

# Performance Analysis of a PV–Solar Collector Hybrid System with Integrated Thermal and Electrical Energy Storage<sup>#</sup>

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## ABSTRACT

This study presents the development and experimental evaluation of a hybrid heating system with integrated electrical and thermal energy storage for domestic hot water production. In this study, the experimental system combined a solar heat collector to generate thermal energy and a photovoltaic (PV) panel to produce electricity. During periods of solar availability, the thermal energy was stored in a water tank, while the electricity was stored in a battery. A heat pump, powered primarily by the PV-charged battery, was used to heat the water to the desired set point after the initial solar heating phase. Experimental results demonstrated that the integrated system significantly reduced grid electricity use and achieved a high system efficiency of around 2.86. Furthermore, the incorporation of the PV-battery subsystem reduced grid power by approximately 23.9%, and the hybrid solar heating system achieved 66.4% electricity savings compared to a conventional electrical heater. This work confirmed the technical feasibility of hybrid solar heating systems in enhancing energy efficiency and promoting renewable energy utilization for residential hot water requirements.

**Keywords:** renewable energy, thermal energy storage, battery, energy performance, technical feasibility

## NONMENCLATURE

### Abbreviations

DHW	Domestic Hot Water
HP	Heat Pump
HTF	Heat Transfer Fluid
RES	Renewable Energy Source
SHC	Solar Heat Collector
TES	Thermal Energy Storage
PV	Photovoltaic

### Symbols

$\eta$	Efficiency
$G$	Solar Radiation

$I$	Current
$\dot{m}$	Flow Rate
$P$	Electrical Energy
$Q$	Heat Energy
$R$	Resistance
$V$	Voltage
<i>Subscripts</i>	
$amb$	Ambient
$in$	Inlet
$tot$	Total

## 1. INTRODUCTION

The integration of renewable energy sources (RESs) into building energy systems is a critical strategy for reducing carbon emissions [1]. Building heating primarily relies on fossil fuels, resulting in large greenhouse gas emissions. The growing demand for sustainable energy solutions has driven development in renewable energy systems [2]. Especially, solar techniques present a clean alternative. Integrating thermal energy storage (TES) and electrical energy storage can enhance the energy performance by addressing the intermittency of solar energy [3]. Using both TES and battery allows for the storage of both thermal and electrical energy produced by solar heat collectors (SHCs) and photovoltaic (PV) panels to balance the mismatch between the supply and demand, even during periods of low solar radiation or high demand [4].

The hybrid solar heating system integrated with thermal and electrical energy storage has gained attention for its potential to provide stable domestic hot water (DHW) for end users. By combining these two storage techniques, hybrid solar heating systems can deliver enhanced efficiency, reduced energy costs, and lower carbon emissions. Moreover, the integration of TES and battery storage provides operational flexibility, reducing reliance on grid electricity.

There are a few studies investigating solar heating systems experimentally. Singh et al. experimentally

tested the thermal performance of a commercial recyclic solar air heater integrated with TES [5]. The solar air heater achieved a maximum thermal efficiency of 53% in June. The findings indicate that the designed solar air heater is a promising solution for providing stable hot air, suitable for applications such as space heating. Guan et al. developed a novel parabolic trough solar air collector to enhance solar energy utilization and experimentally evaluated the effects of design and operation parameters on the system performance [6]. Results identified an optimal air velocity of 5.4 m/s, exhibiting a maximum instantaneous collection efficiency of 76.0% without requiring external insulation. Sun et al. numerically investigated the energy and economic performance of a coupled heating system that integrates data center waste heat and solar energy using seasonal soil heat storage [7]. The system stored thermal energy during the non-heating season and utilized it alongside ground source heat pumps (HPs) for combined heating during the heating season.

While research investigated the performance of solar heating systems and their individual components, there is still a lack of studies focusing on experimental and numerical analysis of hybrid solar heating systems, including both thermal and electrical energy configurations. This work combined the SHC for water heating, PV for electricity generation, HP for supplemental heating, and dual storage to develop a hybrid solar heating system. The system was designed to use solar thermal energy for primary heating and employed a PV-powered HP for boosting temperature. Experimental tests were conducted to examine the technical feasibility and energy performance of this concept, and a simulation platform was also built for further system optimization and economic analysis. System overall efficiency and renewable energy penetration were used to characterize the grid dependence and solar energy utilization of the hybrid solar heating system.

