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Heat Pump Application for Energy Reduction in Compact Heat Exchanger Manufacturing

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Abstract

This study investigates the replacement of electric heaters with a vapour compression heat pump system for hot water production in the cleaning process of compact heat exchangers, where a bath temperature of 60°C must be maintained. A transient computational model was developed to estimate hour-by-hour heat pump performance, accounting for variations in ambient air temperature and part-load operation. The electricity consumption and greenhouse gas emissions of the two systems were quantified and compared. The heat pump system achieved a 67.3% reduction in electricity consumption relative to the electric heater, reducing annual electricity consumption from 51,032 kWh to 16,699 kWh. The coefficient of performance ranged between 2.99 and 3.24 under actual operating conditions in Chonburi Province, reflecting the influence of local ambient temperatures and part-load operation between 55% and 69%. GHG emissions were reduced by 20,551 kg CO_2-eq per annum, with annual electricity cost savings of THB 137,335 and a payback period of 10.2 years. These findings confirm that heat pump technology is a viable and effective approach for reducing energy consumption and carbon footprint in thermal processes within the heat exchanger manufacturing.

Keywords

Heat pump, Energy reduction, Coefficient of performance (COP), Compact heat exchanger, Cleaning

Nomenclature

COP_{HP}	Coefficient of performance of heat pump at 100% load (-)
$COP_{HP,act}$	Actual coefficient of performance of heat pump (-)
f_{PL}	Part load correction factor (-)
PL	Part load (-)
t_a	Ambient air temperature (°C)

1. Introduction

The industrial sector consumes large amounts of energy, resulting in substantial greenhouse gas (GHG) emissions; improving energy efficiency within manufacturing processes can therefore reduce energy usage, generate cost savings, and decrease associated emissions. Thailand is a major manufacturer of automotive parts, particularly within the Eastern Economic Corridor (EEC) region, where approximately 1,450,000 vehicles were produced in 2025 (The Federation of Thai Industries (FTI), 2026), with output distributed across both domestic and export markets. Heat exchanger components — including evaporator and condenser coils for air conditioning systems, and radiators for engine cooling — are essential automotive parts. In the final stage of production, assembled coils undergo a cleaning process to remove metal debris resulting from welding or surface coating. This is achieved by immersing the heat exchanger components in a water bath or solution maintained at 50–90 °C for a specified duration, a process that requires continuous thermal energy input to sustain the required temperature.

1.1 Energy Challenges in Cleaning Processes for Compact Heat Exchanger Manufacturing

Thailand's Eastern Economic Corridor (EEC), encompassing Chonburi, Rayong, and Chachoengsao provinces, is home to numerous automotive component manufacturers, many of which produce compact heat exchangers such as air conditioning condensers, evaporators, and radiators. The manufacturing of these components requires thorough cleaning to remove metal debris, grease, and cutting fluid residues generated during welding and surface coating operations. This is achieved through hot water immersion, whereby components are passed through baths maintained at 50–90 °C, with the precise temperature depending on the manufacturer's specification.

Water heating within these immersion tanks typically relies on electric heaters or natural gas boilers, both of which are energy intensive and contribute to GHG emissions. Natural gas boilers generate Scope 1 emissions through direct on-site combustion, whilst electric heaters produce Scope 2 emissions through grid electricity consumption. These emission scopes are defined under standardised protocols for calculating the carbon footprints of organisations (CFO) and products (CFP), established by the Thailand Greenhouse Gas Management Organisation (TGO) and aligned with international standards ISO 14064-1 and ISO 14067.

Given the high electricity consumption associated with conventional electric heating, adopting an alternative heating method with lower electrical energy demand would enable manufacturers to reduce energy costs and decrease process-related carbon dioxide emissions.

