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Residential space heating electrification through a PV-driven hot water heat pump

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ABSTRACT

As the world progresses towards decarbonisation, solutions for houses dependent on fossil fuels are required. Solar photovoltaic (PV) and heat pumps are attractive in reducing carbon emissions due to their renewable energy generation and outstanding energy efficiency. Therefore, this paper investigates the energy, economic and environmental performance of electrifying fossil fuel-based space heating systems through PV-driven hot water heat pumps. A case study was conducted on a typical Australian house with a 10 kW PV, a hot water heat pump, and a gas-ducted heater. Transient System Simulation (TRNSYS) was employed to simulate the existing space heating and hot water system (ESH): a gas ducted heater + a PV-driven hot water heat pump and the proposed space heating and hot water system (PSH): a heating tank + a heating element + fan coil units + a PV-driven hot water heat pump. The simulated space heating loads, PV generation and heat pump power consumption, were verified using actual measurements. Results demonstrated that PSH eliminated the annual gas demand of 4093 kWh needed for ESH. Additionally, the annual PV self-consumption and self-sufficiency increased by 26 % and 50 %, respectively, from the previous levels of 19 % and 29 % due to the electrification of the space heating system. After determining the optimal sizing of the heating tank and its immersed heating element based on the high PV energy utilization rule, it was discovered that a payback period of 12.3 years was required for transitioning the house from ESH to PSH with an annual carbon emission reduction of 24 %. This work demonstrated the feasibility of electrifying the conventional fossil fuel-based space heating system to fan coil units and a heating tank connected to a PV-driven hot water heat pump, thus contributing to the decarbonization of future homes.

1. Introduction

The escalation of global carbon emissions has been identified as the primary cause of climate change [1], which has posed a significant threat to humanity [2]. Heating and cooling in buildings have been found to be two of the most significant contributors to global carbon emissions; for example, in Europe, they are responsible for half of the total energy consumption, with only 22 % of that energy coming from renewable sources [3], while the majority is derived from fossil fuels [4,5]. A similar situation exists in other areas of the world. Based on data published by the International Energy Agency [6], fossil fuels account for more than 90 % of Australia's energy supply, with coal contributing to 32 % of this proportion, followed by natural gas at 28 % and oil at 32 %. Research has demonstrated that Australian households are accountable for a minimum of 20 % of the nation's overall carbon emissions [2]. The primary factors contributing to this are space heating, space cooling, and domestic hot water (DHW) production, which collectively represent 65 % of residential energy use [7]. As a result, utilising environmentally friendly technologies to decarbonize heating and cooling systems in buildings can play a significant role in attaining global net-zero emissions [8,9].

Heat pumps are recognized as energy-efficient and environmentally friendly technologies. This is because heat pumps operate in refrigeration cycles, absorbing the low-temperature heat from a source and releasing the high-temperature heat to a sink [10]. This process results in heat pumps with a coefficient of performance of up to five, which is significantly higher than electric resistance with efficiencies of one or even lower [11]. Moreover, by using natural refrigerants, such as hydrocarbons, which possess minimal global warming potential and no ozone depletion potential, heat pumps will not present significant hazards to the environment during refrigerant leaks or disposal [12,13]. In

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Nomenclature

AUD	Australian dollar
C_o	Annual operating cost of the system
CDDs	Cooling degree days
C_{rv}	Residual value of the system
CVRMSE	Coefficient of variation of root-mean-squared error
E_t	Electrical demand of the house during each timestep t
DHW	Domestic hot water
G_t	Natural gas demand of the house during each timestep t.
ESH	Existing space heating and hot water system
PV_t^c	The amount of PV energy consumed locally during each timestep t
HDDs	Heating degree days
PV_t	The amount of generated PV energy during each timestep t
LCC	Life cycle cost
S_m	Annual maintenance cost savings
N	Life span
S_o	Annual operating cost savings
PP	Payback period
T_{DHW}	Average temperature of the DHW tank
PSH	Proposed space heating and hot water system
$T_{heating}$	Average temperature of the heating tank
PV	Photovoltaic
i	The discount rate
TRNSYS	Transient System Simulation
n	n^{th} year
C_{ic}	Initial cost of the system
p	Given period
C_m	Annual maintenance cost of the system
t	Time step

addition to providing environmental friendliness and exceptional efficiency in heating and cooling, heat pumps integrated with water storage tanks can shift peak loads in houses and contribute to energy cost reductions, as thermal energy storage can be generated during off-peak electricity demand periods with lower electricity tariffs [14]. Furthermore, global government entities have been actively engaged in the implementation of heat pumps in residential buildings. As an example, the Government of Ireland has set a target to install 600,000 high-efficiency heat pumps by 2030, and Finland aims to attain carbon neutrality by 2035, which involves implementing heat pumps for space heating and DHW production [15]. Therefore, it is anticipated that the widespread implementation of heat pumps in residential buildings will persist, owing to government support and the significant energy efficiency and ecological compatibility provided by heat pumps.

Renewable generation systems, such as solar photovoltaic (PV) systems, have been employed to reduce carbon emissions in the global power sector [16,17], and the PV installation rate has experienced significant growth in residential buildings in recent decades. This trend can be attributed to the modularity and reduced cost of PV technology, enabling consumers to generate their own electricity and become prosumers [18]. In Australian households, for instance, the adoption rate has surpassed 30 %, thereby aiding the transition to clean energy and decarbonization of homes [19]. Despite the increasing installation of PV systems in houses, the percentage of locally consumed PV energy, referred to as self-consumption, remains relatively low. This is due mainly to the time difference between the peak generation of PV energy and the house energy needs [20]. Research has demonstrated that this issue can be alleviated by integrating heat pumps and PV systems to utilise the excess PV energy [21]. Furthermore, the proportion of Australian residences equipped with air-to-water heat pumps or hot water heat pumps, as they are commonly known, is on the rise due to the incentives provided by state governments in the form of discounted initial costs or interest-free loans [7,22]. Nevertheless, it is crucial to highlight that many Australian houses that are equipped with PV and hot water heat pumps rely on fossil fuel systems, such as gas-ducted heaters, for space heating. This activity impedes the progress of the decarbonisation of residential buildings. Therefore, the electrification of conventional fossil fuel-based space heating systems using PV-driven hot water heat pumps for further decarbonization of houses holds great research promise.

An extensive examination of the present academic publications reveals that although there has been considerable interest in the application of PV-driven heat pumps in residential buildings, certain published studies have solely focused on assessing the effects of this system on the energy use of houses for space heating purposes, without taking into account its ability to meet the DWH demand. In addition, the analysis of employing PV-driven heat pumps in residential buildings can be approached from three dimensions: energy, economic, and environmental. However, several studies in the literature focus on only two of these dimensions, neglecting the third and requiring additional study to fill this gap. Furthermore, despite extensive global research on PV-driven heat pumps, there is a notable scarcity of studies in Australia specifically examining the application of PV-driven heat pumps for the electrification of conventional fossil fuel-based systems. Therefore, the purpose of this research is to conduct a comprehensive assessment of the use of PV-driven hot water heat pumps to electrify conventional fossil fuel-based space heating systems in Australian houses from energy, economic and environmental perspectives. In order to accomplish this, a case study will be conducted on a typical Australian household located in Geelong, Victoria. The house is furnished with a gas-ducted heater and a PV-driven hot water heat pump. The concept of electrifying fossil fuel-based space heating system refers to transitioning the gas ducted heater to using fan coil units with a heating tank that is connected to the PV-driven hot water heat pump. The operation of this system will be simulated using the Transient System Simulation (TRNSYS) software.

This study distinguishes itself from previous research by comprehensively analysing the energy, economic, and environmental feasibility of utilising a PV-driven hot water heat pump to electrify a conventional space heating system powered by fossil fuels. Furthermore, the study uses a typical Australian house fitted with a 10 kW solar PV system and a hot water heat pump, whose power generation and consumption were continuously measured, thus increasing the reliability and authenticity of this work. Using an existing hot water heat pump to upgrade the house's space heating system offers further case support and guidance for Australian inhabitants who need further assistance to accomplish this objective. This work primarily contributes to the literature by quantifying the decrease in residential natural gas consumption and carbon emissions, as well as the increase in PV energy consumption, achieved through the intelligent electrification of residential space heating systems utilising PV-driven hot water heat pumps. Moreover, our methodology offers an outline that explicitly illustrates the operational principles of the electrified space heating and hot water system in TRNSYS, thereby assisting researchers engaged in this domain.

The subsequent sections are structured as follows. The literature on the use of PV-driven hot water heat pumps for space conditioning and DHW in residential buildings is reviewed in Section 2. Existing knowledge gaps are also discussed at the end of this section. Section 3 outlines two systems, distinguished by their designs for space heating. One system utilises a gas-ducted heater, while the other employs a fan coil unit and a heating tank connected to a PV-driven hot water heat pump. The operational principles of the two systems are also clarified in this section. Section 4 provides a full explanation of the modelling approach used for the two systems in TRNSYS and the methodology employed for energy, economic, and environmental analyses in this study. Detailed results of the investigation are presented in Section 5. The discussion is offered in Section 6, and the conclusion to this paper is presented in Section 7.

2. Literature review

A comprehensive investigation has been conducted on the utilisation of PV-driven heat pumps to supply both space heating and DHW for residential buildings. For instance, an energy and economic analysis was conducted using TRNSYS simulations for a single-family house in Zurich [13]. The study centred on utilising a PV-driven hot water heat pump to generate electricity, deliver space heating, and supply DHW for the residence. It was discovered that using a 5 kW solar PV system with a 1000 L water tank contributed to the minimum payback period of 17.1 years, which is still considered lengthy. A practical and effective approach would involve employing an additional heating element to raise the tank temperature in the case of surplus PV energy [23], thus saving a greater quantity of electricity from the grid. Furthermore, research attention has been paid to the optimal design and operation of PV-driven heat pumps in houses. In their study, Nordgård-Hansen, et al. [24] developed a mixed-integer linear programming model to efficiently determine the appropriate size and functioning of a PV-driven heat pump in a residential building located in Norway. The model incorporated feed-in tariffs, house energy loads, PV energy generation, heat pump operation, grid power supply, etc, as constraints. As indicated by the results, the economic viability of using PV-driven heat pumps in single-family dwellings with low to moderate heating demands was diminished.

In addition to the application of PV-driven air source heat pumps, research has been conducted on utilising PV to power other types of heat pumps. As an example, a comprehensive analysis was performed to evaluate the energy, economic, and environmental aspects of utilising a PV-driven ground source heat pump to supply electricity to a residential community and provide space heating to a school in the winter season [25]. Upon calculating the optimum capacity of the 26 kW PV system, the project yielded an annual savings of USD 4880 in electricity costs, leading to a discount payback period of 14.5 years. Nevertheless, the authors neglected the potential cost reductions that could have been realised by employing thermal storage systems, such as water tanks, to generate and store additional heating energy prior to exporting surplus PV energy to the grid [26]. Additionally, the considerable expense associated with ground source heat pumps could potentially lengthen the project's payback period [27]. Consequently, it is anticipated that forthcoming research will concentrate on evaluating the viability of comparatively more affordable systems, such as air-to-water heat pumps. Furthermore, a study was conducted to assess the practicality of using a PV-driven ground source heat pump to supply both electricity and space heating for a residence in Tehran, Iran [28]. The study analysed the energy consumption of the house, the overall cost of the system over its lifetime, and the resulting carbon emissions. However, a limitation of the study was that the authors only examined the heat pump's potential for space heating and did not take into account its capability to provide DHW, which is also a significant energy requirement for the house.

Prior research has not only examined the energy efficiency, economic feasibility, and environmental benefits of utilising PV-driven heat pumps exclusively in residential buildings, but has also compared the end results of using these systems with those of using conventional fossil fuel-based systems. Thomaßen, et al. [29] examined the effectiveness of reducing carbon emissions in houses by electrifying heating systems, specifically by using heat pumps in European households. The findings demonstrated that the utilisation of heat pumps for electrification is an effective method of achieving decarbonization in buildings, particularly when there is access to low-carbon energy sources. Walker, et al. [30] conducted a thorough examination in the United States, exploring the energy, economic, and environmental consequences of substituting natural gas furnaces with heat pumps for heating residential spaces. However, their study did not take into account the potential benefits of incorporating solar PV systems, which could have led to even greater energy savings and reduced carbon emissions. Next, Sommerfeldt and Pearce [31] examined the energy and economic benefits of using PV-driven air-to-air heat pumps to retrofit a grid-connected house in North America that uses a natural gas heating system. The results indicated that the electricity tariffs made PV systems unattractive and that more government rebates were expected to reduce the initial cost of heat pumps to replace natural gas systems. It is noteworthy that the authors neglected to incorporate an environmental assessment into their study, which could have demonstrated that substituting natural gas heating systems with PV-driven heat pumps substantially mitigates residential carbon emissions.

TRNSYS software has gained widespread application in the modelling of building service systems. Apart from the aforementioned literature [3,13,21,23,25,26] that has employed TRNSYS, other studies have utilised TRNSYS to simulate building service systems. For instance, Pinamonti, et al. [32] employed TRNSYS to model the integration of solar thermal collectors, a water-to-water heat pump, and water storage tanks for the purpose of space heating and providing DHW in a residential building. Moreover, in their study, Thür, et al. [33] conducted a simulation of a ground source heat pump powered by solar PV for space heating and DHW in a building. The authors specifically examined the impact of including building thermal mass and intentionally overheating the storage tank on the utilisation of PV energy. The results showed that by superheating the storage tank and using building thermal mass, the solar fraction, referring to the heat initially supplied by the PV energy divided by the total heat demand, increases from 11 % to 61 %.

