



Review article

Photovoltaic–thermal advanced technology for real applications:
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ABSTRACT

This study analyzes research trends on photovoltaic–thermal (PVT) systems used in buildings. The applications of PVT systems are also classified into system design, material and fluid types, and operating methods. Although many studies proposed new types of PVT systems and applications to improve system performance, there are few reports on the design and operating methods for the system, which consists of the PVT system and hot water storage tank in real-scale buildings. Therefore, our research team conducted a quantitative evaluation of a small household with a PVT system and hot water storage tank installed, according to design factors. The results of the parametric study showed that electricity production was more sensitive to changes in system capacity than those in heat production. By contrast, the change in heat production was dominant in response to the change in the installation angle and load profile of domestic hot water. Through energy simulation, it was found that the PVT system could provide 95% of the annual thermal energy for the domestic hot water consumption of the target buildings.

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Nomenclature**Abbreviations**

ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
ASHP	Air source heat pump
BHE	Borehole heat exchanger
CCH	Calcium chloride hexahydrate
CdTe	Cadmium telluride
CNT	Carbon nanotube
CPVT	Concentrated photovoltaic–thermal
DDM	Double-diode model
DHW	Domestic hot water
DSHP	Dual-source heat pump
DSSC	Dye-sensitized solar cell
ECPA	Eutectic of capric-palmitic acid
ELM	Extreme learning machine
EPBT	Energy payback time
GP	Genetic programming
GPBT	Greenhouse gas payback time
GSHP	Ground source heat pump
HWST	Hot water storage tank
ITO-EG	Indium tin oxide-ethylene glycol
LCA	Life cycle assessments
MCRT	Monte Carlo ray tracing
MGHE	Modular ground heat exchanger
MLPANN	Multilayer-perceptron artificial neural network
MWCNT	Multi-walled carbon nanotube
PCM	Phase change material
PV	Photovoltaic
PVT	Photovoltaic–thermal
RBFANN	Radial-basis function artificial neural network
SDM	Single-diode model
WMCBs	Wind-PV-hydro multi-energy complementary bases
ZEBs	Zero-energy buildings

the required energy using renewable systems. The application of renewable energy in buildings varies from country to country; however, the primary sources of energy used include solar, geothermal, wind, and hydropower. Among these options, solar energy has the advantages of relatively low costs and ease of installation (Kumar et al., 2023; Abdelrazik et al., 2022). Fig. 1 shows the annual publication frequency of papers related to photovoltaic–thermal (PVT) systems.

Photovoltaic (PV) systems are power systems that use solar energy in PV modules and generate electricity through the photoelectric effect. The distribution of PV systems has rapidly increased in the building and industrial sectors, with installed capacity rising from 17 GW in 2010 to 175 GW in 2021 (IEA, 2022). However, the development of hybrid systems combining PV systems with other heat sources has provided alternatives to PV systems, which are prone to performance degradation, aging, and durability challenges (Skoplaki and Palyvos, 2009; Lamnatou and Chemisana, 2017). PVT systems can achieve higher power generation efficiency than PV systems by controlling the temperature of PV cells through the passage of air or liquid on the rear side of the PV cells. These systems can produce both electricity and heat. They have gained significant attention as a key technology for achieving ZEB.

This study aims to investigate and categorize trends in research regarding PVT system application in buildings and to provide guidelines for practitioners in related fields. This study reports on the recent research trends in building-integrated PVT systems. The systems are discussed in terms of system performance, application, and materials. As the commercialization of PVT systems progresses, issues, such as the increase in thermal and electrical efficiency, the need for optimization, PV cell cooling, the development of new materials, and environmental concerns, during the disposal stage have emerged. In Section 2, we review ongoing research on design aspects, efficiency enhancement through phase change material (PCM) and nanofluid applications, optimization using machine learning, hybrid systems, and waste resource recovery.

Most of the reviewed studies in this paper present analysis or lab-scale experimental results. However, for practical system implementation, it is crucial to sufficiently consider building conditions, such as the thermal load and installation requirements. This study analyzes the performance and potential for power generation and thermal energy utilization in a system that uses PVT systems for hot water supply.

1. Introduction

Since Sweden and Norway declared carbon neutrality in 2017, the United Nations Climate Change Conference and 4468 companies in 136 countries have focused on achieving this goal (Lee and Lee, 2021). In October 2018, through the “global warming 1.5 °C special report” and at the 26th COP held in Glasgow, England in 2021, the Intergovernmental Panel on Climate Change (IPCC) recommended a target of 1.5 °C to curb global temperature increase. Several policies have been proposed to address this issue (IPCC, 2019), resulting in enhanced regulations for low-carbon emissions and taking notice of zero-energy buildings (ZEBs) in the building sector (Carmen et al., 2022; Panagiotidou and Fuller, 2013; Wiik et al., 2018; Silva et al., 2016). To achieve a ZEB, it is necessary to minimize heat gain and loss by using high-performance insulation on building walls and supplying

2. Review of PVT systems

PVT systems can simultaneously generate electricity and heat, and they are capable of harnessing more solar energy than conventional PV systems (Saeed et al., 2021; Asad et al., 2023; Touti et al., 2023). The performance of a PVT system is influenced by different design factors, and numerous studies are currently being conducted in this area. However, owing to the large number of studies and their diverse results, it is difficult to understand the differences and findings quickly and easily. Therefore, the objective of this study is to provide guidelines for researchers and engineers working in PVT-related fields. To this end, we compiled papers from the past ten years that focused on design factors to improve PVT system performance and serve as quick reference materials. Fig. 2 shows the classification of PVT systems.

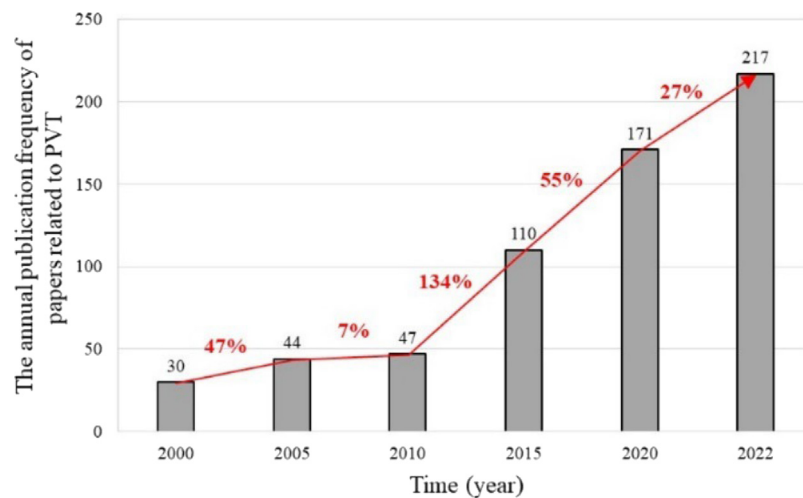


Fig. 1. Annual publication frequency of papers related to PVT.

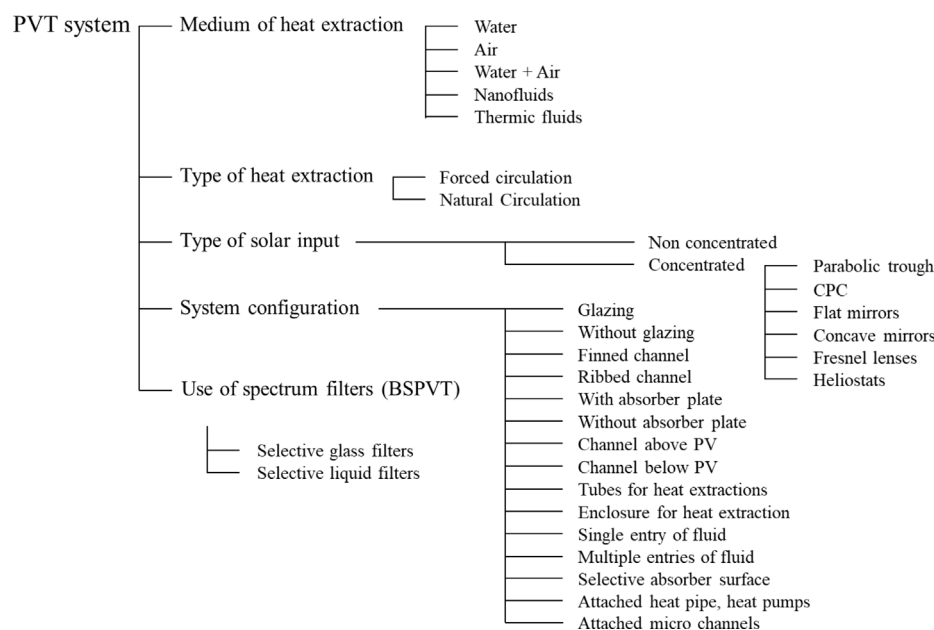


Fig. 2. Classification of PVT systems.

2.1. Design aspects

In this section, we focus on the design aspects of a PVT system including the absorber plate, collector shape, internal fluid flow, and filter. Fig. 3 shows the components of PVT.

Aste et al. (2015) simulated a PVT water collector and roll-bond flat-plate absorber to construct an innovative PVT component design and mathematical model to estimate electricity and heat production. The proposed model considered different factors such as temperature loss, spectral efficiency, and solar-radiation incident angle. The PVT system was manufactured and verified by comparing it with existing flat-type PVTs. Fig. 4 shows the conceptual image of the collector.

Ooshaksaraei et al. (2017) evaluated the performance of four new designs that proposed airflow by classifying the number of cells in the panel where the solar energy was collected in an air-type bifacial PVT module; they selected four, six, nine, and twelve cells. Equations for evaluating the energy and exergy efficiencies were presented, which were solved using MATLAB and verified through experiments. The study found that a single-path collector

had a superior electrical energy flow, whereas the dual-path parallel flow design had a superior thermal energy flow. Fig. 5 shows the schematic image of four designs of bifacial PV panels.

Wu et al. (2017) conducted a comparative analysis of flat-plate, flexible, and concentrated PVT modules and proposed an integrated method for using a heat absorber. This study also compared the advantages and disadvantages of different heat absorber designs including sheet and tube structures, rectangular tunnels with or without fins or flaws, microchannels, and cotton interlining structures. Cetina-Quiñones et al. (2023) proposed a new design for the fin configuration inside the air tunnel of a PVT and conducted a performance analysis using simulation. Optimization methods were suggested through 9E (engineering, environment, energy, economy, education, ethics, aesthetics, equity, and evolution) analysis. The study found that the wavy fin model demonstrated the highest average outlet air temperature of 49.5 °C, and the lowest temperature of the PV panel was 81.1 °C. Conversely, the existing finless air tunnel had an average outlet air temperature of 46.3 °C, and the PV panel temperature was 85.4 °C.

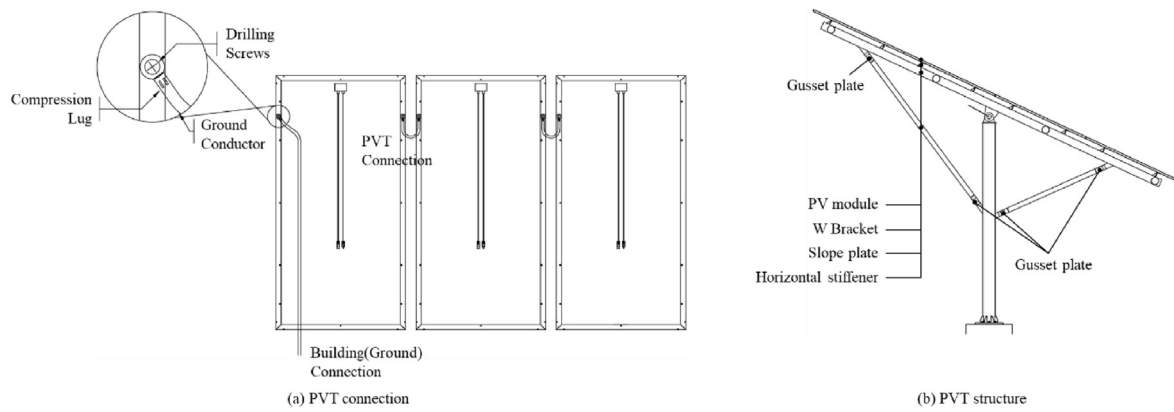


Fig. 3. PVT components.

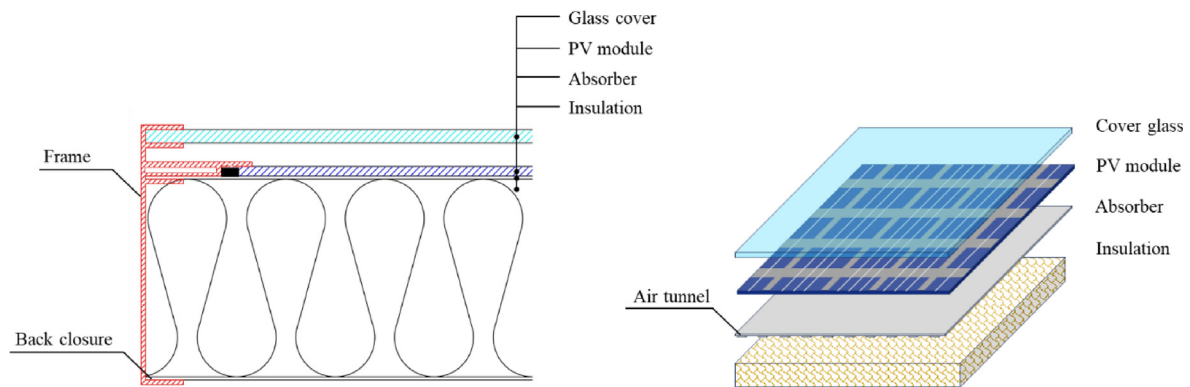


Fig. 4. Conceptual image of collector (Aste et al., 2015).

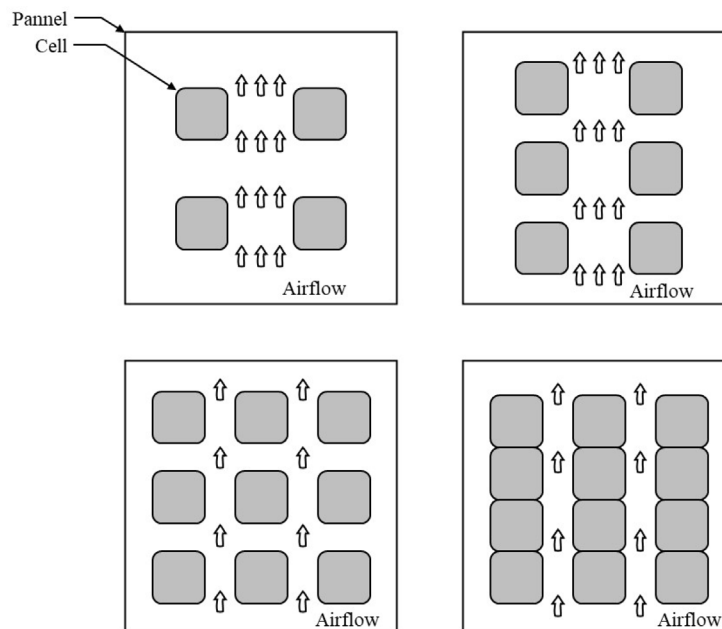


Fig. 5. Schematic of four designs of bifacial PV panels.