1.2 Heat Pump Technology in Industrial Applications

Heat pump systems represent a more energy-efficient alternative to conventional electric heaters for industrial water heating applications. Air-to-water heat pumps are characterised by a Coefficient of Performance (COP) — defined as the ratio of heat output to electrical energy input — that typically ranges between 2 and 5.5 on an annual average basis (Byrne et al., 2021). A COP of 4.0 implies that heat pump water heaters consume approximately one-third of the electrical energy of conventional electric resistance heaters.

Current heat pump technology can produce hot water at temperatures up to 90 °C when using R744 (carbon dioxide) as the working fluid, making it suitable for the full range of immersion cleaning temperatures encountered in compact heat exchanger manufacturing. For processes requiring hot water temperatures not exceeding 70 °C, a conventional vapour-compression heat pump employing standard refrigerants is sufficient. This thermal capability, combined with the inherent efficiency advantage of heat pump operation, makes heat pump systems a compelling replacement for electric heaters in the cleaning processes described in Section 1.1.

1.3 Research Objectives and Scope

This work investigates the replacement of conventional electric heaters with a heat pump system for hot water production in the cleaning process of compact heat exchangers, with the objectives of reducing electricity consumption, decreasing GHG emissions, and assessing investment feasibility. The research is conducted within the context of small-scale heat exchanger production facilities and focuses on quantifying electricity savings and GHG emission reductions achievable through heat pump integration.

The scope is defined by selecting a heat pump heating capacity to meet the target hot water supply and maintenance temperature of 60 °C, representing typical operating conditions for the immersion cleaning processes described in the preceding sections.

2. Literature Review

Within the automotive sector, the utilisation ratios of natural gas and electricity are notably similar, and the overall energy consumption is substantial. Data derived from a study of 17 automotive industrial plants in China (Lv et al., 2026) reveal that electricity accounted for 48.6% and natural gas for 50.6% of the total energy utilised by the facilities. These findings are consistent with energy consumption patterns observed in the Polish automotive industry (Javed et al., 2023), which demonstrated electrical and thermal energy usage of 45.8% and 54.2%, respectively.

2.1 Current Heating Methods in Manufacturing

The final cleaning stage in compact heat exchanger production involves immersing finished components in a hot water bath to remove manufacturing residues, with the water temperature typically maintained at 55 °C (Sakhapov, 2024). The heat source for this process is provided by either electric heaters or combustion-based heating systems, both of which result in high energy consumption that directly impacts production costs.

Among small and medium-scale compact heat exchanger manufacturers in Thailand, electric resistance heaters and natural gas-fired boilers are the predominant heating technologies. Small-scale manufacturers favour electric resistance heaters and small-scale electric boilers owing to their low installation costs and compact footprint. Electric resistance heaters convert electrical energy directly into thermal energy via heating elements, offering the operational advantage of precise and stable temperature control within the water reservoir. Medium-scale manufacturers requiring larger hot water volumes typically employ natural gas-fired boilers; however, combustion-based systems yield lower overall thermal efficiency than electric heater systems, besides generating direct on-site GHG emissions.

2.2 Heat Pump Systems: Principles and Performance

Integrating a heat pump into the process for temperature elevation, as a substitute for conventional electric heaters or gas boilers, is depicted in Figure 1. Operationally, the heat pump absorbs thermal energy from the ambient surroundings through a working fluid within the evaporator. The fluid is then compressed by a vapour compressor to high pressure and temperature. Following this, thermal energy is discharged at the condenser, resulting in a temperature decrease of the working fluid. Ultimately, the fluid undergoes pressure reduction via an expansion valve and re-enters the evaporator to complete the thermodynamic cycle.

