

Performance sensitivity analysis of residential photovoltaic-driven heat pumps with energy storage

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Abstract

Purpose – This study thoroughly investigates how the performance of a PV-driven heat pump with a water storage tank and batteries is affected by various factors, including different electrical load profiles, domestic hot water (DHW) load profiles, heating elements with varying output capacities, battery capacities, and the threshold values for operating the heating elements in residential buildings.

Design/methodology/approach – Using a typical Australian house fitted with an integrated PV-driven heat pump and a water storage tank as a case study. Transient System Simulation (TRNSYS) is used to model the integrated system and validated using the measured hourly PV generation, house electricity consumption, and energy use of the heat pump.

Findings – Adjusting the electrical load profile from low to high enhances annual PV self-consumption by 12%, rising from 7% to 19%. However, the daily distribution of electrical load profiles influences the fraction of the electrical load that can be satisfied by PV energy. Variations in DHW loads can influence the PV and grid energy consumption of the integrated system, but their effect is significantly less pronounced than that of fluctuations in electrical loads, as the *p*-values obtained from the two-way analysis of variance for the annual PV self-consumption and self-sufficiency both exceed 0.05. The utilisation of batteries and heating elements can either store surplus PV energy or convert it into thermal energy storage for household consumption; nevertheless, the effective use of stored thermal energy is essential to prevent redundant energy storage.

Originality/value – These results provide researchers a better understanding of using PV-driven heat pumps with energy storage systems to attain higher levels of building electrification while providing a foundation of knowledge for residents and industry experts in determining the appropriate dimensions of the integrated system according to the energy demands of their homes.

Keywords Electrification, Energy storage, Households, PV-driven heat pumps, Performance sensitivity, TRNSYS

Paper type Research article

1. Introduction

Energy consumption for water heating is substantial on a global scale, with domestic hot water (DHW) production accounting for approximately 25% of residential building energy use in Australia (Wang *et al.*, 2023). As of now, the primary methods of reducing energy consumption for household DHW production include the application of renewable energy-assisted technologies (Lam *et al.*, 2024), such as solar water heaters and gas-boosted solar

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water heaters, or energy-efficient technologies, such as heat pumps (Zukowski and Woroniak, 2023; Shabha *et al.*, 2023). It is reported that global heat pump installations are projected to rise to 600 million units by 2030, with the rate of heat pump installations in individual buildings anticipated to reach 5 million per month by the same year (Song *et al.*, 2023). Air source heat pumps, compared to other types, such as ground or water source heat pumps, require relatively lower initial and maintenance costs (Wang *et al.*, 2021) while offering superior energy efficiency and greater environmental benefits than conventional electric and gas boilers (Zhang *et al.*, 2023). Consequently, air source heat pumps will play a growing role in the electrification and decarbonisation of houses.

The integration of heat pumps with solar photovoltaic (PV) systems is an effective method of electrifying residential service systems, given the increasing prevalence of solar PV in homes (Gunarathna *et al.*, 2024; Geh *et al.*, 2023). By converting excess PV energy into thermal energy and storing it in water storage tanks, heat pumps can mitigate the issue of low PV self-consumption, resulting from the time difference between the peak PV generation and household electrical load (Wang *et al.*, 2024a; Meriläinen *et al.*, 2023), while providing enough hot water for DHW and heating purposes (Wang *et al.*, 2024b). Nevertheless, residential hot water heat pumps typically heat water up to around 60 °C, limited by ambient conditions, refrigerant properties, and heat exchanger efficiency (Hepbasli and Kalinci, 2009). To overcome these constraints, researchers have explored using auxiliary heating elements powered by excess PV energy, which, when properly controlled, can further enhance thermal storage capacity and increase PV self-consumption in homes (Clift and Suehrcke, 2021; Gaonwe *et al.*, 2022). Alternative storage devices, such as batteries, can also enhance residential PV self-consumption by storing surplus PV energy during daylight hours and supplying power to appliances during peak demand periods (Al Khafaf *et al.*, 2022). A study by Thygesen and Karlsson (2014) discovered that the use of batteries and water storage tanks had a nearly identical impact on the increase in PV self-consumption: 89% for batteries and 88% for water storage tanks, but the levelised energy cost of this process was twice as costly for batteries as for water storage tanks. However, while batteries are more expensive, their stored energy can power multiple household devices, offering greater flexibility, whereas thermal storage in water tanks is limited to DHW or space heating applications.

Integrating both batteries and heat pumps with water storage tanks into residential PV can be a promising approach to enhance residential PV energy utilisation and merits research focus. Meriläinen *et al.* (2023) investigated the conversion of a fossil fuel-powered residence into a carbon-neutral one using PV-driven heat pumps with energy storage; however, their analysis only considered variations in heat pump types and sizing. Li *et al.* (2023) examined a PV-driven heat pump with hot and cold water storage for houses, finding that thermal energy storage raised PV self-consumption and self-sufficiency by up to 30%, but the role of batteries in further improving PV energy utilisation was not addressed. Gaucher-Loksts *et al.* (2022) evaluated three PV-driven heat pump systems for a single-family house, using heating elements in the storage tank to raise water temperature during low ambient conditions. The research indicated that heating elements significantly enhanced PV power consumption and thermal energy production on frigid days; however, it did not evaluate the impact of varying heating element capacities on system efficiency. The energy efficiency of integrated PV-driven heat pump systems with energy storage can be influenced by multiple factors, including energy generation capacity, storage capacity, and the level of residential energy demand. However, a key research gap remains: the extent to which these factors impact the overall performance of the integrated system has not yet been thoroughly investigated in the existing literature. Thus, this study investigates the energy performance sensitivity of PV-driven heat pumps with energy storage under variations in key parameters, including residential electrical and DHW load profiles, battery capacity, heating element output capacity and their operation thresholds. Specifically, a parametric study is conducted to examine how variations in the five parameters affect the integrated system's PV and grid energy consumption, as well as the interactions between the PV system and the electricity grid resulting from PV exports and grid imports.

The primary contribution of this study is listed as follows:

- (1) This study quantifies the benefits of batteries and heating elements in enhancing PV self-consumption and self-sufficiency while diminishing reliance on grid electricity. It also analyses the impact of variations in electrical and DHW load profile demands on system performance.
- (2) A real house equipped with a solar PV system and a heat pump with a water storage tank is used as a case study, and hourly data on the PV generation, household electricity consumption, and heat pump energy use were collected to enhance the reliability of the results and provide outcome-based guidance for both industry professionals and residents.
- (3) The integrated system is modelled using Transient System Simulation (TRNSYS) with a short timestep that allows for precise simulation and a comprehensive understanding of the interactions among the PV system, heat pumps, energy storage devices, and the electrical grid.

This research work is structured as follows. [Section 2](#) reviews the existing literature related to the application of batteries and heat pumps with water storage tanks and heating elements in PV homes, and the research gap and aim are then highlighted at the end of this section. [Section 3](#) points out the method and the research design of this work as well as the data acquisition details, including the use of the Transient System Simulation (TRNSYS) modelling of a PV-driven heat pump with energy storage systems and its operating principles and the explanation of several parameters to be considered for analysing the performance sensitivity of the PV-driven heat pump with energy storage systems. The key findings on the performance sensitivity of the PV-driven heat pump with energy storage are presented in [Section 4](#). Specifically, the impact of the electrical load profile, DHW load profile, heating elements with different output capacities, battery capacities, and threshold values used to operate the heating element is explained in sequence in this section. The results are also presented by focusing on the energy performance of the house, such as its annual total electrical loads, PV self-consumption, PV self-sufficiency, etc. [Section 5](#) outlines the discussion, while [Section 6](#) concludes this work.