Currently, there is a need for more research on implementing PV-driven hot water heat pumps for residential service systems in Australia. As governments, such as the Victorian Government, started prohibiting natural gas use in new homes from 2024, the significance of using the electrified space heating and DHW systems grew. Therefore, this work will investigate the impact of using a PV-driven hot water heat pump to electrify the conventional space heating system of a typical Australian house that currently relies on natural gas. This will be achieved from the system modelling in TRNSYS, and the impacts will be examined in terms of the energy, economic, and environmental aspects.

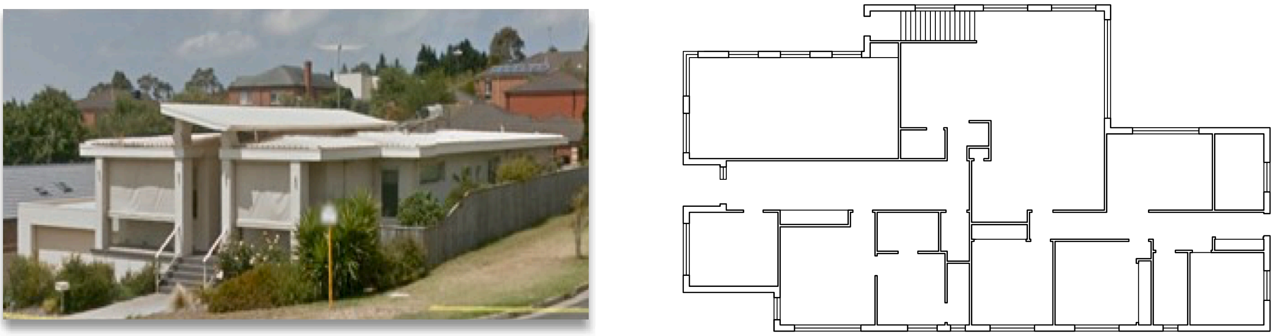
3. Existing and proposed space heating and hot water systems

In order to investigate the impact of electrifying a residential space heating system using a PV-driven hot water heat pump, it is first necessary to explain in detail the existing space heating and hot water system (ESH), and the proposed space heating and hot water system (PSH). Therefore, this section achieves this goal through a case study of a typical Australian house equipped with a 10 kW solar PV system, a hot water heat pump and a gas-ducted heater.

3.1. ESH: A gas-ducted heater + a PV-driven hot water heat pump

The chosen case study house is a single-storey building inhabited by a retired couple in Geelong, Australia. The house comprises three bedrooms, and its exterior view and floor plan are illustrated in Fig. 1. A gas-ducted heater with a rated output of 20 kW provides room heating. Due to the occupants' living patterns and the good thermal characteristics of the building envelope, no mechanical cooling is employed in the house. This is the rationale for limiting the scope of the study to the electrification of residential heating systems.

A hot water heat pump was installed in June 2022 to provide DHW for the house. The hourly electricity consumption of this heat pump has been monitored for a year since its installation. Moreover, this house is



(a) (b)

Fig. 1. (a) Exterior view of the house from the south-west side, and (b) floor plan of the house.

equipped with a 10 kW solar PV system. The detailed specifications of the hot water heat pump and the PV system are provided in Table 1.

A PV system controller monitors the PV generation at fifteen-minute intervals. A smart meter installed in the house accurately monitors the quantity of energy imported and exported at thirty-minute intervals. Fig. 2-(a) shows a schematic diagram of the ESH. Due to the space heating needs of the house being supplied by a gas-ducted heater, natural gas is instantaneously utilised when there is a space heating requirement. Here, the operational principles of supplying DHW throughout the year using the PV-driven hot water heat pump in ESH are explained. The setpoint temperature of the hot water heat pump is determined based on the amount of PV generation. More precisely, if the PV energy is below the threshold, the thermostat is set to 57.5 °C ± 2.5 °C, and the principle of this thermostat setting is to ensure the draw-off point reaches 55 °C to avoid Legionella growth in the DHW tank [34]. When the PV energy exceeds a specific threshold, the main thermostat for the DHW tank is increased to 62.5 °C ± 2.5 °C, which will consume more PV energy to produce hot water and further reduce energy consumption from the electricity grid. The thermostat monitors the average temperature of the DHW tank. Fig. 2-(b) illustrates the operating principles of the hot water heat pump.

3.2. PSH: A heating tank + a heating element + fan coil units + a PV-driven hot water heat pump

An electrified space heating system based on the existing PV-driven hot water heat pumps is proposed here to substitute the gas-ducted heater in the house. As shown in Fig. 3-(a), the hot water heat pump is used to provide DHW for the house all year round, and it is powered by the 10 kW solar PV and the electricity grid. Then, a supplementary tank, named the 'heating tank', is connected to the hot water heat pump to store heating energy, as depicted in Fig. 3-(a). The fan coil unit is connected to the heating tank to allow for the circulation of the stored hot water for space heating. Notably, the heating tank contains an immersed heating element that could further increase the water temperature of the heating tank when needed and ensure the water supplied to the fan coil unit reaches the desired point. In addition, it can be used to raise the temperature of the heating tank when there is excess PV energy, resulting in increased PV self-consumption. In order to facilitate the distribution and control of electricity, an inverter establishes connections between the solar PV system, the electricity grid, the hot water heat pump, and additional electrical appliances. Solar PV energy that is over the house's instantaneous power demand is sent back to the grid. If the PV system is unable to meet the instantaneous electricity demand of the house, any deficit will be compensated through the purchase of energy from the electricity grid.

Table 1
Specifications of the hot water heat pump.

Items	Details
Heat pump heating capacity	3600 W
Electricity supply	220—–240 V alternating current / 50–60 Hz
Compressor type	Rotary
Compressor input capacity	900 W
Refrigerant	Propane
Tank storage capacity	260 L
Maximum water temperature	65 °C
Karra-250Wp PV panels	12 panels
Panel dimension (L x W x H)	1600 × 1000 × 40 mm
Total panel area and installed location	19.2 m^2 and on a north-facing roof with 5 ° pitch
Karra-300Wp PV panels	24 panels
Panel dimension (L x W x H)	1667 × 1000 × 40 mm
Total panel area and installed location	40.0 m^2 and on a north-facing roof with 30 ° pitch

The PV-driven heat pump in PSH works on the same principle as the ESH and provides DHW to the house all year round. The strategy for operating the heating element and supplying hot water from the DHW tank to the heating tank is explained here. First, when the average temperature of the DHW tank is 1 °C higher than the average temperature of the heating tank, the pump between the two tanks will turn on to charge the heating tank and will turn off when the average temperature of the two tanks is the same. Second, the heating element maintains the temperature of the heating tank. Specifically, the first thermostat setting of the heating element is adjusted to 47.5 °C ± 2.5 °C to ensure that the temperature of the water used for space heating is always above 40 °C [35]. The second thermostat setpoint of the heating element is adjusted to 70 °C, i.e., when there is excess PV energy, the heating element is switched on to heat the average temperature of the heating tank to 70 °C. This operation contributes to the consumption of more PV energy and the provision of additional hot water for subsequent space heating. Fig. 3-(b) presents the operating principles of the heating element.

4. Method

Section 4.1 explains the modelling processes of the two system designs in TRNSYS. The methodologies utilised to analyse the energy, economic, and environmental aspects of the two systems are clarified in Sections 4.2, 4.3, and 4.4, respectively.

4.1. Modelling of the ESH and PSH through TRNSYS

In order to determine the energy, economic, and environmental performance of these two systems, their energy demands, including

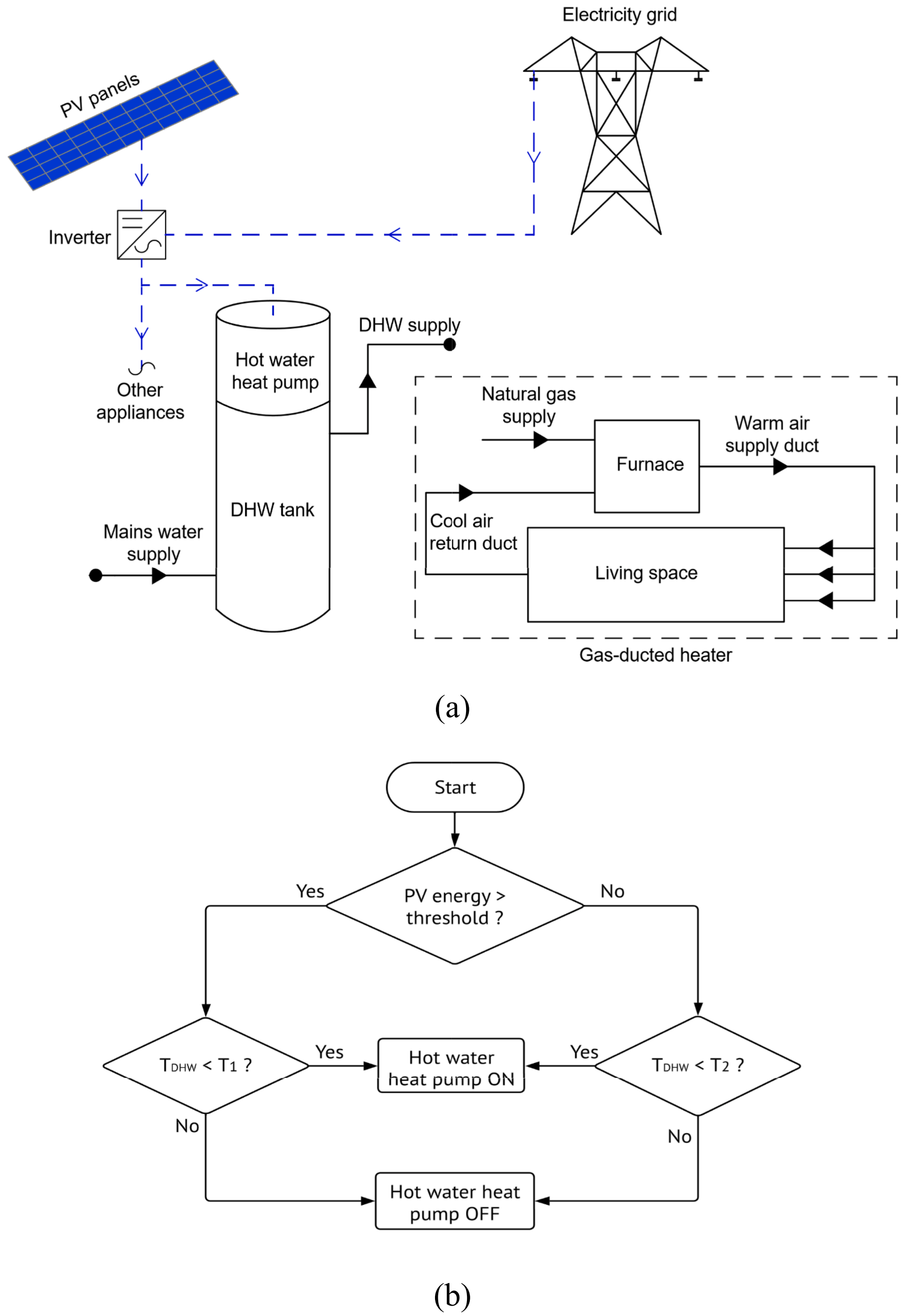


Fig. 2. (a): Schematic diagram of the ESH, and (b): Operating principles for the hot water heat pump in ESH: T_{DHW} = average tank temperature of the DHW tank, and T_1 = 62.5 °C ± 2.5 °C, and T_2 = 57.5 °C ± 2.5 °C.

natural gas consumption, DHW, and electrical demand, need to be first obtained. TRNSYS is a robust software that is extensively used to simulate thermal and electrical systems in the constructed environment. This software enables the simulation of multiple components, including PV, batteries, heat pumps, hydraulic equipment, and multi-zone structures [26]. Therefore, TRNSYS was selected to conduct the simulations and collect necessary data in this work after reviewing its capabilities in system modelling.

