ratio of direct solar irradiance on horizonal and inclined planes, ρ is the ground reflectance and β is the slope of PV array (deg).

The PV generation P_{pv} is conducted via single-diode 5-parameter model [16], as presented:

$$I_{pv} = I_{ph} - I_0\left(e^{\frac{V_{pv}+I\cdot R_{sc}\cdot N_s}{N_s\cdot V_t}} - 1\right) - \frac{V_{pv} + R_{sc}\cdot N_s\cdot I_{pv}}{R_{pc}\cdot N_s}$$

$$P_{pv} = P_{mpp}\cdot \eta_{inv}\cdot (1-\eta_{loss})\cdot N_{ser}\cdot N_{Par}$$

where P_{mpp} is the module output at maximum power point (W), η_{inv} and η_{los} are the inverter efficiency and wire loss efficiency, N_{ser} and N_{par} are the module number in series and parallels.

The battery [17]/ EV [6] status are depicted by state of charge (*SOC*) and state of health (*SOH*), as follows:

$$SOC(i+1) = SOC(i) + \frac{P_{ch}(i)\cdot\eta_{ch} - P_{dis}(i)/\eta_{dis} - P_{sd}(i)}{E_{usa}\cdot SOH(i)}$$

where *i* is the simulation step (hr), P_{ch} and P_{dis} are the charging/discharging power (W), P_{sd} is the self-discharge rate (W), η_{ch} and η_{dis} are the charging/discharging efficiency and E_{usa} is the usable capacity (kWh).

The energy storage in PHS is the gravity energy of the usable water in the upper reservoir [18] and its charging/discharging power P_{pum} and P_{tur} could be shown as [19]:

$$P_{pum} = \frac{q_{wfrp}\cdot\rho_{war}\cdot g\cdot h_p}{\eta_{pum}}$$

$$P_{tur} = \frac{q_{wfrt}\cdot\rho_{war}\cdot g\cdot h_t}{\eta_{tur}}$$

where q_{wfrp} and q_{wfrt} are the water flow rate in pump and turbine (m^3/s), ρ_{war} is the water density (kg/m^3), η_{pum} and η_{tur} are the total energy efficiency for pump and turbine, and h_p and h_t are the elevating/dropping water head (m).

The PHS status could be described by SOC_{phs} [20]:

$$SOC_{phs}(i+1) = SOC_{phs}(i) + \frac{-h_t(i) + h_p(i) - h_{loss}(i)}{h_{urm}}$$

where h_{urm} is the maximum water head for the upper reservoir (m) and h_{loss} is the energy loss in PHS (m).

1.3 Specifications

Key component parameters are shown in Table 1.

Table 1 Specifications of system components

Parameter	Value	Parameter	Value
PV (Roof[21]/ façade[22])		Battery [17]	
V_{oc} (V)	41.5/222.9	V_{nom} (V)	48
I_{sc} (A)	11.77/2.59	A_{bat} (Ah)	50
$P_{mp,stc}$ (Wp)	385/460	DOD (%)	80
$V_{mp,stc}$ (V)	35/188.8	Cycle #	6000
$I_{mp,stc}$ (A)	11/2.44	η_{bat} (%)	93
NOCT (℃)	45	EV	
K_p (%W/℃)	-0.34/-0.32	C_{ev} (kWh)	60
K_v (%V/℃)	-0.27/-0.28	Lifetime(yr)	8
K_i (%A/℃)	0.05/0.04	SOH_{end} (%)	90
Inverter [23]		PHS	
P_{invmax} (W)	5000	η_{phs} (%)	80 [8]
η_{inv} (%)	98.4	V_{res} (m^3)	830

The synthesized load is obtained from Liu et al. via TRNSYS and Energy Plus software [24], presented in Fig.2. The average daily EV driving distance on weekdays is 45.79km, approximately 7kWh for Tesla S, according to the 2020 Transport report in HK [25] and the EV is assumed outside from 8am to 8pm on six weekdays.

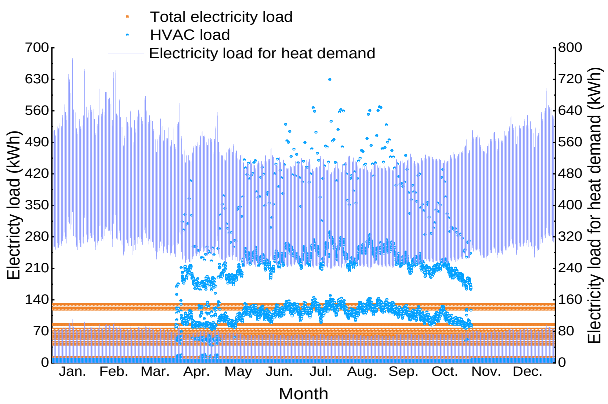

Fig. 2 Load demand for a residential building in HK

The electricity tariff in Hong Kong is now step tariff [26], while the time-of-use (TOU) tariff is the major trend in China and it will be applicable in HK in near future [27] with tested peak hours (6pm-10pm Mon.-Sat.), shoulder hours (9am-6pm Mon.-Sat.) and valley hours (10pm-9am Mon.-Sat., Sun.).