2. Literature review

A comprehensive literature review is conducted to gain knowledge on using the integrated PV-driven heat pumps and energy storage in residential buildings while identifying related research gaps. The literature review primarily utilised two principal databases, Scopus and Web of Science, due to their extensive collection of peer-reviewed journal articles in this research domain. A set of keywords was established for the retrieval of papers: “heat pump” AND “photovoltaic” OR “PV” AND “storage” OR “energy storage” OR “water tanks” AND “residential building” OR “house” OR “home.” The literature screening criteria were as follows: (1) only papers from major journals were included, as they signify superior research quality; conference papers were omitted due to their preliminary nature or their potential evolution into journal papers; (2) only papers published after 2020 were considered to represent the latest research output; and (3) only papers assessing the performance or performance sensitivity of PV-driven heat pumps for energy storage in residential buildings were included. Following the literature review, pertinent international standards and guidelines, journal papers and relevant websites were also examined to establish the theoretical foundation for this study. The study ultimately reviewed and retrieved a total of forty literature sources. The results were analysed based on the type of system configuration, the research method used, the key performance indicators implemented, and the identified challenges.

Integrating heat pumps with energy storage in PV houses has been studied extensively. A study conducted by [Yildirim et al. \(2023\)](#) investigated the performance of a PV/T-driven

heat pump system to supply electricity, space heating, and DHW for a residence in southern Poland. The authors used TRNSYS to model the system and found its strong capability to meet the building's energy demands; however, the study primarily presented monthly energy results and could have also included annual and hourly performance to help understand the system's finer operational dynamics. [Acar and Kaska \(2024\)](#) analysed the performance difference between a solar-assisted ground source heat pump and a natural gas boiler when supplying space heating and DHW to buildings. The solar-assisted ground source heat pump reduced the on-site energy use intensity by 33% compared to the previous level when the natural gas boiler was in use. [Meriläinen et al. \(2023\)](#) validated the efficacy of batteries in enhancing residential PV self-consumption rates and determined that solutions integrating ground source heat pumps with PV provide the optimal average cost-effectiveness. Nonetheless, the considerable capital expenses and installation difficulties associated with ground source heat pumps persist in constraining their worldwide acceptance ([Wang et al., 2021](#)). Air source heat pumps, which are both cost-effective and possess exceptional heating and cooling capabilities, lack empirical evidence and deserve research attention ([Gaucher-Loksts et al., 2022](#); [Rana et al., 2025](#)) and therefore, are the focus of this work.

The performance variations of integrated PV-driven heat pumps with energy storage under different operating scenarios have been thoroughly examined. [Pena-Bello et al. \(2021\)](#) examined various scenarios integrating PV-driven heat pumps with thermal and battery storage to fulfil residential energy requirements, considering the impact of varied water tank sizes and the presence or absence of batteries. The authors determined that decarbonising heating demand with integrated PV-driven heat pumps and energy storage continues to be expensive; nonetheless, the study did not precisely evaluate the influence of battery size or varying load profiles on PV and grid energy consumption, leaving the system's performance sensitivity unaddressed. [Nicoletti et al. \(2022\)](#) claimed that heat pumps need to be appropriately sized in conjunction with PV and battery systems to fulfil space conditioning and electricity requirements. The authors examined the cost sensitivity related to various system sizes; however, they seem to have neglected the influence of thermal storage system size variations on overall energy performance, while optimising thermal storage dimensions might yield significant advantages in enhancing photovoltaic energy utilisation efficiency.

Integrating heating elements into water storage tanks connected to heat pumps is one of the promising approaches to increase thermal energy storage capacity for homes. [Treichel and Cruickshank \(2021\)](#) discovered that heating elements can significantly enhance thermal energy storage, particularly when the ambient air temperature falls below the threshold of 5 °C, at which point the refrigeration cycle of the heat pump water heater ceases to operate. A similar study by [Gaonwe et al. \(2022\)](#) also confirmed the capability of heating elements to increase water temperature; however, their high electricity consumption compared with the heat pump itself can be a disadvantage, particularly when heating elements are activated during peak periods under time-of-use tariffs. Nevertheless, when surplus PV energy is available in households, the outcome can be more favourable, as operating the heating elements can further increase thermal energy storage and reduce PV energy exports.

A review of the aforementioned studies underlines the crucial role of integrated PV-driven heat pumps with energy storage in dwellings. Ground source heat pumps often face implementation constraints due to their high capital and maintenance costs compared to air source heat pumps. Furthermore, the influence of fluctuations in electrical and DHW load profiles and component dimensions, including battery capacity and heating element output capacities, on the overall energy efficiency of these integrated systems remains insufficiently examined. To address these research gaps, this research aims to examine the performance sensitivity of an integrated PV-driven air source heat pump with energy storage in providing electricity and DHW for houses. The varying parameters considered include the electrical load profile, the DHW load profile, battery storage capacity, heating element output capacity, and the threshold used to operate the heating element.

The reasons for selecting these parameters to investigate their impact on the performance of the integrated PV-driven heat pump system with energy storage are explained here: Firstly, electrical and DHW load profiles represent the temporal variations in residential electricity and hot water consumption. These profiles directly affect the energy consumption of the heat pump and the household's overall energy equilibrium between PV generation and grid imports (Li *et al.*, 2022). Secondly, batteries and heating elements play a pivotal role in optimising the energy performance of integrated PV-driven heat pumps with energy storage, particularly in households experiencing intermittent solar generation, as they allow excess PV energy to be stored as both electrical and thermal energy for use during periods of high demand (Chadly *et al.*, 2023). Furthermore, a specified threshold controls the heating elements' functioning based on the availability of PV energy. Adjusting this threshold allows for an examination of the trade-off between the energy consumption of heat pumps and heating elements and PV energy utilisation while ensuring a consistent supply of DHW (Wang *et al.*, 2025a).

3. Research method

Through a case study approach, this research explored the performance sensitivity of a PV-driven heat pump integrated with energy storage in meeting residential electricity and DHW demands. Section 3.1 outlines the overall research design, including the methodology for conducting the sensitivity analysis, the parameters, and the performance metrics used to assess the system's energy performance. Section 3.2 presents a case study house, summarising the specifications of its solar PV system and hot water heat pump. Section 3.3 discusses the use of TRNSYS to simulate the PV-driven heat pump system with energy storage for the case study and explains the operational principles of the modelled system. Section 3.4 describes the statistical parameters employed to validate the TRNSYS model and the methods used to calculate PV self-consumption and self-sufficiency. Finally, Section 3.5 details the input data for the various parameters used in the sensitivity analysis.

3.1 Research design

This study adopted the case study design due to the research gap and its exploratory nature. The topic and question being investigated, the performance sensitivity of the integrated PV-driven heat pumps with energy storage, is not well understood and needs to be further investigated. The study focuses on the specific case of the unit of analysis to provide a rich and detailed understanding of the topic, case and variables or factors under investigation (Mills *et al.*, 2009). The analysis involves using numerical data, statistical techniques, simulation, mathematical equations, and other quantitative techniques to analyse the case (Mills *et al.*, 2009). To accomplish the above objectives, TRNSYS, a versatile and extensively utilised tool for simulating diverse thermal and electrical components in buildings (Yildirim *et al.*, 2023), is utilised to model the integrated PV-driven heat pump with energy storage. A real house, equipped with such an integrated system and located in Geelong, Australia, serves as the case study. The collected data on PV generation, heat pump energy consumption, and household electricity usage, along with supplementary residential load profiles from the Australian Energy Market Operator and DHW demand calculated per AS/NZS:4234 (Standards Australia, 2021), guarantee the robustness and reliability of the research design.

Figure 1 illustrates the overall research design, flow, and the parameters used in the case study. The energy efficiency of using the integrated system to satisfy household electricity and DHW requirements can be influenced by various factors, including energy load profile, energy generation, and energy storage capacity. The electrical and DHW load profiles are the first two parameters examined for this purpose, as their variations directly influence the electrical and thermal energy consumption of the system.

