PRELIMINARY EVALUATION OF AN INDOOR SOLAR COLLECTOR- SHALLOW GROUND HEAT EXCHANGER CONCEPT FOR EXTENDING SUMMER GROWING PERIODS IN GREENHOUSES

Summary

This study proposes a novel concept that combines an indoor EPDM solar thermal collector with a shallow ground heat exchanger (GHE) to reduce cooling energy consumption and extend the crop cultivation period in greenhouses. Four HVAC system configurations were modeled and compared through annual simulations for a single-glazed glass greenhouse (8 m x 8 m) growing tomatoes in Haman, South Korea (35.27 N): (1) Conv-Blr, a conventional greenhouse with an electric boiler; (2) Conv-ASHP, a conventional greenhouse with an air-source heat pump (ASHP); (3) Sol-Ghe-Blr, a greenhouse equipped with an indoor solar collector and GHE, heated by an electric boiler; and (4) Sol-Ghe-ASHP, combining the indoor solar collector and GHE with an ASHP for both heating and cooling. The Sol-Ghe-ASHP configuration achieved 5.4% lower annual electricity consumption (7,381 vs. 7,800 kWh) and 20% fewer cooling unmet hours (309 vs. 387 h) compared to Conv-ASHP, demonstrating the effectiveness of indoor solar collector radiant cooling combined with ground thermal storage.

Keywords: greenhouse climate control, indoor solar thermal collector, shallow ground heat exchanger, air-source heat pump, cultivation period extension

Field of application for the findings: The findings provide preliminary design guidelines for hybrid solar-GHE heat pump systems in greenhouses, with potential relevance to broader climatic conditions pending further validation.

Addressed audience: ***academicians, greenhouse engineers, energy system designers***

1. Introduction

Heating costs constitute a substantial and growing portion of greenhouse operating expenses, particularly as fuel prices continue to rise. Meanwhile, extending the cultivation season through active summer cooling has gained attention as a strategy to improve crop productivity. Conventional greenhouse cooling relies primarily on passive measures including shading screens, natural ventilation, and evaporative cooling pads, which are often insufficient to maintain optimal growing temperatures during peak summer. Active cooling using heat pumps can address this limitation but introduces additional electricity consumption. Recently, the concept of utilizing greenhouse structures as energy-producing hubs has attracted growing interest. By generating renewable energy on-site, greenhouses can offset a portion of their annual energy consumption, thereby improving energy self-sufficiency and reducing operating costs. In this context, this study proposes a novel system that employs an indoor EPDM (ethylene propylene diene monomer) unglazed solar thermal collector installed on the greenhouse floor, coupled with a shallow horizontal ground heat exchanger (GHE) at approximately 2 m depth beneath the greenhouse. The objective is to evaluate the year-round energy performance and cultivation period extension potential of this system through simulation-based comparison with conventional alternatives.

2. Concept of solar thermal collector and ground heat exchanger

The proposed solar thermal and GHE concept installs an EPDM rubber mat collector on the greenhouse floor to intercept a portion of incoming solar radiation before it heats the indoor air. During summer, the absorbed solar heat is circulated via water through horizontal PE pipe coils buried at around 2 m depth, thereby rejecting indoor heat to the ground. This simultaneously reduces the cooling load on the indoor environment and stores thermal energy in the soil. The ground surrounding the uninsulated GHE allows heat to dissipate naturally, functioning as a seasonal thermal buffer. In principle, the system can also operate in winter by collecting excess indoor solar heat during sunny daytime and storing it in the ground, then circulating the warmed water through the collector at night to provide supplementary floor radiant heating. However, in the present study, the collector was deployed only during the cooling season (May to September) and rolled up during the heating season, as the dominant energy challenge for the studied climate and greenhouse scale was summer cooling load reduction rather than winter heat recovery.

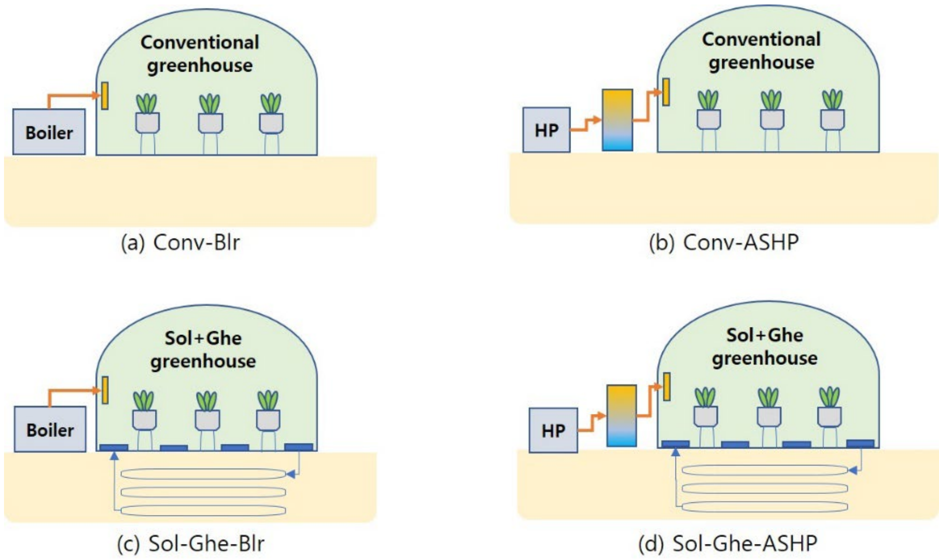

Fig. 1: Schematic of the four HVAC configurations: Conv-Blr (top-left), Conv-ASHP (top-right), Sol-Ghe-Blr (bottom-left), and Sol-Ghe-ASHP (bottom-right)

