# Numerical investigation on the switching logic of a photovoltaic solar-assisted loop thermosiphon/heat-pump hybrid system

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## Introduction

Solar photovoltaic/thermal (PV/T) technology enables simultaneous electricity generation and waste heat recovery, thereby improving the overall utilization of solar energy. However, conventional water-cooled PV/T collectors are limited by corrosion and freezing risks under low-temperature conditions [1]. To improve reliability, two-phase heat-transfer technologies have been introduced into PV/T systems.

Loop thermosiphon-based PV/T systems provide passive operation, low power consumption, freeze resistance, and long-distance heat transfer. However, their thermal output is often insufficient under weak solar irradiation or low ambient temperature conditions. In contrast, photovoltaic solar-assisted heat pump systems can enhance refrigerant circulation through compressor input and provide stronger heating performance, but continuous compressor operation increases electricity consumption [2].

Hybrid PV/T systems have therefore been proposed to combine the advantages of passive and active operating modes [3,4]. Nevertheless, systematic numerical studies on the switching mechanism of PV-SALT/HP systems remain limited. In this study, mathematical models of the LT-PV/T system, PV-SAHP system, and coupled PV-SALT/HP system were developed. Their performance difference and switching logic were analyzed under unified meteorological boundary conditions.

## Numerical Model

A coupled numerical model was developed to describe the dynamic operation and mode-switching behavior of the PV-SALT/HP hybrid system. The system consists of two operating modes: the passive LT-PV/T mode and the active PV-SAHP mode. Both modes share the same PV/T collector-evaporator (Fig. 1) and condenser-coil water tank, which enables the hybrid system to switch between passive solar heat collection and active heat-pump-assisted heating.

For the LT-PV/T mode, the solar radiation incidence model, glass cover model, PV cell model, back-plate model, loop thermosiphon model, and water-tank model were established. The PV/T collector was described using a dynamic energy balance method, in which the glass cover, PV cell, back plate, loop thermosiphon evaporator, condenser section, and storage water were treated as coupled thermal nodes [5]. This model was used to predict the heat transfer from solar radiation to the PV/T module and then to the water tank through the loop thermosiphon.