In addition, given the specifications of the heat pump, which allow a maximum temperature of 70 °C to be obtained when heating elements are used, it is necessary to explore the effect of

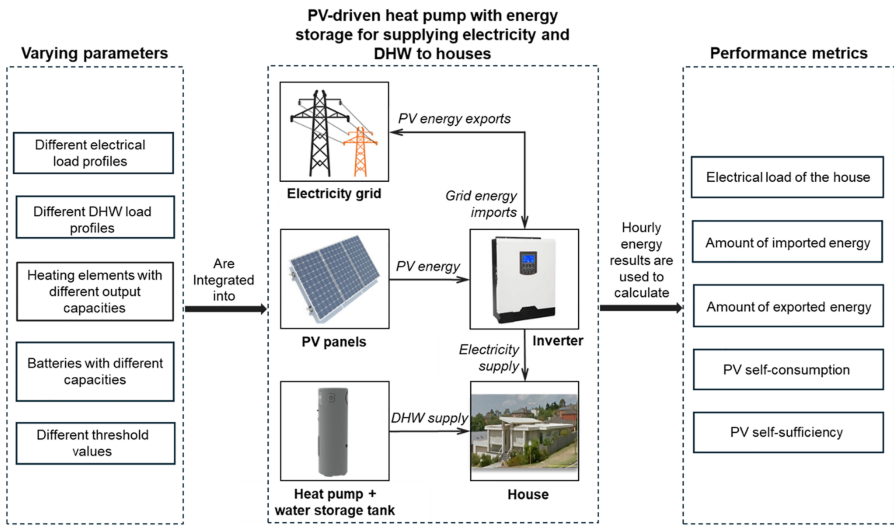


Figure 1. Research design, flow and parameters. Source: Authors' own work

using heating elements with varying output capacities on the energy performance of the integrated system. Batteries are a type of energy storage equipment that might affect the energy performance of the integrated system, as surplus PV energy generated during the day can be stored for use during peak load times or when PV generation is inadequate, thereby reducing grid electricity consumption. As the temperature settings used for the heating element to elevate the average temperature of the water storage tank are dependent upon the availability of PV energy (details of which will be explained in Section 3.3), this study will also examine how varying threshold values influence the electrical and thermal energy generation and storage of the integrated system.

Variations in the data inputs for the previously mentioned five parameters affect the generation, storage, and utilisation of electrical and thermal energy within the residence, thereby affecting the overall PV and grid energy consumption of the integrated system. This study identifies PV and grid electricity as the principal energy sources for the residence; meanwhile, the electrical load of the house, the amount of imported energy, the amount of exported energy, and the PV self-consumption and self-sufficiency also measure the residential PV and grid energy performance. Consequently, these five parameters are used as performance metrics in this work to evaluate the energy performance of the integrated systems. The PV self-consumption measures the percentage of total solar PV generation consumed on-site, and PV self-sufficiency measures the percentage of residential energy loads met by solar PV generation (Wang *et al.*, 2023).

3.2 Case study

This research selects a typical single-storey Australian house with three bedrooms in Geelong, Victoria, as the case study. The house is currently occupied by a retired couple and is equipped with a solar PV system, which is monitored for its energy generation and consumption over a year, as well as a hot water heat pump, whose energy usage is also measured and monitored. The overall PV capacity of this house comes to 10 kW after a 3 kW PV was initially installed on the roof in 2014, and a 7 kW PV was added in 2019. The PV system controller measures the amount of PV generation every fifteen minutes, and the installed smart meter measures the amount of energy imported from and exported to the electricity grid every thirty minutes.

Therefore, the PV generation and electrical load data employed in this study are derived from these measured data, which are aggregated into hourly intervals for subsequent analyses. In June 2022, we installed a hot water heat pump with a power input of 900 W to replace a failed gas hot water system. We have continuously monitored the hourly energy consumption of this hot water heat pump for a year. There is currently no mechanical equipment available for space cooling, and the house is heated by a gas-ducted heater during the heating season. The specifications of the solar PV and the hot water heat pump equipped in the case study house are summarised in [Table 1](#).

3.3 TRNSYS modelling of the PV-driven heat pump with energy storage

The PV-driven heat pump with a water storage tank to supply electricity and DHW is modelled in TRNSYS, as illustrated in [Figure 2](#). The 10 kW PV was modelled independently, using the

Table 1. Specifications of the hot water heat pump and the solar PV system

Equipment	Specifications	Details
Hot water heat pump	Rated heating capacity	3.6 kW
	Power supply	240 V single phase/10 Amp
	Compressor type	Rotary
	Compressor input capacity	900 W
	Refrigerant	Propane
	Tank storage capacity	260 L
	Maximum water temperature	60 °C when using the heat pump alone, 70 °C when using a heating element
Karra-250Wp PV module	Number of PV panels	12
	Panel dimension (L x W x H)	1,667 × 1000 × 40 mm
	Total panel area and installed location	19.2 m ² and on a north-facing roof with 5 ° pitch
	Reference cell temperature and insolation	25 °C and 1000 W/m ²
	Modules short-circuit current at reference conditions	8.8 A
	Module open-circuit voltage at reference conditions	37.7 V
	Module voltage at max power point at reference conditions	30 V
	Module current at max power point at reference conditions	8.3 A
	Number of cells per panel	60
	Number of PV panels	24
Karra-300Wp PV module	Panel dimension (L x W x H)	1,667 × 1000 × 40 mm
	Total panel area and installed location	40.0 m ² and on a north-facing roof with 30 ° pitch
	Reference cell temperature and insolation	25 °C and 1000 W/m ²
	Modules short-circuit current at reference conditions	9.65 A
	Module open-circuit voltage at reference conditions	40.1 V
	Module voltage at max power point at reference conditions	32.93 V
	Module current at max power point at reference conditions	9.11 A
	Number of cells per panel	60

Source(s): Authors' own work

periods of high hot water demand when the heat pump alone is insufficient to meet the heating requirement.

3.4 Statistical validation for the TRNSYS model

To further confirm the accuracy of the PV and heat pump models through numerical results, we used the coefficient of variation of root mean square error (CVRMSE), a widely used statistical technique, as evidence. The CVRMSE is calculated using the following equation:

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i=1}^P (m_i - s_i)^2 / N}{\sum_{i=1}^P (m_i) / N}}}{\sum_{i=1}^P (m_i) / N} \quad (1)$$

Where:

m_i and s_i are the measured and simulated values at an instance. i is the time interval, and P is a given period, and N is the total number of values.

3.5 Energy performance analysis

As mentioned in Section 3.1, PV self-consumption and self-sufficiency are two out of the five performance metrics that are used to assess the energy performance of the PV-driven heat pump with energy storage systems under various scenarios. They can be calculated using the following Equations (2) and (3), respectively.

$$SC_P = \frac{\sum_{i=1}^P E_{ci}}{\sum_{i=1}^P E_{gi}} \quad (2)$$

$$SS_P = \frac{\sum_{i=1}^P E_{ci}}{\sum_{i=1}^P E_{li}} \quad (3)$$

Where:

SC_P and SS_P are the PV self-consumption and self-sufficiency for a given period, respectively. E_{ci} is the amount of PV energy consumed during each time interval, and E_{gi} is the amount of energy generated by solar PV systems during each time interval. E_{li} is the electrical energy load during each time interval.