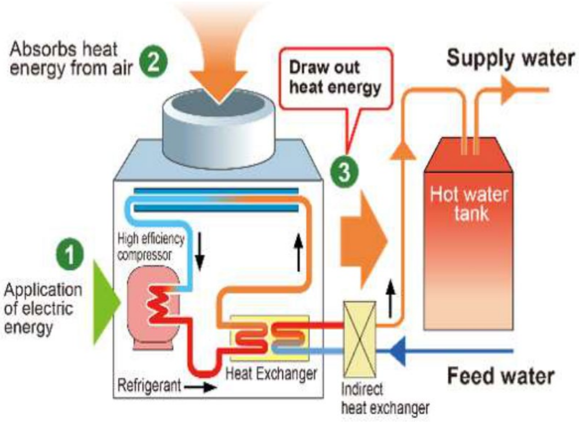

Figure 1. Heat Pump Water Heater System (Mitsubishi Electric Kang Yong Watana Co Ltd, 2022)

The utilisation of heat pumps for hot water generation not only facilitates energy saving but also mitigates GHG emissions because of reduced energy consumption (Javed et al., 2023). It yields an indirect benefit by lowering the ambient temperature of the surroundings (Yamaguchi et al., 2025), since the thermodynamic operation of the heat pump necessitates the extraction of thermal energy from the surrounding environment to heat the water.

3. Methods

This section presents the analytical framework employed to compare the thermal and environmental performance of a heat pump against a conventional electric water heater under equivalent operating conditions. The heat loss analysis, system configuration and sizing, and energy and GHG emissions assessment methods are described establishing the basis for the quantitative analysis reported in Section 4.

3.1 Heat Loss Analysis

The case study facility is a heat exchanger manufacturer in Mueang Chonburi District, Chonburi Province (latitude: 13.34°N, longitude: 101.00°E). Meteorological data were obtained using the Photovoltaic Geographical Information System (PVGIS) tool (Joint Research Centre-European Commission, 2026; Milosavljević et al., 2022), from which a Typical Meteorological Year (TMY) data file was generated. The design-day method (Bagherzadeh et al., 2025) was applied to estimate the maximum required heating capacity. In accordance with the National Renewable Energy Laboratory (NREL) guidance, heating equipment sizing is based on the 99th percentile cold-weather temperature for the location (Grimes-Casey et al., 2024). The day exhibiting the lowest ambient air temperature was therefore selected as the design day for heat pump sizing (Figure 2).

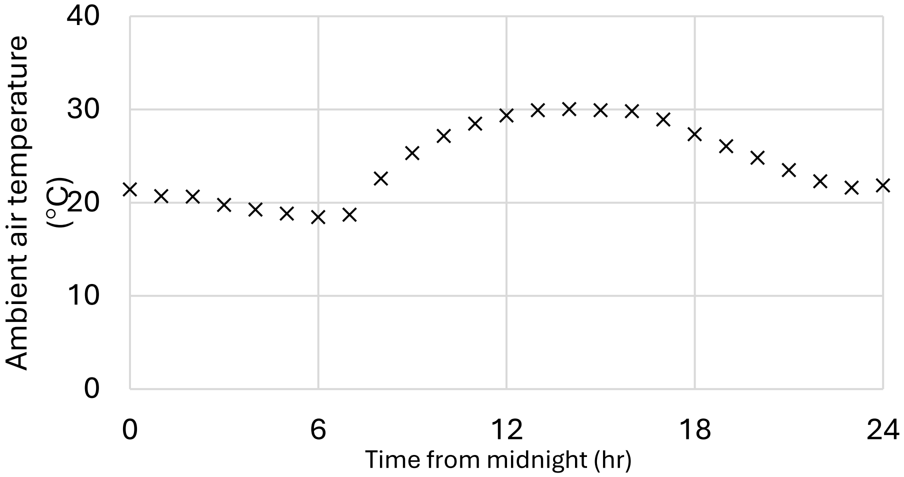

Figure 2. The design day ambient air temperature

For this investigation, the water bath is rectangular with dimensions of 1 m × 1 m × 1.2 m, containing water to a depth of 1 m, corresponding to a total volume of 1,000 L. The upper surface of the bath is open and exposed to ambient air. The components to be cleaned are fabricated from aluminium alloy, with each batch having a mass of 15 kg. The thermophysical properties of aluminium alloy are taken as a specific heat capacity of 0.897 kJ kg^{-1} K^{-1} (Mahdi et al., 2025) and a density of 2,702 kg m^{-3} (HZW Technology, 2023).

