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Performance investigation of transitioning building services system in photovoltaic homes

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ABSTRACT

Growing concern over residential carbon emissions has highlighted the necessity of transitioning conventional fossil fuel-based building services system into one that utilizes renewable energy sources. Therefore, this paper proposes a building services system, including an air-source heat pump, water storage tanks and batteries, for photovoltaic (PV) homes so that all their energy loads are electrified and mostly met by PV power. It aims to investigate the merits of the proposed system in relation to energy, economic and environmental performance by designing three distinct scenarios for power supply, space heating, space cooling, and domestic hot water (DHW). A typical Australian house equipped with a 10 kW solar PV system in Geelong, Victoria, is used as a case study. Three scenarios are modelled using Transient System Simulation (TRNSYS) software, and the simulated PV generation, space heating, and DHW load are validated using actual measured results. Findings show that the proposed system offsets all the natural gas demand of 6915 kWh required by Scenario 1 using the conventional fossil fuel-based system and increases the PV self-consumption and self-sufficiency from 18 % to 24 % in Scenario 1–38 % and 75 %, respectively. After adjusting component sizes following the principle of diminishing returns, the proposed system has a nine-year payback period and reduces carbon emissions by 67 % compared to the conventional system. This study demonstrates the capability of the proposed system to electrify our house loads, thus contributing to a decarbonized residential future.

Nomenclature

AC	Alternating current
AUD	Australian dollar
DC	Direct current
DHW	Domestic hot water
HVAC	Heating, cooling and air conditioning
NPV	Net present value
PV	Photovoltaic
SC	Self-consumption
SS	Self-sufficiency
TRNSYS	Transient System Simulation

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USD	US dollar
C_n	The cash flow in the nth year
E_t	The electrical demand of the house during each timestep t
G_t	The natural gas demand of the house during each timestep t
i	The discount rate
n	nth year
PV_t	The amount of generated PV energy during each timestep t
PV_t^c	The amount of PV energy consumed on-site during each timestep t
T_{ca}	Average cold tank temperature
T_{ct}	Cold tank thermostat setting
T_{ha}	Average hot tank temperature
T_{ht}	Hot tank thermostat setting

1. Introduction

Solar photovoltaic (PV) systems have been increasingly implemented in homes worldwide; for instance, in more than 30 % of Australian households [1]. Despite this, carbon emissions from residential buildings are still relatively high due to their significant consumption of fossil fuels and grid electricity [2]. The residential sector in Australia is responsible for at least 20 % of its total carbon emissions, with each household producing more than 18 tonnes per year [3]. Building services systems can be considered a major contributor to residential energy consumption. Approximately 65 % of energy consumption in Australian households is utilised to meet thermal requirements, of which 40 % is used for space conditioning and 25 % for domestic hot water (DHW) production [4]. Therefore, reducing carbon emissions from residential building operations will contribute significantly towards achieving the global target of carbon neutrality by 2050 [5].

Heat pumps have been recognized as great technology to achieve decarbonization of residential building services due to their effective heating and cooling capabilities [6] and the fact that they can use natural refrigerants with very low global warming potential and zero ozone depletion potential [7]. Air-source heat pumps have been widely used in the residential sector worldwide because they are relatively cost-effective and easy to install compared to ground-source and water-source heat pumps [8,9]. According to the data published by the International Energy Agency [10], air-source heat pumps accounted for more than 60 % of the global market in 2021, and the number of heat pumps installed worldwide is predicted to reach about 600 million in 2030 [11]. Additionally, the coefficient of performance of heat pumps, which measures the ratio of thermal output to their electric input, can reach three to five depending on different temperatures of the heat source and sink [12], demonstrating that they are a superior option to conventional gas or electric heating devices with heating efficiencies below one. Meanwhile, government departments have noticed the potential of heat pumps to reduce greenhouse gas emissions, and they have been supporting residents in purchasing heat pumps and providing related subsidy policies. For instance, according to the hot water rebate enacted by the Victorian government in Australia, local households can apply for a refund of up to AUD 1000 for the installation of a DHW heat pump [13]. In the United States, North Carolina utilities offer rebates of about USD 200 to 500 for each new heat pump installation [14].

In addition to being noted for their outstanding efficiency and environmental friendliness, heat pumps can be used with residential solar PV systems to increase PV self-consumption and potentially enable off-grid operation in homes. Due to the limited simultaneity between the peak PV generation and residential electrical load, the PV self-consumption, measuring the proportion of total PV generation consumed on-site, is relatively low [15]. Moreover, it appears that residents can no longer receive significant revenue by selling the excess PV energy to the grid, either due to the low feed-in tariffs [16] or because the grid is already overloaded [17]. In such cases, heat pumps are a promising approach to increase the solar fraction of the residential loads, as heating and cooling energy used for space conditioning and DHW can be generated and stored in water storage tanks by consuming daily excess PV energy. Furthermore, the use of batteries in residential solar PV systems is becoming appealing, and the excess PV energy generated during the day, instead of being exported to the grid or wasted, can be stored in batteries and consumed during peak load periods.

Using solar PV to charge batteries and to operate heat pumps with water storage tanks to service homes can effectively mitigate the reliance on fossil fuels and grid electricity typically required by conventional residential building service systems. While there are significant advantages associated with using the aforementioned combined system, the specific benefits in terms of grid savings, the increase in PV self-consumption, and self-sufficiency can vary due to the distinctive load profiles of homes [17], different climatic conditions [18], unique control strategies used for system operation [19], etc. When optimizing the benefits of PV-powered heat pumps and energy storage systems, a thorough understanding of these concepts can firstly facilitate the development of more efficient control strategies, and, secondly, it enables homeowners and professionals to gradually determine the appropriate sizing of different system components, such as PV systems, batteries, water storage tanks, and heat pumps. Scholars have studied these issues extensively. A prior study has demonstrated that the utilisation of a PV-powered heat pump with hot and cold water storage tanks in a case study residence located in Brisbane, Australia, with a subtropical climate, resulted in a reduction of around 76 % in grid electricity consumption in comparison to the sole use of a heat pump [17]. In addition to this, the use of hot and cold water storage tanks increased the PV self-consumption and self-sufficiency by 29 % and 46 %, respectively. The effect can differ across regions of the world due to varying climate conditions. For instance, another study by Li et al. [18] revealed that the use of PV-powered heat pumps together with water storage tanks contributed to a 40 % reduction in residential grid loads in the warm climate of Perth, Australia, and a 60 % reduction in

the cold climate of Beijing. Furthermore, the size of hot and cold water tanks can also have different impacts on PV and grid energy use. As an example, in designing a PV-powered heat pump with water storage tanks for residential heating, cooling, and DHW, Wang et al. [19] discovered that increasing the size of the cold water tank resulted in less improvement in PV self-consumption and self-sufficiency when compared to the increase in the hot water tank size. The local climatic conditions and the specific control strategy of the system operation are both potential causes for this phenomenon.