3.6 Input data

The power consumption of the house from 01 January 2021 to 31 December 2021, was measured before the installation of the hot water heat pump; hence, it reflects the base electrical load of the house. To analyse the impact of electrical load variations on the performance of the PV-driven heat pump with energy storage systems, we used electrical load profile data from the Australian Energy Market Operator's website (AEMO, 2024). The profile data contains half-hourly residential electrical load demands for various regions in different states of Australia. It was subsequently adjusted and scaled down to obtain two different load profiles of a single residential building (Sharma *et al.*, 2019). Three different electrical load profiles were obtained, categorised as high, medium, and low, with the

measured base electrical load of the case study house representing the medium electrical load profile. Figure 3 presents the hourly distribution of these three different electrical load profiles over a year.

The sensitivity analysis explored the DHW as the second energy load. As per AS/NZS:4234 (Standards Australia, 2021), Australia has five different climate zones and four different types of residential DHW load profiles: a large DHW load profile for over six occupants, a medium DHW profile for four to five occupants, a small DHW profile for two to three occupants, and a very small DHW profile for one occupant. The city of Geelong, where the case study house is located, is designated as HP-5 Au. The previously validated DHW load for the heat pump model is based on two occupants, categorising it as a small DHW load profile per AS/NZS: 4234. Given the potential for additional family members to occupy the house, we have also computed a large DHW load profile and a medium DHW load profile, adhering to the above standard. Figure 4 depicts the hourly distribution of the three different DHW load profiles over a year. The small DHW load pattern is significantly different from the other two, as demonstrated in the figure. It exhibits lower temporal consistency and irregular fluctuations. This variability is primarily due to occupant-specific behaviours and periods of absence, such as holidays, which can significantly impact hot water utilisation. DHW demand is highly stochastic and closely linked to individual lifestyle patterns, in contrast to space heating or electrical loads, which typically follow more predictable diurnal or seasonal trends. The observed differences in DHW use patterns provide an instructive illustration of how behavioural factors can influence the overall energy performance of the integrated system and the alignment between energy demand and on-site PV generation and consumption.

The output capacities of the heating elements, the capacity values of the batteries, and the threshold values can be modified directly in TRNSYS models, allowing for the execution of the simulated system to assess the performance sensitivity of variations in these values for the integrated system.

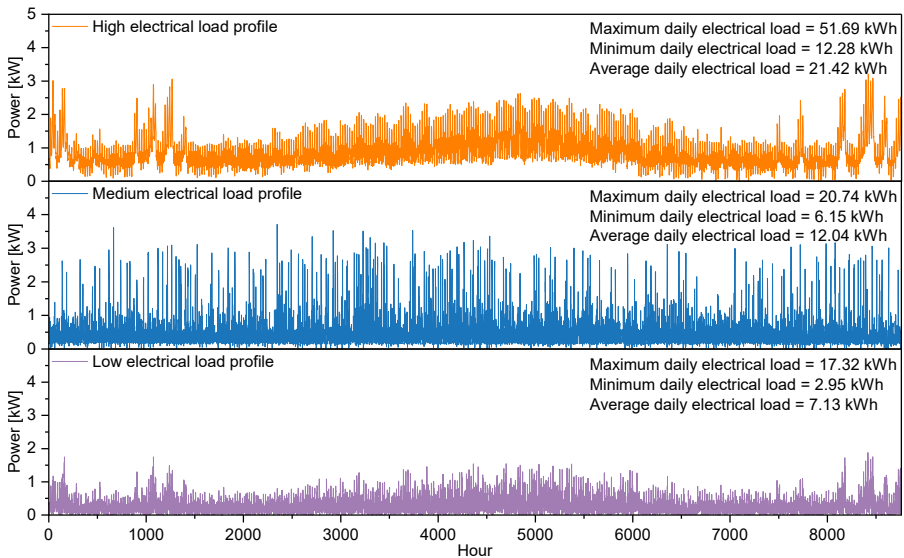


Figure 3. Hourly distribution of three categories of electrical load profiles (high, medium, and low) over a year. Source: Authors' own work

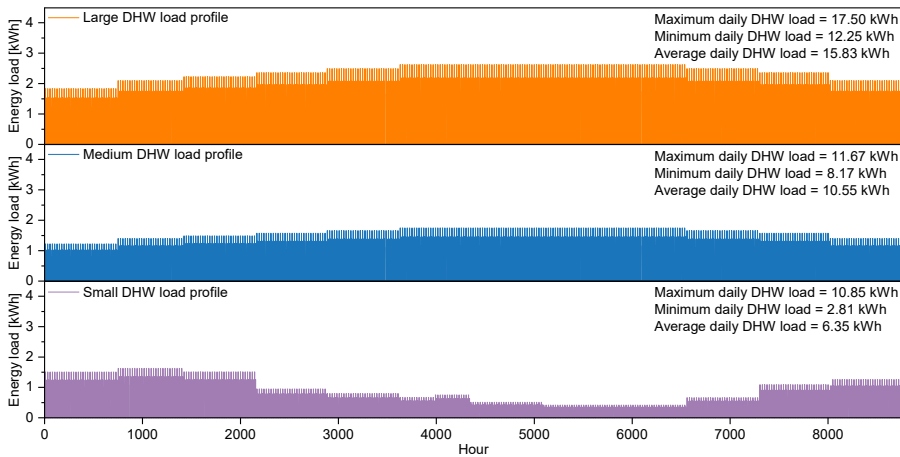


Figure 4. Hourly distribution of three different DHW load profiles (high, medium and low) over a year. Source: Authors' own work

4. Results

This section presents the results of the study, beginning with the validation of the TRNSYS models for the PV and heat pump systems. It then examines the effects of variations in electrical load profiles, DHW load profiles, heating element output capacities, battery capacities, and the threshold values for heating element operation on the overall energy performance of the integrated system.

4.1 Validation of TRNSYS models for PV and heat pump

To validate the accuracy of the TRNSYS models for the 10 kW PV system and the hot water heat pump, we initially selected a day of peak PV generation in each summer month, i.e. December, January, and February, and compared the simulated hourly PV output with the corresponding measured data. Likewise, for the heat pump, a day of peak power consumption was selected for each winter month, including June, July, and August. The findings of the comparison are presented in Figure 5. It can be discovered from the figure that the simulated PV power and heat pump power profiles closely align with their measured results, with minor deviations at the peaks. The variations can be attributed to several factors, including the difference between the weather data files used in TRNSYS and the actual meteorological conditions, as well as the variance between the real operating and performance parameters of the heat pump and those configured in the simulation.

To more numerically figure out the accuracy of the two models, we computed the two CVRMSE values utilising the monthly simulated and measured PV power and the monthly simulated and measured power use of the hot water heat pump. The results are summarised in Table 2. According to ASHRAE (2002), a model is considered calibrated if the CVRMSE is less than or equal to $\pm 15\%$ when using monthly data. The calculated CVRMSE values for the monthly PV generation and the monthly heat pump power use are 8.19% and 12.07%, respectively, both of which fall within the acceptable threshold. These results indicate that the TRNSYS models for the 10 kW PV system and the hot water heat pump are sufficiently calibrated and can be considered reliable for further analyses.