## 2. MATERIALS AND METHODS

### 2.1 Experimental apparatus

An experimental setup for the hybrid solar heating system was established, as shown in Fig. 1. The SHC heated water by transforming solar energy radiation into thermal energy. The PV panel was introduced to capture solar energy and convert it to electricity.

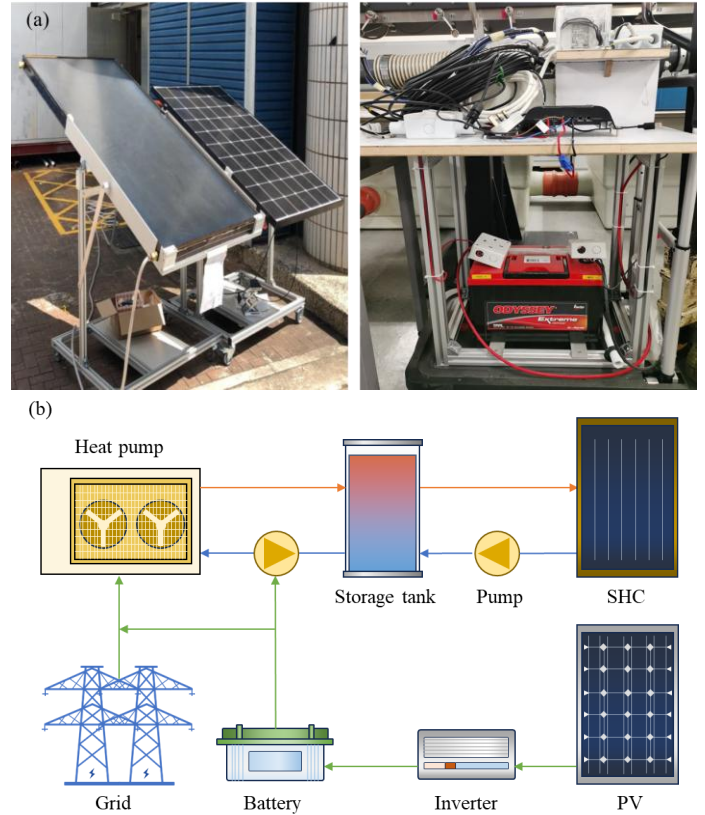


Fig. 1. (a) Photos and (b) schematic diagram of the hybrid solar heating system integrated with thermal and electrical energy storage

During the charging process, both SHC and PV were operated under solar available periods. The produced electricity and heat were stored in energy storage solutions, the battery and water tank, respectively. After the solar heating process, HP was applied to further heat the water tank to reach the desired temperature. Besides, the battery charged by the PV panel was used to provide electrical energy for HP. After the battery was discharged, the connection between the battery and the HP was removed, and the device was connected to the grid power source. Electricity from the grid was then introduced to charge the system.

The SHC used in the experimental setup was a flat-plate collector with a gross area of 2 m<sup>2</sup>, while the PV panel consisted of a 300 W mono-crystalline module with a 1.6 m<sup>2</sup> gross area. An air-to-water HP employing R134a as refrigerant provided a nominal heating capacity of 2 kW. Energy conversion and storage were facilitated by a regulator and a 100 Ah battery, respectively. A circulation pump was used to ensure water flow through the collector loop, and a frequency converter was used to regulate motor operation. The solar heat meter, power meter, and temperature meter were used to record experimental data during the test.

### 2.2 Performance indicator

The potential benefits of combining both thermal and electrical energy storage techniques were characterized by the overall efficiency of the whole system,  $\eta_{sys}$ , which was calculated as follows:

$$\eta_{sys} = \frac{Q_{tot}}{P_{tot}} = \frac{Q_{solar} + Q_{HP}}{P_{PV} + P_{grid}} \quad (1)$$

where  $Q$  is the heat energy,  $P$  is the electrical energy.

### 2.3 Numerical model

A simulation platform was built on TRNSYS to predict dynamic system performance. To validate the numerical model, the simulation platform includes the same components and configurations as the experimental test rig. The efficiency of the SHC was given as follows:

$$\eta_{SHC} = a_0 - a_1 \frac{(T_{SHC,in} - T_{amb})}{G} - a_2 \frac{(T_{SHC,in} - T_{amb})^2}{G} \quad (2)$$

where  $G$  is the radiation incident,  $a_0$ ,  $a_1$ , and  $a_2$  are the collector parameters.