The assumed operational schedule is from 08:30 to 16:30, with the 08:00–08:30 timeframe reserved for preparation, 16:30–17:00 for teardown and cleaning, and a 1-hour midday break. The actual machine operational time is therefore 7 hours.

In the cleaning process of compact heat exchanger products, 1,000 litres of water are heated to 60 °C. The system operates five days per week, Monday to Friday. Heat losses from the bath during shutdown from the evening until the following morning, as well as over the weekend shutdown period, were considered.

Heat losses within the process are categorised into three primary mechanisms:

1. *Product heat absorption:* The product is assumed to have an initial temperature equal to the ambient air temperature prior to immersion.
2. *Heat carried by adhering water:* Thermal energy exits the system via a water film adhering to the product surfaces upon extraction from the reservoir.
3. *Ambient heat dissipation:* Heat loss occurs from the tank water to the surrounding ambient air.

The calculated heating rate requirements (kW) throughout a typical day are shown in Figure 3.

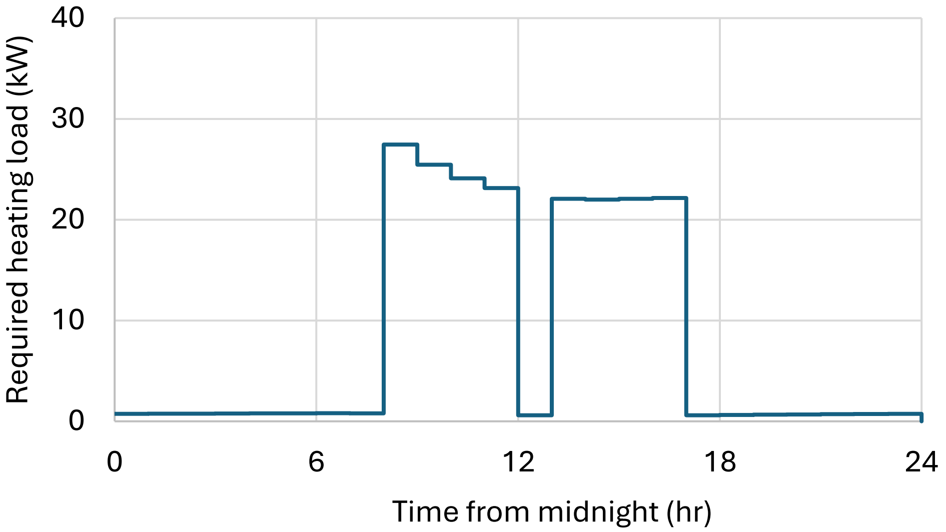

Figure 3. The required heating energy

3.2 System Description and Configuration

The two hot water production configurations compared in this study are illustrated in Figure 4. In the electric heater configuration (Figure 4a), electricity is supplied directly to a heater coil immersed in the bath, raising and maintaining the water temperature at 60°C. In the heat pump configuration (Figure 4b), heat is generated at the condenser via refrigerant-to-water heat exchange, and the heated water is subsequently circulated into the bath by a dedicated water pump. Based on the required heating load (Figure 3) and the system sizes available in the market, the total capacity of the heating system is selected to be 40 kW. Tables 1 and 2 provide the full-load capacity and full-load power input of the heat pump at various intake air temperatures and three outlet water temperatures. The estimated corresponding coefficients of performance (COPs) are presented in Table 2.