Pal Singh et al. (2019) presented a new mathematical model that included the air mass as well as the optimal shape and shape factor of the absorber plate in air PVT systems. They analyzed the performance of an absorber plate with V-shaped and curved

grooves using the corresponding equation. The results confirmed that the overall efficiency increased with the number of bent grooves on the absorber plate. The study also confirmed that the air distribution was dependent on the pressure loss involved,

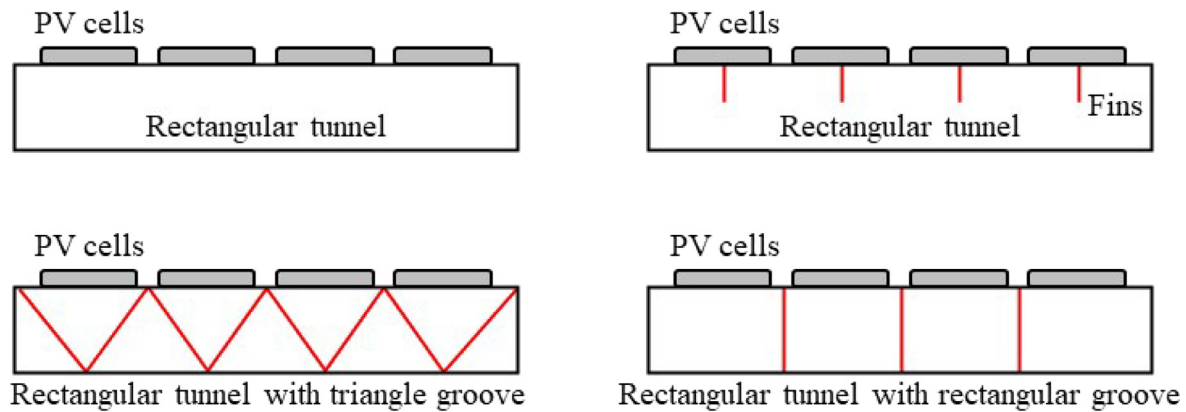


Fig. 6. Schematic of the rectangular tunnels as thermal absorbers for PVT modules.

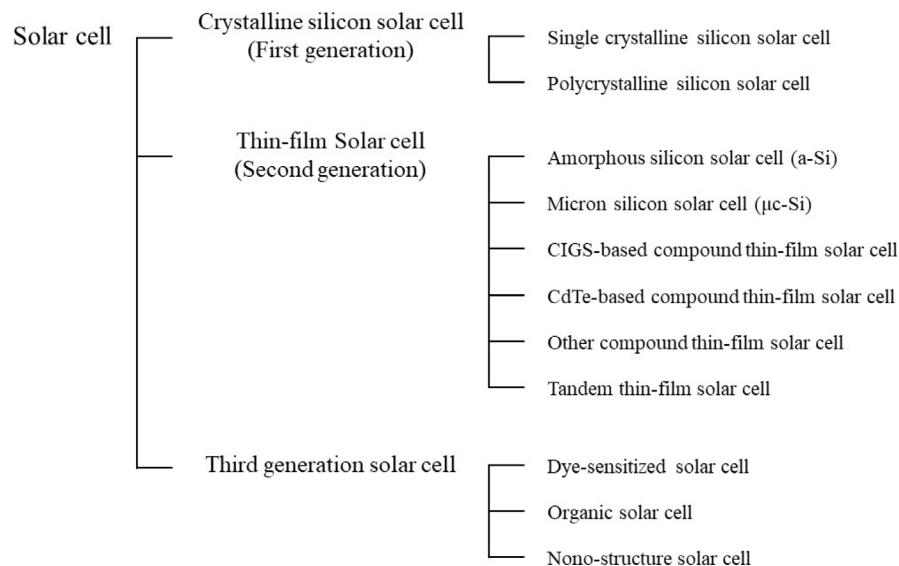


Fig. 7. Types of solar cells.

as air takes the path of least resistance to ensure a uniform flow. The design of the inlet and outlet headers was also crucial because it determined the distribution of the flow. Fig. 6 shows the schematic image of rectangular tunnels as thermal absorbers for PVT modules.

Technology development is progressing from the existing crystalline solar cell (1st generation) to the thin-film solar cell (2nd generation), and from the thin-film to the dye-sensitized solar cell (DSSC) and organic solar cell (3rd generation). The main types of thin-film solar cells are cadmium telluride (CdTe) and copper indium gallium (di) selenide (CIGS) thin films. Bosio et al. (2018) shed light on the potential of the product by conducting market research and a review of the production process of next-generation CdTe/CdS-based solar cells to improve solar cell efficiency. Although there are problems such as interface defects and CdTe doping, technological development is underway with the goal of achieving a high efficiency of greater than 25% and a low cost of 0.3 US\$/Wp. Fig. 7 shows the types of solar cells.

Wang et al. (2021a,b) proposed a new PVT system that used a linear Fresnel reflector (LER) concentrator and an indium tin oxide-ethylene glycol (ITO-EG) nanofluid-based optical filter. The optical and operational behaviors of the PVT system were estimated using a combination of Monte Carlo ray tracing (MCRT), CFD simulation, and theoretical calculations. The results demonstrated that the nanofluidic optical filter exhibited an average

absorption rate of 30.9% and a transmittance of 69.1% in the solar spectral range of 205.0 to 2500.0 nm; the total light efficiency was 93.54%. Table 1 shows the review articles related to design aspects.

2.2. Phase Change Material (PCM)

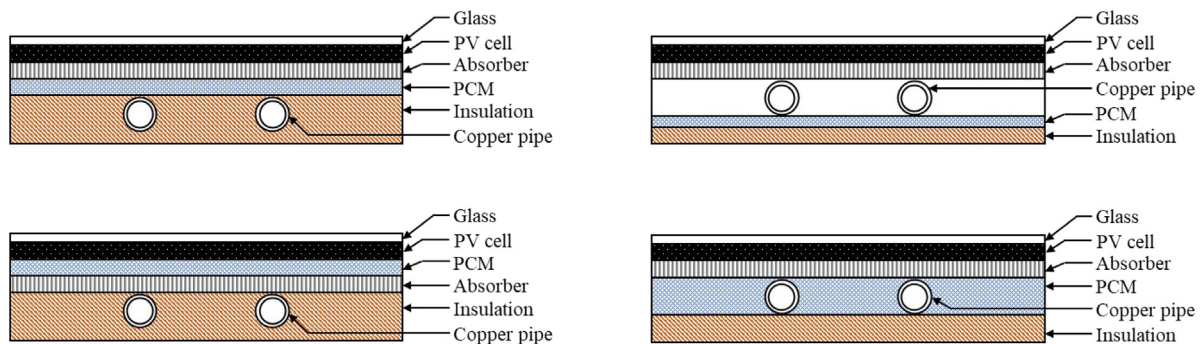
The performance of a PVT system can deteriorate owing to temperature increase, making proper thermal control essential for improving PVT efficiency. Considerable research is being conducted on this, and researchers are focusing on PCM. However, commercialization of PCM has been delayed owing to concerns regarding future disposal, volume change, and questions regarding economic feasibility. Despite these challenges, PCM has a high potential for technological development because it can store energy and reduce temperature. Fig. 8 shows the conceptual image of a PVT system that uses PCM.

Browne et al. (2015) experimentally compared a PVT-PCM system that applied RT27-PCM to liquid PVT with a conventional PVT system. Results demonstrated that the PVT-PCM system provided up to 50% (average 33%) greater heat storage capacity than the conventional PVT system. Moreover, it was confirmed that the heat-use period was extended by 75 to 100% owing to the use of PCM. Compared to a PVT-water system, the module temperature was found to be reduced by 6 °C, and the power efficiency was improved by 9%.

Table 1

Review articles related to design aspects.

Authors	Year	PVT type	Highlights
Aste et al.	2015	Fluid	- Presenting a new dynamic model using a liquid PVT collector and a roll-bonded flat-plate absorber. - Model validation through experiments.
Ooshaksaraei et al.	2017	Air	4 new design collector plates. - Suggestion of energy and exergy efficiency evaluation equations. - Model validation through experiments. - Efficiency analysis according to air flow in the panel.
Wu et al.	2017	Air/Fluid	- Various PVT comparisons. - Comparison of advantages and disadvantages of heat sinks.
Bosio et al.	2018	Air	Introducing the current status and development of CdTe/CdS-based solar cells.
Pal Singh et al.	2019	Air	- Proposal of optimal absorber plate shape. - Performance analysis of V-shaped and curved grooves. - It was confirmed that the efficiency increased as the number of curved grooves increased.
Wang et al.	2021a, 2021b	Fluid	- Presenting a new PVT system with LER concentrator and nanofluid-based optical filter. - Estimation of optical and operational behavior of PVT systems. - Overall light efficiency of 93.54% confirmed.
Cetina-Quiñones et al.	2023	Air	- Presenting a new design of the internal pin configuration of the air tunnel. - Proposal of optimization plan through 9E analysis.

**Fig. 8.** Conceptual image of PVT system that uses PCM.

Hasan et al. (2015) evaluated the performance of PCM in reducing the temperature of PV panels under two different climatic conditions: Dublin, Ireland, which has a cool climate, and Vehari, Pakistan, which has a warm climate. The study used two different types of PCMs: eutectic of capric-palmitic acid (ECPA), PCM (1) and calcium chloride hexahydrate (CCH), PCM (2). The experiment was conducted on three 65 W-class polycrystalline PV panels measuring 771 mm × 665 mm facing south; measurements were taken from 09:00 to 07:00 the next day. The results indicated that the use of PCM effectively reduced the PV temperature and increased the power efficiency, particularly under hot and stable climatic conditions. PCM 2 performed better than PCM 1 at both sites, with a maximum temperature difference of 3 to 4 °C. Fig. 9 shows the schematics of energy flow in the PV-PCM system.

Fu et al. (2021) proposed a multilayered heat exchanger that uses expanded graphite-PCM (EG-PCM) for a PVT system and experimentally verified its performance. They also numerically evaluated the effect of the type and thickness of the PCM layer on system performance. Results indicated that the system performance improved as additional EG-PCM was included in winter weather conditions. Specifically, when the EG-PCM ratio was 15%, the thermal and electrical efficiencies increased by 0.9% and 24.3%, respectively. The study confirmed that the effect of PCM on meteorological conditions in winter was significant, and the average power efficiency and instantaneous thermal efficiency of a 1 cm-thick PCM layer were the highest.

Su et al. (2017) investigated the optimal performance of a PVT-PCM system under different conditions. They compared the location of PCM (top and bottom) and the existing system and found that the top location had the best efficiency, with an improvement of 10.7% over the existing system. Moreover, they found that a thickness of 3 cm was optimal among the three thicknesses tested (2, 3, and 5 cm).

Yang et al. (2018) applied PCM to improve the energy performance of a PVT module and analyzed its efficiency. From the experiment, they confirmed that the backplane temperature decreased by up to 15.8 °C. They also found that the thermal and electrical efficiencies were improved by 11.99% and 1.18%, respectively.

Fayaz et al. (2019) built a PVT-PCM system using A44-PCM at an experimental site. They confirmed a reduction in PV cell temperature by 12 °C in the PVT-PCM system, and their numerical and experimental results demonstrated electrical efficiencies of 13.98% and 13.87%, respectively. This represents an improvement of approximately 7% compared to the existing PVT system. Fig. 10 shows the Cross-sectional view diagram of PVT system using PCM; (a) PVT module, (b) heat exchanger.

Maatallah et al. (2019) experimentally examined the possibility of applying paraffin wax to PVT. Paraffin wax RT30 was used as the PCM. Results confirmed that the temperature of the PV cell with the PCM was lower than that of the PV cell without the PCM throughout the day. The electrical output increased by an average

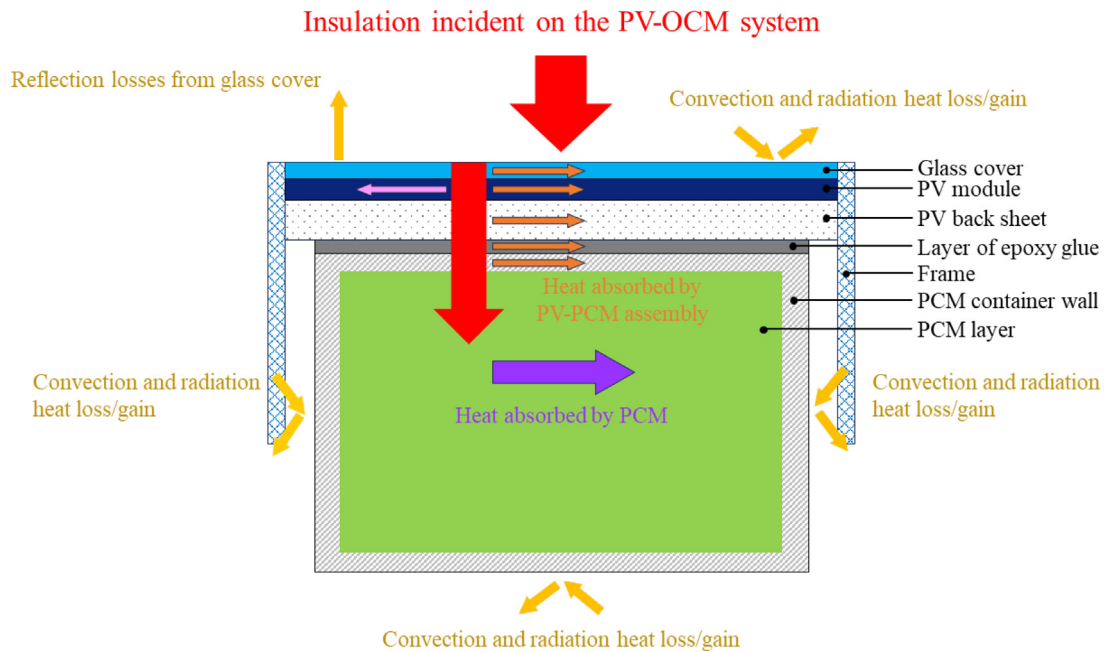


Fig. 9. The schematics of the energy flow in the PV-PCM system (Hasan et al., 2015).

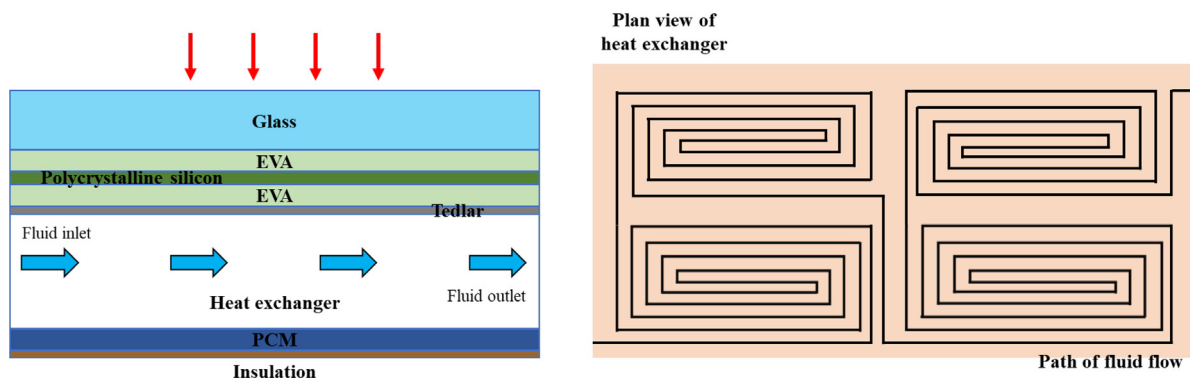


Fig. 10. Cross-sectional view diagram of PVT system using PCM; (a) PVT module, (b) heat exchanger (Fayaz et al., 2019).