In the ESH, space heating is realized by an existing gas-ducted heater, all of whose natural gas consumption is available through gas bills. Therefore, there is no need to model the space heating system in this system design. To model the DHW requirements for the house to be serviced by the hot water heat pump, we initially calculated the yearly hourly DHW consumption for two occupants in accordance with the Australian/New Zealand Standard AS/NZS 4234:2021 [36]. Then, the computed hourly hot water energy requirement was used to model the electrical demand of the hot water heat pump in TRNSYS. The performance of the hot water heat pump was modelled by utilising performance data provided by the manufacturer, which encompassed a variety of water outlet temperatures recorded in various ambient conditions. The DHW demand is validated and adjusted by comparing the simulated electrical demand of the hot water heat pump with the measured electrical consumption of the hot water heat pump used in the case study house, and Fig. 4-(a) presents the hourly DHW demand of the case study

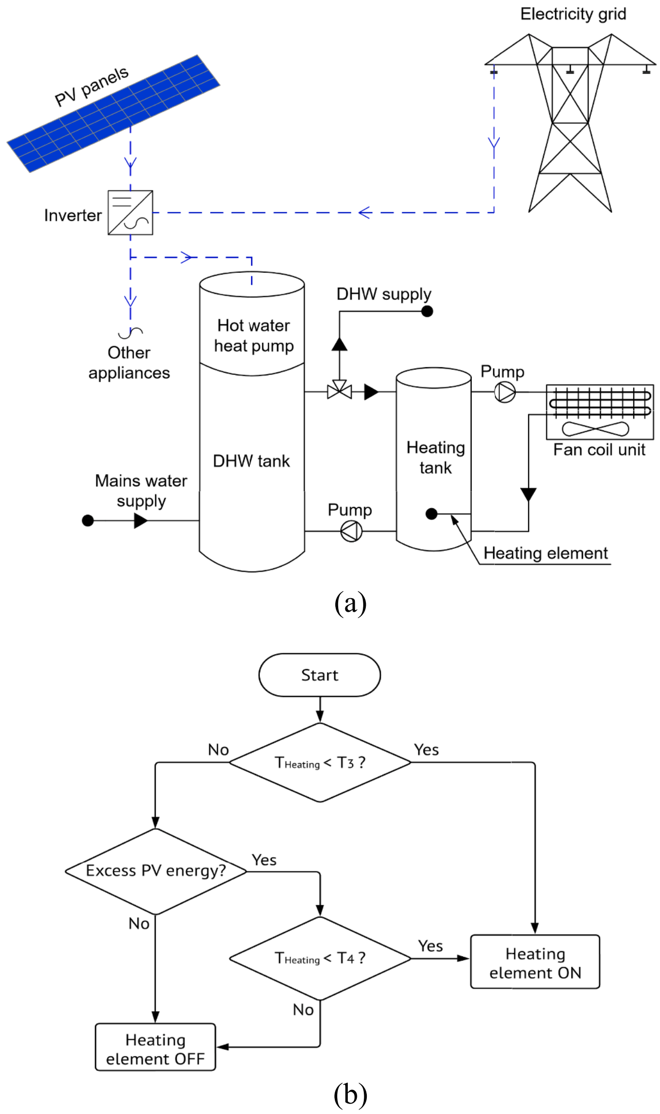


Fig. 3. (a): Schematic diagram of the PSH, and (b): Operating principles of the heating element: $T_3 = 47.5\ ^\circ C \pm 2.5\ ^\circ C$, and $T_4 = 70\ ^\circ C$.

house over a year.

In addition, the smart meter and PV measurement data from 2021 were used to determine the house's yearly hourly power usage, and given that the house depended on gas-based equipment for space heating and DHW production in 2021, this electrical data served as the base electrical load for the house (see Fig. 4-(b)). Also, the hourly DHW and electrical load of the house on the first day of the year are presented in Fig. 4-(c) and (d). respectively. Furthermore, the climatic data for Geelong was generated using Meteonorm (refer to Fig. 4-(e) and (f)) and used in the TRNSYS model to simulate the energy generation of the 10 kW PV. The simulated results were then compared to the actual measured data of the house's 10 kW PV generation in 2021 to verify the accuracy of the simulation. This is followed by the thermostat settings of the hot water heat pump based on the comparison between the PV generation and the threshold. Fig. 5 shows the TRNSYS simulation of the PV-driven hot water heat pump in the ESH.

In the PSH, space heating is designed to be met by fan coil units, a heating element and a heating tank connected to a PV-driven hot water heat pump. The heating demand of a household is significantly influenced by local climatic conditions and the thermal performance of the dwelling [31,37], and the main parameters of the house envelope are presented in Table 2.

To determine the heating load of the house, we divided this house into two thermal zones, named the bedroom and living room in TRNSYS, with the total volume of both zones, which needed to be conditioned, amounting to 588.32 m^3 [37]. Given the absence of any mechanical cooling equipment in the house, only the heating load was considered in this modelling, and the bedroom is modelled as occupied from 9 pm to 7 am at a temperature of 20 °C, and unoccupied from 7 am to 9 pm at a temperature of 15 °C. The living area is occupied during the hours opposite to those of the bedroom, specifically from 7 am to 9 pm, maintaining a temperature of 20 °C, and remains unoccupied from 9 pm to 7 am, with a temperature of 15 °C. Then, the simulated space heating loads were compared to the actual gas usage of this case study house for June to September 2022 and May 2023. This was done to verify the accuracy of the simulated space heating loads, as these months correspond to the period when the simulated heating loads occur, and the gas was exclusively utilised for space heating and home cooking. Fig. A1 in the a ppendix illustrates the monthly natural gas usage of the house from June 2022 to May 2023. Then, a heating tank connected to the hot water heat pump was simulated to store hot water for space heating. Furthermore, a heating element was incorporated into the heating tank to maintain the average heating tank temperature. After that, two fan coil units were connected to the heating tank and used to fulfil the space heating needs of the two thermal zones. The modelling of the 10 kW PV and base electrical load of the house were obtained from the modelling for the ESH. The TRNSYS simulation of the PSH is presented in Fig. 6, and the simulation procedure of this work is shown in Fig. 7.

The appropriate sizing for various equipment used in the ESH and PSH needs to be determined prior to conducting simulations and analyses. The rated output capacity of the gas-ducted heater and the input capacity and tank size of the hot water heat pump are determined based on their actual specifications. The rated output capacity of the heating element used in the PSH is determined based on the sizes of the DHW and heating tanks, as well as the simulated peak heating load. The PV output threshold is determined to be 5 kW according to the maximum hourly electricity consumption of the home and the input capacity of the hot water heat pump. Table 3 presents an overview of the sizing of each system component employed in the two systems.

4.2. Energy analysis

The primary aim of this study is to evaluate the energy, economic, and environmental effectiveness of replacing ESH with PSH in the case study house. The three primary energy sources utilized in the two space heating and hot water system designs are natural gas, grid electricity, and PV energy. Specifically, the ESH relies on natural gas for space heating and grid electricity and PV energy for domestic appliances, and the PSH only requires grid electricity and PV energy for home use. Thus, two parameters, i.e., PV self-consumption and self-sufficiency, are explained here to comprehensively understand the energy results of both ESH and PSH. PV self-consumption is calculated by dividing the locally consumed PV energy by the total amount of PV generation, while PV self-sufficiency is calculated by dividing the locally consumed PV energy by the total amount of electrical and natural gas consumption. The equations for calculating these two parameters are expressed as follows:

$$SC = \frac{\sum_0^p PV_t^c}{\sum_0^p PV_t} \tag{1}$$

$$SS = \frac{\sum_0^p PV_t^c}{\sum_0^p (E_t + G_t)} \tag{2}$$

Where: SC is the PV self-consumption, and SS is the PV self-sufficiency. p represents a given period, such as a month or a year. PV_t is the amount of generated PV energy during each timestep t. PV_t^c is the amount of PV energy consumed locally during each timestep t. E_t is the electrical de-

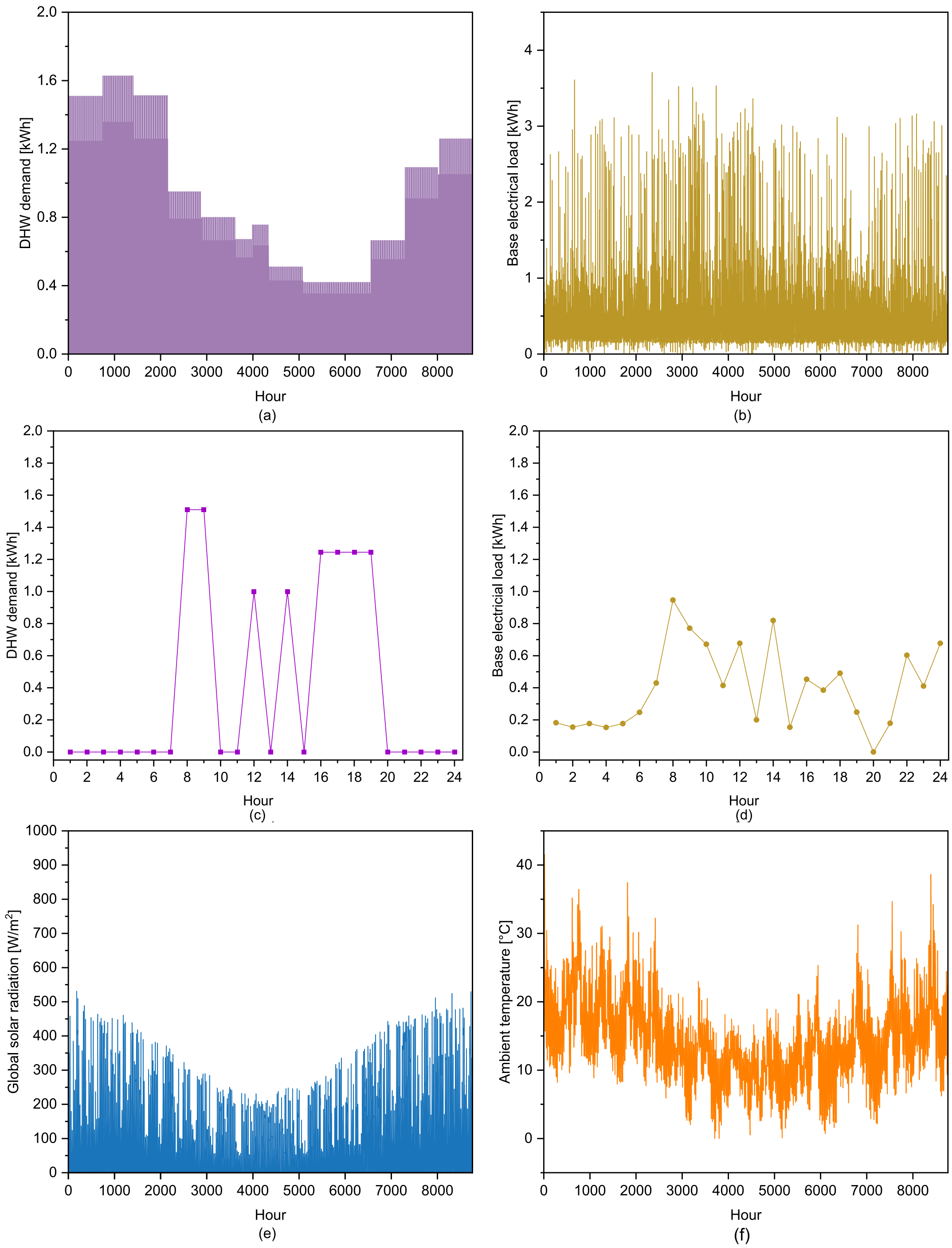


Fig. 4. (a): Annual hourly DHW demand of the house, (b): Annual hourly base electrical load of the house, (c): Hourly DHW demand of the house on the first day of the year, (d): Hourly base electrical load of the house on the first day of the year, (e): Annual hourly global solar radiation of Geelong, Australia, and (f): Annual hourly ambient temperature of Geelong, Australia.

mand of the house during each timestep t, and G_t is the natural gas demand of the house during each timestep t.

4.3. Economic analysis

The costs related to the installation of ESH and PSH can differ depending on the country or region. Hence, an economic evaluation will be carried out to determine the economic feasibility of the two systems within the Australian market. For this purpose, two indicators, including life cycle cost (LCC) and payback period (PP), are used. LCC refers to the total discounted cost comprising the initial cost, operating and maintenance costs, and residual value of a system over its lifespan. The LCC is calculated using the following equation.

$$LCC = C_{ic} + \sum_{n=1}^{N}\left[(C_o + C_m)\times\left(\frac{1}{(1+i)}\right)^{n-1}\right] - C_{rv} \quad (3).$$

Where: C_{ic} represents the initial cost of the system, C_o is the annual operating cost of the system, C_m represents the annual maintenance cost of the system, assumed to be 3 % of C_{ic} [38], and the residual value of the system, denoted as C_{rv}, is assumed to be 10 % of the initial cost [39]. n is the n^{th} year, and N is the lifespan of the system, considered to be 20 years for both systems in this work. i is the discount rate, taken as 3 % [40].