A review of the existing literature reveals that most of the studies either only use batteries or heat pumps with water storage tanks to couple to the PV system or use both but only partially meet the electrical, heating, cooling and DHW loads of houses. This paper proposes a building services system, including an air-source heat pump, water storage tanks and batteries, for photovoltaic (PV) homes so that all their energy loads are electrified and mostly met by PV power. Furthermore, the proposed system and the conventional fossil fuel-based building services system are modelled using the Transient System Simulation (TRNSYS) software, aiming to investigate the advantageous aspects of the transition of building services systems. The novelty of this paper compared to the existing literature is that it examines the feasibility of using PV-connected heat pumps with water storage tanks and batteries to satisfy all electrical and thermal loads of homes in a simulated real-world context. In addition, actual-measured PV generation and electrical demand obtained from a case study house are used in the analysis, making the results more realistic and trustful. Compared to previous research, this work provides a more comprehensive evaluation of the energy, economic, and environmental benefits of using the proposed building services system in PV homes.

The remaining sections are organized as follows. Section 2 examines the existing literature on using PV-driven heat pumps and energy storage systems and concludes with a discussion of the knowledge gaps identified. Section 3 explains the conventional and proposed building services systems that provide electricity, space heating, space cooling and DHW to a case study house. Section 4 presents three scenarios based on conventional and proposed building services systems and their operational principles. In addition, this section describes the modelling process of these three scenarios in TRNSYS as well as the energy, economic, and environmental analysis methods used in this study. Section 5 presents the results of the study in detail. Section 6 presents the discussion, and Section 7 draws a conclusion for this paper.

2. Literature review

A number of scholars have studied the impact of using heat pumps with energy storage systems as building services systems in PV homes. For example, the potential to reduce grid electricity consumption through a PV-powered air-to-water heat pump with a hot water tank was investigated using TRNSYS [20]. The authors only considered the use of the combined system for space heating and DHW in a single house, ignoring the possibility of using the heat pump for space cooling through cold water storage. Another study was done by Li et al. [17], who used air-source heat pumps and water storage tanks to provide space heating, space cooling and DHW for PV houses but did not consider using batteries to store excess PV energy. Pinamonti et al. [21] analysed the effect of improving PV energy utilisation by integrating a heat pump with a solar PV system. The authors neither considered using heat pumps for space cooling nor electrical batteries for storing excess PV energy, which has been proven to be a great solution in decarbonising building energy loads.

In addition to using air-source heat pumps, Kimiaei et al. [22] investigated the performance of a building services system that uses ground-source heat pumps with water storage tanks and batteries to store heat and electricity during off-peak hours by consuming grid electricity to offset building loads and peak grid demand. However, solar PV, which can provide a renewable energy supply, was not included in the study. The possible impact of increasing PV self-consumption using ground-source heat pumps with thermal energy storage was analysed [23]. The authors discovered that the solar fraction increased from 11 % to 61 % using a 2000 L water storage tank and building thermal mass to supply space heating and DHW. Knuutinen et al. [24] investigated the effectiveness of utilising a PV-powered ground-source heat pump with four different control strategies to reduce DHW heating costs in Finland. The impact of coupling a ground source heat pump with a building-integrated PV system on reducing residential energy consumption and carbon emissions was analysed in Iran [25]. It is noteworthy that ground-source heat pumps are more suited to regions with extreme climates [9], so their potential for saving costs and energy in moderate climates needs investigation. Alternatively, air-source heat pumps have the most significant installation worldwide due to their low installation costs and high performance, so research on them may be more widely accepted.

When studying the performance of building services systems in homes, most studies have only focused on their energy performance and ignored economic or environmental performance. For instance, the seasonal performance of PV coupled with water storage tanks and phase change materials for supplying DHW in a typical residential building was studied experimentally [26], but only the energy analysis was conducted in the work. Another study by Fitzpatrick et al. [27] analysed the influence of using a heat pump coupled with a water storage tank for supplying space heating and DHW for buildings. The authors focused on the energy and cost performance of the proposed system but did not consider the environmental benefits it might achieve. Nordgård-Hansen et al. [28] created a mixed integer linear programming model to examine the effect of government policies, such as electricity tariffs, on the energy and cost-effectiveness of ground source heat pumps with batteries for solar houses. However, the environmental benefits that combined systems can offer were not examined in the paper.

TRNSYS software is widely used to model residential solar PV systems with heat pumps and energy storage systems, such as water storage tanks and batteries. In addition to the previously mentioned literature [17,20,21,23,25], there is some other literature where TRNSYS was used in the work to simulate the investigated system. Da et al. [29] modelled a PV-powered air-source heat pump with water storage tanks for space heating and DHW using TRNSTS, and the simulated model was validated using empirically measured results. In the study by Jafarian et al. [30], the authors used TRNSYS to simulate a combined system, including a heat pump, PV/thermal collectors, a battery, etc., and the energy, economic and environmental performances of the system were analysed.

Based on the discussion of the literature review, also presented in Table 1, the following research gaps have been discovered. First, the viability of using the building services system, including solar PV and heat pumps with water storage tanks and batteries, to satisfy all of the electrical, heating, cooling, and DHW loads of houses has not been assessed on a practical level. Second, the energy, economic, and environmental impacts of implementing the proposed building services system have not been analysed in a single study. Thus, in this study, due to its outstanding ability to simulate electrical and thermal systems in a realistic context, TRNSYS is applied to model conventional fossil fuel-based building services system and the proposed system, including an air-source heat pump, two water storage tanks, solar PV, and batteries. Then the constructed models, including the PV generation, heating and DHW loads of the case study house, are verified using empirically measured results, which will be explained in detail in Sections 4.2 and 5.1. Additionally, rule-based control strategies are proposed for operating the building services systems and are embedded in TRNSYS models. Furthermore, three scenarios are created to supply a case study house with electrical and thermal energy in order to examine the benefits and drawbacks of the proposed building services system in terms of energy, cost and environmental friendliness through a multifaceted evaluation.