Table 2
Review articles related to PCM.

Authors	Year	PCM material	Thermal conductivity (W/m K)	Melting temperature (°C)	Latent heat (kJ/kg)	Volume expansion (%)
Browne et al.	2015	RT27	0.20	25–28	35	10.0
Hasan et al.	2015	ECPA CCH	0.14 0.14	22.5 29.8	173 191	– –
Su et al.	2017	–	0.2	28.0	245	14.2
Yang et al.	2018	Capric acid	0.149	30.1	158	10.5
Fayaz et al.	2019	A44	0.18	44.0	268	–
Maatallah et al.	2019	RT30	0.24	57.0	210	–
Fu et al.	2021	EG	0.20	32.42	124.57	–
Carmona et al.	2021	RT35	0.20	29–36	160	12.5

of 17%, and the system efficiency increased by 29% compared with the existing PV panel.

Carmona et al. (2021) compared and analyzed the performance of a PVT-PCM system and an existing photovoltaic module (PV). Rubitherm RT-35 was used as the PCM. The experiment indicated that the temperature of the panel could be managed 10–17 °C less than that of the existing PV system, and up to 20.45% more energy could be extracted from solar radiation than with the existing solar system. Table 2 shows the review articles related to PCM.

2.3. Nanofluid

The performance of PVT systems is significantly influenced by several factors. Among these, the fluid flowing in the heat exchanger has been extensively studied. However, owing to the reduced thermal conductivity of fluids compared with metals, significant performance improvements have not been achieved. Recently, researchers have proposed the use of nanofluids as alternatives to traditional refrigerants. Nanofluids are fluids wherein nanoparticles with sizes of 100 nm or less are dispersed. They

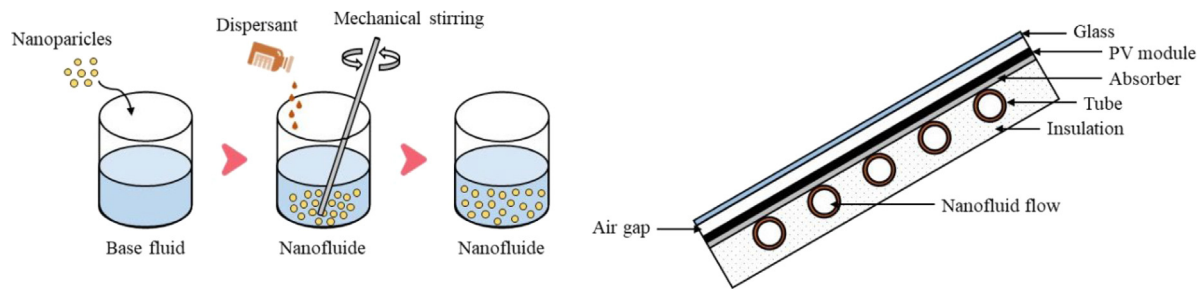


Fig. 11. Conceptual image of nanofluid applied to PVT system.

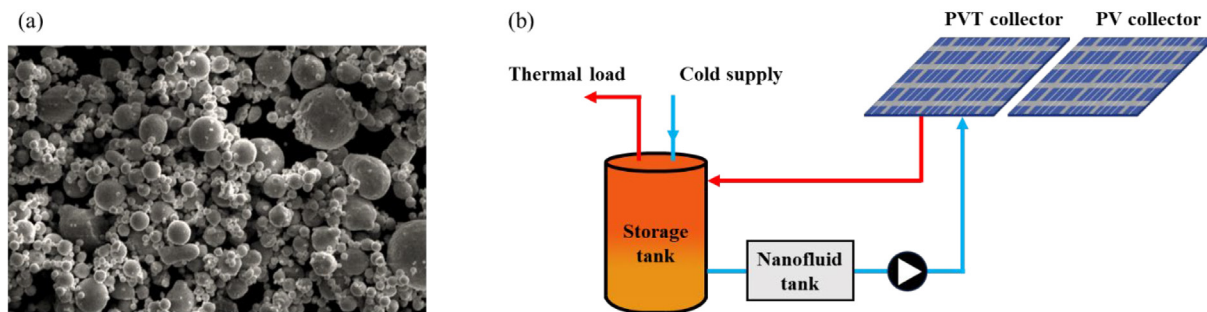


Fig. 12. Image of (a) SiC nanoparticles and (b) experimental rig (Al-Waeli et al., 2017).

have higher thermal conductivities at considerably reduced particle concentrations compared with traditional refrigerants. The heat transfer rate is improved by three main mechanisms: Brownian motion, fluid layer effect, and clustering effect. In this section, we review the studies that have applied nanofluids to PVT systems. Fig. 11 shows the conceptual image of nanofluid applied to PVT system.

Sardarabadi et al. (2014) analyzed the effect of changing from pure water to a silica/water nanofluid (SiO_2 /pure water) as circulating water in a PVT system. The concentrations of the nanofluids were set to 1 wt% and 3 wt%. There was a marginal temperature reduction effect due to the influence of the nanofluids. The energy efficiency increased by approximately 3.6% at a concentration of 1 wt% and 7.9% at 3 wt% compared to that of the system that used pure water. It was reported that the use of silica/water nanofluids significantly improved the performance of the PVT system, confirming that the thermal efficiency increased by 7.6% for 1 wt% and 12.8% for 3 wt%.

Al-Waeli et al. (2017) evaluated the improvement in thermal and electrical efficiency using SiC-water nanofluid instead of water to cool a PVT system. At a concentration of 3 wt%, the nanofluid increased in density by 8.2%, viscosity by 5.18%, and thermal conductivity by 4.3%. The nanofluid improved the thermal efficiency by approximately 100.19% and electrical efficiency by up to 24%. Furthermore, the long-term measurement for six months indicated that the decrease in thermal conductivity did not exceed 0.003 W/m·K, indicating its stability. Fig. 12 shows the image of (a) SiC-water nanoparticles and (b) experimental rig.

Nasrin et al. (2018) performed simulations using a multi-walled carbon nanotube (MWCNT)-nanofluid instead of circulating water and compared the performance with that when conventional water was used. The simulation was verified experimentally. Results confirmed that the thermal efficiency was increased by 3.81% and the electrical efficiency by 4.11% when using the MWCNT-nanofluid instead of conventional water.

Alous et al. (2019) applied 0.5 wt% distilled water, MWCNT-nanofluid water, and graphene nanoplatelet-water nanofluid as the circulating fluid in a PVT system. The temperature reduction effects of the distilled water, MWCNT-nanofluid water, and

graphene nanoplatelet-water nanofluid were 14 °C, 16 °C, and 14 °C, respectively, compared with the PV surface temperature of the existing system. Graphene nanoplatelet-water nanofluid was confirmed to be improved by 9.0%. In addition, it was confirmed that the MWCNTS-nanofluid water exhibited superior stability compared with the graphene nanoplatelet-water nanofluid at high temperatures during solar radiation. Fig. 13 shows the samples image of nanofluids; (a) graphene nanoplatelets, (b) MWCNTs nanoparticles.

Rahmanian and Hamzavi (2020) performed simulations to analyze the effects of carbon nanotube (CNT) nanofluids on a PVT system. When 0.1% (v/v) CNT nanofluid was applied, the thermal and electrical efficiencies increased by 0.04% and 0.1%, respectively, compared with those of the existing PVT system.

Hissouf et al. (2020) compared the performances through numerical analysis when a PVT system used both Cu-water and Al_2O_3 -water nanofluids as circulating fluids under different conditions instead of conventional water. It was confirmed that Cu-water nanofluids improved the performance by 4.1% for heat and 1.9% for electricity compared with conventional water, and 2.7% for heat and 1.2% for electricity for Al_2O_3 -water nanofluids.

Sreekumar et al. (2022) performed simulations to examine the thermal and electrical properties of MXene nanofluids, which had not been previously studied. The efficiency of three concentrations of 0.01, 0.1, and 0.2 wt% was analyzed. The thermal and electrical efficiencies were the highest at 0.2 wt%, and improved by 21% and 0.65%, respectively, compared with those of the existing PVT (water) system.

Alktranee et al. (2023) used ZrO_2 -water as a cooling fluid in a PVT system and experimentally confirmed the extent of its effect compared with that of DI water. It was confirmed that the PVT system temperature decreased by 21.2%, the electrical efficiency increased by 54%, and the thermal efficiency increased by 16.15%. Fig. 14 shows the image of the experimental setup of the PVT system using ZrO_2 nanoparticles. Table 3 indicates the review articles related to nanofluid.

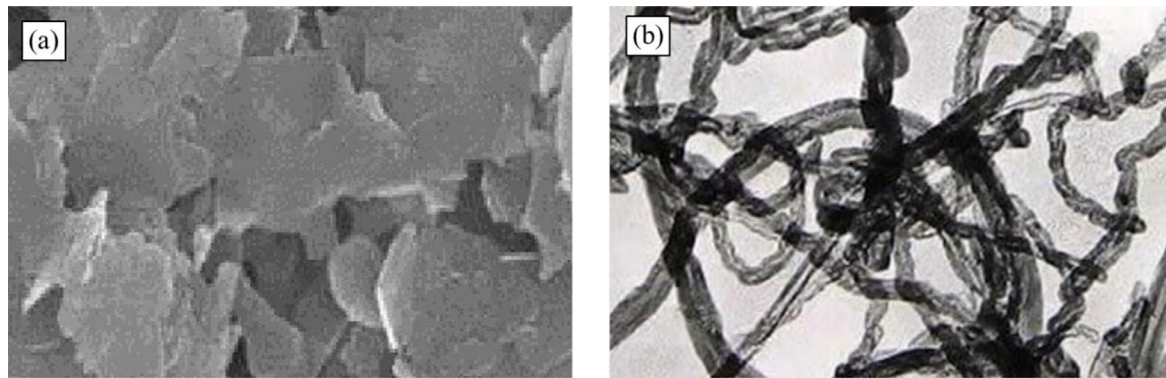


Fig. 13. Samples image of nanofluids; (a) graphene nanoplatelets, (b) MWCNTs nanoparticles.

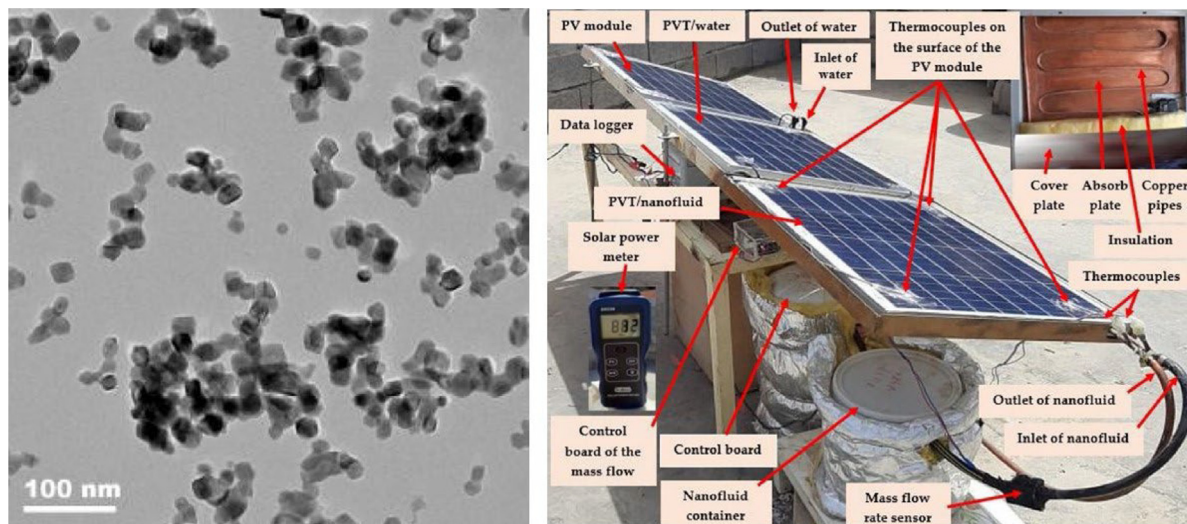


Fig. 14. Experimental setup of PVT system using ZrO_2 nanoparticles (Alktrane et al., 2023).

Table 3
Review articles related to nanofluid.

Authors	Year	Nanofluid	Efficiency elevation (%)	
			Heat	Electricity
Sardarabadi et al.	2014	SiO_2 -water	12.8	1.5
Al-Waeli et al.	2017	SiC -water	101.2	24.1
Nasrin et al.	2018	MWCNT-water	3.8	4.1
Alous et al.	2019	MWCNTS-water	8.6	10.6
		Graphene nanoplatelets-water	22.1	9.0
Rahmanian and Hamzavi	2020	CNT-water	0.04	0.1
Hissouf et al.	2020	Cu -water	4.1	1.9
		Al_2O_3 -water	2.7	1.2
Sreekumar et al.	2022	Mxene-water	21.0	0.7
Alktrane et al.	2023	ZrO_2	16.1	54.0

2.4. Machine learning

Numerous studies have been conducted and computational models have been developed to predict the thermal and electrical performances of PVT systems. However, the limitations of mathematical simulations based on numerical analysis have been reached. To overcome this problem, research is being conducted to reduce the calculation time and achieve high prediction accuracy using artificial intelligence. Fig. 15 shows the prediction models that use machine learning.

Kalani et al. (2017) proposed three methods, namely the multilayer-perceptron artificial neural network (MLPANN), radial-basis function artificial neural network (RBFANN), and adaptive neuro-fuzzy inference system (ANFIS), to model PVT systems under different conditions. These methods were compared with experimental data, where three input data points were used to output one data point. All three methods provided reasonably accurate predictions. The MLPANN and RBFANN models demonstrated values similar to the experimental data in predicting electrical efficiency, whereas ANFIS was found to be superior to MLPANN and RBFANN in predicting the PVT outlet temperature.