The payback period (PP) denotes the duration required for the sys-

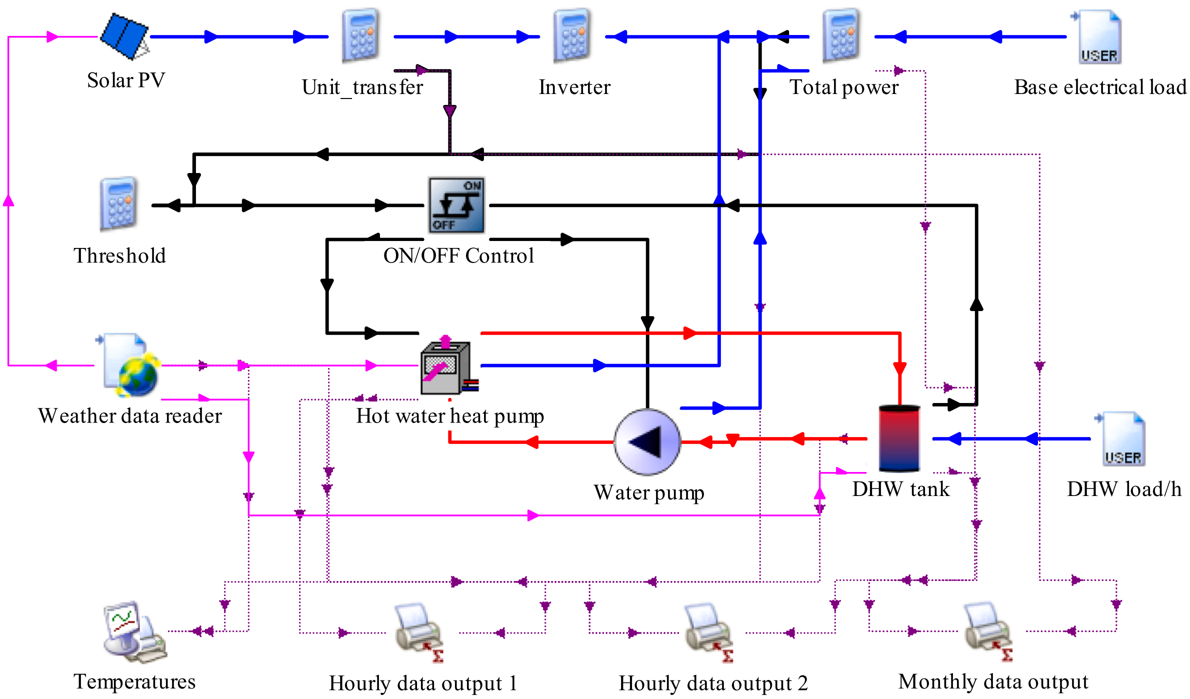


Fig. 5. TRNSYS Simulation of the PV-driven heat pump in the ESH.

Table 2
Thermal properties of the house envelope.

Construction type	Thickness (mm)	U-value ($W/m^2 \bullet K^{-1}$)
External walls	220	0.38
External roof	500	0.124
Adjacent wall	110	1.038
Ceiling	260	0.896
Floor	376	0.295
External windows	20	1.69

tem to recover its initial investment from the savings generated during operation. The ESH is currently being implemented in the case study house. When calculating the payback period of using the PSH, the initial costs to be considered include the costs for purchasing two new fan coil units, a heating tank with heating elements, and the costs for associated auxiliary equipment. The initial costs of each of these components are obtained through interviews with suppliers or direct online searches. The calculation of operating costs for the two systems considers parameters, including the cost of natural gas and grid electricity, their daily supply charge, and the revenue generated from selling excess PV energy to the grid. The annual maintenance cost of the two systems is assumed to be 3 % of their initial cost [41]. The PP can be calculated using Equation (4). Table 4 summarizes the relevant parameters used for the economic analyses.

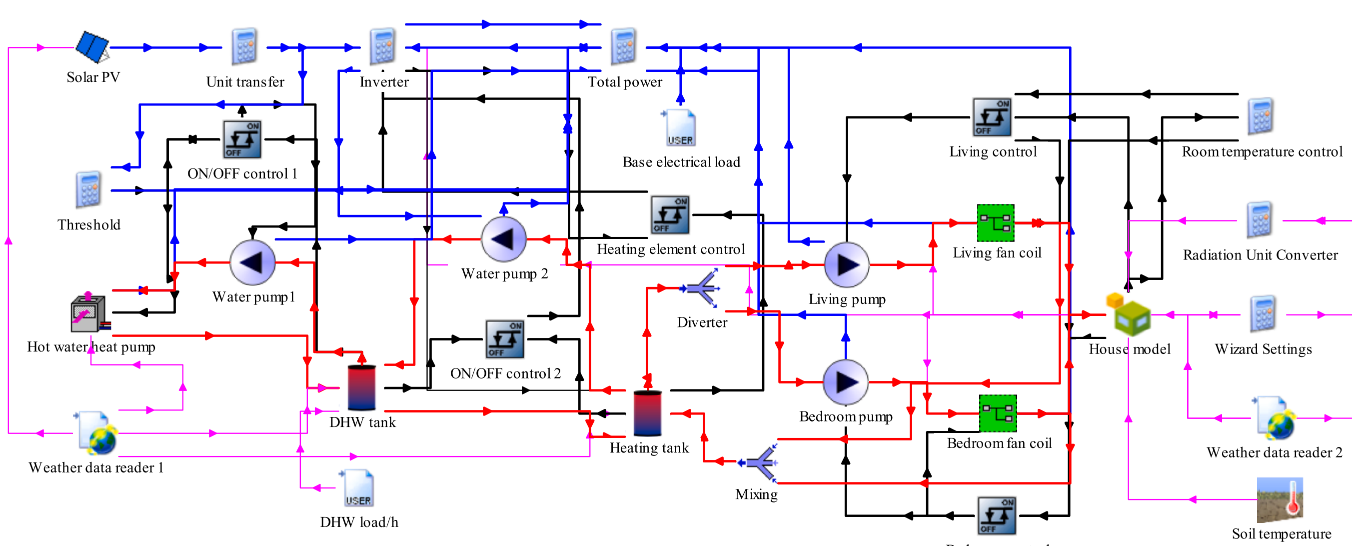


Fig. 6. TRNSYS simulation of the PSH.

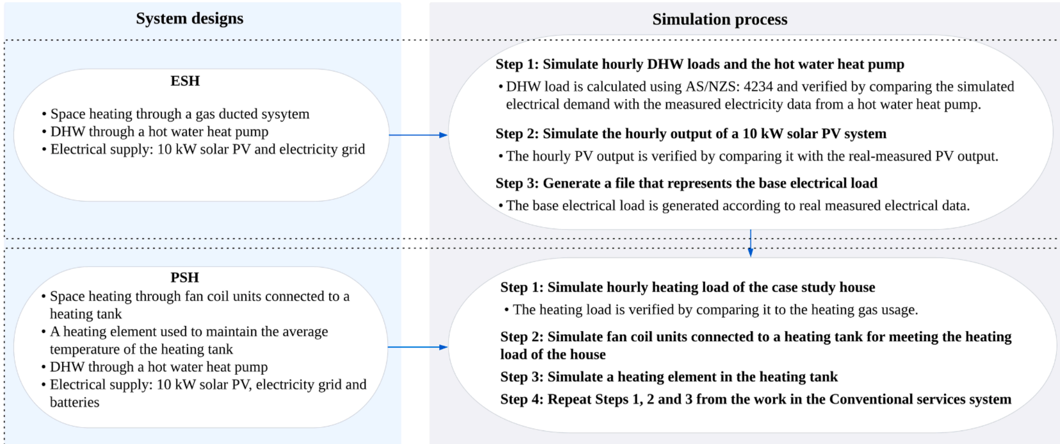


Fig. 7. TRNSYS simulation procedure of this work.

Table 3
An overview of the sizing of each system component used in ESH and PSH.

System designs	PV system (kW)	Hot water heat pump input capacity (kW)	DHW tank (L)	Gas-ducted heater (kW)	Heating tank (L)	Heating element output capacity (kW)
ESH	10	0.9	260	20	–	–
PSH	10	0.9	260	–	300	3

Table 4
A summary of relevant parameters used for the economic analyses.

Economic parameters	Value	References
Grid electricity tariff	AUD 0.329/kWh	[42]
Daily supply charge of grid electricity	AUD 1.300 per day	[42]
Feed-in tariffs	AUD 0.049/kWh	[43]
Natural gas tariff	AUD 0.120/kWh	[44]
Daily supply charge of natural gas	AUD 1.362 per day	[44]

$$C_{ic} = \sum_{n=1}^{PP}[(S_o + S_m)\times(\frac{1}{(1+i)})^{n-1}] \quad (4)$$

Where: S_o represents the annual operating cost savings of using PSH compared to ESH, and S_m is the annual maintenance cost savings of utilizing PSH compared to ESH

4.4. Environmental analysis

Electrifying the gas-ducted heater using PV-driven hot water heat pumps can be a viable approach to reducing natural gas consumption and, thus, carbon emissions [13,17]. The use of PV-driven hot water heat pumps with a heating tank in the PSH is expected to increase the local PV energy utilization. Thus, an environmental assessment is undertaken to evaluate the variance in carbon emissions between the two systems that are designed to fulfil the residential electricity, space heating, and DHW requirements. The analysis focuses on the carbon emissions that arise from using grid energy and natural gas consumption in the two systems. The carbon emission factors for using fossil fuels to generate 1 kWh of grid electricity and for consuming 1 kWh of natural gas are 0.47 kg/kWh and 0.185 kg/kWh, respectively [45].

5. Results

5.1. Verification of three TRNSYS models

To determine the accuracy and reliability of the modelled 10 kW PV, DHW demand and space heating loads for the simulated case study house, the simulation results were compared with the corresponding actual measurements to adjust the model, and the coefficient of variation of root-mean-squared error (CVRMSE) was computed based on the simulated and measured results to demonstrate the successful calibration of the TRNSYS models [46]. A summary of the comparison between the simulation results and the actual measurements is shown in Fig. 8. First, it is apparent that the simulated 10 kW PV yields an annual power generation of 14,642 kWh, representing a marginal increase of 1.93 % over the recorded annual power generation of 14,365 kWh, and the monthly CVRMSE of this PV system modelling is determined to be 6.73 %, which is below the acceptable criteria of 15 % established in the ASHRAE guidelines [47]. Second, as can be seen in Fig. 8-(b), the simulated annual electrical consumption of the hot water heat pump is 804 kWh, representing a slight reduction in comparison to the actual measured value. In addition, the monthly power usage of the two values is highly comparable. The monthly CVRMSE of this hot water heat pump modelling is identified at 12.07 %, which also satisfies the criteria mentioned above. Thirdly, the simulated space heating load for the house is 3423 kWh from May to September, whereas the actual consumption of natural gas in the house during this period is 4569 kWh. It is noteworthy that natural gas was utilised for both space heating and domestic cooking during this period. By subtracting 5 % for home cooking [48] and multiplying the resulting natural gas consumption by the 90 % efficiency of the gas-ducted heating system [49], we obtained a space heating load of 3684 kWh, closely matching the simulated space heating load, and the monthly CVRMSE of this space heating load modelling is calculated at 13.58 %, which is within the acceptable criteria of 15 %, indicating successful calibration of the house model. In summary, following proper calculations and calibrations to the models in TRNSYS, all three models, including the 10 kW solar PV system, DHW demand, and space heating load, are deemed accurate and can be employed for further evaluation.

5.2. Energy performance of ESH and PSH

To gain insight into the influence of space heating system electrification on the energy usage of the house in the case study, the TRNSYS models of ESH and PSH were configured to operate continuously for an entire year. The resulting data on energy consumption was subsequently gathered and visually represented in Fig. 9. As can be seen from the

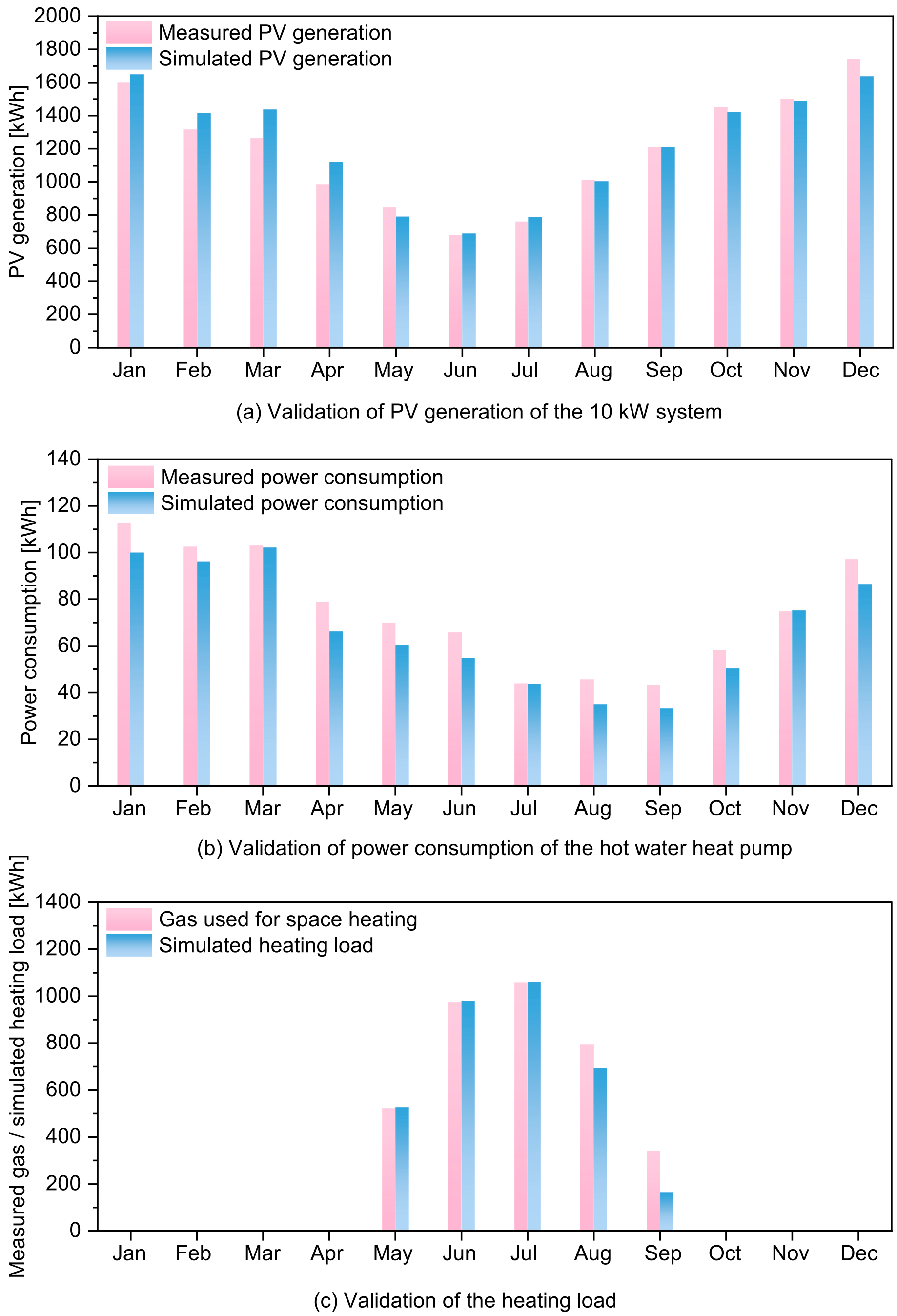


Fig. 8. A validation summary of the simulated results from TRNSYS.