4.2 The impact of electrical load profiles

In order to figure out the effect of different electrical load profiles on the energy performance of the integrated system of the PV-driven heat pump with energy storage systems while

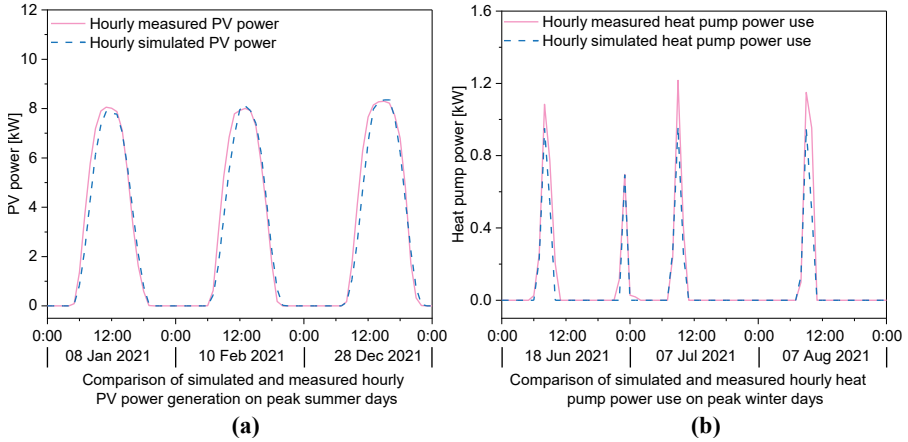


Figure 5. Comparison of measured and simulated PV power and heat pump power use during typical days in summer and winter. Source: Authors' own work

Table 2. CVMRSE values for TRNSYS model validation

TRNSYS modelling	Calculated monthly CVMRSE	Monthly criteria for CVMRSE
Monthly energy generation of the 10 kW PV system	8.19%	Within $\pm 15\%$ (ASHRAE, 2002)
Monthly energy consumption of the heat pump	12.07%	Within $\pm 15\%$ (ASHRAE, 2002)

Source(s): Authors' own work

meeting the residential DHW and electricity requirements, we ran the TRNSYS model with three different electrical load profiles, named as high, medium, and low electrical load profiles, respectively, and summarised and plotted their annual energy results in Figure 6.

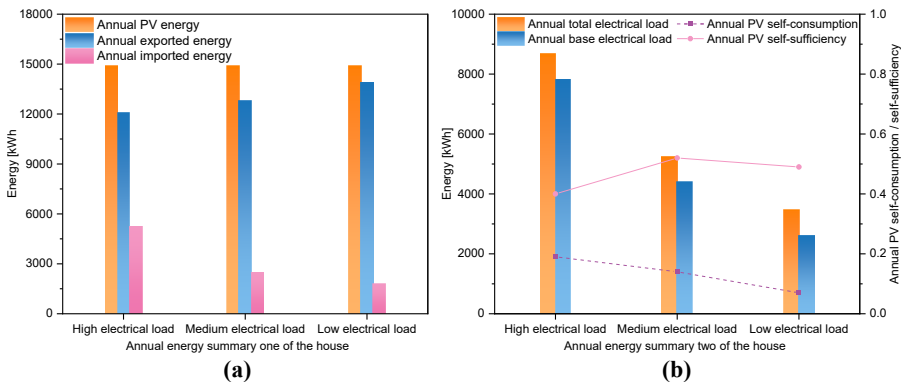


Figure 6. Annual energy summary of the house under three different electrical load profiles (DHW load: small DHW load profile, output capacity of the heating element: 0 kW, threshold: 0 kW, and battery capacity: 0 kWh). Source: Authors' own work

The annual PV energy of 14,905 kWh remains constant for the three scenarios, as illustrated in [Figure 6\(a\)](#); however, the annual exported energy gradually increases from 12,048 kWh to 12,786 kWh and finally to 13,906 kWh. This increase is a result of the annual base electrical load profile being adjusted from a high of 7,816 kWh to a medium of 4393 kWh and finally to a low of 2,604 kWh at the end, as shown in [Figure 6\(b\)](#). Additionally, as observed in [Figure 6\(b\)](#), the difference between the annual total electrical load and the annual base electrical load remains consistent across all three scenarios, amounting to 852 kWh. This result arises from the identical DHW load profile, resulting in equivalent energy consumption for the heat pump and water pump in each scenario.

As illustrated in [Figure 6\(b\)](#), the annual PV self-consumption diminishes progressively from 19% to 14% and ultimately to 7%; nevertheless, the scenario featuring the medium electrical load profile exhibits the highest annual PV self-sufficiency at 52% among the three scenarios. This is primarily because of the varying annual total electrical load throughout the three scenarios; a lower total electrical load results in reduced PV energy consumption, leading to decreased PV self-consumption. Moreover, it can be explained that a higher portion of the medium electrical load profile occurs during daylight hours when PV energy is available, in contrast to the other two scenarios. This observation can also be supported by the findings in [Figure 6](#), indicating that among the three scenarios, the one with the medium electrical load profile exhibits the lowest ratio of annual imported energy to annual total electrical load, thereby achieving the highest annual PV self-sufficiency of the three scenarios. Therefore, it can be said that the electric load profile can have a significant impact on the energy performance of the PV-driven heat pump with energy storage, and the distribution of the electric load profile can affect the proportion of PV energy that meets the energy needs of the house, leading to variations in PV self-consumption and self-sufficiency.

4.3 The impact of DHW load profiles

To explore how different DHW load profiles impact the energy performance of the integrated system, we cross-matched the three DHW load profiles with the three electrical load profiles and integrated them into the TRNSYS simulations for execution. [Table 3](#) summarises the results of the nine simulations. It can be discovered that the annual energy use of the heat pump remains the highest when the large DHW load profile is applied, as the heat pump needs to operate more frequently to produce DHW for occupants. This is also the reason that the first simulation exhibits the highest values for both annual total electrical load and annual imported energy among the nine simulations.

In addition, among the three simulation sets with the same DHW load profiles, the annual PV self-sufficiency of the simulation with the medium electrical load profile surpasses the values of the other two simulations within that set. This is first because the total value of the medium electrical load profile is lower than that of the high electrical load profile; therefore, a larger portion of the medium electrical load scenario is satisfied by PV during daylight hours, resulting in a higher annual PV self-sufficiency. Secondly, as elucidated in [Section 4.2](#), the medium electrical load profile exhibits a greater daytime distribution compared to the low electrical load profile. Consequently, the simulation utilising the medium electrical load profile demonstrates superior annual PV self-sufficiency compared to the one employing the low profile, despite the higher total annual electrical demand. Thus, it can be stated that the DHW load profile influences the energy consumption of the heat pump, thereby affecting the energy performance of the integrated system. The distribution of the electrical load profile also appears to significantly impact residential PV and grid energy consumption.

Since the simulation of using the large DHW and high electrical load profiles has the highest annual imported energy and PV self-consumption, alongside a comparatively low annual PV self-sufficiency relative to the other simulations, we use the combination of these two load profiles in the following sensitivity analyses to assess the efficacy of alternative strategies, including using a heating element and battery storage, in enhancing the energy performance of the integrated system.

Table 3. Annual energy summary of the house with three different DHW load profiles and three different electrical load profiles: (output capacity of the heating element: 0 kW, threshold: 0 kW, and battery capacity: 0 kWh)

DHW and electrical load profiles	Annual energy use of heat pump/ kWh	Annual imported energy/ kWh	Annual exported energy/ kWh	Annual total electrical load/ kWh	Annual PV self-consumption	Annual PV self-sufficiency
Large DHW and high electrical loads	2,081	5,930	11,335	10,055	24%	41%
Large DHW and medium electrical loads	2,081	3,166	12,027	6,633	19%	52%
Large DHW and low electrical loads	2,081	2,369	13,074	4,844	12%	51%
Medium DHW and high electrical loads	1,287	5,517	11,799	9,201	21%	40%
Medium DHW and medium electrical loads	1,287	2,791	12,533	5,777	16%	52%
Medium DHW and low electrical loads	1,287	2,039	13,628	3,989	9%	49%
Small DHW and high electrical loads	792	5,222	12,048	8,669	19%	40%
Small DHW and medium electrical loads	792	2,499	12,786	5,245	14%	52%
Small DHW and low electrical loads	792	1,769	13,906	3,456	7%	49%

Source(s): Authors' own work

4.4 The impact of heating elements with varying output capacities

To evaluate the performance sensitivity of using heating elements in the simulated PV-driven heat pump with energy storage systems, we incorporated heating elements with varying output capacities into the TRNSYS simulation and executed the model with the high electrical load and large DHW profiles, and the threshold is determined to be 5 kW based on the peak hourly electrical load profile and the input power of the heat pump and the water pump. The results are presented in Figure 7, and they reveal that the annual energy use of the heat pump decreases progressively as the output capacity of the heating element increases, as evidenced by the figure; however, this trend reaches a plateau when the output capacity of the heating element exceeds 2.5 kW. This phenomenon is because operating the heating element elevates the average temperature of the water storage tank, thereby diminishing the operational duration of the heat pump and, thus, decreasing its energy consumption. However, as the output capacity of the heating element increases, the volume of hot water in the storage tank increasingly becomes underutilised and redundant. Thus, further increases in the output capacity of the heating element will merely accelerate the water heating rate without enhancing the overall temperature of the water storage tank, resulting in a gradual stabilisation of the annual energy consumption of both the heating element and the heat pump.