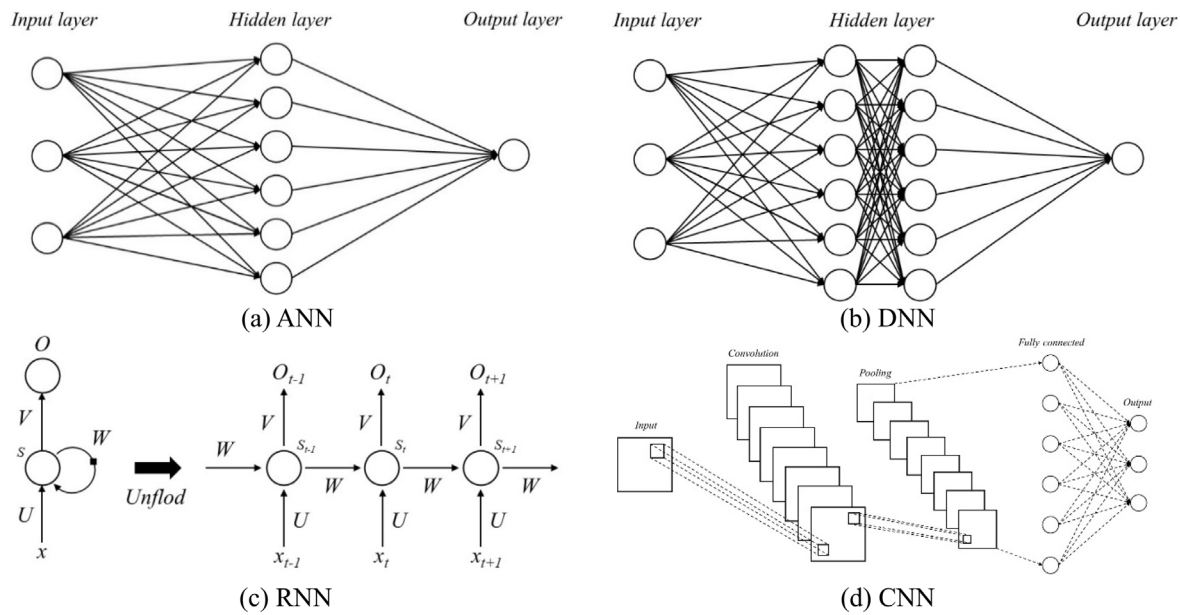


Fig. 15. Prediction models using machine learning.

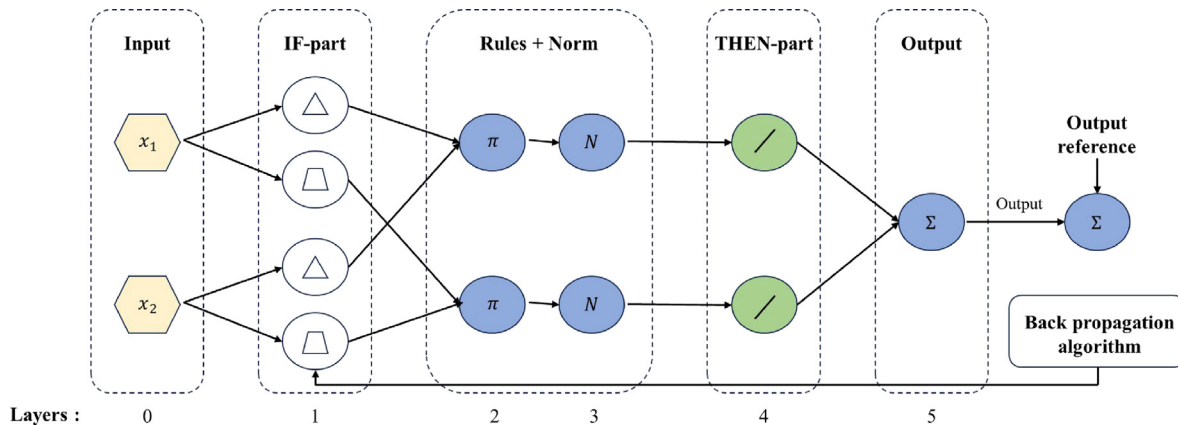


Fig. 16. Conceptual image of ANFIS (Kalani et al., 2017).

This confirms that ANFIS, MLPANN, and RBFANN are suitable for PVT system modeling. Fig. 16 shows the conceptual image of ANFIS.

Mojumder et al. (2017) used the extreme learning machine (ELM) algorithm to predict the thermal and electrical efficiency of a PVT system and compared it with genetic programming (GP) and artificial neural network (ANN) models. They concluded that ELM is a promising method for predicting the thermal and electrical efficiencies of PVT systems.

Al-Waeli et al. (2018) used three ANN models (MLP, SOFM, and SVM) to predict electrical efficiency and production based on field experiment data from a PVT system. They compared the predicted values with the collected data and found that all three models exhibited significant accuracy. SOFM demonstrated the highest prediction accuracy. The results of MLP were generally more similar to the experimental results, whereas SVM was less accurate, yet remained within an acceptable range.

Maria and Chaibi (2020) proposed a hybrid algorithm that combined a single-diode model (SDM) and double-diode model (DDM) for more accurate performance prediction of PV modules and compared it with SDM and DDM for single use. SDM was determined through six classification algorithms: classification trees (coarse tree), k-nearest neighbors (cubic), discriminant analysis

(quadratic), naïve Bayes (kernel), SVM (Gaussian), classification ensembles (boosted trees-AdaBoost), and DDM application priorities. Higher reliability with reduced errors was realized when only SDM and DDM were used. Fig. 17 shows the equivalent circuit diagram; (a) SDM, (b) DDM.

Motahar and Bagheri-Esfah (2020) evaluated solar thermal systems in the heating-dominant region of Iran using ANN. Learning was performed using the MLP model by applying six input variables (solar radiation, temperature, relative humidity, wind speed, insolation angle, and household power consumption). Solar irradiance and ambient temperature were found to be the main parameters influencing the GCPVT system.

Yousif and Kazem (2021) predicted power and heat production using an ANN model based on experimental data from a PVT system located in Sohar, Oman. Training was performed with 50% input, 20% cross-validation, and 30% testing using MLP, SOFM, and SVM models using a dataset of approximately 450. Excellent MSE results were achieved for generating current values of 0.00043, 0.00030, and 0.00041 for each model (MLP, SOFM, and SVM), respectively. Fig. 18 shows the conceptual image of MLP and SOFM.

Chaibi et al. (2021) developed an ANN model to predict the thermal and power efficiencies of an air-type PVT system. The

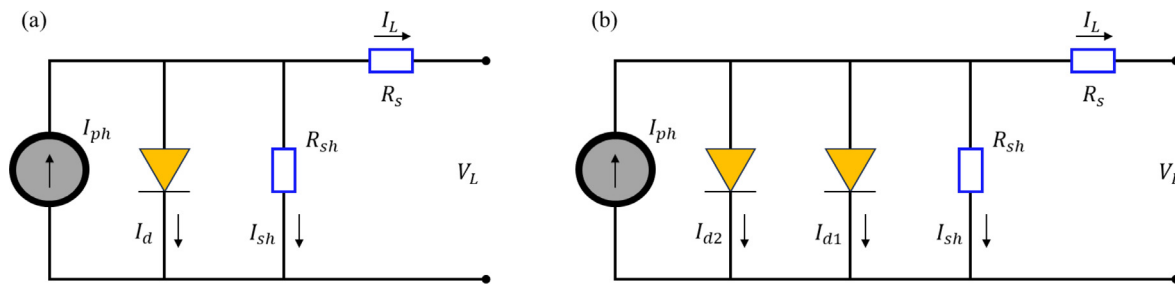


Fig. 17. Equivalent circuit diagram; (a) SDM, (b) DDM (Zhou et al., 2021).

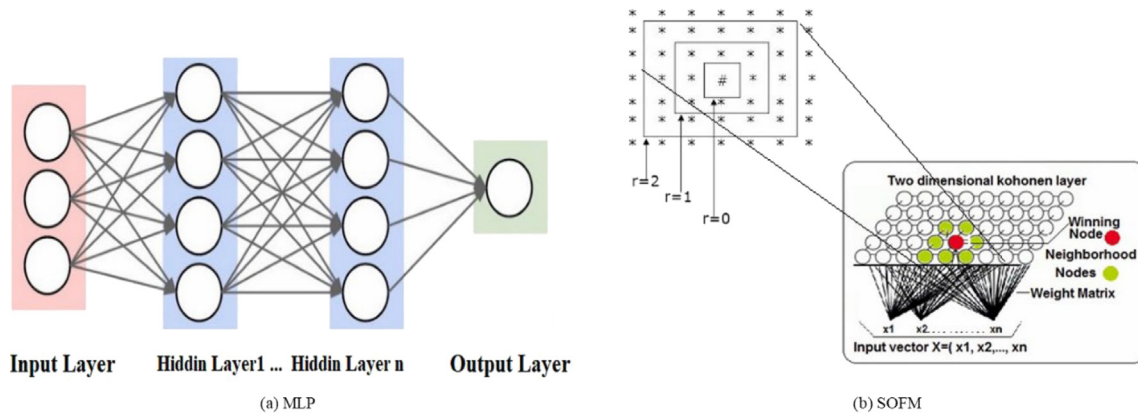


Fig. 18. Conceptual image of MLP and SOFM (Yousif and Kazem, 2021).

model calculated the input variables by analyzing Pearson's correlation coefficient based on meteorological data. A case study was conducted by applying sunlight, module temperature, humidity, and wind speed as input variables and testing the model predictions. The same variables were also entered into an LS-SVM model for verification and the differences were compared. The results indicated that the ANN model had a lower mean absolute error (MAE) for thermal and power efficiency (0.0078% and 3.3607%, respectively) than the LS-SVM model (2.6936% and 6.1546%, respectively), confirming that the ANN model was more accurate. Table 4 shows the review articles related to machine learning.

2.5. Hybrid system

As the global focus shifts toward low-carbon emissions through the use of new and renewable energy sources, the solar energy market is experiencing exponential growth. However, owing to issues such as usage time, installation location, and space, it is difficult to respond quickly to building loads, and installation is limited (Wang et al., 2021b; Rossi et al., 2013). To address these challenges, there is active research being conducted on hybrid systems that combine PVT systems with other energy sources to achieve rapid load response, mutual complementation, stability, and economic feasibility.

Jafari et al. (2019) proposed a home hot water supply system that combined a PVT-PEMFC and verified its performance through simulation. The electricity produced by the PVT was supplied to the battery, and when more than the required load was produced, it was supplied to the fuel cell to produce hydrogen and oxygen. The produced oxygen could also be sold and used for medical purposes. It was confirmed that 291 kg of hydrogen and 2309 kg of oxygen could be produced per year with the surplus electricity produced by PVT.

Bae et al. (2022) proposed a hybrid system that combined a PVT system and modular ground heat exchanger (MGHE), and

analyzed its performance through simulation. The life cycle cost of the existing VGHE system was analyzed and compared with that of the PVT-MGHE system. The system COP achieved 93% of the PVT-VGHE, and the initial investment cost was reduced by 23.1%, suggesting that the PVT-MGHE system was an appropriate alternative to PVT-VGHE. Fig. 19 shows the conceptual image of the PVT-MGHE hybrid system.

Bae et al. (2022) developed a hybrid system combining a PVT system and ground source heat pump (GSHP) system and analyzed the cooling and heating performance through an empirical experiment. A return on investment (ROI) analysis was performed based on four scenarios. The COP of the heat pump was 4.0 and 2.64 for cooling and heating, respectively, and considering the heat and electricity production of the PVT, the average COP of the system was 6.9 and 8.3 for cooling and heating, respectively, confirming the excellence of the hybrid system. Fig. 20 shows the conceptual image of the PVT-GSHP hybrid system.

Chang et al. (2023) proposed a building envelope-type hybrid PVT system that combined an air-geothermal dual-source heat pump (DSHP) by applying PVT as a curtain wall. The PVT supplied additional heat to the air-source side of the heat pump. Compared with the DSHP system without a PVT curtain wall, the COP of the heat pump (air source) increased from 3.1 to 3.3, and the system COP increased from 2.64 to 2.8, representing an improvement of 6% and 5%, respectively. Fig. 21 shows the conceptual image of the PVT-DSHP system.

Mi et al. (2020) proposed a multi-heat source hot water supply system that combined a PVT system and water-source heat pump system for public baths. The production of hot water was compared by integrating an existing air heat pump, water-source heat pump, and electric boiler into the PVT and water-source heat pump systems. When using the proposed integrated system, the daily hot water production was significantly improved (by approximately 82%) compared with the existing system, and the cost of hot water supply was reduced by approximately 49%.

Table 4
Review articles related to machine learning.

Authors	Year	Use model	Highlights
Kalani et al.	2017	MLP RBF ANFIS	- Model the PVT system using three methods and compare with experimental values - It was confirmed that ANFIS is better at predicting PVT outlet temperature than MLP and RBF
Mojumder et al.	2017	ELM GP	- Prediction of thermal and electrical efficiency of PVT systems - Comparison of ELM and GP models - ELM draws promising conclusions in predicting PVT system performance
Al-Waeli et al.	2018	MLP SOFM SVM	- Prediction of electrical efficiency and production of PVT system using three ANN models - Confirm that SOFM shows the highest prediction accuracy
Maria and Chaibi	2020	SDM DDM	- Presenting a hybrid algorithm combining SDM and DDM to predict PV module performance - Priority determination through 6 classification algorithms - Hybrid approach shows higher reliability than single approach
Motahar and Bagheri-Esfah	2020	MLP	- ANN learning by applying six input variables (solar radiation, temperature, relative humidity, wind speed, insolation angle, house power consumption) - Confirmed that solar irradiance and ambient temperature are the main influencing parameters affecting the output energy of the GCPVT system.
Yousif and Kazem	2021	MLP SOFM SVM	- Perform learning using three ANN models based on experimental data - Demonstrated achievement of excellent MSE results for generation of current values according to each model
Chaibi et al.	2021	LS-SVM	- Prediction of thermal and electrical efficiency of pneumatic PVT systems - Verification using LS-SVM model - Confirm that the ANN model exhibits higher accuracy

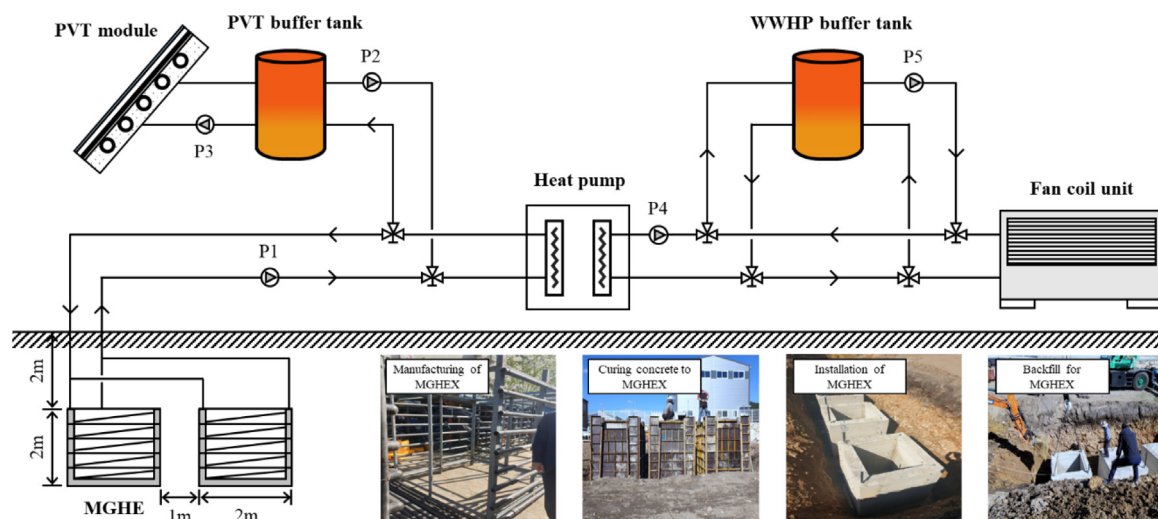


Fig. 19. Conceptual image of PVT-MGHE hybrid system (Bae et al., 2022).