figure, ESH necessitates an annual natural gas consumption of 4093 kWh for space heating. Additionally, it requires an annual electrical load of 5267 kWh, with 2555 kWh being supplied by the grid and the remaining amount being met by PV energy. This results in 11,930 kWh of the 14,642 kWh of PV energy being exported to the grid, contributing to a PV self-consumption and self-sufficiency of 19 % and 29 %, respectively. In comparison, PSH exhibits an annual electrical demand of 7731 kWh, representing a 47 % increase over the conventional services system. Additionally, PSH has an annual grid energy consumption of 3893 kWh, which is 52 % higher than the annual grid energy consumption of ESH. It is worth noting, however, that there is no demand for natural gas when the space heating system is electrified in the PSH. More importantly, by electrifying the space heating system, the utilization of PV energy is enhanced for PSH, specifically increasing from 2711 kWh to 3838 kWh. This leads to a rise in PV self-consumption and self-sufficiency to 26 % and 50 %, respectively. Therefore, it can be argued that the electrification of the space heating system based on a PV-driven hot water heat pump has a significant impact on the reduction of natural gas demand and the increase of PV energy utilization.

In order to further investigate the impact of electrification of the space heating system on the energy consumption of the case study house, we analysed the monthly data obtained from the TRNSYS models and plotted the results in graphs as shown in Fig. 10. There is a notable variance in grid energy and natural gas use between the two systems from May to September, while energy usage remains relatively consistent throughout the rest of the year. This is because May to September is the time when the heating load occurs. Furthermore, it is evident that the grid energy use of ESH is greater during the winter than in other periods of the year. This is attributed to the extended nighttime hours during winter, leading to higher electrical demand than other seasons.

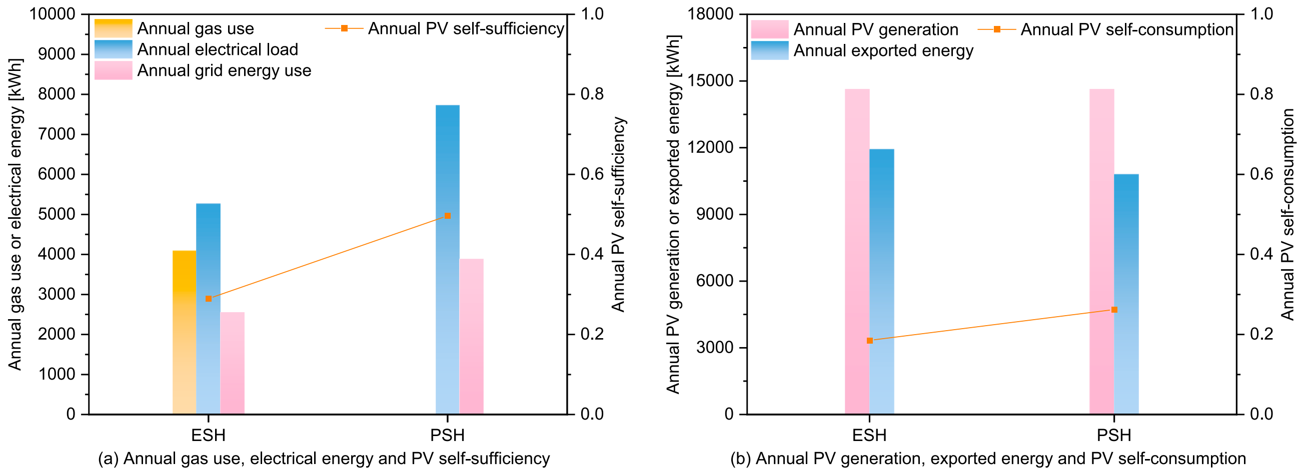


Fig. 9. Annual energy summary of ESH and PSH.

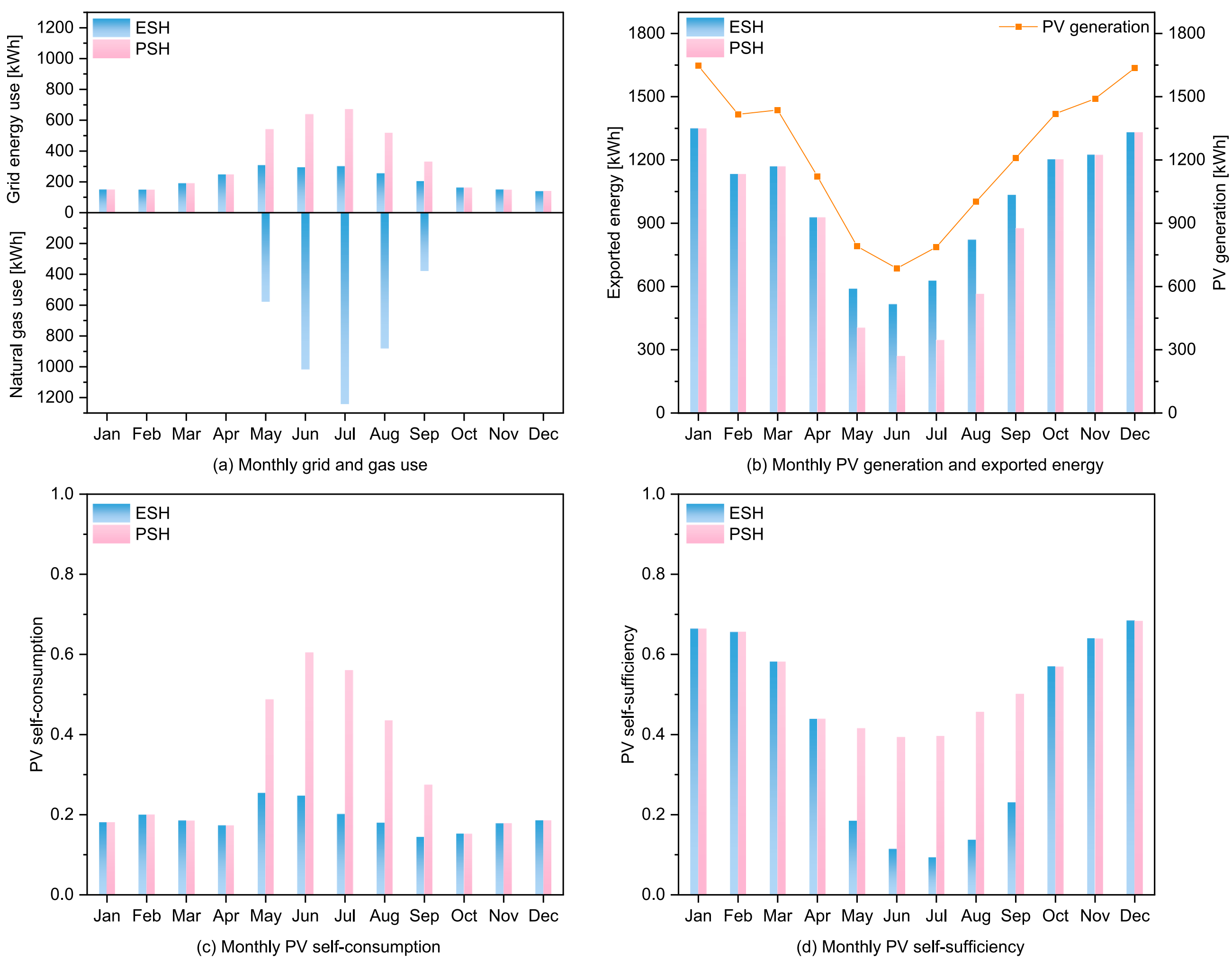


Fig. 10. Monthly energy summary of ESH and PSH.

Moreover, the transition from ESH to PSH substantially increases grid energy use in winter. Specifically, the overall electricity usage surged from 1364 kWh to 2700 kWh between May and September, as shown in Fig. 10-(a). This phenomenon is caused by space heating load occurring mainly during periods of minimal or absent solar radiation with insufficient PV energy. When the thermostat of the heating tank is triggered, the hot water heat pump or the heating element has to operate using grid energy to heat the water to the desired temperature, resulting in more grid energy consumption.

Additionally, as indicated in Fig. 10-(b), PV generation is comparatively lower during the winter due to the reduced daylight hours and solar radiation compared to other seasons. Furthermore, PSH incorporates a heating tank that enhances the utilisation of PV energy in the house. The effect occurs because a more significant proportion of the

PV energy is transformed into thermal energy, which is then stored in the water tank and utilised for space heating. The implementation of PSH led to a substantial rise in PV self-consumption and self-sufficiency between May and September, as compared to the conventional one (refer to Fig. 10-(c) and (d)). Thus, it can be said that electrification of the space heating system can dramatically affect the monthly use of natural gas, PV energy, and grid energy during winter.

As discussed above, operating a PV-driven heat pump connected to a heating tank to supply hot water for DHW and space heating can have a substantial effect on increasing residential PV energy and decreasing natural gas consumption. To examine the correlation between DHW and space heating demand and these energy uses, we selected the day (15th

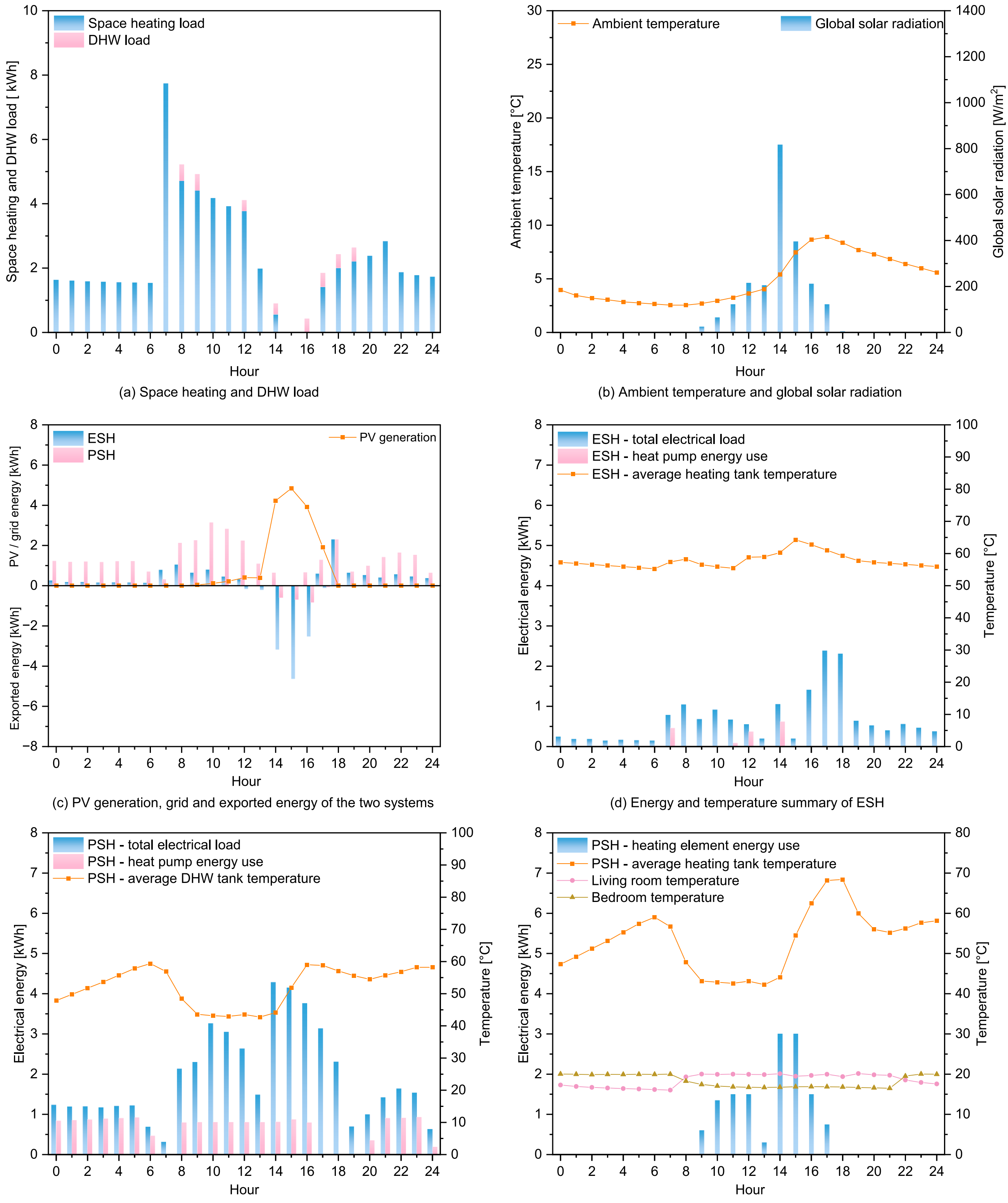


Fig. 11. Hourly energy summary of ESH and PSH on the day (15th July) in winter with the highest heating and DHW load.