These results can also be reflected in the findings shown in Figure 7(b), where the annual PV self-consumption and self-sufficiency reach their highest at 38% and 51%, respectively, when the output capacity of the heating element is increased to 2.5 kW. Thus, it can be summarised that using a heating element can increase the PV energy utilisation of the house with the simulated integrated system, but the output capacity of the heating element needs to be determined to achieve better energy efficiency.

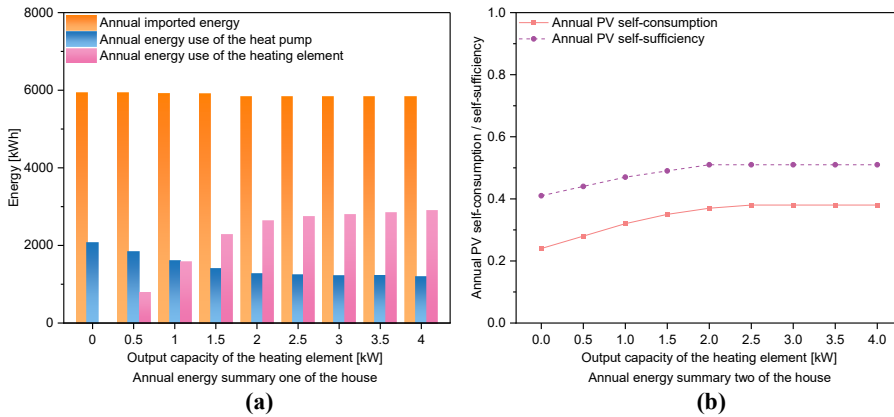


Figure 7. Annual energy summary of the house with the large DHW and high electrical load profiles at different output capacities of the heating element (threshold: 5 kW, and battery capacity: 0 kWh). Source: Authors' own work

4.5 The impact of battery capacities

To further explore the potential of using batteries in conjunction with PV-driven heat pumps and water storage tanks to enhance residential PV energy utilisation and decrease residential grid energy consumption, we adjusted the battery capacity from 0 to 10 kWh and ran simulations, and the results of the TRNSYS models are summarised in Figure 8. It is evident that the use of batteries can effectively increase the annual PV self-consumption and self-sufficiency of the house, and this effect is more pronounced when the battery capacity is increased. This advantage is due to the fact that the battery can store the excess PV energy during the day, which can be utilised when the electrical demand is high or when there is a shortage of PV energy, thus reducing the grid energy consumption.

To further demonstrate the performance sensitivity of using both batteries and a heating element in the PV-driven heat pump with energy storage systems, we summarised the hourly temperature and energy results of the two simulations on the days with peak PV generation in

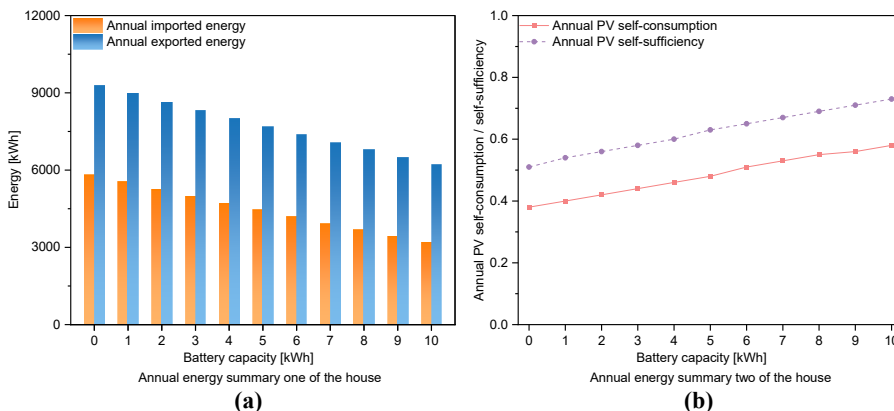


Figure 8. Annual energy summary of the house with the large DHW and high electrical load profiles at different battery capacities (output capacity of the heating element: 2.5 kW, and threshold: 5 kW). Source: Authors' own work

summer and winter and plotted the results in Figures 9 and 10, respectively. The two simulations both feature the large DHW and high electrical load profiles, but one simulation does not have batteries or a heating element, named Simulation 1, and the other simulation, named Simulation 2, has a battery with a storage capacity of 10 kWh and a heating element with an output capacity of 2.5 kW. It can be observed from Figure 9(a) that using a 10 kWh battery in Simulation 2 eliminates the imported energy that Simulation 1 has from 0:00 to 2:00 and after 20:00. In addition, the hourly exported energy during the daytime is diminished in Simulation 2 in comparison to Simulation 1 because the heating element in Simulation 2 starts its operation when the PV generation exceeds the threshold of 5 kW from 8:00 onwards (see Figure 9(a) and 9(b)), gradually increasing the average temperature of the water storage tank to 70 °C, as illustrated in Figure 9(c). The remaining excess PV energy is then stored in batteries before being exported to the electricity grid, as indicated in Figure 9(a).

Furthermore, Figure 9(d) demonstrates that the electrical load of Simulation 2 is significantly higher than that of Simulation 1 during the daytime. This phenomenon is because the heating element with an input power of 2.5 kW in Simulation 2 operates frequently during the daytime, as illustrated in Figure 9(b), increasing its power consumption. Furthermore, the heat pump in Simulation 2 rarely operates during the daytime, as the average temperature of the water storage tank is basically maintained at over 55 °C, preventing the heat pumps from being activated. This behaviour is consistent with the operation principle of the heat pump, as described in Section 3.1. Finally, it is important to note that the average temperature of the