3. Conventional and proposed building services systems

Since the purpose of this work is to examine the energy, economic, and environmental benefits of transitioning from conventional fossil fuel-based systems to residential building services systems with batteries and heat pumps with water storage tanks, this section will describe in detail the conventional systems that are currently prevalent in residential buildings and the new proposed building services system. For clarity, a typical Australian house furnished with a conventional fossil fuel-based building services system will be used as a case study in this section, as well as the subsequent analysis of this work.

3.1. Conventional fossil fuel-based building services system

Conventional building services system, in this study, refers to a house whose energy needs are largely met by fossil fuels or grid electricity. To explain this concept further, a single-family house located in Geelong, Australia, is introduced here as a case study. This house is a single storey building with three bedrooms. A gas-ducted system provides space heating, and there is no mechanical equipment utilised for space cooling. In June 2022, a hot water heat pump was installed to replace a failed gas-boosted solar hot water system, and the power consumption of the heat pump has been measured since its installation. Due to the replacement of the hot water

Table 1

A Summary of the reviewed literature and this work on residential building services systems.

References	Location	System components	Function	Type of study	Performance analysis
Li et al. [17]	Brisbane, Australia	Solar PV, air-source heat pump, and hot and cold water tanks	Electricity, space heating, space cooling, DHW	TRNSYS modelling	Energy and economic analysis
Wang et al. [19]	Geelong, Australia	Solar PV, air-source heat pump, and hot and cold water tanks, batteries	Electricity, space heating, space cooling, DHW	Theoretical work	Energy analysis
Heinz and Rieberer [20]	Zurich, Switzerland	Solar PV, air-source heat pump, and a hot water tank	Electricity, space heating, DHW	TRNSYS modelling	Energy and economic analysis
Pinamonti et al. [21]	Ottawa, Canada	Solar PV, water-to-water heat pump, and a hot water tank	Space heating, DHW	TRNSYS modelling	Energy analysis
Kimiaei et al. [22]	Montr'eal, Canada	Ground-source heat pump, a water tank, and batteries	Electricity, space heating, space cooling	Theoretical work	Energy analysis
Thür et al. [23]	Innsbruck, Austria	Solar PV, ground-source heat pump, and a hot water tank	Space heating, DHW	TRNSYS modelling	Energy and economic analysis
Knuutinen et al. [24]	Lappeenranta, Finland	Solar PV, ground-source heat pump, and a hot water tank	Electricity, space heating, DHW	MATLAB modelling	Energy and economic analysis
Ashrafi et al. [25]	Damavand, Iran	Building integrated PV, ground-source heat pump, and a hot water tank	Electricity, space heating, space cooling, DHW	TRNSYS modelling	Energy, economic and environmental analysis
Colarossi and Principi [26]	Ancona, Italy	Solar PV, and a hot water tank	DHW	Experimentation	Energy analysis
Fitzpatrick et al. [27]	Stuttgart, Germany	Air-to-water heat pump, a gas boiler, and a hot water tank	Space heating, DHW	MATLAB modelling	Energy and economic analysis
Nordgård-Hansen et al. [28]	Grimstad, Norway	Solar PV, ground-source heat pump, and batteries,	Electricity, space heating, DHW	Theoretical work	Energy and economic analysis
Da et al. [29]	Kunming, China	Solar PV, air-source heat pump, and hot and DHW water tanks	Space heating, DHW	TRNSYS modelling	Energy analysis
Jafarian et al. [30]	Dubai, UAE and Barcelona, Spain	PV/thermal collectors, air-source heat pump, battery, hot tank, etc.,	Electricity, space heating, space cooling, DHW	TRNSYS modelling	Energy, economic and environmental analysis
This work	Geelong, Australia	Solar PV, air-source heat pump, hot and cold water tanks, and batteries	Electricity, space heating, space cooling, DHW	TRNSYS modelling	Energy, economic and environmental analysis

system, natural gas consumption in the house from June 2022 to May 2023 was solely used for space heating and home cooking. A smart meter, installed in the house in 2013, keeps a record of the electricity imported from and exported to the grid on a half-hour basis. The power supplier offers a CSV file that can be downloaded online and contains data from the smart meter from the last two years [31]. The home also features a 10 kW rooftop solar PV system, of which 3 kW is composed of 12 panels rated at 250 W, and the remaining 7 kW is made up of 24 panels rated at 300 W. Data of PV generation is recorded by a PV system controller every quarter of an hour.

In order to demonstrate that the energy required to operate homes is primarily derived from fossil fuels, a conventional building services system, also referred to as Scenario 1 below, is designed as a reference case. Specifically, a gas-ducted heating system and an instantaneous gas hot water system provide space heating and DHW for the case study house, respectively. Despite currently not employing equipment for space cooling in the home, the cooling load is taken into consideration in this paper and is assumed to be met by split air conditioners, given the potential rise in ambient temperature driven by global climate change [32]. In addition, the power source in this scenario is a 10 kW solar PV system and the electrical grid.

3.2. Proposed building services system: batteries and heat pump with water storage tanks

A new building services system is proposed here for retrofitting the conventional system in Scenario 1, aiming to reduce the consumption of fossil fuels and grid electricity by increasing the self-consumption of PV energy. The proposed system is presented in Fig. 1, which includes an air-source heat pump, two water storage tanks, a fan coil unit, batteries and other auxiliary components, such as water pumps, mixing valves, diverting valves, control valves, etc. The air-source heat pump selected here has two operating modes, including heating mode and cooling mode, and the produced heating and cooling energy is stored in two water storage tanks. The fan coil unit is connected to two water storage tanks so that the stored hot and cold water can be circulated for space heating and cooling, and the hot water can also be used for DHW use in the home. The air-source heat pump and other electrical appliances are powered primarily by the 10 kW solar PV system, followed by batteries, and the electricity grid, and these power sources are connected via an inverter that can provide control over the distribution of electricity. Excess PV energy that is above the instantaneous demand is stored in batteries for use at night or during peak load periods. The electricity grid is used to supply additional power when PV energy is not available and the batteries are fully discharged.