July) with the highest DHW and space heating demand and the day (4th September) with the lowest DHW and space heating demand in winter. The hourly energy and temperature results for these two days are summarized and plotted in Figs. 11 and 12, respectively. It can be discovered from Fig. 11-(a) that the house exhibits a notably high demand for space heating between 7 am and 12 pm on 15th July. However, the global solar radiation during this period is relatively low, resulting in minimal PV generation, as shown in Fig. 11-(b) and (c). Fig. 11-(f) illustrates a significant fall in the average heating tank temperature from 56.7 °C at 7 am to 43.2 °C at 9 am when PSH is used. This decline is attributed to the utilization of stored hot water to meet the high space heating demand during this period. As a result, the heating element is operated from 9 am to raise the average temperature of the heating tank, when it is below 45 °C. Furthermore, the average DHW tank

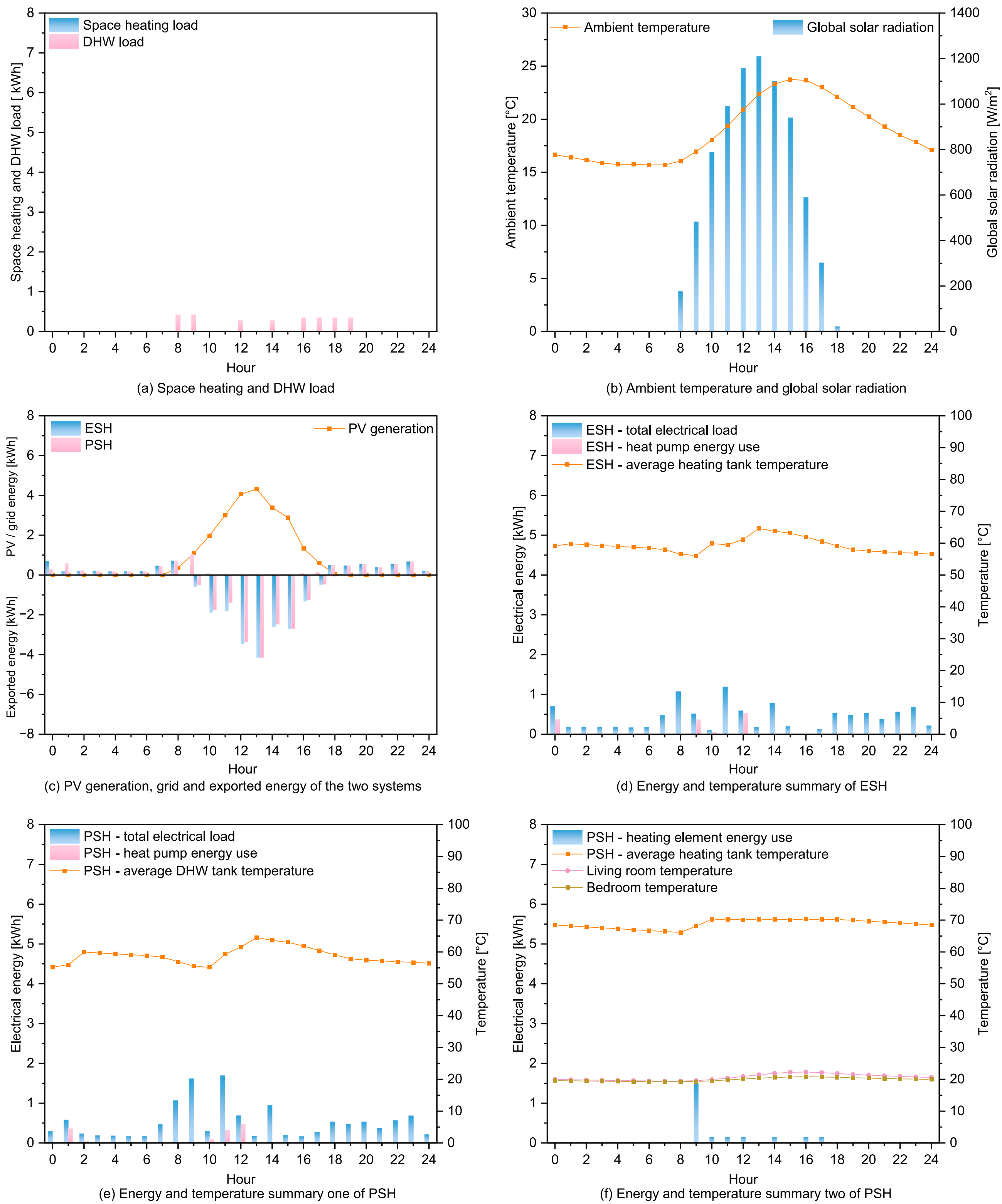


Fig. 12. Hourly energy summary of ESH and PSH on the day (4th September) in winter with the lowest heating and DHW load.

temperature in PSH likewise declines at 7 am, as shown in Fig. 11-(e). This is because the hot water stored in the DHW tank is pumped to charge the heating tank. This energy transfer occurs when the average temperature difference between the two tanks exceeds 1 °C, as explained in Section 3.2.

It is also worth noting that on this day, the PV generation reaches 14.9 kWh from 2 pm to 5 pm, as presented in Fig. 11-(c); nevertheless, PSH only has an exported energy of 2.2 kWh during this period. This is because the hot water heat pump and the heating element consume most of the PV energy for producing hot water. This is corroborated by the

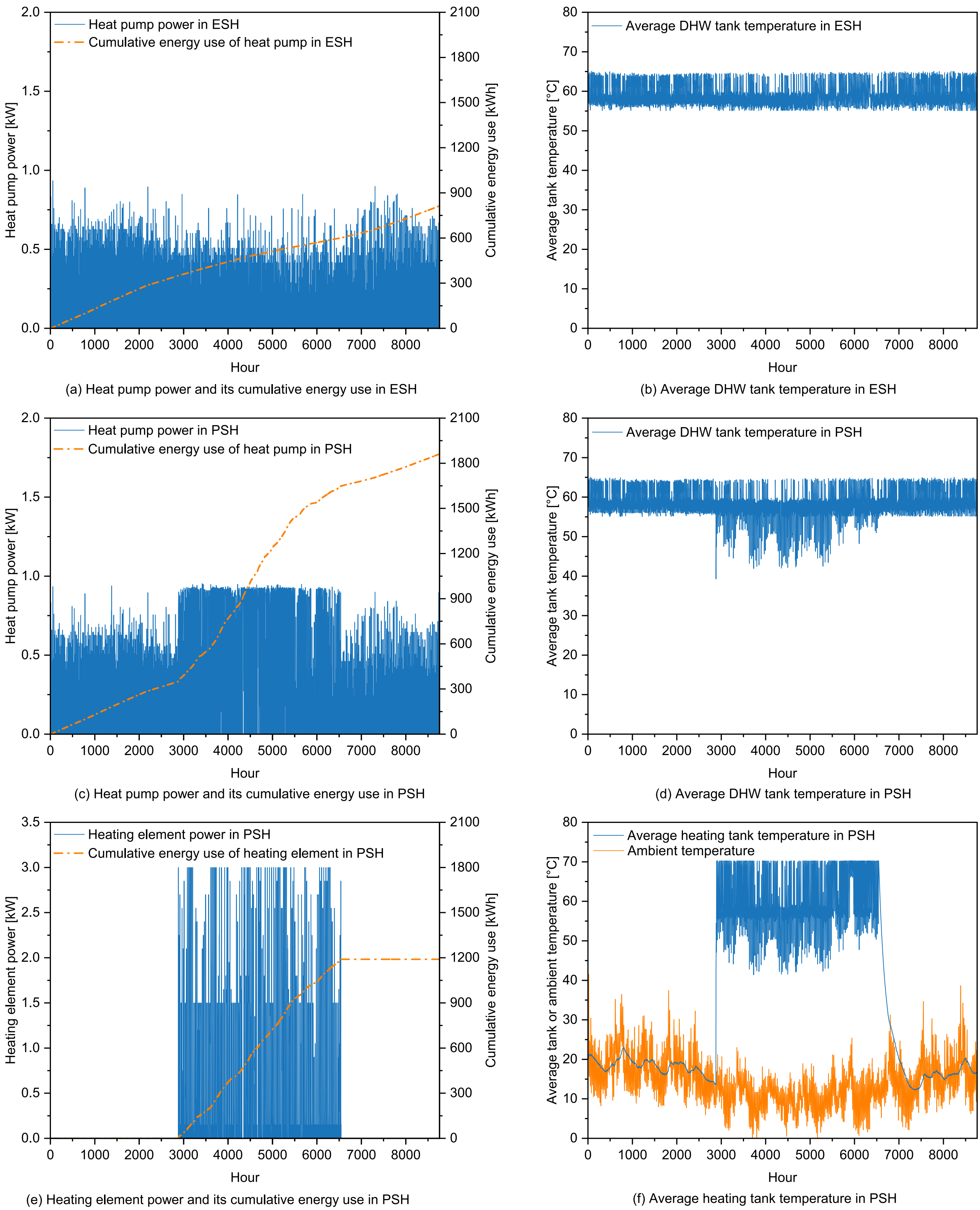


Fig. 13. Hourly power, cumulative energy use and temperature summary of ESH and PSH.

observation that the temperatures of the DHW tank and the heating tank substantially rise to 60 °C and 70 °C, respectively, at around 5 pm, as depicted in Fig. 11-(e) and (f). By contrast, when a gas-ducted heater is employed for space heating in ESH, 10.5 kWh out of its total 14.9 kWh of PV energy is sent back to the grid from 2 pm to 5 pm, as shown in Fig. 11-(c). Despite the hot water heat pump effectively increasing the average temperature of the DHW tank to approximately 65 °C, as illustrated in Fig. 11-(d), a considerable portion of the PV energy is exported due to its limited capabilities in energy storage. More importantly, as shown in Fig. 11-(f), the temperatures in the bedroom and living room exhibit a mirror effect and remain between 15 °C and 20 °C throughout the day. This is due to the fact that they are occupied for opposite periods of time, with the temperatures set to 20 °C and 15 °C during occupancy and non-occupancy, respectively, as outlined in Section 4.1. Hence, it can be claimed that the utilisation of PV energy can be greatly enhanced by electrifying the space heating system using a hot water heat pump connected to a heating tank, and the design of the space heating electrification can ensure good thermal comfort in the house.

On September 4th, the demand for space heating and domestic hot water (DHW) reaches its lowest point for the winter season. Given the elevated ambient temperature and global solar radiation, there is no need for space heating in the home, as seen in Fig. 12-(a) and (b), and the warm ambient condition results in the bedroom and living room being maintained at around 20 °C, satisfying the comfort conditions outlined in Section 4.1. Furthermore, it can be discovered that 19.1 kWh out of 23.1 kWh of PV energy is exported to the grid, when ESH is used, as shown in Fig. 12-(c). The value is nearly identical when using PSH, amounting to 18.0 kWh of exported energy. This is due to the fact that in the absence of space heating demand and with relatively low DHW demand, hot water heat pumps and the heating element cease operation when their average tank temperatures rapidly reach their maximum levels, as shown in Fig. 12-(d), (e) and (f). Consequently, the exported energy remains quite high for both system designs. Thus, it can be summarized that while a heating tank is used to supply space heating for the house, the primary factors influencing local consumption of PV energy and its energy export to the grid are space heating and DHW demand.

As previously stated, the combined operation of the heating element and the hot water heat pump in the PSH results in considerable alterations to the PV and grid energy use, in contrast to an ESH that only uses a hot water heat pump. To determine the energy use of the hot water heat pumps or the heating element in the two systems, their cumulative energy consumption, average tank temperature per hour and energy consumption per hour per year were summarised, and the results are shown in Fig. 13. The hot water heat pump in ESH consumes a total of 813 kWh of electricity annually, as presented in Fig. 13-(a). Furthermore, the overall energy usage of its hot water heat pumps experiences a much slower increase throughout the winter compared to other seasons. This observation is further supported by the fact shown in Fig. 13-(b) that the average temperature of its DHW tank is less likely to exceed 60 °C in winter in comparison to other seasons. This is because PV generation is reduced during winter compared to other seasons due to less solar radiation. The heat pump increases the temperature of the DHW tank to 65 °C in accordance with the control strategy only when there is an excess of PV energy, which occurs infrequently during the winter months. In comparison, the annual electricity consumption of the hot water heat pumps in PSH is shown in Fig. 13-(c) to be 1,861 kWh. Most of this electricity is used during winter, mainly to charge the heating tank for space heating. These findings are well supported by Fig. 13-(d), which shows that the average temperature of the DHW tank falls below 55 °C frequently for PSH, whereas this temperature never does so in ESH, where the heat pump only supplies hot water. Furthermore, according to Fig. 13-(e), the cumulative yearly energy usage of the heating element in PSH is 1190 kWh. This consumption is exclusively observed between May and September when the space heating demand is located. It is important to point out that the heating tank is only employed during the space heating season, as depicted in Fig. 13-(f); its temperature is relatively low during other seasons, closely matching the ambient temperature. On top of that, it is clear that the heating element can raise the average temperature of the heating tank to 70 °C. This occurs when the surplus PV energy is utilised and transformed into thermal energy, which is then stored in the heating tank.