Fig. 22 shows the conceptual image of a multi-heat pump system using PVT and water source.

Allouhi (2021) presented a hybrid PVT–wind system and reviewed the self-sufficiency rate of heat and electricity for a single-family building. The self-sufficiency rates of heat and electricity were 64.8% and 43.08%, respectively. From an environmental perspective, it demonstrated the potential to reduce annual CO₂ emissions by up to 54% compared with conventional energy supply systems. Fig. 23 shows the conceptual image of the PVT–wind system.

Chhugani et al. (2023) developed a hybrid system combining a PVT system and heat-pump system through simulation, and compared the system performance for each heat source combination. They compared the performance of eight systems: PVT-HP (heat pump), PVT-BHE (borehole heat exchanger)-HP, ASHP (air source heat pump), PV-ASHP, BHE-HP, PV-BHE-HP, gas boiler, and solar collector-gas boiler. The results indicated that the performance of the PVT-BHE-HP system was the highest, and that of the PVT-HP system was 14% higher than that of the existing ASHP system.

Compared with gas boilers, the PVT-HP system reduced CO₂ by up to 57%; the PVT-BHE-HP system reduced CO₂ by 63%.

Zhao et al. (2022) developed an integrated system based on wind-PV-hydro multi-energy complementary bases (WMCBs) and presented a performance evaluation method. It was confirmed that the optimal capacity could be derived by identifying the relationship between the complementarity of the system and capacity. The proposed method was verified through its installation on the Yalong River in China. It was confirmed that the ratio of hydropower and wind-PV in the system installed at the test site should be maintained between 1:1 and 1.5:1. Table 5 presents the review articles related to hybrid systems.

2.6. CPVT

The technology for collecting and utilizing solar energy has been continuously developed since the 1970s (Evans et al., 1978; Gibart, 1981). A concentrated photovoltaic (CPV) system consists of optical components such as lenses, mirrors, and glass and

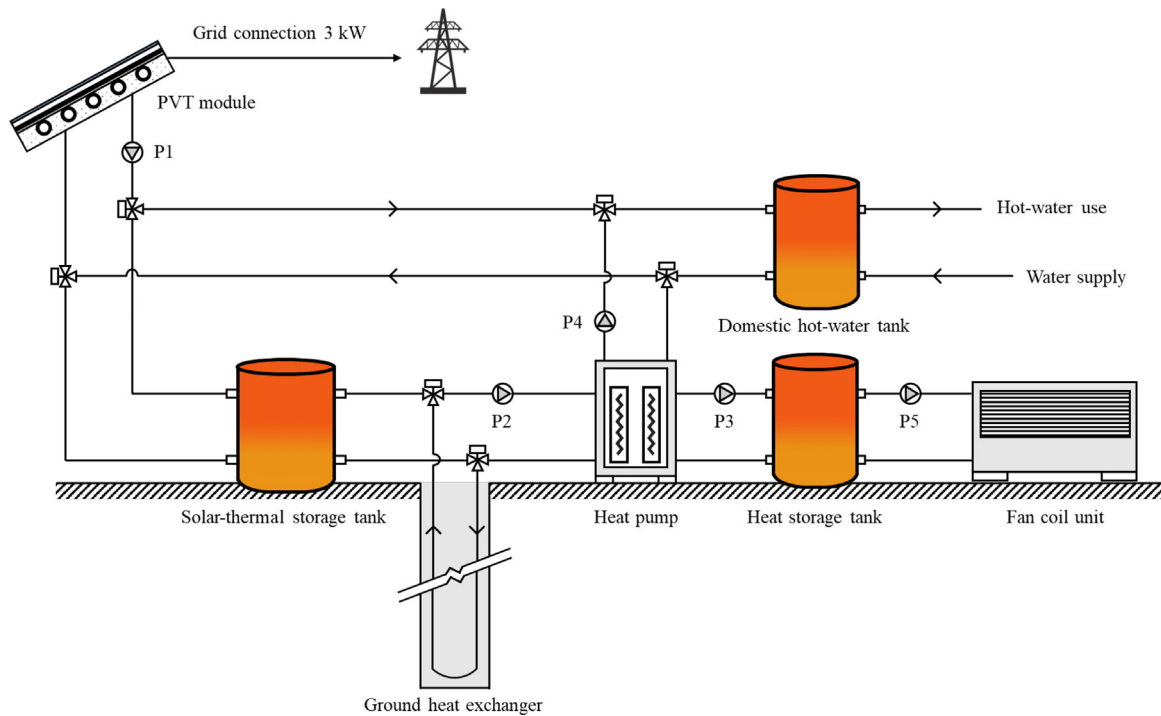


Fig. 20. Conceptual image of PVT-GSHP hybrid system (Bae and Nam, 2022).

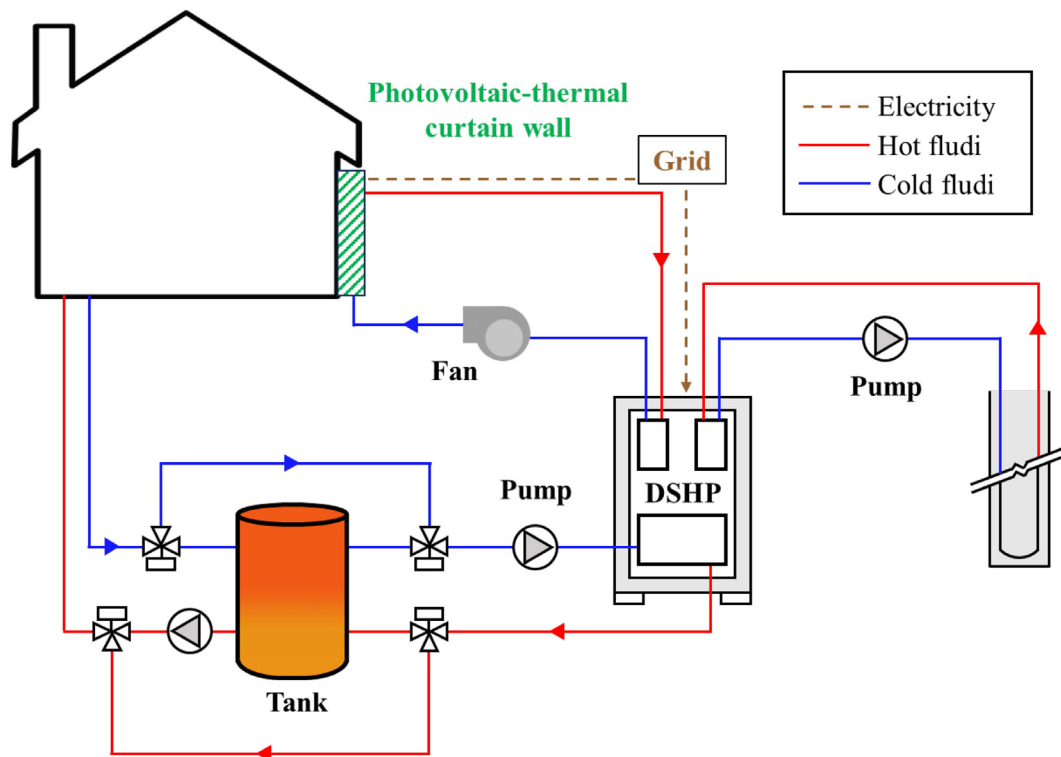


Fig. 21. Conceptual image of PVT-DSHP system (Chang et al., 2023).

generates power by concentrating sunlight. CPV systems attract researchers because they generate more power at a lower cost than PV systems with silicon solar cells. Kurtz and Geisz (2010), Shanks et al. (2016), Bamisile et al. (2020) and Dogahe et al. (2022) Since CPVs concentrate lots of solar energy per unit area, it results in a decrease in system efficiency due to the increasing temperature of PV cells. The concentrated photovoltaic-thermal

(CPVT) systems, which combine CPV and PVT systems have been studied to solve these temperature increases of the PV cells. It is possible to use the heat energy as well as generate electricity.

This section summarizes the concentrator unit—the main element of the CPVT system. The general types of concentrator units are dish parabolic, parabolic trough, and linear Fresnel reflectors. Daneshazarian et al. (2018) The dish parabolic type has rotational

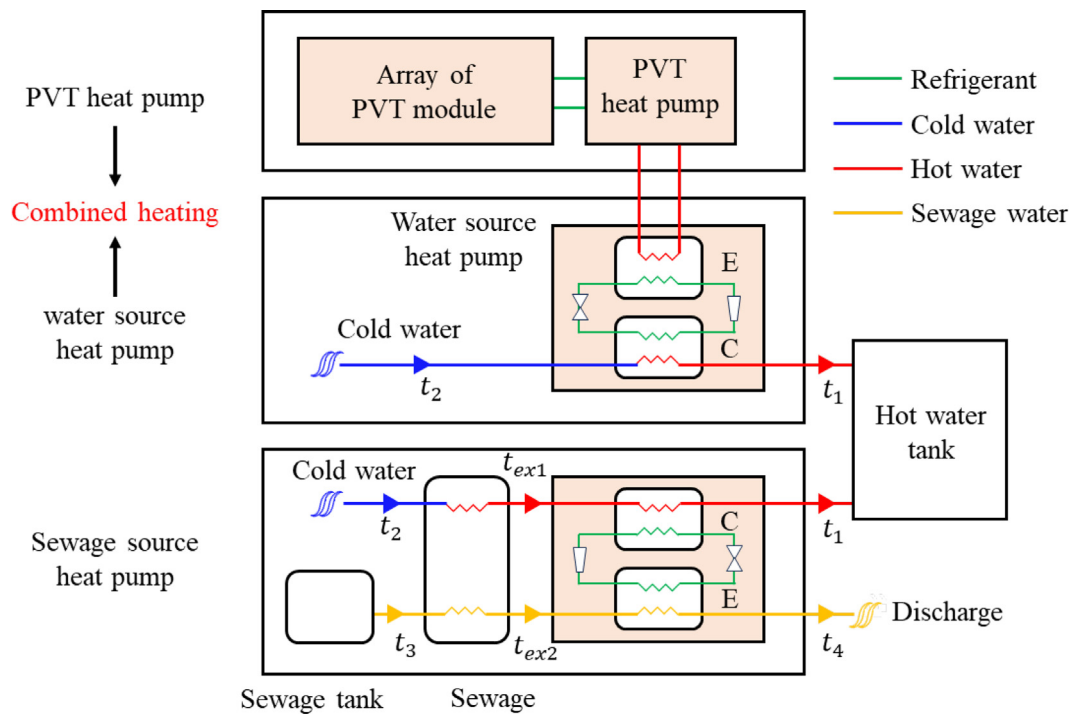


Fig. 22. Conceptual image of multi heat pump system using PVT and water source (Mi et al., 2020).

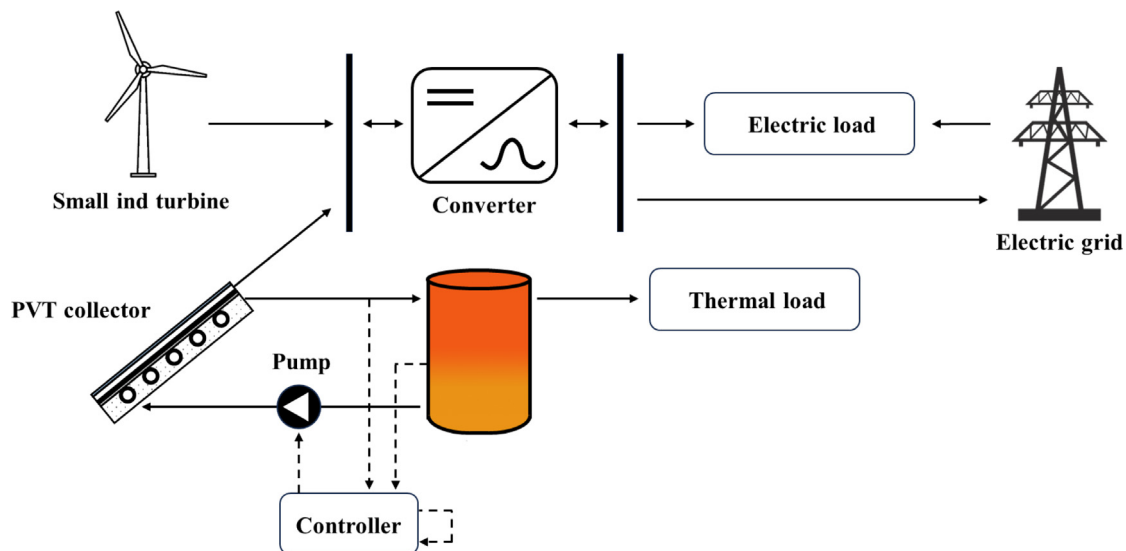


Fig. 23. Conceptual image of PVT-wind system (Allouhi, 2021).

symmetry and concentrates solar energy at a single point. Wang et al. (2017) presented a novel two-stage concentrator that uses four mirrors in a two-stage dish-type concentrator and analyzed its performance. The two-stage concentrator with four mirrors has a better optical performance than the two-stage concentrator with two mirrors. Li et al. (2023) introduced the components of a non-confocal two-stage parabolic dish CPVT (NTPD-CPVT) hybrid system that uses spectral beam splitting technology (SBS) and proposed a novel design approach. The efficiency of the PVT system was improved by 17.6% and 10.2%, respectively. Fig. 24 shows a schematic image of the NTPD-CPVT system.

However, few studies have focused on the dish parabolic type during the last 3–5 years. Kribus et al. (2006), Kandilli (2013), Buonomano et al. (2013) and Li et al. (2014). Recently, there has been more research on the parabolic trough than the dish

parabolic. The parabolic-trough type has linear symmetry and concentrates solar energy on a line. Karathanassis et al. (2017) presented a new parabolic-trough CPVT system and evaluated its performance. The results showed thermal and electrical efficiencies of 44% and 6%, respectively. Afzali Gorouh et al. (2022) designed a new CPVT collector using parabolic troughs and tested its thermal and electrical performance under various conditions; the thermal and electrical efficiencies were 69.6% and 6.1%, respectively. Habchi et al. (2023) presented a new parabolic-trough concentrator unit, and found that the thermal and electrical efficiency increased to 86% and 2.9% by increasing the insolation concentration ratio from 1 to 30. Fig. 25 shows the parabolic-trough CPVT system.

Fresnel lenses have been widely used in CPVT systems because they are easy and economical to mass-produce. Karimi

Table 5
Review articles related to hybrid systems.