4. Method

Two different building services systems, including the conventional and proposed systems, are explained in Section 3. Noted, conventional systems lack a storage system because they are transient mechanical devices, which means they consume natural gas and electricity anytime there is a thermal or electrical energy load. As a consequence, the generated PV energy is either wasted or exported to the grid when it exceeds the instantaneous electricity demand, with negligible benefit. In comparison, heat pumps with energy storage tanks can utilise daily PV energy or grid electricity (when PV energy is insufficient) to meet residential space heating, space cooling and DHW loads, thereby offsetting natural gas consumption. More importantly, the excess solar PV energy can still be

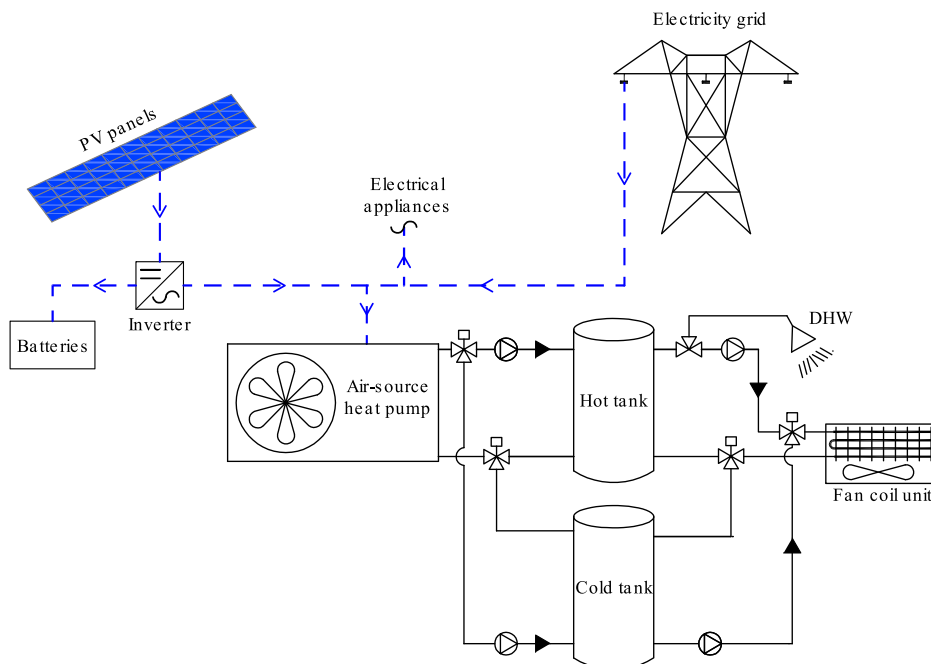


Fig. 1. Schematic of the proposed building services system.

transferred into thermal energy and stored in hot and cold water tanks via heat pumps, increasing PV self-consumption and self-sufficiency. Another interesting point, as explained in Section 1, is that batteries can also store excess PV energy during the day and discharge it during peak load periods, thus leading to further increased PV energy utilisation in houses. Therefore, three scenarios are designed to quantify the energy, economic and environmental performance of a stage transitioning building services systems from the conventional one to the proposed one. Specifically, Scenario 1 is a house with the conventional fossil fuel-based system, and Scenario 2 uses the proposed system but does not have batteries for storing excess PV energy. Finally, Scenario 3 refers to the house equipped with the proposed system exclusively. The details of the three scenarios are explained in Section 4.1, along with their operational principles. Following the implementation of the three scenarios in TRNSYS, Section 4.2 will clarify the modelling details of the three scenarios and the associated energy load collection and validation. Sections 4.3 and 4.4 then outline the energy, economic, and environmental analysis methodology.

4.1. Operational principles for three different scenarios

4.1.1. Scenario 1: fossil fuel-based system

As explained in Section 3.1, Scenario 1 uses the conventional fossil fuel-based building services system. When space heating, space cooling, DHW and electrical loads occur, the energy sources, including natural gas and electricity, are consumed instantaneously. The electrical supply for Scenario 1 consists of PV and grid energy. Notably, the house will first utilise PV energy for electrical load, followed by grid electricity if PV energy is insufficient. The excess PV energy over the instantaneous electrical load of the house will be exported to the grid.

4.1.2. Scenario 2: heat pump with water storage tanks

Based on the proposed building services system, another two scenarios are designed for this study. Scenario 2 refers to the house equipped with the proposed building services system except for batteries. The principles for operating the PV-powered heat pump with water storage tanks are as follows. We set the temperature of the two water storage tanks in accordance with the amount of PV generation, which further regulates the ON and OFF of the air-source heat pump. For instance, when the PV energy is higher than the threshold, the main thermostat setting for the hot tank is $62.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$, and when it is lower, it is set to $57.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$. Similar to this, the main thermostat for the cold tank is adjusted to $7.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$, and $12.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$, respectively, depending on whether the PV energy exceeds or undercuts the threshold. The temperature monitored by the thermostat is the average water temperature of the two storage tanks. With these settings, it is anticipated that more PV energy will be used to provide heating and cooling energy storage, which will help to reduce the amount of grid electricity used. The thermostat settings for the two water storage tanks are summarized in Table 2.

The annual operation of the air-source heat pump is divided into a summer schedule and a non-summer schedule, considering the annual DHW need and the cooling demand solely in the summer. When the thermostats of both water storage tanks are activated simultaneously in the summer schedule, the air-source heat pump operates in the heating mode to supply hot water in priority. Then, it switches to the cooling mode to provide cold water for space cooling. In addition, similar to the operational principles in Scenario 1, the house will first utilise PV energy for electrical load, followed by grid electricity if PV energy is insufficient. The excess PV energy over the instantaneous electrical load of the house will be exported to the grid. The strategies for controlling the operation of the air-source heat pump are shown in Fig. 2.

4.1.3. Scenario 3: batteries and heat pump with water storage tanks

Scenario 3 describes the house that features the proposed building service systems exclusively. By comparing Scenarios 2 and 3, the effect of battery storage on the performance of the proposed system can be investigated. The operational principles of the air-source heat pump in Scenario 3 are the same as in Scenario 2. Therefore, the power distribution strategies between solar PV, the grid, and batteries are explained here. When the PV energy is greater than the total electrical load, batteries are charged using excess PV energy. Any extra PV energy that remains after the batteries are fully charged is exported to the grid. When the PV energy is less than the total electrical load, batteries are discharged to meet the electrical load. When batteries are fully depleted, the remaining load is satisfied by importing electricity from the grid. Fig. 3 shows the operational principles for the power distribution between solar PV, the grid, and batteries.