The primary components utilised for space heating in PSH are the heating tank and the heating element. Their sizing was determined primarily by the peak hourly heating demand and the corresponding tank volume, potentially leading to redundant capacities. To determine the impact of their sizing on the energy consumption of the house, we adjusted the rated output capacity of the heating element and the sizing of the heating tank. Twenty-five simulation models are obtained by cross-matching the five different output capacities of the heating element with five different sizes of the heating tank. The energy consumption results of these 25 simulation models are summarized in Table 5. As shown, 9 of the 25 simulation models are not presented with results because, upon model execution, it was discovered that the average temperature of their heating tank fell below 40 °C during the space heating period, which is the minimum temperature of hot water used for space heating [35]. This finding suggests that the rated output capacity of their heating element and the sizing of their heating tank were inadequate to satisfy the peak heating demand. As a consequence, their simulation outcomes are omitted from the table. In order to ascertain the optimum sizing of the heating element and the heating tank, the annual PV self-consumption and self-sufficiency metrics are used as the criteria. These metrics quantify the proportion of locally consumed PV power and the proportion of house load met by PV power, respectively. According to this criterion, we can determine that the fifth simulation, which has a heating tank size of 300 L and a heating element output capacity of 2 kW, has the greatest annual PV self-consumption of 26 % and self-sufficiency of 51 % among all simulations. Furthermore, the annual grid energy usage of this simulation comes to 3747 kWh, making it the lowest among all the simulations listed in the table. Therefore, the energy results of the selected fifth simulation, including its annual electric load, annual grid energy use, annual exported energy, and annual PV generation, will be used in the subsequent economic and environmental analyses of this work.

5.3. Economic performance of ESH and PSH

Since the hot water heat pump and the gas-ducted heater are now implemented in the house, their sizing is determined based on actual specifications. Based on the results in Table 5, it was determined that the optimum sizing of the heating rank and the heating element for the PSH are 300 L and 2 kW, respectively. The service life of all listed equipment is assumed to be 20 years, except for heating elements, for which a service life of 5 years is assumed. As a result, the cost of four heating elements is factored into the calculation. PSH consists of two fan coil units, each dedicated to one thermal zone. The initial cost for each item used in ESH and PSH is summarized in Table 6.

The first parameter, LCC, is employed to assess the economic performance of the two system designs. The LCC is calculated by considering the initial cost, annual operating costs, annual maintenance costs, and the residual value of the equipment, as outlined in Section 4.3. The cumulative cost of the two systems over twenty years is depicted in Fig. 14-(a). As shown in Table 6, the cost of PSH in the first year is greater than that of ESH due to the higher initial investment. After four years, ESH's overall costs surpass those of PSH. This is mainly because of the higher annual operating costs and daily supply charges associated with ESH's natural gas use. On the other hand, PSH does not incur these expenses since its space heating system is powered by electricity. It is assumed that the small quantity of natural gas used for cooking at home can be met using portable gas bottles. After a period of 20 years, the LCCs of ESH and PSH are AUD 33923 and AUD 28468, respectively, indicating that the electrification of the residential space heating system

Table 5
A summary of energy consumption for 25 simulation models with different sizing of the heating element and the heating tank.

Simulation No.	Heating tank size (L)	Heating element rated output capacity (kW)	Annual grid energy use (kWh)	Annual exported energy (kWh)	Annual electrical load (kWh)	Annual heating element energy use (kWh)	Annual PV self-consumption	Annual PV self-sufficiency
1	300	4	4073	10,907	7807	1296	26 %	48 %
2	300	3.5	3983	10,850	7775	1250	26 %	49 %
3	300	3	3893	10,804	7731	1190	26 %	50 %
4	300	2.5	3816	10,774	7684	1126	26 %	50 %
5	300	2	3747	10,767	7623	1041	26 %	51 %
6	250	4	4070	10,992	7720	1200	25 %	47 %
7	250	3.5	3986	10,932	7697	1170	25 %	48 %
8	250	3	3908	10,882	7668	1128	26 %	49 %
9	250	2.5	3824	10,857	7610	1051	26 %	50 %
10	250	2	3754	10,840	7556	976	26 %	50 %
11	200	4	4072	11,082	7632	1102	24 %	47 %
12	200	3.5	3992	11,027	7607	1068	25 %	48 %
13	200	3	3775	9648	7133	1028	26 %	47 %
14	200	2.5	–	–	–	–	–	–
15	200	2	–	–	–	–	–	–
16	150	4	4105	11,189	7559	1029	24 %	46 %
17	150	3.5	4028	11,143	7527	984	24 %	46 %
18	150	3	–	–	–	–	–	–
19	150	2.5	–	–	–	–	–	–
20	150	2	–	–	–	–	–	–
21	100	4	4112	11,337	7417	861	23 %	45 %
22	100	3.5	–	–	–	–	–	–
23	100	3	–	–	–	–	–	–
24	100	2.5	–	–	–	–	–	–
25	100	2	–	–	–	–	–	–

Table 6
Initial costs of various equipment used in ESH and PSH.

System designs	List of equipment	Initial cost of each equipment (AUD)	Number of each equipment	Total initial cost of each services system (AUD)
ESH	Hot water heat pump	2400	1	
	Gas-ducted heating system	3000	1	5400
PSH	Hot water heat pump	2400	1	
	Heating tank (300 L)	1600	1	
	Heating element (2 kW)	100	4	
	Fan coil unit	1000	2	
	Auxiliary devices	1000	1	7400

based on the PV-driven hot water heat pumps can result in significant cost savings.

The economic advantages of electrifying the residential space heating system are also determined by calculating the PP, and the findings are illustrated in Fig. 14-(b). As the house is presently equipped with a hot water heat pump, the cost of transitioning from ESH to PSH is AUD 5000, which is obtained by subtracting the initial cost of the hot water heat pump from the total initial cost of AUD 7,400 for PSH in Table 6. In such a case, the payback period would be 12.3 years, as shown in Fig. 14-(b), which is relatively close to the real life of PV panels. Furthermore, due to the present prohibition by the Victorian Government on using natural gas in new residences, it also anticipates local governments providing financial incentives for electrifying conventional fossil fuel-based heating systems for existing dwellings. Should the government offer assistance for residential heating space electrification initiatives, the corresponding PPs for transitioning from ESH to PSH would be reduced to 10.8, 8.8, and 5.6 years, respectively, under the assumption that initial costs are diminished by 10 %, 25 %, and 50 %.

5.4. *Environmental performance of ESH and PSH*

According to the results in Section 5.2, ESH requires an annual consumption of 4093 kWh of natural gas and 2555 kWh of grid electricity. By contrast, the annual grid consumption of 3747 kWh is needed when PSH is used. Additionally, renewable energy systems that do not generate carbon emissions supply 32 % of Australia's overall grid electricity [50]. A calculation suggests that transitioning from PSH to ESH will lead to a 24 % decrease in annual carbon emissions, from 1574 kg to 1198 kg. It is crucial to acknowledge that with the ongoing increase in the percentage of electricity derived from renewable sources in Australia, there will be a corresponding annual reduction in the carbon emissions associated with grid electricity production. Furthermore, it should be noted that while the case study house relies solely on electricity to meet its energy needs when PSH is implemented, a considerable quantity of PV energy (specifically, 10,767 kWh out of the total 14,642 kWh generated in the fifth simulation presented in Table 5) is sent back to the grid. The use of alternative methods, such as battery storage, can further increase the efficiency of local PV energy utilisation and consequently decrease annual grid energy consumption.

6. Discussion

The electrification of the space heating system in this study increased the household's reliance on grid electricity, particularly during the winter months, as illustrated in Fig. 13. This result is consistent with that of Thomaßen, et al. [29], who observed that cross-sectoral effects may result from the electrification of building heating due to increased demand for grid electricity, which was not taken into consideration in the initial design of the grid. Utilising additional storage devices, such as batteries, could be one solution to this issue [19] since there is still a significant amount of exported energy during the winter months when using PSH, as shown in Fig. 10. Smart energy communities are now gaining popularity since they allow users to take advantage of excess PV power from their neighbouring homes [51]. Based on this concept, community-based heating tanks can be established to enable each user to produce additional heat storage for their neighbours in the community by consuming excess PV energy. Furthermore, by

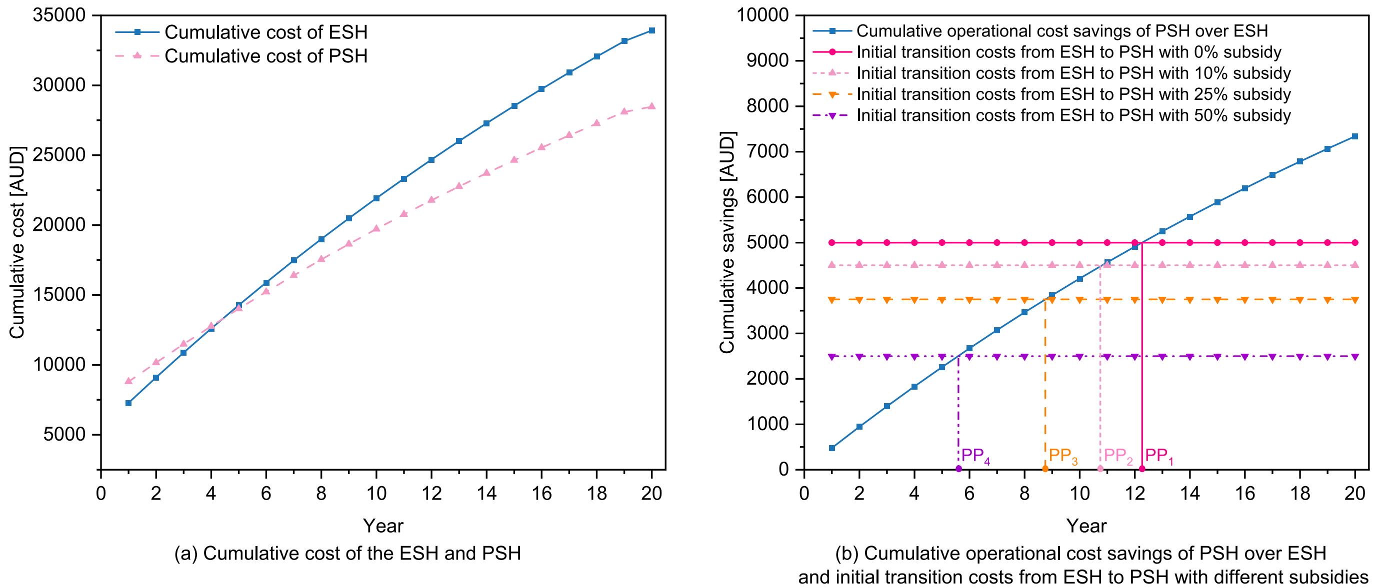


Fig. 14. Cumulative cost and savings summary of ESH and PSH: $PP_1 = 12.3$ years, $PP_2 = 10.8$ years, $PP_3 = 8.8$ years, and $PP_4 = 5.6$ years.

incorporating the day-ahead scheduling principle [16], generating heating energy by utilising low-demand electricity from the grid before the heating period becomes feasible. This approach allows for the shaving and reduction of the peak heating load of communities.

Given the heating-oriented nature of Geelong, Australia, where the case study house is located, and the absence of mechanical equipment for space cooling, this paper exclusively examines the use of PV-driven hot water heat pumps to fulfil space heating and DHW requirements. Nevertheless, based on the ambient temperature data in Fig. 4-(f) and the base temperature of 18.3 °C established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers [52], we computed the heating degree days (HDDs) and cooling degree days (CDDs) of Geelong to be 1638 and 241, respectively, underscoring the necessity of considering a PV-driven heat pump to adequately fulfil the space heating, space cooling, and DHW of the residence. This development would provide constructive recommendations for residents living in various regions of Australia. Our prior research has theoretically examined the viability of this concept [7]. Future studies will use TRNSYS to analyse the feasibility of using PV-driven heat pumps to achieve residential energy autonomy in a simulated real-world environment.

The economic analysis in this work revealed that the payback period for the electrification of the space heating system is 12.3 years, which is considered a long time without financial assistance from the government. It is imperative to realise that space heating is essential for this house. Conventional gas-ducted heaters do not offer a payback period when used in PV homes, as they provide space heating through the combustion of natural gas. In addition, excess PV energy is not utilised effectively during daylight hours due to load limitations, and the decreasing income from selling electricity to the grid further reduces the economic viability of solar PV systems. The payback period for this space heating electrification becomes more attractive by subtracting the cost of the gas-ducted heating system from the initial cost of PSH. The increased utilisation of PV energy makes this space heating electrification an ideal case study for residents and also offers compelling evidence for local governments to gradually eliminate the use of natural gas in residential buildings.