Authors	Year	Multi-energy	Highlights
Jafari et al.	2019	PVT Fuel cell	· Suggested a home hot water supply system combining PVT-PEMFC · Confirmed that 291 kg of hydrogen can be produced annually with PVT surplus electricity
Mi et al.	2020	PVT Hydrothermal	· Multi-system application to public baths, performance comparison with existing systems · Increased daily hot water production by 82% and reduced supply cost by 49% compared to before
Allouhi	2021	PVT Wind	· Present PVT–wind hybrid system for single-family building · It was confirmed that 64.8% of heat and 43.08% of electricity could be supplied.
Zhao et al.	2022	PV Wind Hydrothermal	· Development and verification of multi-system using three energy sources · It was suggested that the ratio of hydro and wind-PV in WMCB should be between 1.1 and 1.5:1.
Bae et al.	2022	PVT Geothermal	· A system with a PVT system and a modular underground heat exchanger is proposed. · COP is 93% compared to the existing system, but the initial investment cost is reduced by 23%
Bae et al.	2022	PVT Geothermal	· Combining PVT and geothermal heat to conduct demonstration experiments and analyze ROI · System average COP was 6.9 for cooling and 8.3 for heating, confirming the superiority of the system
Chang et al.	2023	PVT Air Geothermal	· PVT is applied as a curtain wall to transfer heat to the air heat source side · System performance improved by 5% compared to the previous one
Chhugani et al.	2023	PVT Geothermal Air	· Comparison of systems combining PVT, geothermal, and air thermal · Confirmed 14% higher performance than existing ASHP · 57% less CO₂ emission than gas boiler

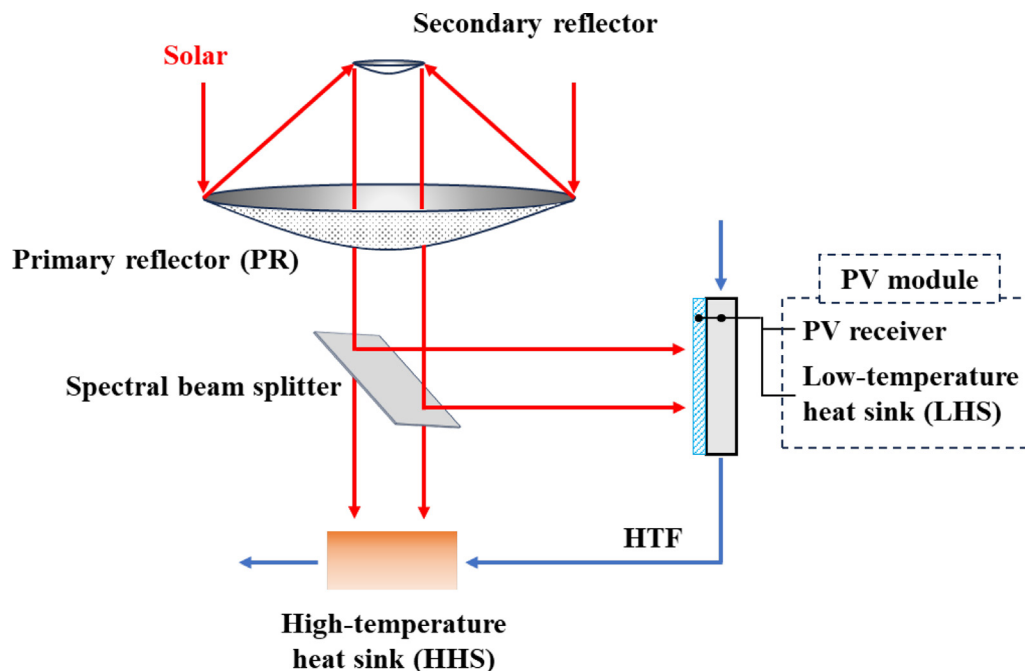


Fig. 24. Schematic image of NTPD-CPVT system (Li et al., 2023).

et al. (2017) presented the design, fabrication, and experimental evaluation of a new CPVT system using a linear Fresnel lens. The electric efficiency of PV cells decreased from 10.9% to 7.63% due to solar concentration, but their output power increased to 28%. They also found that the CPVT system performed better than the conventional solar water heater. Gupta et al. (2021) proposed

a novel CPVT system that combines a Fresnel lens concentrator with a translucent solar panel. The translucent solar panels were tested with red and blue filters; the red filter generated more overall energy than the blue filter. Meraje et al. (2022) conducted the design and dynamic modeling of a Fresnel lens-based CPVT system and verified its performance through experiments. The

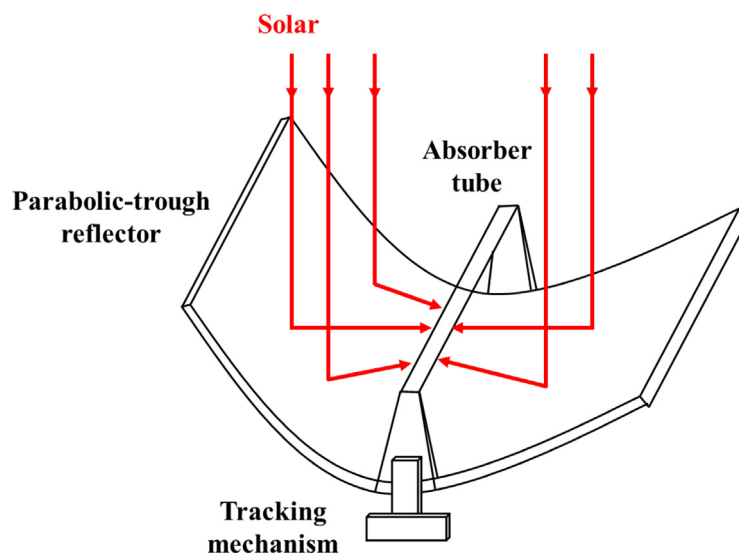


Fig. 25. Schematic image of parabolic-trough CPVT system.

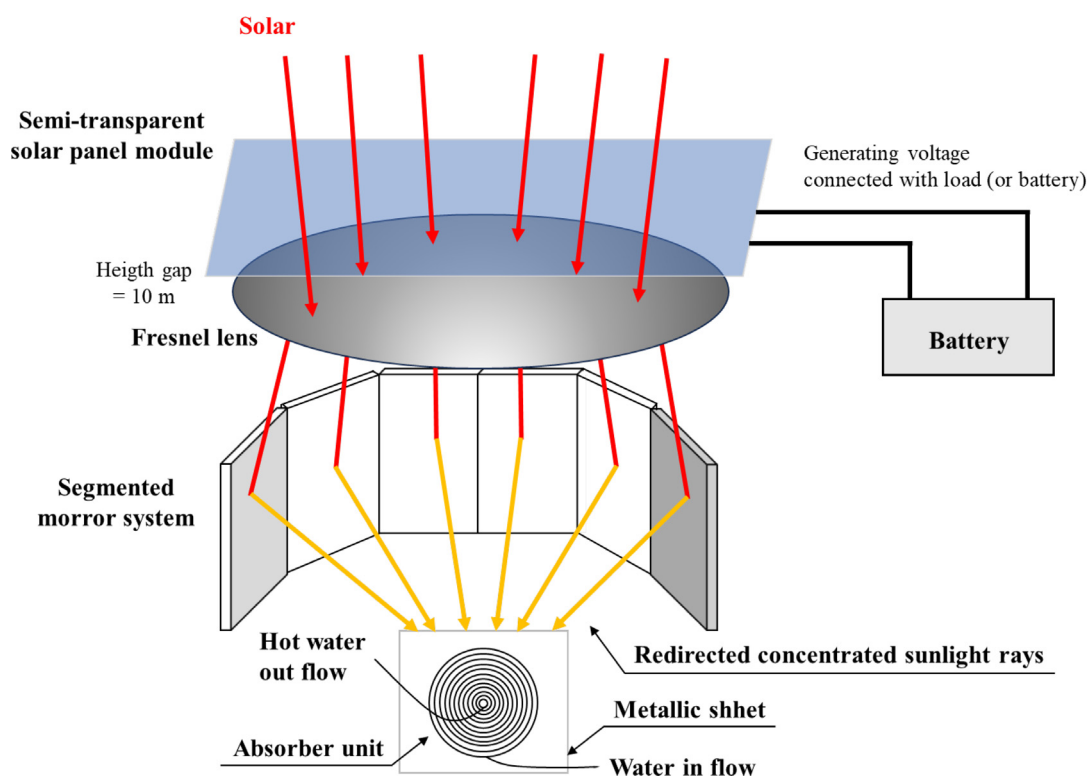


Fig. 26. Schematic image of CPVT system used Fresnel lens (Gupta et al., 2021).

energy savings of the conventional CPVT system and CPVT system with ZnO nanofluid were 56.5% and 76.1%, respectively. Fig. 26 shows the CPVT system that uses Fresnel lens.

2.7. Environmental aspects

Many countries are making efforts to expand the use of sustainable renewable energy by reorganizing the energy mix centered on solar power generation. However, waste panel disposal has become a major concern as the solar industry grows (Aman et al., 2015; Nain and Kumar, 2020). It is time to consider the waste panels that have a service life of 15–20 years. Some countries, such as the EU member countries and Japan, have been

exploring proper disposal methods and developing recycling technologies since the early 2010s. The Korean government raised the recycling rate of solar waste panels to more than 80% within three years (Jo et al., 2018), and there are plans to expand the number of waste recycling companies from the existing two to seven (Coordination, 2023). Few studies have considered the environmental aspects of PVT system waste disposal such as end-of-life disposal, including waste panel disposal, GHG emissions, and CO₂ emissions. This section reviews the CO₂ reduction effect of PVT systems from an environmental perspective, the payback period, and waste recycling.

Good (2016) reported on life-cycle assessments (LCA) of PVT systems. They found that most studies focused on energy payback

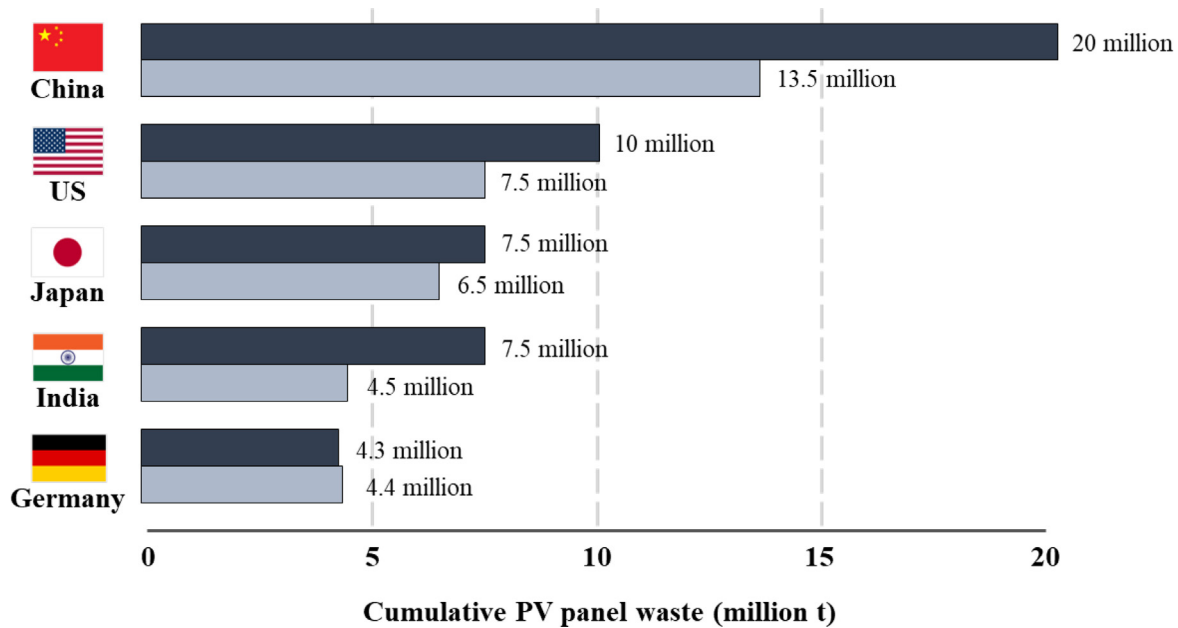


Fig. 27. Cumulative waste volumes of PV panels by 2050, by country (IRENA).

time (EPBT) and greenhouse gas payback time (GPBT). The EPBT and GPBT presented in most studies were 1–4 years and 0.8–4 years. Lamnatou and Chemisana (2017) reviewed literature on PVT systems from an environmental perspective. They dealt with environmental concerns, recycling of certain materials and components, and durability and lifetime of materials and components with respect to performance factors, which affect the performance of the PVT, such as PV cell materials, heat transfer fluids, and CPVT configuration. Abadeh et al. (2018) performed economic and environmental analyses using three different nanofluids; TiO₂-water, Al₂O₃-water, and ZnO-water as coolants in PVT systems. They found that the system size and materials can be reduced by 32%, 33%, and 24% in the order of TiO₂, ZnO, and Al₂O₃. In addition, they found that emission generation (NO_x, SO₂, CO, CO₂, etc.) could be reduced by 17% compared to conventional PV systems. Kazemian et al. (2020) tested a mixture of ethylene glycol (EG) and pure water from an energy, exergy, and environmental perspective. Results showed a CO₂ reduction of up to 36.25 kg/three months compared to a conventional PV system. Tirupati Rao and Raja Sekhar (2022) examined the EPBT and CO₂ reduction for PVT systems. They found 6.53 to 11.38 years of EPBTs and CO₂ emission reduction of up to 18.09 tons for lifetime mitigation. Fig. 27 shows the cumulative waste volumes of PV panels by 2050, by country.

Recycling PV/PVT waste is not only important from an environmental perspective, but also for resource recovery and economic reasons. In OECD countries, approximately 29 million tons of PV waste are expected to be generated by 2058 (Mahmoudi et al., 2021). Many studies have focused on environmental protection and resource recovery. Domínguez and Geyer (2019) investigated the estimated cumulative waste volume of end-of-life PV systems in the United States and analyzed the reusable metals, including gold, silver, cadmium, gallium, indium, and tellurium. The metals are listed according to their economic value as aluminum (27%), silicon (23%), gold (13%), steel (13%), copper (12%), and silver (6%). Fig. 28 shows the percentages of the metals used in PV installations and economic value; (a) mass of metals, (b) economic value.

Faircloth et al. (2019) analyzed the PV waste situation in Thailand and evaluated the environmental and economic benefits of landfilling versus recycling. It was found that Thailand will

accumulate 5000 tons of waste by 2025 and generate at least 8000 tons of waste per year by 2030. Recycling PV waste generated revenues of up to \$0.48/kg. and had environmental and economic benefits. Maani et al. (2020) analyzed the environmental impact of different recycling methods for crystalline silicon (c-Si) and CdTe panels. They performed an LCA considering the delamination and material separation stages of the PV panels. Results showed that thermal-based recycling methods had a lower environmental impact than chemical and mechanical methods. Gautam et al. (2021) estimated that PV installations in India will reach 347.5 GW by 2030 and generate approximately 2.95 million tons of waste between 2020 and 2047. It was found that 70% of the \$64.5 trillion worth of waste metals could be recycled.

2.8. Summary

This study reviewed the research trends of PVT systems and categorized them according to fields such as design aspects, PCM, nanofluid, machine learning, hybrid system, CPVT, and environmental aspects for the last 10 years. The contents of each section are as follows.

- Design aspects: Absorber plate, collector shape, internal circulating fluid flow, filters, etc.
- PCM: Temperature reduction and efficiency increase
- Nanofluid: Performance evaluation according to the fluid used
- Machine learning: Evaluation of excellence, accuracy of models used
- Hybrid system: Combination with other renewable energy sources, performance improvement, compatibility
- CPVT: Performance evaluation by type of concentrator
- Environmental aspects: LCA, EPBT, GPBT analysis, waste resource recovery

Regardless of the classified fields mentioned above, the following topics were discussed with similarities in content.