4.2. Modelling of the three scenarios through TRNSYS

To investigate the energy, economic and environmental performance of the three scenarios using different building services system, their energy requirements, such as fossil fuel, thermal and electrical demands, need to be obtained. TRNSYS is a powerful software widely used for thermal and electrical energy modelling [33], and this software has a library that contains a large number of components, such as controllers, electrical, heating, ventilation and air conditioning (HVAC) units, hydronics, thermal storage, etc. Previous research indicated that modelling building services system in TRNSYS was feasible and rational to simulate a zero-energy building [34]. The building was powered by PV panels and utilised hydrogen energy storage in conjunction with batteries to store

Table 2

Thermostat settings for the two water storage tanks.

Case description	Hot tank thermostat setting	Cold tank thermostat setting
PV energy > threshold	$T_{ht1} = 62.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$	$T_{ct1} = 7.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$
PV energy \leq threshold	$T_{ht2} = 57.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$	$T_{ct2} = 12.5\text{ }^{\circ}\text{C} \pm 2.5\text{ }^{\circ}\text{C}$

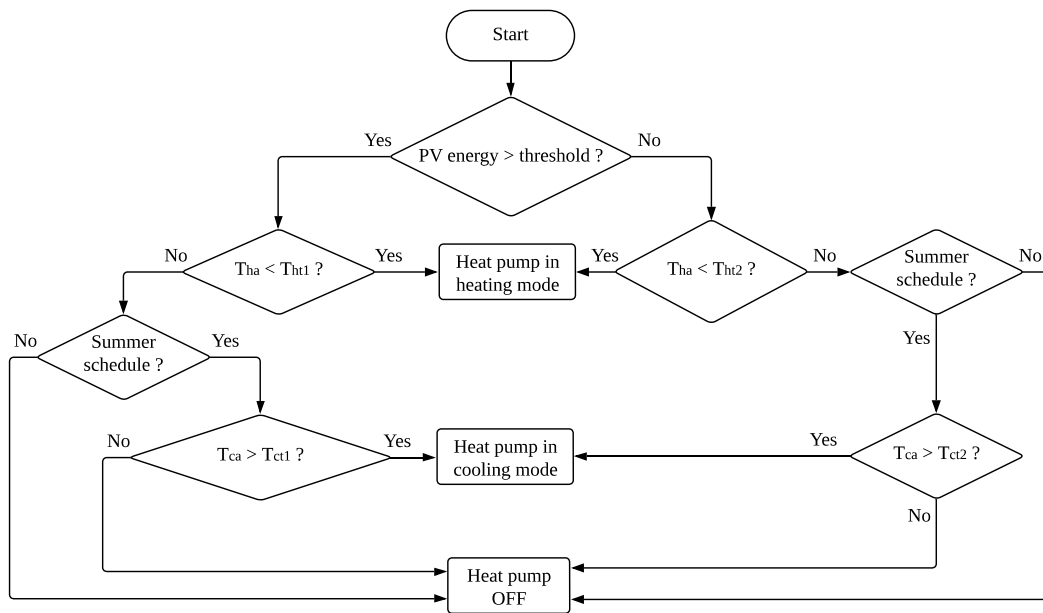


Fig. 2. Operational principles for the air-source heat pump: T_{ha} = average hot tank temperature, and T_{ca} = average cold tank temperature.

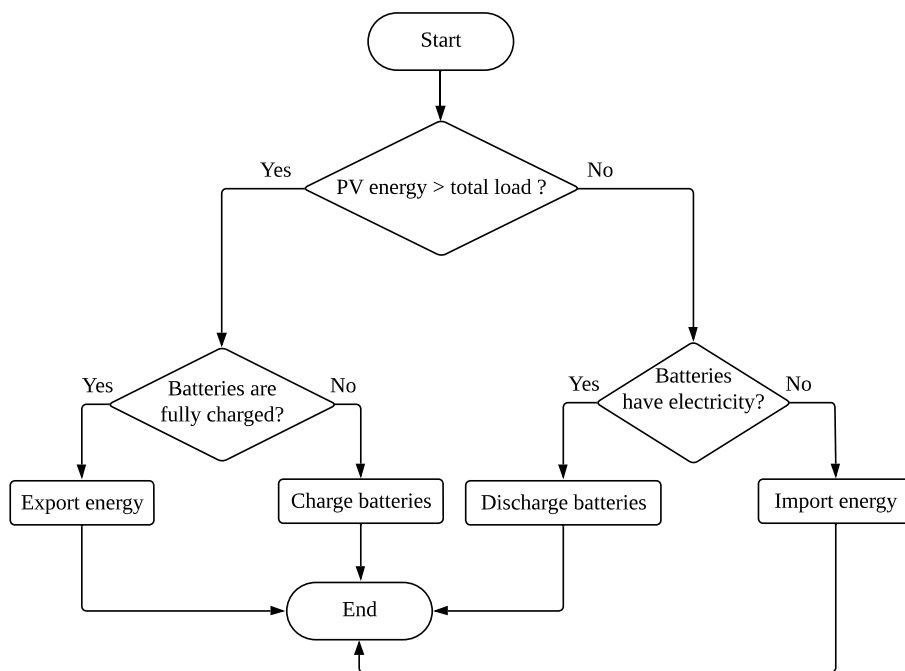


Fig. 3. Operational principles for the power distribution between solar PV, the grid, and batteries.

surplus PV energy. In addition, the researchers simulated a solar collector connected to a hot water tank to provide DHW and hot water to a heating coil for heating the space, as well as a water-cooled absorption chiller for cooling purposes. However, upon inspection of their work, it was found that they did not validate the simulation model. In order to resolve this issue, we conducted model validation in this study. The validation procedure will be elaborated upon further in this section, and the outcomes of the validation will be thoroughly discussed in Section 5.1.