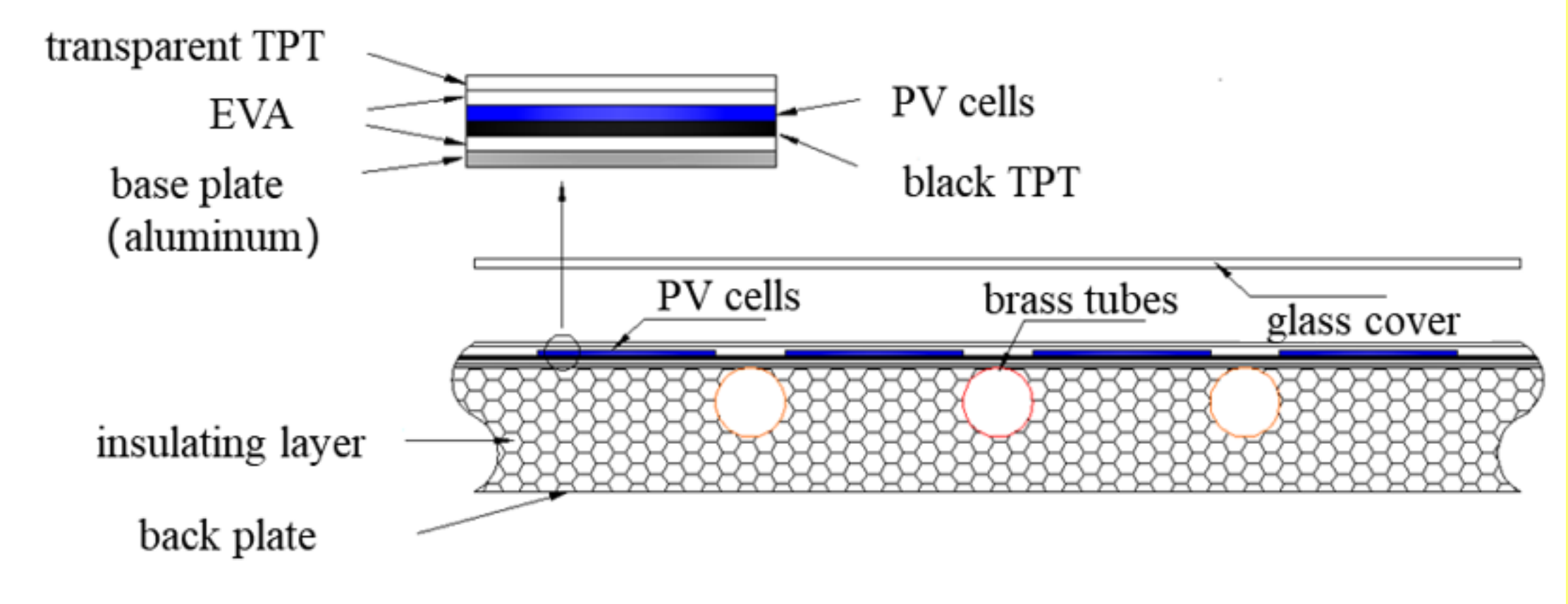

**Fig. 1.** Cross section of the hybrid PV/T collector-evaporator

For the PV-SAHP mode, the refrigerant flow model, PV/T evaporator model, compressor model, expansion valve model, condenser model, and water-tank model were developed. The refrigerant was assumed to undergo one-dimensional flow, and the two-phase region was simplified using a homogeneous flow assumption. The refrigerant pressure drop was mainly evaluated using the Müller-Steinhagen-Heck correlation [6], while the heat-transfer process was calculated according to the refrigerant state in the evaporator and condenser.

The LT-PV/T and PV-SAHP models were dynamically coupled through the collector-evaporator temperature field and the tank-water temperature. As illustrated in Fig. 2, both modes were first calculated independently for a 1-min time step under