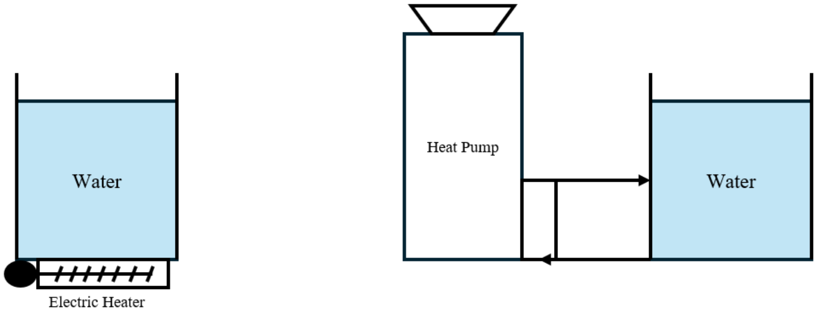

Figure 4. (a) Electric heater. (b) Heat pump water heater.

Table 1. Heat pump capacity (full load)

Capacity (kW)		Intake air temperature (°C)						
		16	20	25	30	35	40	43
Outlet water temperature (°C)	55	49.3	54.4	60.7	63.0	64.9	65.7	66.2
	60	45.4	49.8	56.1	61.0	65.8	66.5	67.1
	65	44.8	49.1	55.4	60.8	66.3	66.9	67.4

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Table 2. Heat pump power input (full load)

Power input (kW)		Intake air temperature (°C)						
		16	20	25	30	35	40	43
Outlet water temperature (°C)	55	17.4	17.7	18.6	19.1	19.6	19.9	20.1
	60	18.1	18.6	19.1	20.4	20.9	21.3	21.5
	65	19.4	19.8	20.4	21.3	22.4	22.7	22.9

Table 3. Heat pump coefficient of performance (COP) at full load

COP (-)		Intake air temperature (°C)						
		16	20	25	30	35	40	43
Outlet water temperature (°C)	55	2.83	3.07	3.26	3.30	3.31	3.30	3.29
	60	2.51	2.68	2.94	2.99	3.15	3.12	3.12
	65	2.31	2.48	2.72	2.85	2.96	2.95	2.94

3.3 Heat pump transient performance estimation

Hour-by-hour electricity consumption of the heat pump for the design day was estimated based on the hourly COP changes with respect to ambient air temperature and a load correction factor. The computational model development is presented as follows.

The COP of the heat pump water heater for an outlet water temperature of 60°C (Table 3) was fitted to a second-order equation (Equation 1). The coefficient of determination (R^2) was found to be 0.985.

$$COP_{HP} = 1.3229 + 0.0925t_a - 0.0012t_a^2 \qquad \text{Eq. (1)}$$

The part load COPs at various loads for a hot water outlet temperature of 60°C are provided in Figure 5. Based on Figure 5, the part load correction factor (Neto et al., 2024; Socal, 2021) has been developed (Equation 2). The actual COP of the heat pump is calculated using Equation 3.

$$f_{PL} = 0.9599 + 0.4140PL - 0.3746PL^2, \quad 0.5 \le PL \le 1.0 \qquad \text{Eq. (2)}$$