The 3D model of the case study house is created in TRNSYS3D and edited in TRNBuild to obtain its space conditioning loads [19]. The house was divided into two thermal zones, such as bedrooms and living areas, with a total volume of 588.32 m³ required for

conditioning. The garage, laundry room and bathroom were not considered for calculating the heating and cooling loads of the house, due to their short daily occupation time. After obtaining the simulated thermal loads for space heating and cooling, we verified the space heating load by comparing it to the total gas consumption of the house from June to September 2022 and from April to May 2023 since this is the period in which the simulated heating load was located and when gas was used only for space heating and home cooking. In addition, the daily DHW requirements for this single-family house with two occupants were calculated using Australian/New Zealand Standard AS/NZS 4234:2021 [35]. By using the calculated daily energy requirement for DHW, we simulated the electrical energy consumption for a hot water heat pump in TRNSYS, and the model was verified by comparing the simulated electrical demand against the metered electrical consumption of the hot water heat pump. After these comparison and validation, the simulated hourly heating, cooling and DHW load results were accepted for use in the subsequent modelling. Fig. 4 illustrates the floor plan and the finished 3D geometry of the house.

For Scenario 1, we modelled the electrical energy demand required to cool the house using two split air conditioners (one for each thermal zone). Next, smart meter data and PV measurements for 2021 were used to calculate the electricity consumption of the house, and this value was used as the base electrical load since the space heating and DHW production were achieved through gas-based systems during the year. In addition, the climate data of Geelong was created in Meteonorm and loaded into the TRNSYS model to simulate the energy generation of a 10 kW solar PV system, and the simulated results were verified against the actual measured PV generation data for 2021. For Scenarios 2 to 3, the proposed building services system was modelled, and the main components include an air-source heat pump, two water storage tanks, heating and cooling coils, fans, controllers, circulation pumps, and some other auxiliary components. In this work, the heating and cooling performance of the air-source heat pump was simulated based on its performance mapping defined by the testing results provided by the manufacturer, including the various water outlet temperatures obtained at different ambient conditions. Two water storage tanks were also modelled to provide hot and cold water for space heating, space cooling and DHW. Then, the base electrical load of the house and the PV generation modelling were directly derived from the simulation work in Scenario 1. Finally, we added the simulation of batteries in Scenario 3 compared to Scenario 2, allowing excess PV energy to be stored before being exported to the grid, thus increasing the PV self-consumption and reducing grid consumption. Fig. 5 illustrates the simulation process of this work.

Next is to determine the sizing of key components used in three scenarios. The peak cooling loads in the two thermal zones of the house were used to calculate the cooling capacity of the two split air conditioners in Scenario 1. While the capacity of the instantaneous gas heater is decided using the peak hourly DHW load, the output capacity of the gas-ducted heating system is determined by the actual specifications of the system installed in the home. The peak hourly heating, cooling, and DHW loads of the house define the heating and cooling capacities of the air-source heat pump utilised in Scenarios 2 and 3, while the peak daily heating, cooling, and DHW loads of the house decide the sizes of the two tanks. Due to their great performance, we considered employing lithium batteries in Scenario 3, which were sized based on the peak hourly base electrical load of the house. Moreover, the PV output threshold is determined as 5 kW according to the peak hourly base electrical load of the house and the input capacity of the air-source heat pump. Table 3 summarises the sizing of each system component in three scenarios.

4.3. Energy analysis

As explained in Section 4.2, the base electrical load for the case study home is determined by actual measurements of the PV generation and smart meter data during the year of 2021. In Scenario 1, it has been assumed that the DHW and space heating are satisfied by natural gas. Additionally, space cooling is achieved through the utilisation of split air conditioners. Consequently, the energy loads in Scenario 1 encompass the base electrical load, the electricity used to operate the air conditioners, and the corresponding natural gas load. In Scenarios 2 and 3, space heating, space cooling and DHW loads rely solely on an air-source heat pump. The electrical loads for these two scenarios encompass the base electrical load, the electrical load associated with operating the air source heat pump, and auxiliary components, such as fans and circulation pumps. It is noteworthy that neither Scenario 2 nor Scenario 3 exhibit any demand for natural gas. Moreover, Scenario 3 includes a supplementary battery in comparison to Scenario 2.

In the study by Guo et al. [34], the energy analysis was conducted based on the hydrogen tank pressure and battery state of charge, since the tank and battery were utilised for the storage of surplus PV energy. Nevertheless, the efficiency of PV energy utilisation is not detailed. In comparison, a variety of energy sources, including natural gas, grid electricity and PV energy, are used in the three

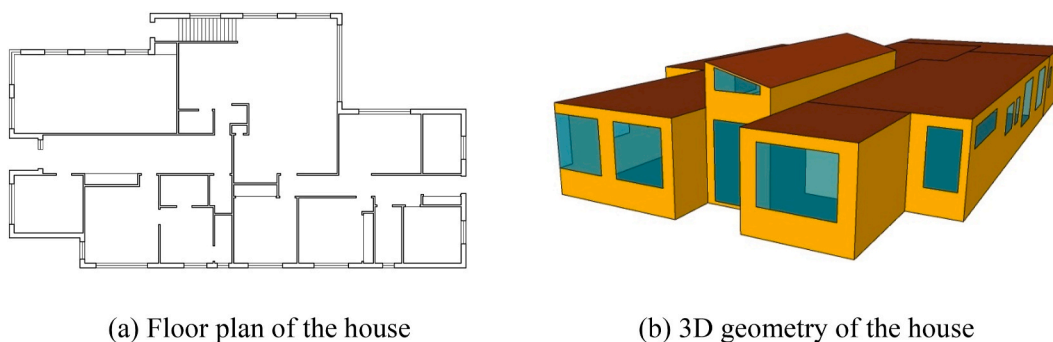


Fig. 4. (a): Floor plan and (b): 3D geometry of the house.