identical meteorological boundary conditions. The OTE values obtained from the two modes were then compared, and the mode with the higher OTE was selected as the operating mode for the current step. Subsequently, the temperature field and tank-water temperature of the selected mode were transferred to the next time step as the updated initial conditions. Through this temperature transfer matrix, the hybrid system could continuously update its thermal state and operate in the more favorable mode under variable solar irradiation and ambient temperature. The same procedure was also applied when OEE was used as the switching criterion.

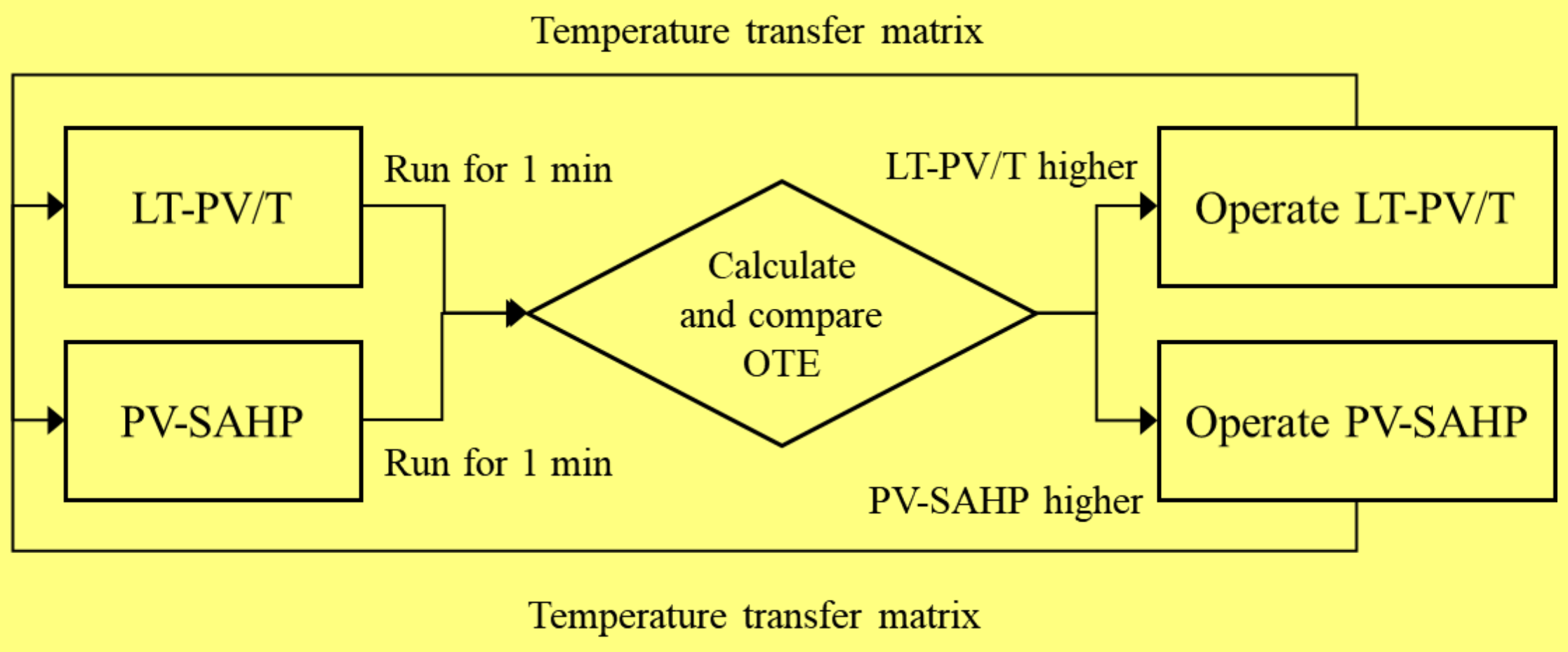
Temperature transfer matrix
LT-PV/T
Run for 1 min
PV-SAHP
Run for 1 min
Calculate
and compare
OTE
LT-PV/T higher
Operate LT-PV/T
PV-SAHP higher
Operate PV-SAHP
Temperature transfer matrix