- Increasing thermal and electrical efficiency of PVT systems
- The need for PVT system optimization
- Exploration of different solutions for heat dissipation in collector plates

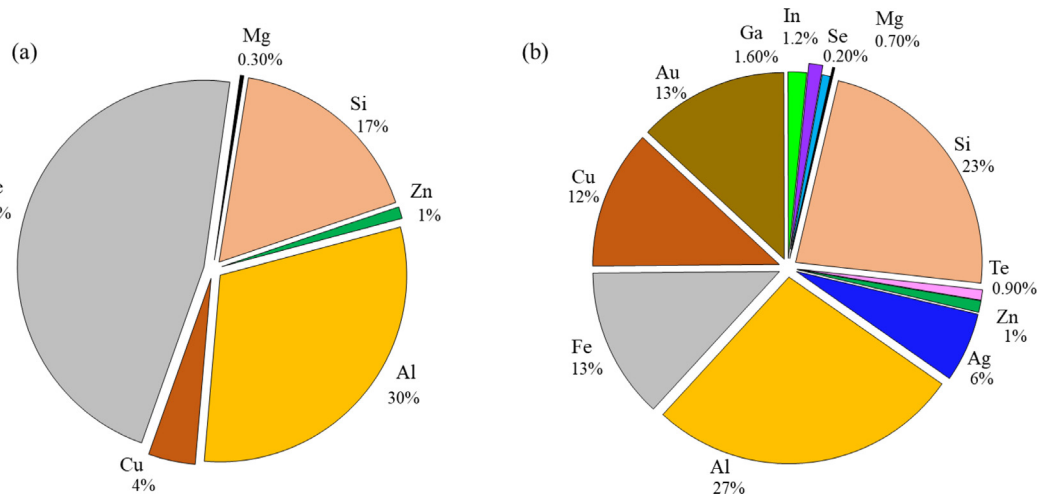


Fig. 28. The percentages of the metals used in PV installations and economic value; (a) mass of metals, (b) economic value (Domínguez and Geyer, 2019).

- Development of new materials
- Recognizing the environmental challenges of end-of-life PVTs
- Need for standardization of installation, maintenance, disposal, etc.

The main research trends in each sector are the development and application of new materials and the combination of systems. Since the 1970s, there has been a lot of research on improving the performance of solar energy systems. At this point, it is considered that there are limits to performance improvements, except for new approaches such as new materials and combinations of systems. On the other hand, lots of research dealt with environmental concerns as follows. They have already evaluated the economic feasibility of recovering waste materials and have been focusing on the concepts of resource recovery such as precious and critical metals. It is necessary to prepare countermeasures on recycling plans and environmental regulations because the waste of end-of-life PV modules increases over time.

Many studies focused on the performance increase in PVT systems considering design factors and performed lab-scale and simulation-based tests. It is essential to consider the design factors of the PVT system to apply on actual buildings, considering thermal load, installation, and climate conditions. Our research team conducted an energy simulation by applying a real-scale test of the PVT system connected with hot water storage in a typical residential house and analyzed the heat and electric production.

3. Simulation

The thermal energy of PVT systems installed in small houses is typically supplied as domestic hot water. However, there is only minimal quantitative analysis of how much the amount of heat generated from the installed system can supply toward the required amount of domestic hot water. Therefore, in this study, a simulation model was built using TRNSYS 18, a dynamic energy analysis program, to analyze the effect of the PVT system on the domestic hot water supply of small houses. Fig. 29 shows the schematic diagram of the PVT system.

3.1. Conditions of the simulation model

Fig. 30 shows the simulation model. The target building was a small-scale house (standard for four people). The hot water usage and operating schedules were set based on the ASHRAE Handbook 2011 HVAC application. Considering the target building, the

Table 6

Component conditions.

Parameter	Value
Location	Kagoshima Ulsan Seoul Toronto
Building model	Small-scale Residential building
DHW schedule	254 L/day
DHW temperature	60 °C
Supply water temperature	16 °C
PVT module (Type 560)	Size 1800 × 900 × 10EA
	Collector slope 30°
Heat storage tank (Type 4c)	Volume 0.3 m ³
Circulating pump (Type 3b)	Flow rate 50 L/min
	Power consumption 0.37 kW

capacity of the PVT module was 3 kW. The PVT module size was 1.8 m × 4.5 m, and the two modules were positioned in parallel. Hot water from the PVT was supplied to the hot water storage tank (HWST). When the temperature of the hot water was below 60 °C, it was heated by a boiler. The temperature of the tap water to fill the tank was set to 16 °C. Table 6 shows the component conditions.

In addition, a case study was conducted based on the PVT installation location, angle, installation capacity, and hot water load to quantitatively identify the effect of each design factor on the system performance. Table 7 indicates the case conditions.

3.2. Results

This study performed a simulation to analyze the effect of a PVT system on the hot water load in small-scale houses.

3.2.1. Heat and electricity production by location

To compare the heat and power production of PVT systems by considering latitude and climate, the target cities were Seoul and Ulsan in the Republic of Korea, Kagoshima in Japan, and Toronto in Canada. Fig. 31 shows the climatic condition according to locations; (a) target cities, (b) monthly solar radiation.

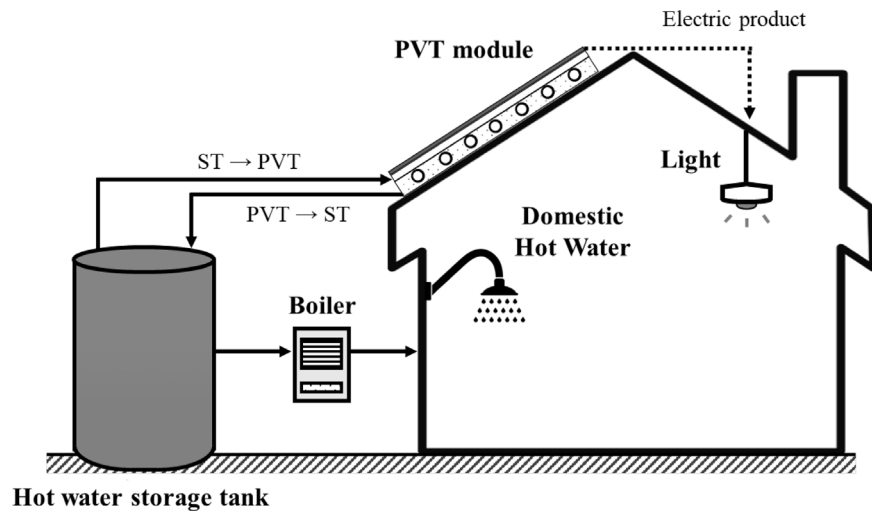


Fig. 29. Schematic of PVT system.

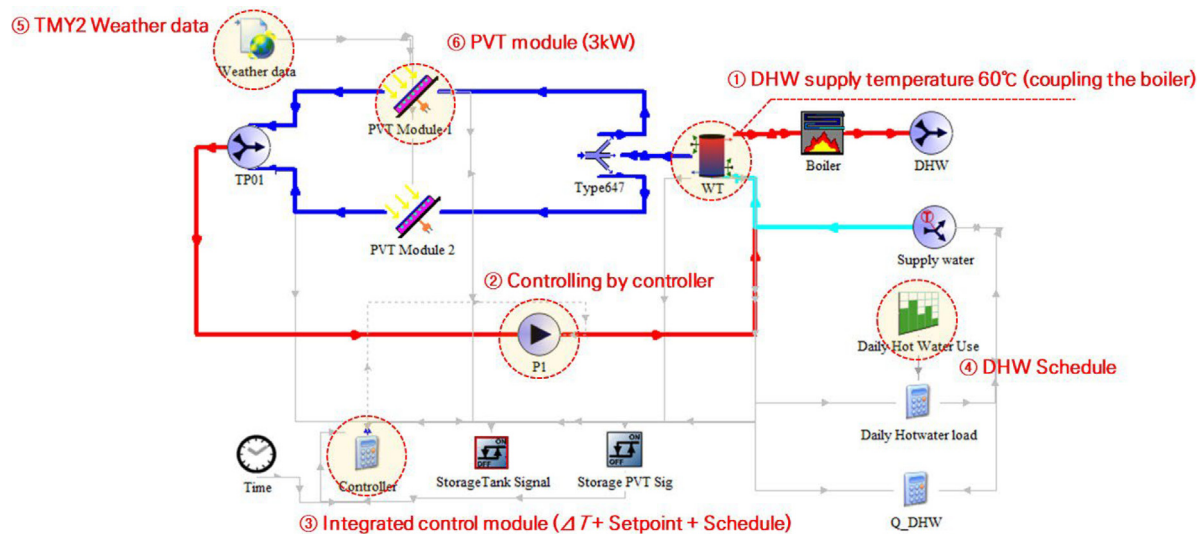


Fig. 30. Simulation model.

Table 7
Case conditions.

Case	Capacity (kW)	Location (Latitude)		Angle (°)	DHW (L/day)
Case 1	1-1	Kagosima (31° 33')	Japan	0	254
	1-2			30	
	1-3			60	
Case 2	2-1	Ulsan (35° 32')	Korea	0	
	2-2			30	
	2-3			60	
Case 3	3-1	Seoul (37° 33')		0	
	3-2		30		
	3-3		60		
Case 4	4-1	Toronto (43° 71')	Canada	0	
	4-2			30	
	4-3			60	
Case 5	3	Seoul (37° 33')	Korea	45	330
Case 6	6				
Case 7	10				
Case 8	3				178
Case 9					

Fig. 32 shows the annual energy production and system efficiency for each city. PVT systems in cities with low latitudes can

generate higher annual heat. Kagoshima produced 4406 kWh of heat annually, 22% more than Seoul, which generated the lowest

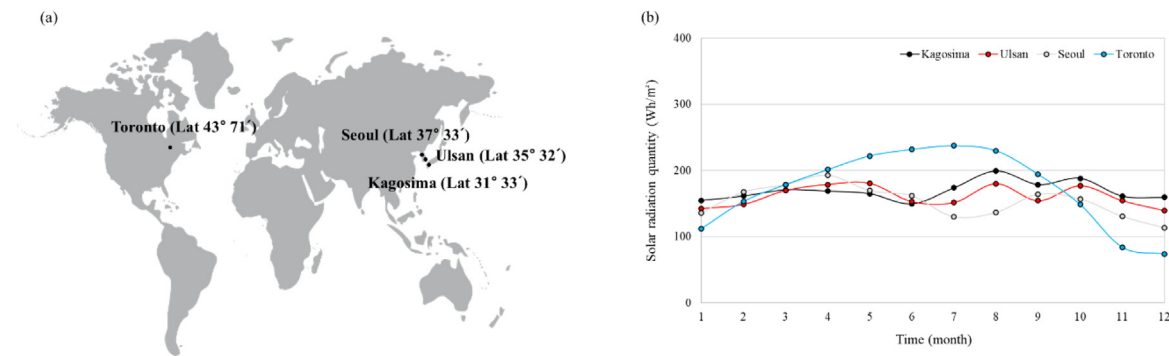


Fig. 31. Climatic condition according to locations; (a) target cities, (b) monthly solar radiation.

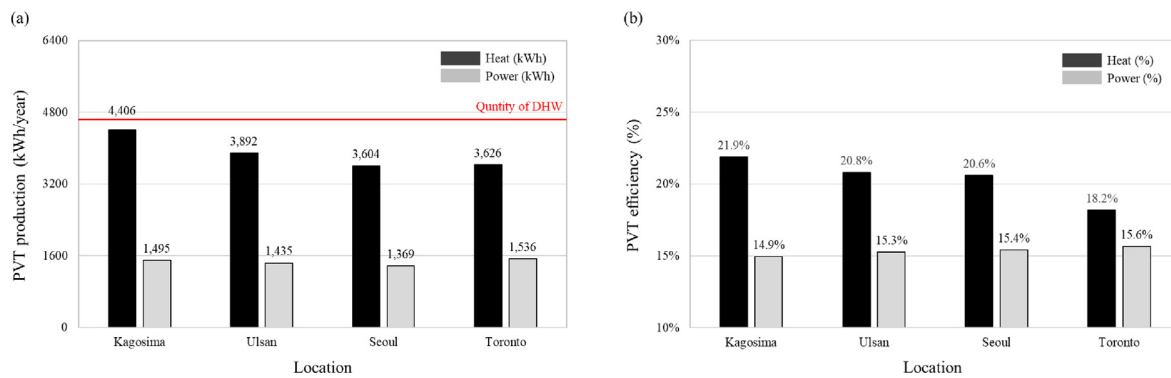


Fig. 32. Annual performance according to locations; (a) energy production, (b) energy efficiency.

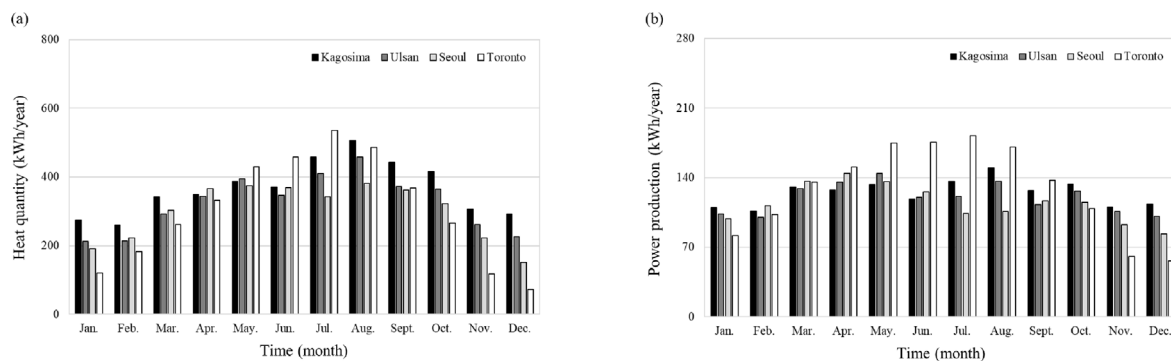


Fig. 33. Monthly performance according to locations; (a) heat production, (b) electricity production.

heat. Seoul and Toronto had similar heat production. Electricity production had a similar trend; Toronto produced the highest annual output of 1536 kWh, whereas Seoul produced the lowest. 1369 kWh. The difference in electricity production between the cities was 12%.

The monthly energy production at an installation angle of 30° was higher in each region during summer and lower during winter. Kagoshima had the highest overall annual production. There was no significant difference in monthly patterns between Seoul and Toronto, with Seoul showing a relatively small monthly difference of up to 61 kWh. However, Toronto had a larger difference between summer and winter (126 kWh). Fig. 33 shows the monthly performance according to locations; (a) heat production, (b) electricity production.

3.2.2. Heat and electricity production by angle

In general, for PV power generation, an appropriate angle is selected considering the latitude. However, because PVT must consider both thermal demand and production simultaneously,

it is necessary to review what angle is the most efficient at a specific latitude. Therefore, the analysis was performed by setting the installation angles of 0°, 30°, and 60° for each region.