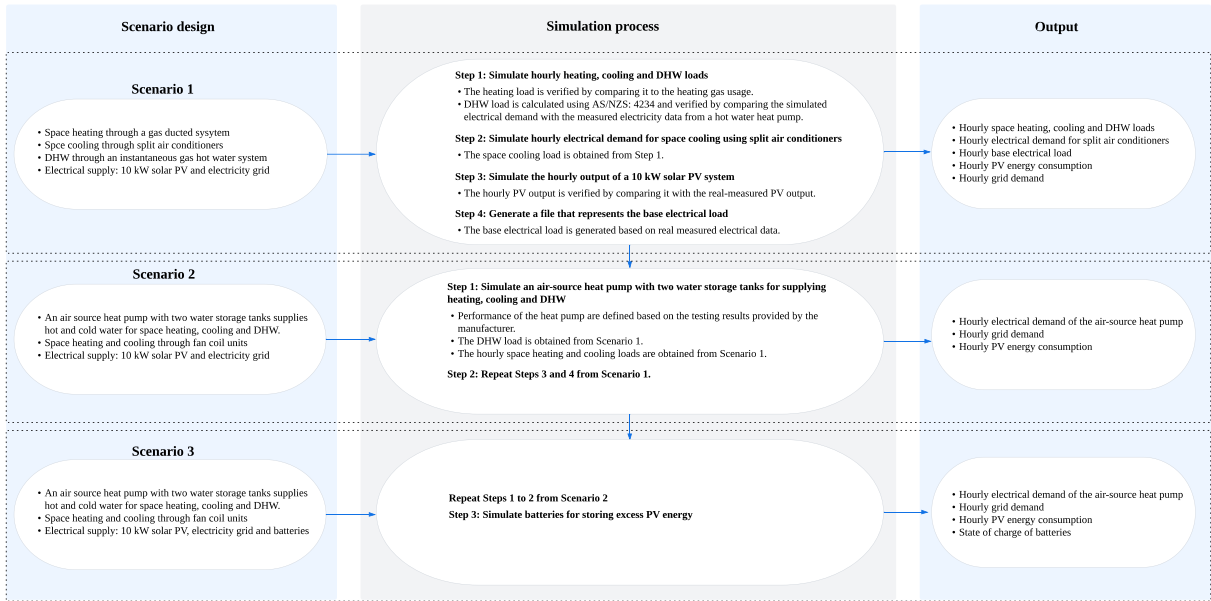


Fig. 5. Simulation process of this work.

Table 3
Sizing of each system component in three scenarios.

Scenarios	PV system (kW)	Two split air conditioners		Gas ducted heater (kW)	Instantaneous gas water heater (kW)	Air-source heat pump		Water storage tanks		Batteries (kWh)
		Total cooling capacity (kW)				Heating capacity (kW)	Cooling capacity (kW)	Hot tank (m ³)	Cold tank (m ³)	
Scenario 1	10	12	20	2	–	–	–	–	–	–
Scenario 2	10	–	–	–	6	7	2.6	3.6	–	–
Scenario 3	10	–	–	–	6	7	2.6	3.6	5	–

different scenarios of this study. Moreover, the purpose of this paper is to assess the effectiveness of the proposed building services system in reducing the fossil fuels and grid electricity needed for the conventional system and increasing the use of PV energy. Therefore, PV self-consumption and self-sufficiency are essential parameters for evaluating this objective, as they measure the proportion of total PV energy consumed on-site and the proportion of household load fulfilled by PV energy, respectively. These two parameters can be calculated 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 on-site during each timestep t. E_t is the electrical demand of the house during each timestep t, and G_t is the natural gas demand of the house during each timestep t.

4.4. Payback period and carbon emission analysis based on energy demand

The proposed system, comprising heat pumps with water storage tanks and batteries, aims to increase the use of locally generated

photovoltaic energy while decreasing the demand for grid electricity and natural gas from the conventional system. Cost savings and carbon emission reductions are anticipated as a consequence of the transition from the conventional system to the proposed system. This section elucidates the methodology employed to assess the payback period and carbon emission of the proposed system in comparison to the conventional system.

Prior to evaluating the cost-effectiveness of implementing the proposed system, its capital expenditure must be taken into account. Costs associated with using batteries and heat pumps with water storage tanks may vary by country or region. We present an economic analysis using the Australian market as an example to find out the payback period of the proposed building services system. Since the equipment listed in Scenario 1 is already in use in the case study house, we use Scenario 1 as a reference case to examine the benefits deriving from the energy savings in Scenarios 2 and 3 as well as the capital costs of their system components. The costs of an air-source heat pump, hot and cold water tanks, batteries, etc., are collected from the Australian market or from the interviews of suppliers. Then, the energy savings benefits in Scenarios 2 and 3 refer to the cost savings resulting from reduced demand for natural gas and grid electricity compared to Scenario 1. In addition, revenues from the sale of excess PV to the grid are considered.

Net present value (NPV) is a profit indicator that calculates the difference between the present values of cash inflows and outflows [36]. Notably, the return on investment occurs when the NPV equals zero, which indicates the payback period. In order to calculate the cumulative NPV of using the proposed building services system, the following equation is used [25]:

$$NPV = \sum_{n=0}^n \frac{C_n}{(1+i)^n} \quad (3)$$

Where: n is the n th year. C_n is the cash flow in the n th year, and i is the discount rate. Also, the relevant data for calculating the cash flows and the NPV are listed in Table 4.

More than one-third of the global energy-related carbon emissions are attributable to the building sector [2]. Three-quarters of the total energy consumption in the building sector is accounted for by residential buildings, presenting a great opportunity to improve their energy efficiency [41]. Because fossil fuel technologies dominate heating and DHW production [12], replacing inefficient fossil fuel-based heating systems can be one of the most efficient ways of saving energy and reducing carbon emissions [20]. In addition, the use of fossil fuels to generate electricity is another contributor to carbon emissions [42]. There has been a significant shift in the global installed capacity of renewable energy technologies, including an increase in the installation rate of solar PV systems and a substantial rise in the worldwide acceptance and installation of high-performance technologies, such as heat pumps, which play an essential role in reducing global carbon emissions from the residential sector.

Here, an environmental analysis is conducted to determine the impact of using the proposed building services system on reducing residential carbon emissions compared to conventional systems. It concentrates on carbon emissions from the consumption of natural gas and grid energy in three scenarios. According to the data provided by the Department for Environment Food & Rural Affairs [43], the carbon emissions from burning one kWh of natural gas and generating one kWh of electricity are 0.185 kg and 0.47 kg, respectively. Therefore, the carbon emissions for the three cases can be calculated using their respective natural gas and utility electricity consumption as well as the aforementioned carbon emission factors.