**Fig. 2.** Schematic of the switching principle of the PV-SALT/HP hybrid system

## Results

The developed numerical models were validated against experimental data. For the LT-PV/T system, the mean relative errors of water temperature, electrical efficiency, and thermal efficiency were 3.07%, 5.76%, and 4.50%, respectively. For the PV-SAHP system, the corresponding errors were 2.39%, 7.28%, and 2.88%, respectively. These results confirm that the models can reliably predict the dynamic performance of both operating modes.

As shown in Fig. 3, when OTE was used as the switching criterion, the hybrid system required two mode switches during daytime operation. The system operated in PV-SAHP mode from 08:00 to 09:07, switched to LT-PV/T mode from 09:07 to 13:02, and then returned to PV-SAHP mode from 13:02 to 16:00. The LT-PV/T mode was more favorable in the intermediate period because no compressor power was consumed, while the PV-SAHP mode performed better during the start-up and later stages owing to its stronger refrigerant circulation and heating capacity.

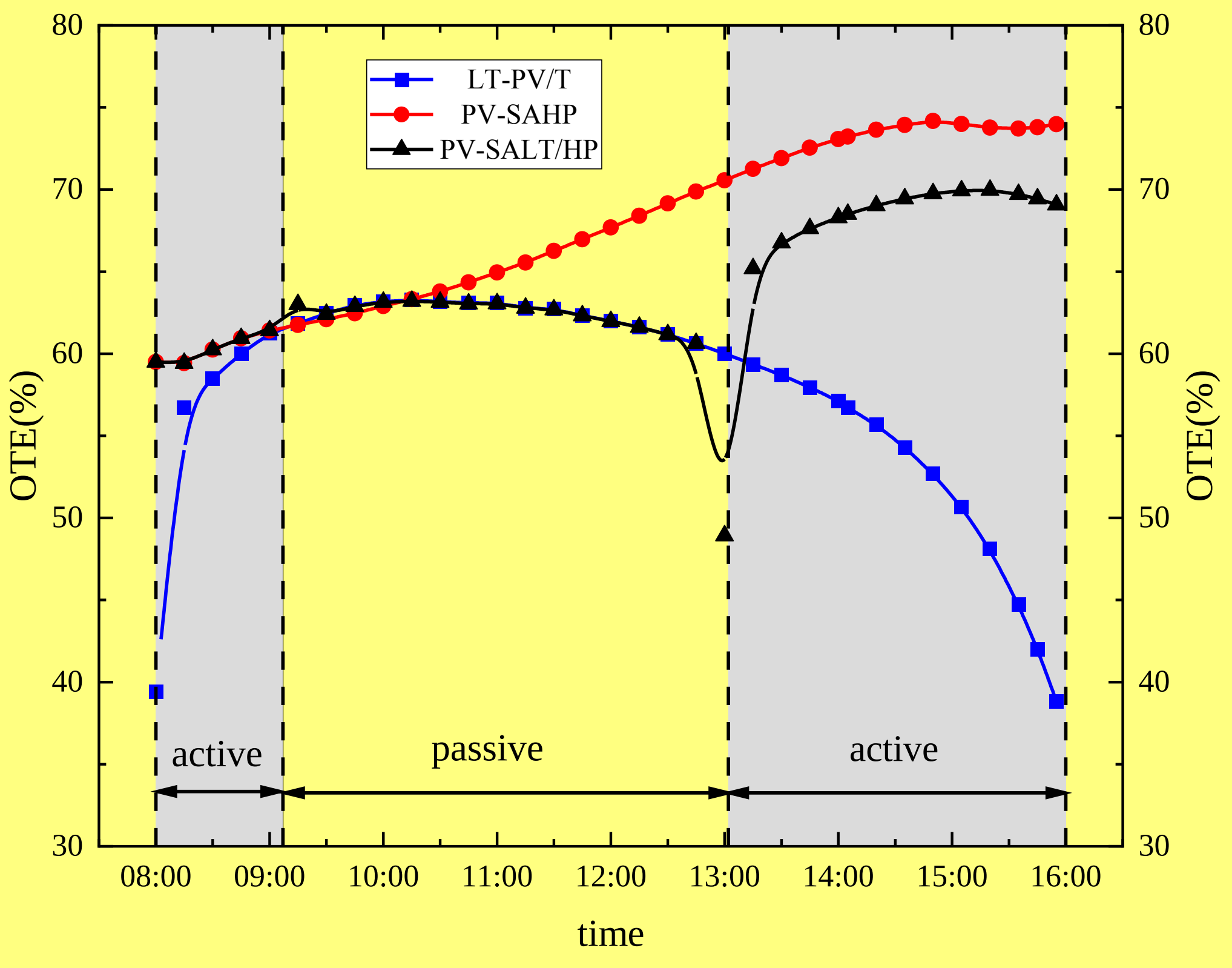

**Fig. 3.** Variation of OTE with time

As shown in Fig. 4, when OEE was adopted as the evaluation criterion, only one mode switch was required. The system first operated in LT-PV/T mode and then switched to PV-SAHP mode at 09:12. This indicates that the passive mode has an early advantage by avoiding compressor power consumption, whereas the heat pump mode becomes more beneficial as the water temperature increases and higher-grade thermal output is required.