In terms of heat production, the highest production was observed in the order 30°, 60°, and 0°. Kagoshima, which is located close to the equator, demonstrated a relatively low difference of approximately 12% between 30° and 0° compared to other cities (Fig. 34). For Toronto, which is located farthest from the equator, the difference between 30° and 0° was approximately 25%, which was the largest. However, when comparing 30° and 60°, Kagoshima had the largest difference, at 10%, whereas Toronto had the least difference, at approximately 7%. Similarly, the 30° sample exhibited the highest power output. However, when comparing 0° and 60°, Kagoshima, located closest to the equator, produced approximately 3% greater yields at 0° than at 60°.

In addition to the comparison of regional energy production conducted in Section 3.2.1, the effect of each angle was examined in more detail by adding 45° and 90° to the previously studied angles of 0°, 30°, and 60°, considering the subsequent empirical

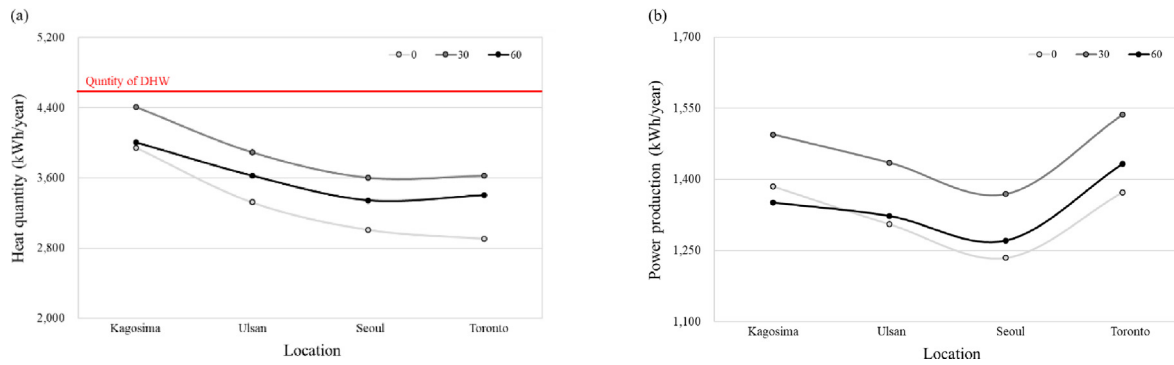


Fig. 34. Annual energy production by angles in cities; (a) heat production, (b) electricity production.

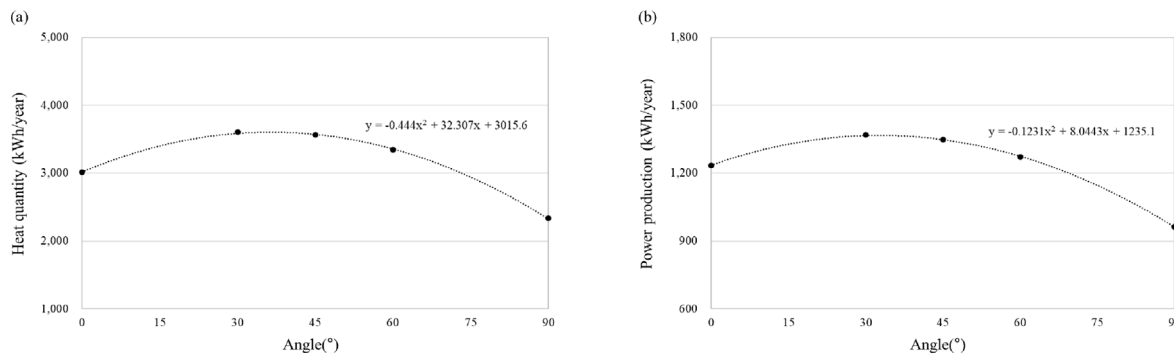


Fig. 35. Annual energy production by angles in Seoul; (a) heat production, (b) electricity production.

Table 8

Heat and electricity production by angle derived through simulations and equations.

Classification		0°	30°	35°	40°	45°	60°	90°
Heat	Simulation	3010	3604	–	–	3565	3343	2332
	Formula	3016	3585	3602	3597	3570	3356	2327
Power	Simulation	1234	1369	–	–	1348	1271	963
	Formula	1235	1366	1366	1360	1348	1275	962

experiments. Fig. 35 shows the annual energy production by angles in Seoul; (a) heat production, (b) electricity production.

If the resulting relationship between each angle is expressed as an equation, it would be as follows:

$$\text{Heat} = -0.444x^2 + 32.307x + 3015.6 \quad (1)$$

$$\text{Power} = -0.1231x^2 + 8.0443x + 1235.1 \quad (2)$$

Table 8 lists the heat and electricity production by angle derived through the simulations and equations. If 0°, 30°, 45°, 60°, 90°, 35°, and 40° are added and substituted into the equation, the result is as follows;

The error rates of the values derived from simulations and equations show a maximum of 0.53% and 0.31% for heat and electricity, respectively, and an average of 0.29% and 0.14%, respectively. In the case of production derived by the equation, both heat and electricity showed maximum values at 35°. For heat production, the highest value was observed at 35°, followed by 40°, 30°, 45°, 60°, 0°, and 90°. For electricity production, the order from the highest values was 35°, 30°, 40°, 45°, 60°, 0°, and 90°. Because PVT must consider both heat and electricity production, the installation angle should be selected considering both factors.

3.2.3. Heat and electricity production by capacity

To conduct subsequent empirical experiments, the energy production of the different regions was compared based on changes

in capacity using the Seoul area as the baseline case. As the capacity increased from 3 kW, the electricity production increased by approximately 195% and 321% for 6 kW and 10 kW, respectively, demonstrating a similar increase in capacity. However, for heat production, the increase in capacity was not as large, with increases of approximately 96% and 107% for 6 kW and 10 kW, respectively. Regarding efficiency, there was no significant difference in electricity production by capacity (less than 0.1%). Conversely, for heat production, the difference in efficiency was more significant, with a greater difference observed as the capacity decreased, reaching approximately 9%. Fig. 36 shows the annual energy production and efficiency by capacities.

3.2.4. Heat and electricity production by domestic hot water supply

A case study was conducted to predict PVT performance based on domestic hot water (DHW) consumption. The study involved increasing the consumption to 330 L/day and decreasing it to 178 L/day, with the base case being 254 L/day, as presented by ASHRAE.

Regarding heat production, when DHW consumption increased by 30%, approximately 11% more heat was produced than in the base case. When the amount decreased by 30%, production was approximately 15% lower.

Conversely, in the case of electricity production, the difference in production based on the increase and decrease in DHW consumption did not show a large difference at the maximum level (approximately 1%). Production efficiency demonstrated a similar pattern to production, with average efficiencies of approximately 21.0%, 22.2%, and 18.7% for heat, and approximately 15.4% for electricity, a marginal difference in all cases. Fig. 37 shows annual energy production and efficiency by DHW supply.

3.2.5. Summary

In this study, the DHW consumption of small households was reviewed by considering different design conditions to evaluate

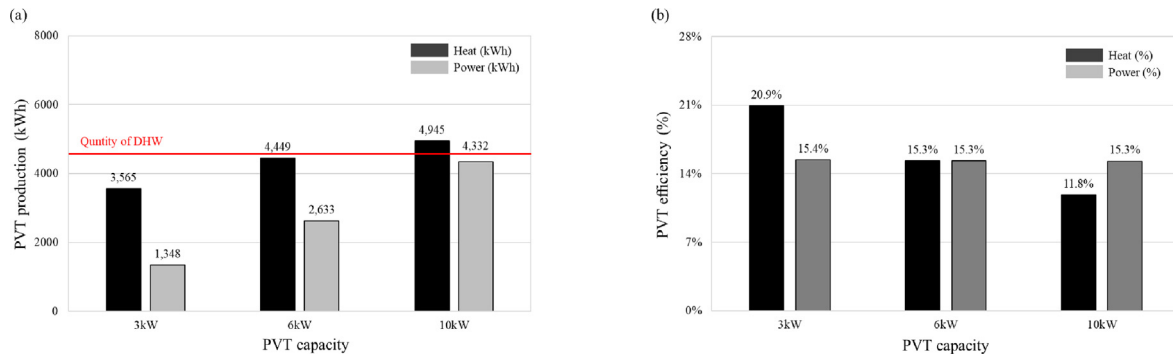


Fig. 36. (a) Annual energy production by capacities and (b) Annual energy efficiency by capacities.

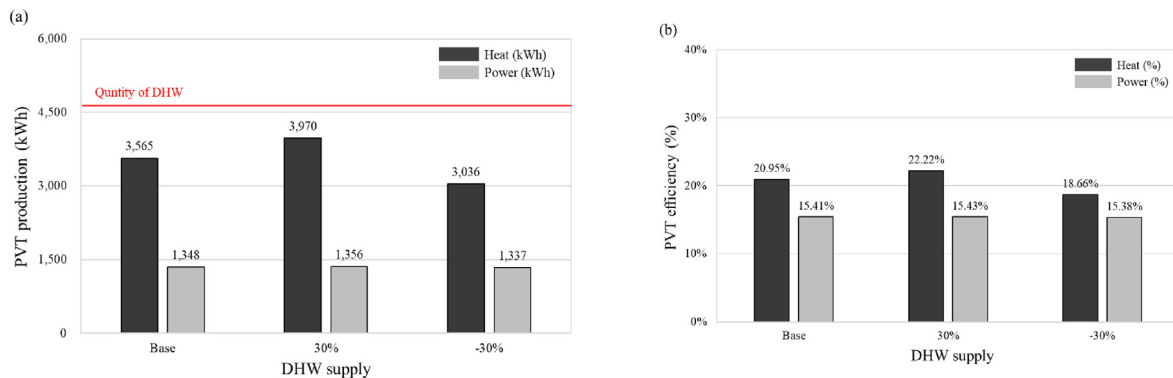


Fig. 37. (a) Annual energy production by DHW supply and (b) annual energy efficiency by DHW supply.

the supply of the PVT system. The system performance was evaluated based on changes in the location (latitude), installation angle, installation capacity, and DHW consumption. Table 9 shows the simulation results.

- Based on regions (latitude), Kagoshima, which had the highest heat production, produced 22% more heat than Seoul, which had the lowest. Toronto, which had the highest electricity production, produced 12% more heat than Seoul, which had the lowest.
- For small households (based on four people), it was confirmed that a 3 kW PVT system could supply approximately 95%, 84%, 78%, and 78% of the DHW consumption in Kagoshima, Ulsan, Seoul, and Toronto, respectively.
- For heat production based on the installation angle, the production at 30° was on average 18% higher than that at 0° and 8% higher than that at 60°. Electricity production at 30° had an average of 10% more than at 0° and 9% more than at 60°, indicating a marginal difference compared to that of heat.
- For heat and electricity production based on the change in capacity, electricity increased by 195% and 321% for 6 kW and 10 kW, respectively, compared with 3 kW, indicating a similar pattern to the increase in capacity. However, heat production increased by only 96% and 107%, respectively, indicating a marginal increase.
- Regarding heat production based on the change in DHW consumption, 11% more heat was produced when the usage increased by 30%, and 15% less heat was produced when the usage decreased by 30%. In the case of electricity, the difference was insignificant at the 1% level.

4. Conclusions

We reviewed studies from the last ten years to confirm the status of PVT system technology development, use, and performance by field and to present quick and referenceable guidelines for those working in related fields. The applicability of a hot water supply system using a PVT module was reviewed using a dynamic energy analysis program. The results are as follows.

- The design structure of a PVT system has a significant influence on its performance. Several studies have analyzed the effects of different components of PVT modules. Research has progressed from the design change of the heat collecting part—which has been studied steadily since the PVT system was first introduced—to performance analysis based on the change in important components such as new materials and shapes of the absorber, shape of the air channel geometry, adhesives, and glazing. Research on performance analysis, long-term durability, and maintainability based on changes in more detailed components such as coating materials is also being conducted.
- Combining the PVT module with PCMs and the use of nanofluids as circulating water suggests future research directions for the PVT module market, which is becoming established. Research is being conducted to improve and confirm the thermal properties, heat transfer improvement, durability, environmental impact, and compatibility of PCMs and nanofluids.
- Regarding heat and electricity production by installation location (Kagoshima, Ulsan, Seoul, Toronto), the closer to the equator, the more the heat production. However, in terms of electricity production, Toronto, which is farthest from the equator, had the highest production. This is thought to

Table 9
Simulation results.

Classification		Angle	Heat		Power	
			Efficiency (%)	Production (kWh)	Efficiency (%)	Production (kWh)
Location (Latitude)	Kagoshima (31° 33')	0°	21.1	3,946	15.0	1,385
		30°	21.9	4,406	14.9	1,495
		60°	22.5	4,005	15.0	1,351
	Ulsan (35° 32')	0°	19.5	3,323	15.3	1,305
		30°	20.8	3,892	15.3	1,435
		60°	21.3	3,625	15.3	1,323
	Seoul (37° 33')	0°	19.3	3,010	15.5	1,234
		30°	20.6	3,604	15.4	1,369
		60°	21.2	3,343	15.4	1,271
	Toronto (43° 71')	0°	15.9	2,909	15.7	1,373
		30°	18.2	3,626	15.6	1,536
		60°	18.8	3,402	15.7	1,432
Capacity	3 kW	45°	20.9	3,565	15.4	1,348
	6 kW		15.3	4,449	15.3	2,633
	10 kW		11.8	4,945	15.3	4,332
Hot water load	254 L/day	45°	20.9	3,565	15.4	1,348
	330 L/day		22.2	3,970	15.4	1,356
	178 L/day		18.7	3,036	15.4	1,337

be the result of the difference in solar radiation during the summer. Therefore, it is necessary to consider the external environment of an area based on the required energy (heat or electricity).

- Targeting small-scale households (based on four people), a 3 kW-class PVT system demonstrated a maximum supply rate of 95% and a minimum of 78%. Further research is required on usable thermal energy.
- Regarding heat and power production based on installation angles (0°, 30°, 60°), the highest production was at 30°, regardless of the region (latitude). However, the design should consider the regional characteristics of the target area and period of use of the building because of the large difference in production by season.
- Electricity production had a similar pattern as the capacity increased (3 kW, 6 kW, 10 kW); however, the difference in heat was insignificant.
- Regarding heat and electricity production based on changes in DHW usage (70%, 100%, 130%), more heat was produced when the usage was high and less when the usage was low; however, the difference in electricity was only 1%. Therefore, additional installations should be considered when a significant amount of DHW is used. If the purpose is to generate electricity, it is considered that the change in the installed capacity has no significant effect.
- Only a small number of studies within the last ten years in each part were reviewed; differences in the overall flow in PVT research were revealed.
- In addition, there is a limit to the comparison of targets in the performance analysis based on the design factors. Thus, a comprehensive analysis that considers more diverse conditions will be performed in future.

The PVT system is an important element and energy technology for achieving a low-carbon green architecture. However, only limited PVT modules are commercialized and usable. Currently, numerous studies are being conducted and efforts are being made to improve the performance and commercialize PVT systems by combining them with different application fields. We believe that

future researchers will quickly refer to it through an ongoing review and design factor analysis to accelerate commercialization. In addition, it is expected that the dissemination of practical technologies will be activated by securing economic feasibility and performance through optimization and continuous technology development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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