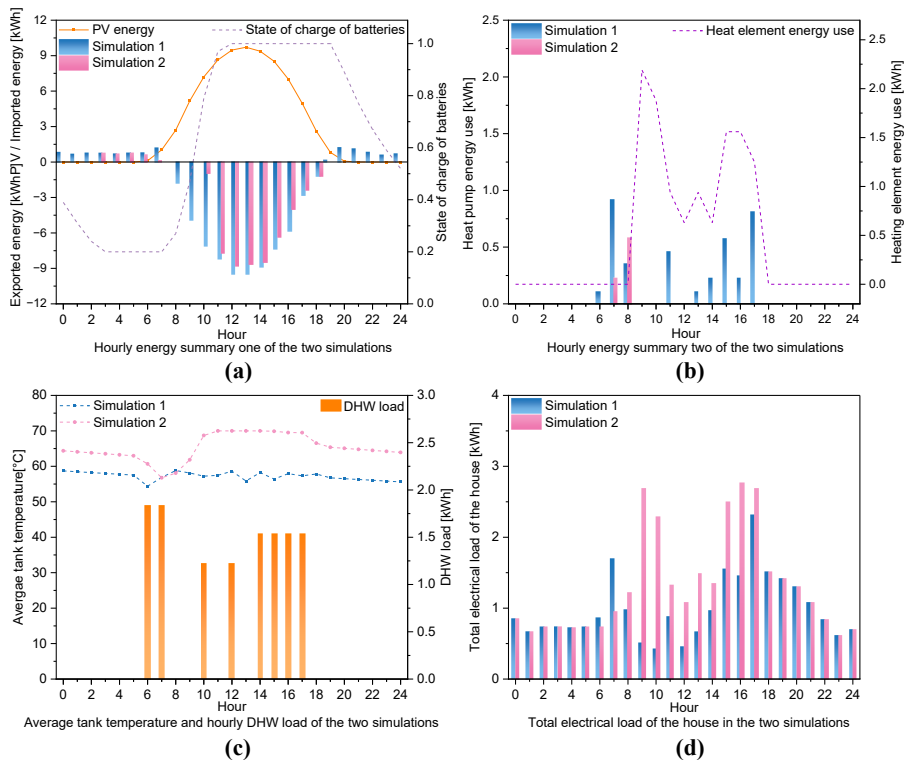


Figure 9. Hourly energy summary of the two simulations featuring the large DHW and high electrical load profiles on the peak PV generation day (04 January) of summer: Simulation 1 has no heating element or batteries, and Simulation 2 has a 10 kWh battery and a heating element with the output capacity of 2.5 kW and the threshold of 5 kW. Source: Authors' own work

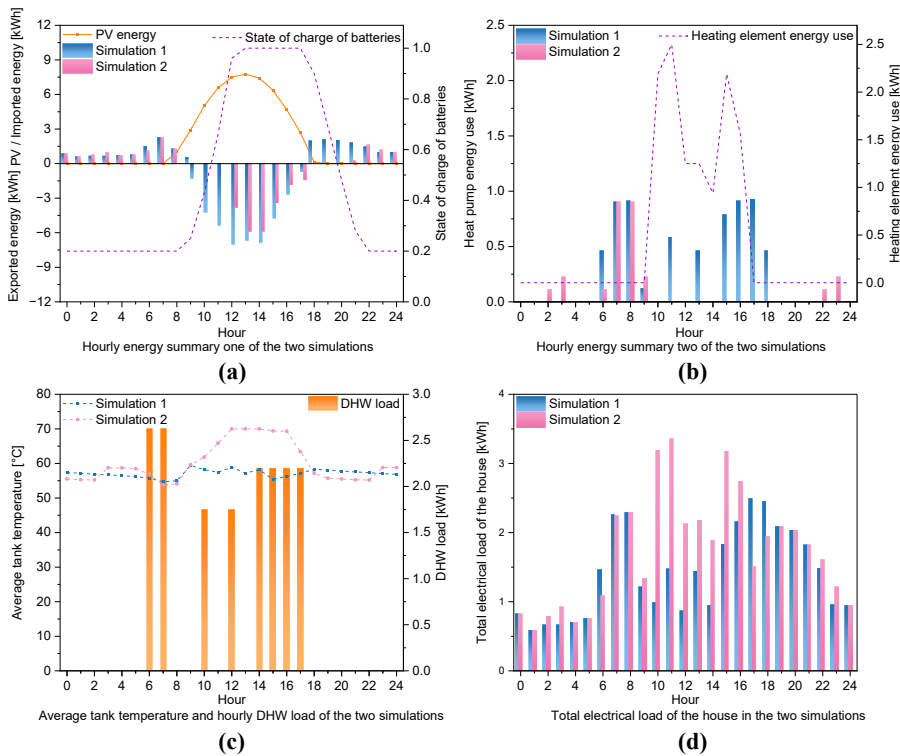


Figure 10. Hourly energy summary of the two simulations featuring the large DHW and high electrical load profiles on the peak PV generation day (28 August) of winter: Simulation 1 has no heating element or batteries, and Simulation 2 has a 10 kWh battery and a heating element with the output capacity of 2.5 kW and the threshold of 5 kW. Source: Authors' own work

water storage tank increases from 50 to 60 °C in Simulation 1 and to 70 °C in Simulation 2, as shown in Figure 9(c), when the heating element is employed. Nevertheless, the thermal energy stored in the tank is not well utilised and seems to be rather redundant, despite the enhancement of PV energy usage during this process. Consequently, it can be asserted that the incorporation of batteries and a heating element enhances the utilisation of home PV energy, but the effective use of generated energy to prevent energy redundancy is also essential.

Figure 10 presents the energy summary for both simulations on the day with peak PV generation in winter. The battery storage cannot compensate for the energy demand of Simulation 2 in the early morning due to being depleted to their minimal state of charge (see Figure 10(a)); hence, both simulations exhibit the same amount of imported energy before 8:00 a.m. It is also found from Figure 10(b) that the heat pump in Simulation 2 needs to operate from 6:00 to 8:00 a.m., as in Simulation 1, to meet the DHW demand due to its PV energy being insufficient and below the threshold. However, the situation changes from 9:00, and the heating element in Simulation 2 gradually increases the average tank temperature to 70 °C, leaving the heat pump essentially off during this period, as shown in Figure 10(b) and 10(c).

Furthermore, similar to the results depicted in Figure 9, integrating batteries and a heating element in the simulated DHW and electrical system reduces the total exported energy of the day. However, it remains significant after declining from 39.51 kWh in Simulation 1 to 22.06 kWh in Simulation 2. Moreover, the average tank temperature in Simulation 2 consistently exceeds 55 °C, see Figure 10(c), surpassing the minimum threshold of 40 °C

4.6 The impact of threshold values

The threshold value was previously determined based on the peak hourly electrical load profile and the input power of the heat pump and the water pump, so its value may affect the operation of the heating element. To clearly demonstrate how the threshold level impacts the energy performance of the simulated DHW and electrical system, we varied the threshold value from 0 to 6 kW and conducted simulations. The results of these simulations are summarised in Figure 11. The annual energy use of the heating element decreases as the threshold value increases, as illustrated in Figure 11(a). This decrease is because the higher the threshold value, the shorter the time of day during which the PV generation exceeds the threshold value. As a result, the heating element's operation time decreases, leading to a rise in the heat pump's annual energy consumption. Furthermore, as illustrated in Figure 11(a), the annual imported energy decreases as the threshold increases, and it reaches a minimum value of 3,148 kWh at a threshold of 4.0 kW, which is consistent with the trend of the annual PV self-sufficiency, as illustrated in Figure 11(b). This phenomenon is because the heating element consumes a greater quantity of grid energy when the threshold value is reduced as a result of insufficient PV generation. Therefore, it can be summarised that the threshold value affects both the heating element and heat pump operations, which in turn influences the energy performance of a house equipped with an integrated system of PV-driven heat pumps and energy storage.

5. Discussion

This study examines the impact of differing parameter values on the energy performance of a PV-driven heat pump with energy storage systems. To further clarify the difference in the influence of electrical and DHW loads on the energy performance of the integrated system, we conducted a two-way analysis of variance using the annual values associated with three electrical and DHW loads, and the results are summarised in Table 4. The table shows that the p -values of the electrical load for four performance metrics were less than 0.05, indicating that changes in the electrical load had a statistically significant impact on the four performance metrics of the integrated system (White *et al.*, 2022). The DHW load also significantly affects