1.4 Strategies

Different priorities of the energy storage systems: EV, battery and PHS are dispatched based on the basic maximum self-consumption (MSC) strategy. The strategy A S2 is shown in Fig. 3.

Strategy A: PV partly sold to the grid. Maximum self-consumption (MSC):

a) S1 Priority: EV>battery>hydro, high efficiency first.
b) S2 Priority: Battery>EV>hydro
c) S3 Priority: Hydro>Battery>EV

1.5 Evaluation index

Self-consumption rate (SCR) and self-sufficiency rate (SSR) are two common technical index for renewable usage [17]. Also, the peak grid transmission and usage rate and load fulfillment ratio of different storage system are used for the grid and storage assessment.

2. RESULTS

The technical index comparison of three strategies with different storage priorities are shown in this part.

2.1 PV installation recommendation

The PV slope variation to the renewable output is depicted in Fig.4 (a) and the 10-50 deg slope is recommended in HK. The simulation is based on Solargis 2018 data which may be smaller than the practical test.

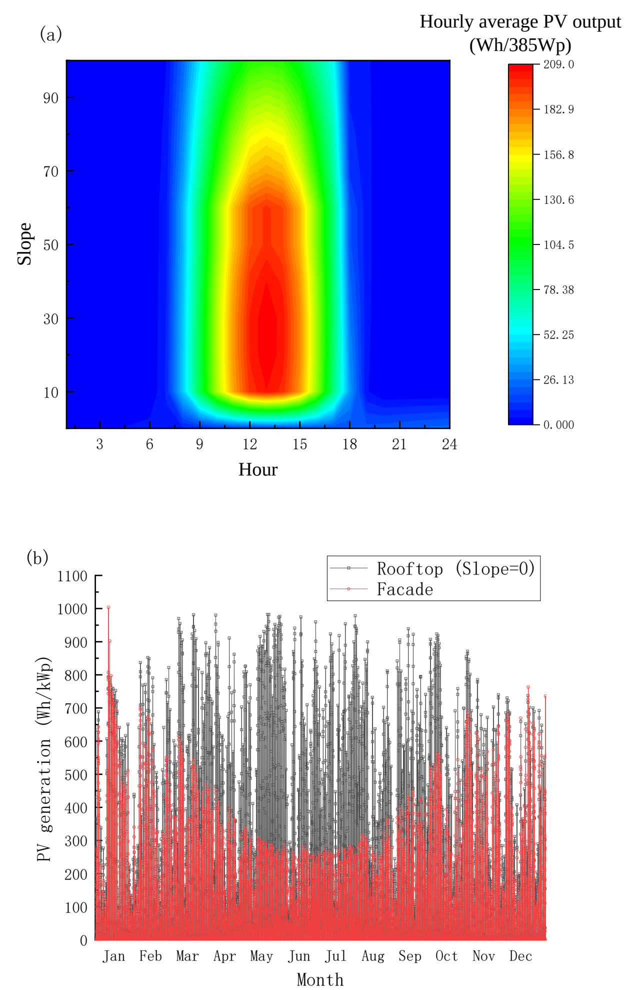

Fig. 4 PV generation: (a) Rooftop panel under different slope; (b) Rooftop and façade generation.

The rooftop and façade PV generation difference is depicted in Fig.4 (b). The facade generation is affected obviously by the extreme slop from Apr. to Sep., while the power generation difference in winter is small.

2.2 Renewable energy usage and energy storage dispatch under different priorities in Strategy A

The SCR, SSR and peak grid transmission (bought electricity from the grid and sold electricity to the grid) are shown in Fig. 5. Under the MSC strategy, the disparity of renewable usage of different storage priorities is small. The SCR and SSR of the first priority to EV, battery and PHS lie in (98.99, 17.74), (99.16, 17.77), and (90.79, 16.29). The low efficiency of PHS reduces the renewable consumption at user side, but it could also reduce the peak grid transmission due to the large storage capacity. The low SSR recommends the system to introduce more renewable production.

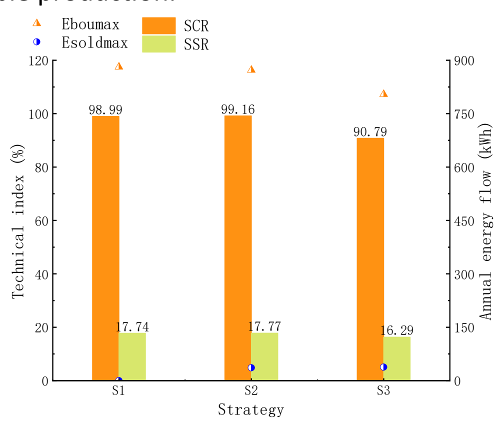

Fig. 5 Technical performance (SCR, SSR) for renewable usage of different strategies and grid peak transmission

The annual cycle number of the three storage systems and the total energy efficiency through storage at the user side is displayed in Fig. 6. Due to the only charging energy from surplus PV, the use rates of the storage systems are low, indicating the need of grid charging. The PHS storage reduces the energy efficiency.