The outlet temperature of the HP condenser was calculated as follows:

$$T_{HP,out} = T_{HP,in} + \frac{\dot{Q}_{HTF}}{\dot{m}_{HTF} C_{p,HTF}} \quad (3)$$

The current-voltage equation of the PV panel was given as follows:

$$I = I_L - I_o \left[ \exp\left(\frac{V + IR_s}{a}\right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (4)$$

where  $I$  is current,  $V$  is the voltage, and  $R$  is the resistance.

## 3. RESULTS

### 3.1 Experimental results

The weather parameters during the experimental test are shown in Fig. 2. The system performance was evaluated under two clear-sky days in Hong Kong. The solar radiation exhibited a sharp increase after around one hour following sunrise. The insolation intensity reached a peak of approximately 1000 W/m<sup>2</sup> with an average value of 808.8 W/m<sup>2</sup>. At the same time, the ambient air temperature remained stable at a mean value of around 20.7°C.

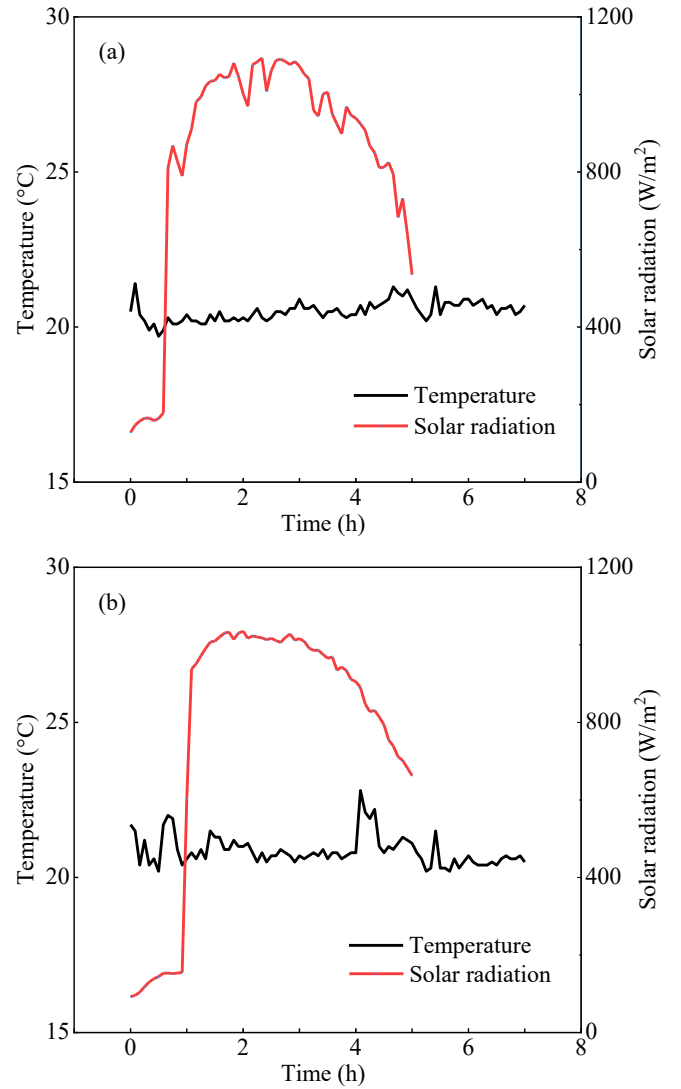


Fig. 2. Weather parameters of experimental tests on two clear-sky days: (a) Day 1 and (b) Day 2

Temperature variations of the water tank during the solar and HP heating periods are depicted in Fig. 3. Initially, the water temperature increased gradually due to low solar radiation in the early hours. As solar radiation increased, the temperature rise rate accelerated due to more efficient thermal energy collection by the SHC subsystem. This solar heating phase ended when the available solar radiation almost diminished, and the water tank temperature reached approximately 45°C at the end of the first heating phase. Subsequently, the water was further heated by the HP to heat the temperature to the target set point of 50°C, ensuring the TES was fully charged to meet DHW demand.