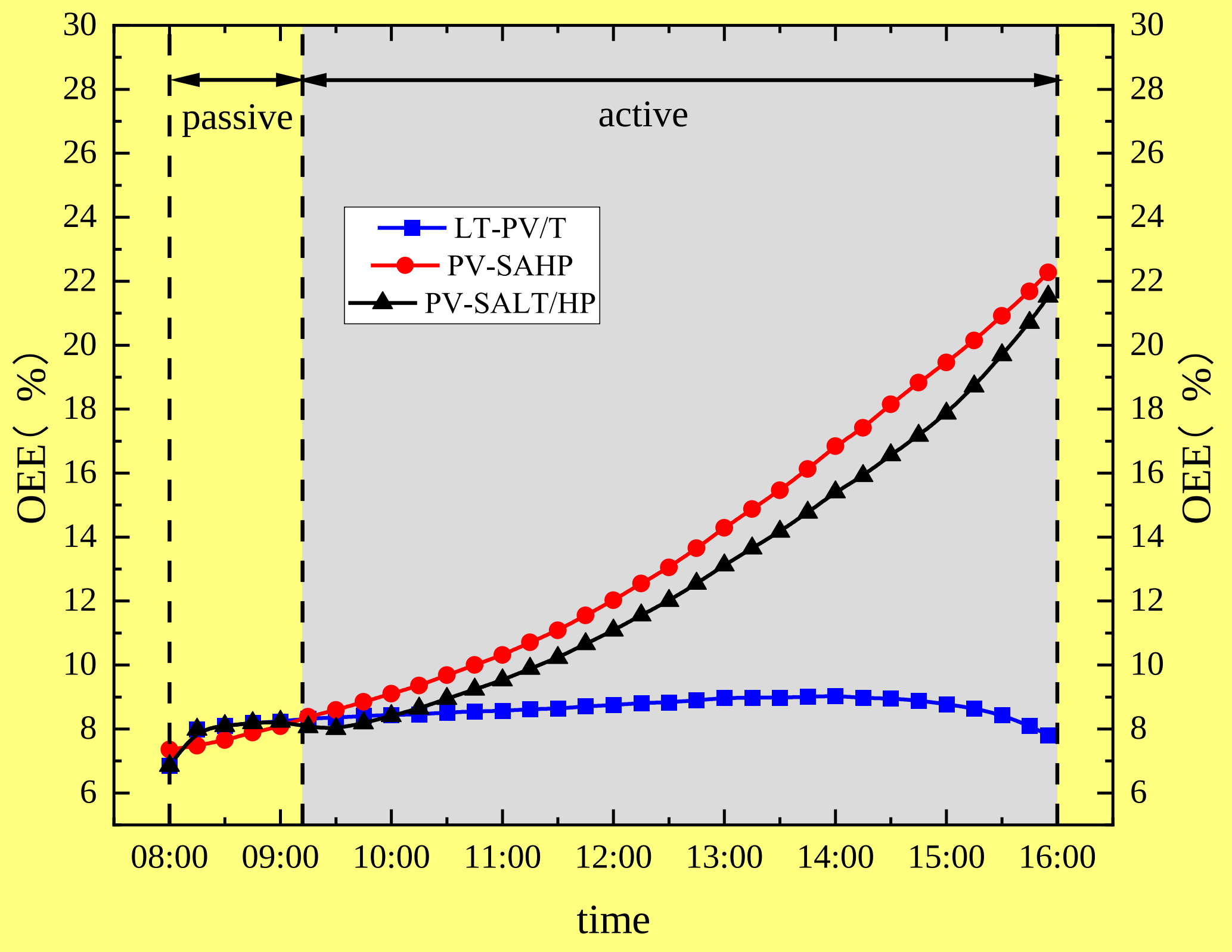

**Fig. 4.** Variation of OEE with time

Compared with standalone operation, the PV-SALT/HP hybrid system achieved a better balance between water-heating capacity and energy utilization. To quantify this improvement, the key performance indicators of different operating modes are summarized in Table 1. The OTE-based strategy achieved the highest daily average OTE of 70.35%, while the OEE-based strategy obtained the highest daily average OEE of 13.57%. Meanwhile, both hybrid strategies maintained a final water temperature above 67 ° C, showing a clear advantage over the standalone LT-PV/T mode in hot-water supply.

**Table 1.** Performance comparison of different operating modes

| Mode | Final Tw (°C) | Efficiency | Output factor |
|---|---|---|---|
| LT-PV/T | 35.0 | OTE 58.99%;OEE 8.63% | / |
| PV-SAHP | 69.9 | OTE 67.98%;OEE 13.08% | $f_{OTE}$ 1.83, $f_{OEE}$ 0.67 |
| PV-SALT/HP-OTE | 67.2 | OTE 70.35% | $f_{OTE}$ 3.26 |
| PV-SALT/HP-OEE | 68.9 | OEE 13.57% | $f_{OEE}$ 1.18 |

## Conclusions

The main conclusions drawn from this work are:

-The developed coupled model can reliably predict the dynamic performance of both LT-PV/T and PV-SAHP modes, providing a basis for switching-performance analysis;

-The LT-PV/T mode shows better energy-saving potential due to passive operation, while the PV-SAHP mode provides stronger water-heating capacity through compressor-assisted heating;

-For OTE-based operation, two switches are required: from PV-SAHP to LT-PV/T at 09:07, and then back to PV-SAHP at 13:02. The highest daily average OTE of 70.35% is achieved;

-For OEE-based operation, only one switch is required from LT-PV/T to PV-SAHP at 09:12, and the highest daily average OEE of 13.57% is obtained;

-The proposed switching logic enables the hybrid system to balance hot-water supply, energy-saving performance, and solar energy utilization under variable meteorological conditions.

## References

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