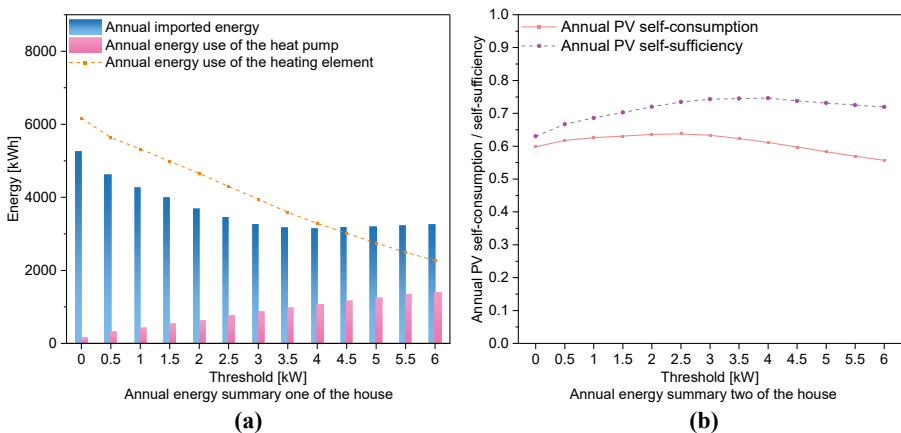


Figure 11. Annual energy summary of the house with the large DHW and high electrical load profiles at different thresholds (output capacity of the heating element: 2.5 kW, and battery capacity: 10 kWh). Source: Authors' own work

Table 4. Summary of ANOVA p -values for the influence of DHW and electrical load profiles on the energy performance of the integrated system: (output capacity of the heating element: 0 kW, threshold: 0 kW, and battery capacity: 0 kWh)

	p -value			
	Annual PV self-consumption	Annual PV self-sufficiency	Annual imported energy	Annual exported energy
Electrical load	<0.05	<0.05	<0.05	<0.05
DHW load	0.61	0.16	<0.05	<0.05

Source(s): Authors' own work

annual imported and exported energy of the integrated system, evidenced by p -values below 0.05; however, its influence on the other two metrics is statistically insignificant, with p -values of 0.61 and 0.16, respectively. Thus, it can be argued that managing electrical load profiles offers more significant potential for enhancing the energy performance of the integrated system, especially by maximising PV energy utilisation and reducing grid dependence.

Moreover, the batteries in this study are employed to store surplus daily PV energy and discharge it at night or during peak demand periods to diminish grid energy usage and increase PV energy utilisation. This outcome aligns with [Meriläinen et al. \(2023\)](#), who mentioned that batteries could enhance the use of PV energy in households while also claiming that batteries could facilitate electricity sales during peak pricing periods in the morning and evening. The result can be attributed to feed-in tariffs surpassing the retail price of grid electricity, as indicated by the authors in their study ([Meriläinen et al., 2023](#)), while in Australia, feed-in tariffs are considerably lower than retail electricity prices ([Wang et al., 2023](#)), thereby making on-site consumption of PV energy more advantageous.

Furthermore, a comparison of the results in [Figures 7 and 8](#) indicates that improving battery capacity is more effective than increasing thermal storage via heating elements to increase PV energy utilisation. This is consistent with the findings of [Pena-Bello et al. \(2021\)](#), who asserted that batteries and heat pumps with energy storage are crucial for improving PV self-consumption and self-sufficiency, yet emphasised that batteries are superior to thermal storage in this context. The main reason for this is that the electrical energy stored in batteries can be utilised for plug loads for common household appliances; however, the stored thermal energy is restricted to space heating or DHW. The coefficient of performance of modern heat pumps is usually more than three. This is especially true when advanced parts like suction heat exchangers are used for internal heat recovery or when shell-and-tube heat exchangers are used to improve heat transfer between the refrigerant and water ([Wang et al., 2024c](#)). Consequently, further increasing PV energy utilisation through heat pumps becomes less effective, as the continuous improvement in the coefficient of performance of heat pumps reduces the proportion of PV energy required for generating heating energy. This issue may be alleviated by retrofitting conventional fossil fuel-based systems with hydronic radiant systems for space conditioning ([Do et al., 2025a](#)), as, compared with scenarios only considering DHW, this approach increases the overall residential thermal demand, thereby increasing the thermal output required from heat pumps. Moreover, the adoption of hydronic radiant conditioning systems can also reduce natural gas consumption, contributing to a more sustainable household energy profile ([Do et al., 2025b; Weiss, 2021](#)).

While this study demonstrates that variations in battery capacity could enhance the utilisation of PV energy relative to grid electricity, thereby supporting the gradual transition toward residential electrification, battery adoption in Australian households remains constrained due to substantial capital, operational, and maintenance expenses, even with government rebates ([Symeonidou et al., 2021](#)). Large aggregators, such as energy retailers or regulators, can also integrate and manage batteries and PV systems through virtual power

plants. In this setup, households can send extra PV energy to the virtual power plants and sell it to the wholesale markets when retail electricity prices are high (Ge *et al.*, 2025; Wang *et al.*, 2025b). Conversely, batteries can be charged when excess PV energy is available or when retail prices are low, generating financial returns for PV households. Nevertheless, the autonomy of participating households is frequently constrained, especially concerning the trading of surplus PV energy after it is delivered to the virtual power plants and the transparency of the associated profits (Li *et al.*, 2024). In contrast, using PV-driven heat pumps with energy storage predominantly generates economic benefit by directly reducing home energy costs while providing households with greater autonomy in using their PV energy. This work presents results from a parametric evaluation of the energy performance of PV-driven heat pumps with energy storage, considering variations in five different parameters, which provide foundational knowledge for homeowners to make informed decisions when selecting effective strategies to maximise the benefits of their PV systems.

6. Conclusion

This study examines the performance sensitivity of the integrated system of a PV-driven heat pump with energy storage across various parameters, including different electrical load profiles of the house, DHW load profiles of the house, the use of heating elements with varying output capacities, battery capacities and threshold values used for operating the heating element. The integrated system from a case study house is modelled in TRNSYS, and the impact of the above parameters on the energy performance of the simulated integrated system is explored in sequence in this work.

The findings indicated that both the variation in the electrical and DHW load profiles significantly influence the PV and grid energy consumption of the house. Adjusting the annual base electrical load of the residence from high to medium and subsequently to low progressively enhances the annual exported energy from 12,048 kWh to 12,786 kWh and ultimately to 13,906 kWh. It was discovered that the distribution of the annual electrical load profile determines the ratios of the load satisfied by PV and grid energy, thereby influencing PV self-consumption and self-sufficiency. Furthermore, the results from the two-way analysis of variance indicate that the influence of the electrical load profile on the annual PV self-consumption and self-sufficiency is statistically substantially greater than that of the DHW load profile. Also, the heating element could significantly enhance the PV energy; for instance, annual PV self-consumption and self-sufficiency rise from 24% and 41%–38% and 51%, respectively, as the output capacity of the heating element increases from zero to 2.5 kW. Nevertheless, additional increases in its output capacity result in minimal increases in the average temperature of the water storage tank and redundant energy storage. This underscores the importance of a more precise determination of the heating element size and the effective utilisation of the stored energy to optimise energy efficiency. Batteries, undoubtedly, can increase PV energy consumption and reduce grid energy use effectively, as they can store excess PV energy during daylight hours and distribute it to appliances during peak load periods or at night. Adjusting the threshold influences the duration that PV generation surpasses this threshold, which in turn affects the operational time of both the heating element and the heat pump, thereby impacting the energy performance of the simulated system.

This study provides the foundational knowledge required for operating heat pumps with energy storage in PV houses and demonstrates the significant benefits of such systems in reducing grid energy consumption and enhancing on-site PV energy utilisation. Policymakers could consider providing additional rebates or incentives to encourage residents to adopt heat pump technologies not only for DHW production but also for space conditioning. Encouraging the transition from conventional air-source heating and cooling systems to hydronic radiant systems in houses would further demonstrate the capability of integrated systems to meet residential energy needs while accelerating the electrification of residential building services. Thus, future research can focus on evaluating the performance of PV-driven heat pumps with

energy storage systems for supplying electricity, space heating, space cooling, and DHW in residential buildings. In addition, considering one of the key limitations of this work is that only a single case study house was used to explore the performance sensitivity of the integrated system as a function of five varying parameters, future studies should apply such integrated systems to multiple case study houses across different climate zones.

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