$$COP_{HP,act} = f_{PL} \cdot COP_{HP} \qquad \text{Eq. (3)}$$

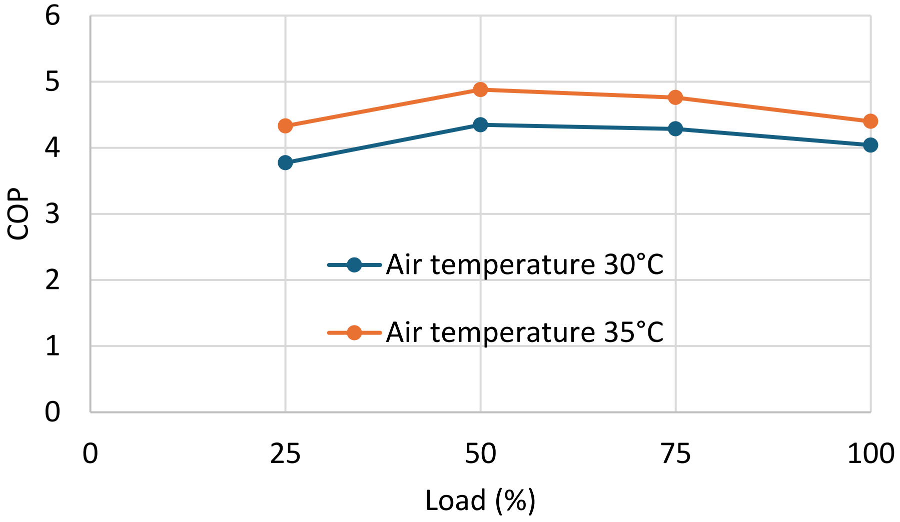

Figure 5. Part load COPs

4. Results and Discussion

This section presents the results of the performance analysis of the heat pump, energy consumption comparison, and financial and emissions assessment for the two hot water production configurations. The performance of the heat pump system is evaluated using COP under part-load and varying ambient conditions. The electricity consumption and GHG emissions of the two heating systems are quantified and compared. The electricity cost saving and payback period of the heat pump hot water system are quantified.

4.1 Coefficient of Performance (COP) Analysis

The coefficient of performance of the heat pump system varies with the ambient air temperature and the load. Figure 6 presents the COP of the heat pump system for a typical day, ranging between 2.99 and 3.24 and operating at part-load (between 55% and 69%). These COP values are lower than the rated value at the reference conditions specified in the manufacturer's data.

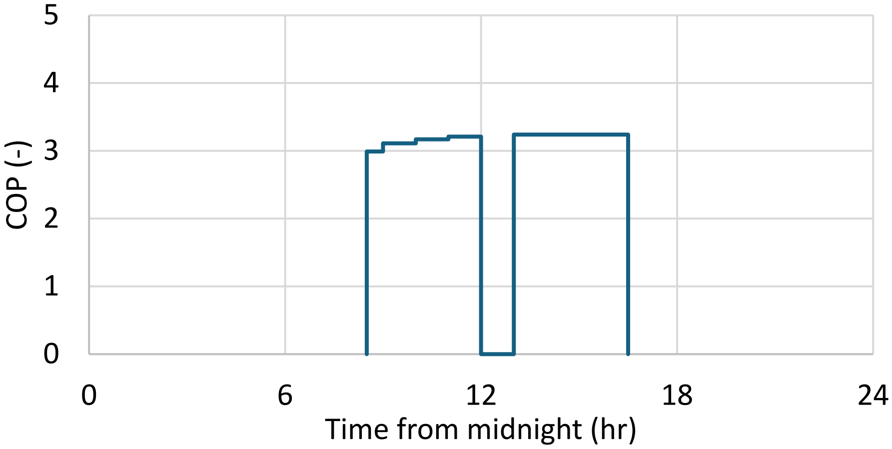

Figure 6. The COP of the heat pump hot water system

4.2 Energy Consumption Comparison

From Figure 3, when the system starts up in the morning, it generates heat to raise the water temperature in the bath back to 60°C and to compensate for heat lost to the environment. The tank requires the highest heating rate during startup because of heat lost throughout the night and the relatively low ambient air temperature. Once the production process is running, the water temperature in the system is maintained, and the primary heat requirement comes from heat absorbed by the products. In this cleaning process, the cycle time is 40 s, operating from startup until the system shuts down at 16:30. Using the method described in Section 3.3, the daily and weekly electricity consumptions of the heat pump hot water system were calculated (Table 4). The heat pump system consumes 67.3% less electricity than the electric heater, resulting in significant electricity savings.

Table 4. Electricity consumption comparisons

Day	Electric Heater (kWh)	Heat Pump Water Heater (kWh)
Mon	211.48	78.45
Tue	192.48	60.67
Wed	192.48	60.67
Thu	192.48	60.67
Fri	192.48	60.67
Week	981.39	321.13

4.3 Financial and Emissions Assessment

A financial analysis comparing the heat pump system with the electric heater was conducted; the results are shown in Table 5. The current electricity price of THB 4 per kWh was used for the analysis. It was found that the heat pump system can save THB 137,335 per year in electricity costs compared to the electric heater system. The payback period was found to be 10.2 years, because of the significantly higher capital cost of the heat pump system compared to the electric heater system.