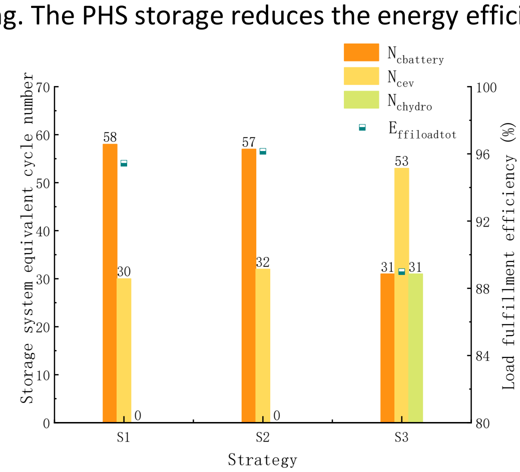

Fig. 6 Technical performance for energy storage system

The annual SOC variation of battery system is demonstrated in Fig. 7 under three strategies. When the battery is given higher priority in Fig. 7 (b), the usage is more obvious, while variation is still not obvious due to the limited PV and lack of grid charging.

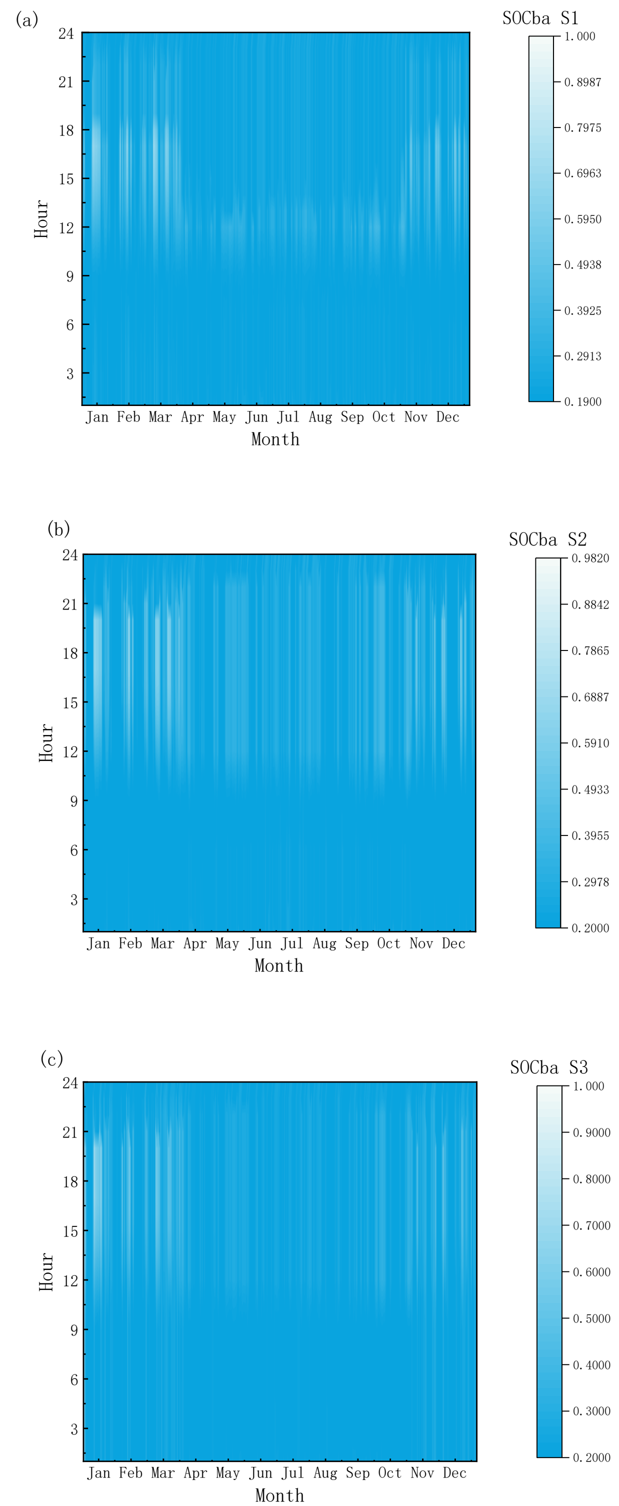

Fig. 7 Annual SOC figure for battery storage system.

3. CONCLUSION

This study established a model for future building energy system with onsite photovoltaic (PV) system and hybrid storage system, including battery, electric vehicle (EV) and pump-hydro storage (PHS) system. The technical performance comparison is conducted to maximum PV self-consumption strategy with different priorities to EV (S1), battery (S2) and PHS (S3). The self-consumption rate and self-sufficiency rate (SSR) of S1, S2 and S3 are (98.99, 17.74), (99.16, 17.77), and (90.79, 16.29). The low SSR recommends the system to introduce more renewable production such as remote PV plant. The low annual cycle number of three storage systems emphasizes the need of grid charging to increase the storage use rate.

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