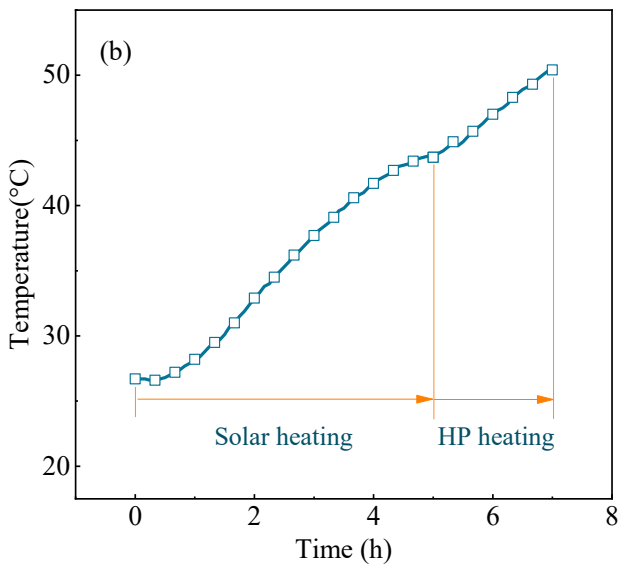
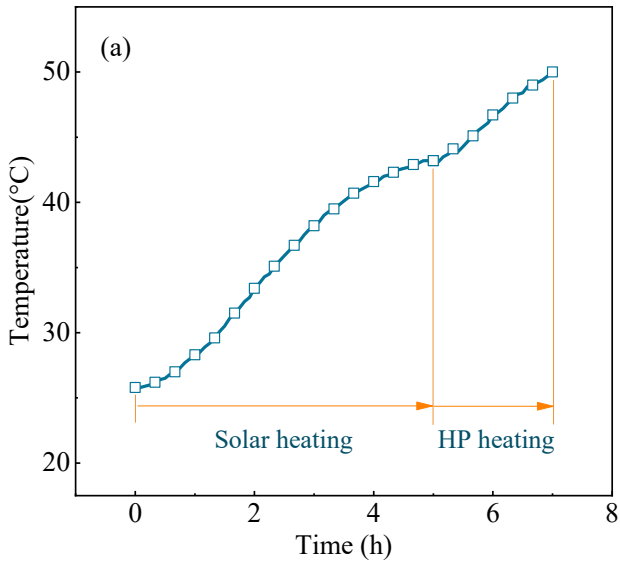


Fig. 3. Temperature variation of the water tank tested on two clear-sky days: (a) Day 1 and (b) Day 2

Energy distribution of the hybrid solar heating system with integrated thermal and electrical energy storage is depicted in Fig. 4. Approximately 23.9% of the total electricity used was supplied by the PV subsystem, with the rest provided by the grid. Simultaneously, solar energy provided 70% of the total heat, while the HP supplied the remaining part. By introducing the PV and SHC to increase the RES utilization and minimize the grid dependence, this integrated configuration achieved an overall system efficiency of 2.86, resulting in significant energy savings of 66.4% compared to a conventional electric heating system.

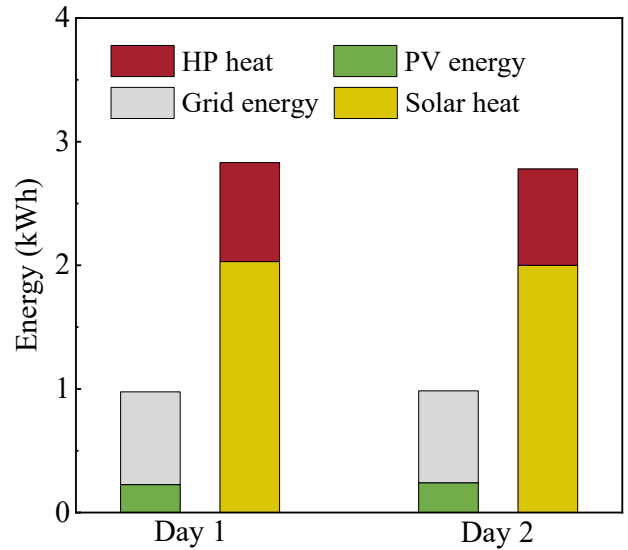
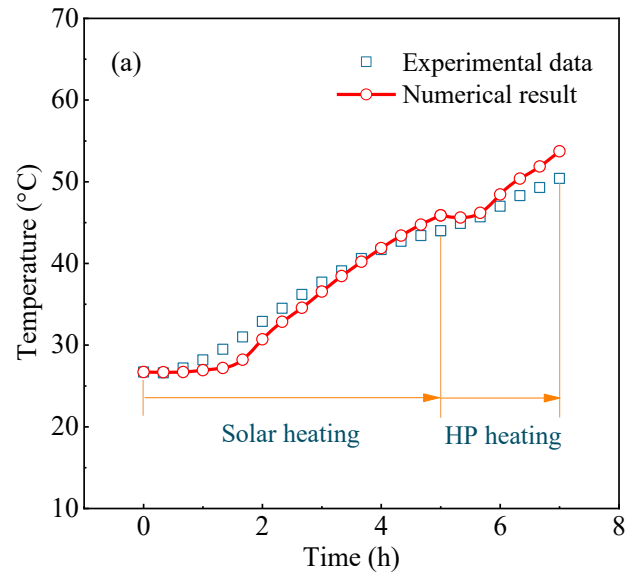