For analysing the reduction in GHG emissions, an emission factor of 0.5986 kg CO_2-eq per kWh referenced from (The Thailand Greenhouse Gas Management Organization (TGO), 2023) was applied. The heat pump system reduces GHG emissions by 20,551 kg CO_2-eq annually compared to the electric heater system.

Table 5. Financial analysis of hot water production systems

Item	Electric heater	Heat pump water heater
Annual electricity consumption (kWh)	51,032	16,699
Annual GHG emissions (kg CO_2-eq)	30,547	9,996
Annual cost of electricity (THB)	204,129	66,794
Initial cost (THB)	-	1,399,900
Payback period (a)	-	10.2

5. Conclusions

This work investigated the replacement of electric heaters with a heat pump system for hot water production in the cleaning process of compact heat exchangers, to conduct energy and financial performance analyses. The heat pump system achieved a 67.3% reduction in electricity consumption relative to the conventional electric heater, reducing annual electricity use from 51,032 kWh to 16,699 kWh. Under actual operating conditions in Chonburi Province, the coefficient of performance ranged between 2.99 and 3.24, reflecting the influence of local ambient temperatures and part-load operation between 55% and 69%. The heat pump system reduced GHG emissions by 20,551 kg CO_2-eq per annum. The financial analysis demonstrated annual electricity cost savings of THB 137,335 and a payback period of 10.2 years.

Despite the relatively long payback period, the substantial energy savings and emissions reductions confirm that heat pump technology is a viable approach for reducing the carbon footprint of thermal processes in heat exchanger manufacturing. It should be noted that the computational model was applied to the design day, with weekly calculations conducted assuming worst-case conditions; the results therefore represent a conservative estimate of system performance. Future work should extend this analysis to hour-by-hour simulations over a full annual cycle. Field validation of the model-predicted performance is also recommended.

CRediT authorship contribution statement

Pramote Laipradit: Conceptualisation, Data curation, Formal analysis, Funding acquisition, Investigation, Software, Visualisation, Writing – original draft. **Lu Aye:** Conceptualisation, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualisation, Writing – original draft, Writing – review & editing.

Data availability

The data that support the findings of this work are available from the corresponding author (LA) upon reasonable request.

Declaration of competing interest

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

AI Usage Statement

A large language model was used to support language refinement and structural editing during manuscript preparation. The authors retain full responsibility for the manuscript's content, and all analyses, interpretations, and conclusions were developed and independently verified by the authors. AI assistance was limited strictly to improve clarity and readability.

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Biographies

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Lu Aye is the leader of the Renewable Energy and Energy Efficiency Group in the Department of Infrastructure Engineering at the University of Melbourne, Australia. With more than 45 years of engineering experience, he has built an international reputation as an expert in low-carbon technologies for built environment applications, spanning university teaching, research, development, demonstration, and commercialisation of renewable energy and energy efficiency technologies. Professor Aye's research focuses on heating, ventilation, air-conditioning and refrigeration (HVAC&R) systems, waste-to-resources applications, and complex systems modelling. He applies phenomenological modelling and simulation approaches to optimise energy systems, while also using computational and participatory methods for modelling socio-ecological systems under deep uncertainty. His system models serve practical purposes, identifying the effects of policy interventions. They also support robust decision-making processes. Professor Aye has been recognised as a leading expert in modelling, simulation, optimisation, and forecasting of complex systems behaviours. Through his work, Professor Aye bridges rigorous engineering research with real-world implementation, supporting industry, government, and community partners in accelerating the transition to sustainable operations. His contributions continue to inform policy development and guide the adoption of energy-efficient technologies across Australia and beyond.