7. Conclusion

This paper analyses the energy, economic and environmental performance of transitioning residential conventional gas-ducted space heating systems to an electrified system, where space heating is achieved by using fan coil units and a heating tank connected to a PV-driven hot water heat pump. This transition aims to increase PV energy utilization and reduce the fossil fuel usage of houses. To achieve this aim, a typical Australian house was used as a case study, and ESH and PSH are simulated in TRNSYS. The energy performance of the two systems was evaluated based on their annual, monthly and daily energy consumption and two energy metrics, i.e., PV self-consumption and PV self-sufficiency. In addition, the economic benefits involved were examined in light of the payback period for this transition and the environmental benefits were analysed according to the difference in annual carbon emissions using the two system designs.

The findings indicated that PSH incurred an annual grid electricity demand of 3893 kWh, surpassing that of ESH by 47 % at 2555 kWh. Nevertheless, PSH eliminated the yearly natural gas demand of 4093 kWh from ESH. In addition, space heating electrification increases PV self-consumption and self-sufficiency from 19 % and 29 % to 26 % and 50 %, respectively. The monthly summary showed that electrification of the space heating system significantly increased grid energy consumption from May to September. In addition, by considering annual PV self-consumption and self-sufficiency as factors, the optimum sizing for the heating tank and the heating element is determined to be 300 L and 2 kW, respectively. The economic analysis revealed that the payback period for transitioning from ESH to PSH was 12.3 years, without any financial subsidy. By providing subsidies amounting to 10 %, 25 %, and 50 % of the initial retrofit cost, the payback period could be shortened to 10.8, 8.8, and 5.6 years, respectively. Due to the higher demand for grid electricity, PSH had an annual carbon emission of 1198 kg, which is 24 % less than 1574 kg generated by ESH.

This work demonstrated the feasibility of electrifying the gas-ducted heaters to fan coil units and a heating tank connected to a PV-driven hot water heat pump from the energy, economic and environmental perspectives. Additionally, it offers solid support for local governments seeking to prohibit the use of natural gas in homes and for residents desiring to increase local PV energy utilization. Future studies will investigate the viability of utilising PV together with batteries, heat pumps, and water storage tanks to fully meet the electrical and thermal energy needs of residential buildings.

CRediT authorship contribution statement

Zheng Wang: Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Mark Luther:** Supervision, Data curation, Conceptualization. **Peter Horan:** Supervision, Data curation. **Jane Matthews:** Supervision. **Chunlu Liu:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

Appendix A

Table A1
Natural gas usage of the case study house from June 2022 to May 2023.

Month periods	Natural gas usage / kWh
01/6/2022 to 30/06/2022	1140.16
01/7/2022 to 31/07/2022	1235.18
01/8/2022 to 31/08/2022	927.08
01/9/2022 to 30/09/2022	397.32
01/10/2022 to 31/10/2022	265.90
01/11/2022 to 30/11/2022	177.27
01/12/2022 to 31/12/2022	39.68
01/1/2023 to 31/01/2023	26.45
01/2/2023 to 28/02/2023	42.17
01/3/2023 to 31/03/2023	25.30
01/4/2023 to 30/04/2023	260.81
01/5/2023 to 31/05/2023	608.55

Data availability

Data will be made available on request.

References

[1] U. Berardi, S. Jones, The efficiency and GHG emissions of air source heat pumps under future climate scenarios across Canada, *Energ. Buildings* 262 (2022) 112000.
[2] Z. Wang, M.B. Luther, A. Siamas, J. Matthews, C. Liu, Development and performance testing of a polyvalent heat pump for hot and cold water production, *Archit. Sci. Rev.* (2023) 1–12.
[3] M. Herrando, A. Coca-Ortegón, I. Guedea, N. Fueyo, Experimental validation of a solar system based on hybrid photovoltaic-thermal collectors and a reversible heat pump for the energy provision in non-residential buildings, *Renew. Sustain. Energy Rev.* 178 (2023) 113233.
[4] P.A. Østergaard, N. Duic, Y. Noorollahi, S. Kalogirou, Renewable energy for sustainable development, *Renew. Energy* 199 (2022) 1145–1152.
[5] M. Arbulu, X. Oregi, L. Etxepare, Environmental and economic optimization and prioritization tool-kit for residential building renovation strategies with life cycle approach, *Build. Environ.* 228 (2023) 109813.
[6] International Energy Agency, Total energy supply by source in Australia. 2023. http://bit.ly/41Xs5fH. (Accessed 10th November 2023).
[7] Z. Wang, M.B. Luther, P. Horan, J. Matthews, C. Liu, On-site solar PV generation and use: Self-consumption and self-sufficiency, *Build. Simul.* (2023) 1–15.
[8] E. Ohene, A.P. Chan, A. Darko, Review of global research advances towards net-zero emissions buildings, *Energ. Buildings* 266 (2022) 112142.
[9] B.R. Park, M.H. Chung, Analysis of the additional energy-saving potential of residential buildings after mandatory zero-energy buildings to achieve carbon neutrality in South Korea, *Build. Environ.* 228 (2023) 109908.
[10] C. Ermel, M.V. Bianchi, A.P. Cardoso, P.S. Schneider, Thermal storage integrated into air-source heat pumps to leverage building electrification: A systematic literature review, *Appl. Therm. Eng.* 118975 (2022).
[11] E. Atasoy, B. Çetin, Ö. Bayer, Experiment-based optimization of an energy-efficient heat pump integrated water heater for household appliances, *Energy* 245 (2022) 123308.
[12] D. Wu, B. Hu, R. Wang, Vapor compression heat pumps with pure Low-GWP refrigerants, *Renew. Sustain. Energy Rev.* 138 (2021) 110571.
[13] A. Heinz, R. Rieberer, Energetic and economic analysis of a PV-assisted air-to-water heat pump system for renovated residential buildings with high-temperature heat emission system, *Appl. Energy* 293 (2021) 116953.
[14] M.H. Abbasi, B. Abdullah, M.W. Ahmad, A. Rostami, J. Cullen, Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology, *Sustainable Energy Technol. Assess.* 48 (2021) 101630.
[15] X. Shen, P. Liu, Y. Qiu, A. Patwardhan, P. Vaishnav, Estimation of change in house sales prices in the United States after heat pump adoption, *Nat. Energy* 6 (1) (2021) 30–37.
[16] M. Tostado-Véliz, A.R. Jordehi, S.A. Mansouri, F. Jurado, Day-ahead scheduling of 100% isolated communities under uncertainties through a novel stochastic-robust model, *Appl. Energy* 328 (2022) 120257.
[17] A.A. Aliabadi, X. Chen, J. Yang, A. Madadizadeh, K. Siddiqui, Retrofit optimization of building systems for future climates using an urban physics model, *Build. Environ.* 243 (2023) 110655.
[18] A. Pena-Bello, P. Schuetz, M. Berger, J. Worlitschek, M.K. Patel, D. Parra, Decarbonizing heat with PV-coupled heat pumps supported by electricity and heat storage: Impacts and trade-offs for prosumers and the grid, *Energ. Conver. Manage.* 240 (2021) 114220.
[19] Z. Wang, M. Luther, P. Horan, J. Matthews, C. Liu, Technical and economic analyses of PV battery systems considering two different tariff policies, *Sol. Energy* 267 (2024) 112189.
[20] U. Mulleriyawage, P. Wang, T. Rui, K. Zhang, C. Hu, W. Shen, Prosumer-centric demand side management for minimizing electricity bills in a DC residential PV-battery system: An Australian household case study, *Renew. Energy* 205 (2023) 800–812.
[21] Y. Li, G. Rosengarten, C. Stanley, A. Mojiri, Electrification of residential heating, cooling and hot water: Load smoothing using onsite photovoltaics, heat pump and thermal batteries, *J. Storage Mater.* 56 (2022) 105873.
[22] M. Hammerle, P.J. Burke, From natural gas to electric appliances: Energy use and emissions implications in Australian homes, *Energy Econ.* 110 (2022) 106050.
[23] D.H. Clift, H. Suehrcke, Control optimization of PV powered electric storage and heat pump water heaters, *Sol. Energy* 226 (2021) 489–500.
[24] E. Nordgård-Hansen, N. Kishor, K. Midttømme, V.K. Risinggård, J. Kocbach, Case study on optimal design and operation of detached house energy system: Solar, battery, and ground source heat pump, *Appl. Energy* 308 (2022) 118370.
[25] A. Allouhi, Techno-economic and environmental accounting analyses of an innovative power-to-heat concept based on solar PV systems and a geothermal heat pump, *Renew. Energy* 191 (2022) 649–661.
[26] A. Dezhdar, E. Assareh, N. Agarwal, S. Keykhah, M. Aghajari, M. Lee, Transient optimization of a new solar-wind multi-generation system for hydrogen production, desalination, clean electricity, heating, cooling, and energy storage using TRNSYS, *Renew. Energy* 208 (2023) 512–537.
[27] Z. Wang, M.B. Luther, M. Amirkhani, C. Liu, P. Horan, State of the art on heat pumps for residential buildings, *Buildings* 11 (8) (2021) 350.
[28] H. Biglarian, S. Abdollahi, Utilization of on-grid photovoltaic panels to offset electricity consumption of a residential ground source heat pump, *Energy* 243 (2022) 122770.
[29] G. Thomaßen, K. Kavvadias, J.P.J. Navarro, The decarbonisation of the EU heating sector through electrification: A parametric analysis, *Energy Policy* 148 (2021) 111929.
[30] I.S. Walker, B.D. Less, N. Casquero-Modrego, Carbon and energy cost impacts of electrification of space heating with heat pumps in the US, *Energ. Buildings* 259 (2022) 111910.
[31] N. Sommerfeldt, J.M. Pearce, Can grid-tied solar photovoltaics lead to residential heating electrification? A Techno-Economic Case Study in the Midwestern US, *Applied Energy* 336 (2023) 120838.

[32] M. Pinamonti, I. Beausoleil-Morrison, A. Prada, P. Baggio, Water-to-water heat pump integration in a solar seasonal storage system for space heating and domestic hot water production of a single-family house in a cold climate, *Sol. Energy* 213 (2021) 300–311.
[33] A. Thür, T. Calabrese, W. Streicher, Smart grid and PV driven ground heat pump as thermal battery in small buildings for optimized electricity consumption, *Sol. Energy* 273 (2018).
[34] M.Z. Pomianowski, H. Johra, A. Marszal-Pomianowska, C. Zhang, Sustainable and energy-efficient domestic hot water systems: A review, *Renew. Sustain. Energy Rev.* 128 (2020) 109900.
[35] K. Du, J. Calautit, Z. Wang, Y. Wu, H. Liu, A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges, *Appl. Energy* 220 (2018) 242–273.
[36] SAI Global (2021).
[37] Z. Wang, M. Luther, P. Horan, J. Matthews, C. Liu, Performance investigation of transitioning building services system in photovoltaic homes, *Journal of Building, Engineering* (2024) 108540.
[38] S.S. Alrwashdeh, H. Ammari, Life cycle cost analysis of two different refrigeration systems powered by solar energy, *Case Stud. Therm. Eng.* 16 (2019) 100559.
[39] L. Liu, W. Liu, J. Yao, T. Jia, Y. Zhao, Y. Dai, Life cycle energy, economic, and environmental analysis for the direct-expansion photovoltaic-thermal heat pump system in China, *J. Clean. Prod.* 434 (2024) 139730.
[40] Independent Pricing and Regulatory Tribunal, Local Government discount rate. 2023. https://bit.ly/44fL6uw. (Accessed 10th November 2023).
[41] A. Hassan, Y.M. Al-Abdeli, M. Masek, O. Bass, Optimal sizing and energy scheduling of grid-supplemented solar PV systems with battery storage: Sensitivity of reliability and financial constraints, *Energy* 238 (2022) 121780.
[42] Essential Services Commission, Victorian default offer price determination 2023-24. 2023. https://bit.ly/3S1lZbb. (Accessed 14th November 2023).
[43] Essential Services Commission, Minimum feed-in tariff review 2023-24. 2023. https://bit.ly/41YhNfP. (Accessed 2nd April 2024).
[44] Energy Australia, Electricity and gas plans. 2023. https://bit.ly/3PNlilc. (Accessed 10th December 2023).
[45] Department for Environment Food & Rural Affairs, Guidelines to Defra's GHG conversion factors for company reporting, in, 2007.
[46] F. Tüysüz, H. Sözer, Calibrating the building energy model with the short term monitored data: A case study of a large-scale residential building, *Energ. Buildings* 224 (2020) 110207.
[47] ASHRAE, ASHRAE's Guideline 14-2002: Measurement of Energy Demand and Savings, in, Atlanta, GA, USA, 2002.
[48] Standards Australia, AS/NZS 5263.1.2 - Gas appliances, in, SAI Global, Sydney, Australia, 2020.
[49] The Equipment Energy Efficiency Program, Gas sapce heaters - performance testing and energy labelling in, 2015.
[50] E. Department of Climate Change, the Environment and Water,,, Electricity generation. 2024. https://bit.ly/4ai6Ubk. (Accessed 10th January 2024).
[51] D. de São José, P. Faria, Z. Vale, Smart energy community: A systematic review with metanalysis, *Energ. Strat. Rev.* 36 (2021) 100678.
[52] L.D. Harvey, Using modified multiple heating-degree-day (HDD) and cooling-degree-day (CDD) indices to estimate building heating and cooling loads, *Energ. Buildings* 229 (2020) 110475.