Fig. 4. Energy distribution from each source tested on two clear-sky days

### 3.2 Model validation

The numerical model of the hybrid solar heating system integrated thermal and electrical energy storage was validated against experimental data obtained from the test rig. Key performance indicators, including the water tank temperature, the total delivered heat energy, and electrical energy generated from the PV subsystem, were compared in Fig. 5. The results showed great agreement between the simulated and experimental data, with an average difference of approximately 6.5%. This alignment shows that the simulation platform was reliable for predicting the overall energy performance of the proposed hybrid solar heating system.



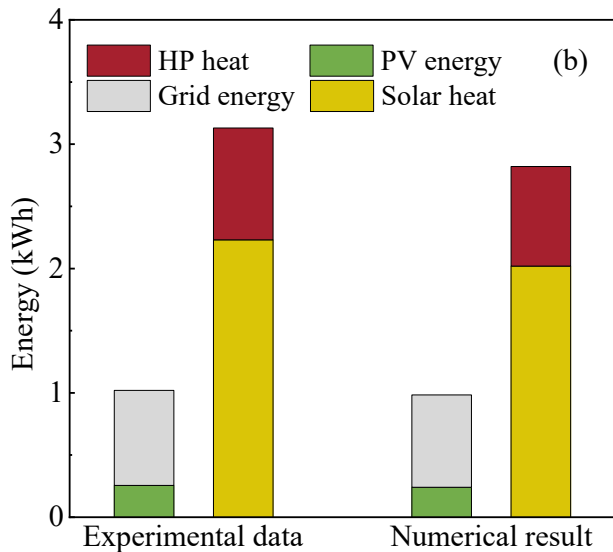


Fig. 5. Experimental data and numerical results comparison on (a) temperature variation of the water tank and (b) energy distribution

The validated simulation platform can be employed to predict the long-term energy performance and annual efficiency of the hybrid solar heating system with integrated electrical and thermal storage in our future work. Furthermore, system optimization and advanced control strategies can be implemented to optimize system configuration and maximize the system economic return by using this simulation platform.

#### 4. CONCLUSIONS

Solar energy offers a promising renewable energy solution for building heating supply. This work has developed a hybrid solar heating system integrated with thermal and electrical energy storage for DHW production. The system used SHC for primary heating and HP powered mainly by PV for boosting temperature. The technical feasibility and energy performance of the heating system were experimentally evaluated.

The experimental results showed that the system operated at a high overall efficiency of 2.86. Further, it greatly reduced reliance on grid electricity, achieving a 23.9% reduction through the PV-battery subsystem and 66.4% savings compared to a conventional electric heater. The results exhibited the significant potential of this hybrid solar heating system for enhancing energy efficiency and increasing renewable energy penetration. The validated model developed in this work also proved to be reliable for further system analysis. A more sustainable heating solution could then be achieved by using this developed simulation platform for further design and control optimization.

#### ACKNOWLEDGEMENT

This work was supported by the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Actions, grant agreement No 101110852, and the Combined Electrical and Thermal Microgrid (ELTERM) project granted by the Research Council of Norway (No. 356039)

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