3. Models and simulation method

Four greenhouse HVAC configurations were modeled as shown in Fig. 1. Conv-Blr represents the baseline conventional greenhouse using an electric boiler for heating and passive cooling (shading, ventilation, evaporative cooling). Conv-ASHP replaces the boiler with an air-to-water heat pump providing both heating and cooling via a buffer tank and fan coil unit (FCU). Sol-Ghe-Blr adds the indoor solar collector and GHE to the conventional boiler system. Sol-Ghe-ASHP combines the solar collector and GHE with an ASHP, enabling both direct solar-ground thermal management and active heat pump operation. The simulation employs a simplified 3-zone indoor climate model with lumped thermal capacitance, an experimentally calibrated shallow ground thermal model (Eze et al., 2024), an ASHRAE Standard 96 collector efficiency model for the EPDM absorber, and a literature-based linear COP model for the ASHP. Hourly TMY weather data for Haman, South Korea (35.27 N, 128.41 E) from PVGIS were used. A 2-year warm-up period preceded the analysis year to stabilize ground temperatures. The cultivation period was determined as the interval during which indoor temperature was maintained within the acceptable range for tomato (below 28 C daytime, above 18 C nighttime) for at least three consecutive days.

4. Results and discussion

Tab. 1 summarizes the annual simulation results. Conv-ASHP reduced total electricity by 71% compared to Conv-Blr (7,800 vs. 26,550 kWh), confirming the dominant effect of heat pump adoption. Sol-Ghe-ASHP (Ra = 30%) achieved 315 growing days with 7,381 kWh total electricity, which is 5.4% lower than Conv-ASHP (7,800 kWh, 324 days). The simulation indicated that year-round cultivation became achievable when the collector area ratio exceeded 40%. Cooling unmet hours represent the cumulative hours during the growing season when the indoor air temperature exceeded the cooling setpoint plus a 1 C dead-band, indicating insufficient cooling capacity. The cooling unmet hours of Sol-Ghe-ASHP were 309 h, a 20% reduction from the 387 h of Conv-ASHP, attributed to the cooling effect of the collector surface maintained below the indoor temperature via GHE cold water circulation. During the equal-period comparison (Conv-ASHP crop period forced on both models), Sol-Ghe-ASHP consumed 7,376 kWh compared to 7,795 kWh for Conv-ASHP, a 5.4% reduction, with the largest savings occurring in June through August where HP cooling electricity was reduced by 40%. Sol-Ghe-Blr reduced total electricity by 33% compared to Conv-Blr (17,871 vs. 26,550 kWh), demonstrating that the solar-GHE concept provides meaningful benefits even without a heat pump, although the growing season was shorter (241 vs. 247 days) due to the absence of active cooling.

Tab. 1: Comparison of annual simulation results for the four HVAC configurations

Model		Growing days (From to To)	Total electricity (kWh)	HP cooling (kWh)	HP heating (kWh)	Cooling unmet (h)	Heating unmet (h)
Conv-Blr		247 (1/1~6/26+10/23~12/31)	26,550	0	26,123	919	212
Conv-ASHP		324 (1/1~8/11+9/22~12/31)	7,800	632	5,267	387	195
Sol-Ghe-Blr		241 (1/1~6/19+10/22~12/31)	17,871	0	17,110	156	161
Sol-Ghe-ASHP	Ra=10%	354 (1/1~9/11+9/22~12/31)	7,822	693	4,938	556	176
	Ra=20%	317 (1/1~8/4+9/21~12/31)	7,015	556	4,953	308	173
	Ra=30%	315 (1/1~8/3+9/22~12/31)	7,381	556	4,992	301	175
	Ra=40%	365 (year round)	7,764	721	5,062	518	172
	Ra=50%	365 (year round)	7,684	703	5,135	519	175

5. Conclusions

A novel concept of indoor solar thermal collector coupled with a shallow ground heat exchanger was proposed and evaluated through simulation for year-round greenhouse. The Sol-Ghe-ASHP configuration achieved 5.4% lower annual electricity consumption for the equal-period comparison and 20% fewer cooling unmet hours compared to the Conv-ASHP model, with the collector operated during the cooling season (May to September) and rolled up during the heating season. The simplicity of the system, requiring only an unglazed rubber mat collector, shallow PE pipe coils, and a circulation pump in addition to a standard ASHP, makes it a practical and cost-effective option for greenhouse operators seeking to improve summer cooling performance. Future work will include more detailed model simulation and experimental validation.

6. References

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