5. Results

5.1. Validation of simulated results

To ensure the correctness of the model created in TRNSYS, several validations have been carried out, and the results are compiled and presented in Fig. 6. After importing the calculated DHW demand using AS/NZS 4234:2021 into the simulation model, the simulated power consumption of the hot water heat pump was compared with the actual measured power consumption of 896 kWh. Then, we made corresponding adjustments to the DHW load data. The final results are shown in Fig. 6-(a), which shows that the two sets of monthly power consumption values are very close. The annual total power consumption of the simulated hot water heat pump is 894 kWh, which is also very close to the actual value. By comparing the simulated values to the actual readings, the annual energy generation of the 10 kW solar PV system is also verified. It has been discovered that the simulated annual PV generation of 14905 kWh is only 3.7 % higher than the measured annual PV generation of 14365 kWh. The monthly power generation trends between the simulated and actual data are also quite similar, as illustrated in Fig. 6-(b). Finally, the simulated heating load of the house from April to September was compared with the gas consumption measured during this period, and the results are depicted in Fig. 6-(c) as 4515 kWh and 4569 kWh, respectively. After subtracting 5 % of the gas utilised for home cooking and then multiplying by 90 % of the efficiency of the gas-ducted heater [44,45], the difference between the actual and simulated heating load is around 13.5 %, which can be explained by several reasons, such as the individual habits of the occupants, the deviation of the real thermostat settings from those considered in the simulation, the difference between the real heat gains and the heat gain considered in the simulation. Given the

Table 4
Economic data used in calculating the NPV of using the proposed building services system.

Economic parameters	Value	References
Discount rate	3 %	[37]
Electricity purchase tariff	AUD 0.384/kWh	[38]
Feed-in tariffs	AUD 0.052/kWh	[39]
Gas purchase tariff	AUD 0.120/kWh	[40]

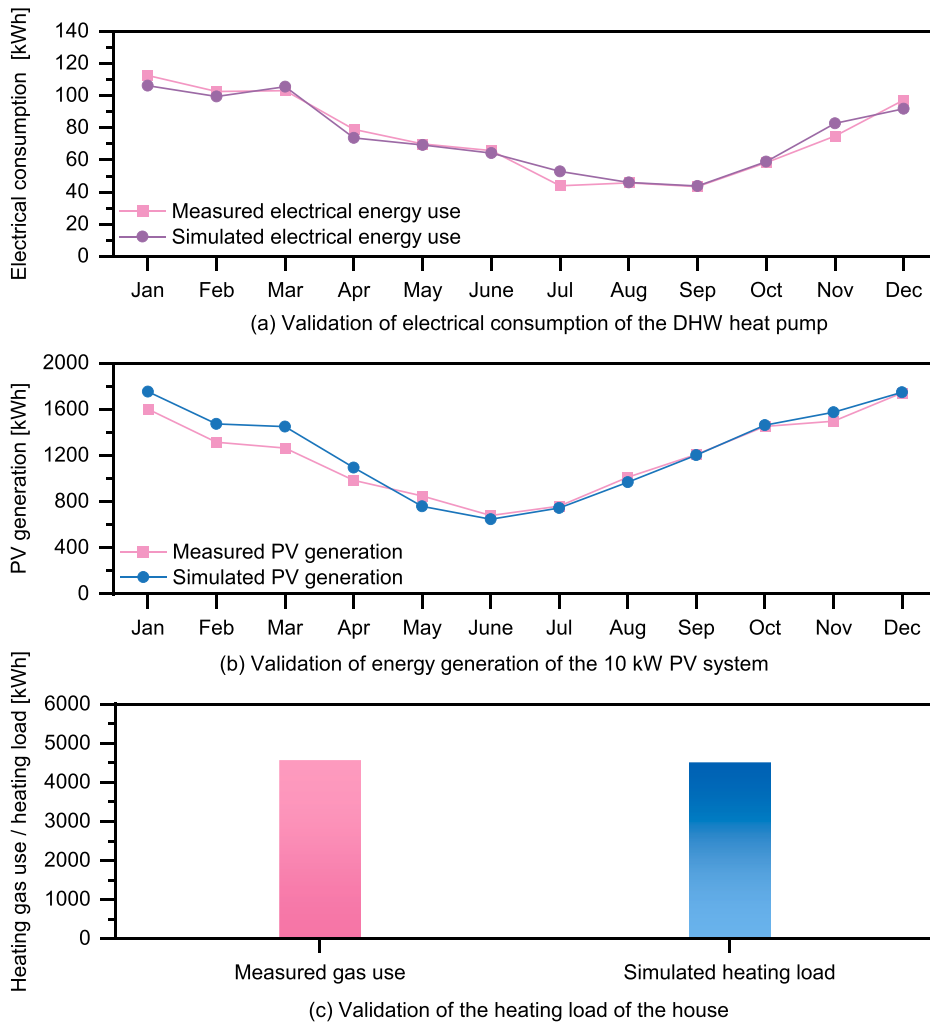


Fig. 6. Validation of simulated results.

diversity and numerous dependencies between simulation and reality, this level of accuracy is considered acceptable.

5.2. Energy performance of the three scenarios

To investigate the energy performance of the three scenarios, three sets of simulations are run to obtain energy results, which are then processed and plotted in Fig. 7. As can be seen, Scenario 1 requires 6915 kWh of natural gas per year for space and hot water heating. 3475 kWh of the household electrical demand is met by the electricity from the grid, and the remaining energy is provided by the PV system, resulting in an annual PV self-consumption and self-sufficiency of 18 % and 24 %, respectively. In comparison, the annual grid demand of 3468 kWh in Scenario 2 is slightly lower than that in Scenario 1. However, it is worth noting that there is no demand for natural gas in Scenario 2, as it is offset by the increased consumption of PV energy to electrify the house load. This is further supported by the decline in annual exported energy from 12292 kWh in Scenario 1 to 10982 kWh in Scenario 2, and the annual PV self-consumption and self-sufficiency increase to 26 % and 56 %, respectively. Additionally, the annual grid demand in Scenario 3 is reduced to 2018 kWh owing to the inclusion of 5 kWh batteries, while the annual PV self-consumption and self-sufficiency rise to 38 % and 75 %, respectively. These significant reductions in demand for grid electricity and fossil fuels can be attributed to more PV energy being consumed through batteries and the air-source heat pump with water storage tanks.

To examine the energy performance of the three scenarios in further detail, we calculate and compile their monthly data results and plot them in Fig. 8. It is clear from Fig. 8-(a) that Scenario 1 requires a significant amount of natural gas in winter due to space and hot water heating requirements. It is also evident that the monthly grid demand is more significant in the winter than in the summer for all three scenarios. The effectiveness of solar PV systems in generating energy to satisfy household demand is one of the reasons for this, which can be supported by the fact shown in Fig. 8-(b), where the PV generation yields a more outstanding performance in summer than in winter. Another explanation could be the increased night-time loads in winter due to the shorter daylight hours.

Additionally, it can be discovered from Fig. 8-(c) and (d) that the monthly PV self-consumption and self-sufficiency experience a

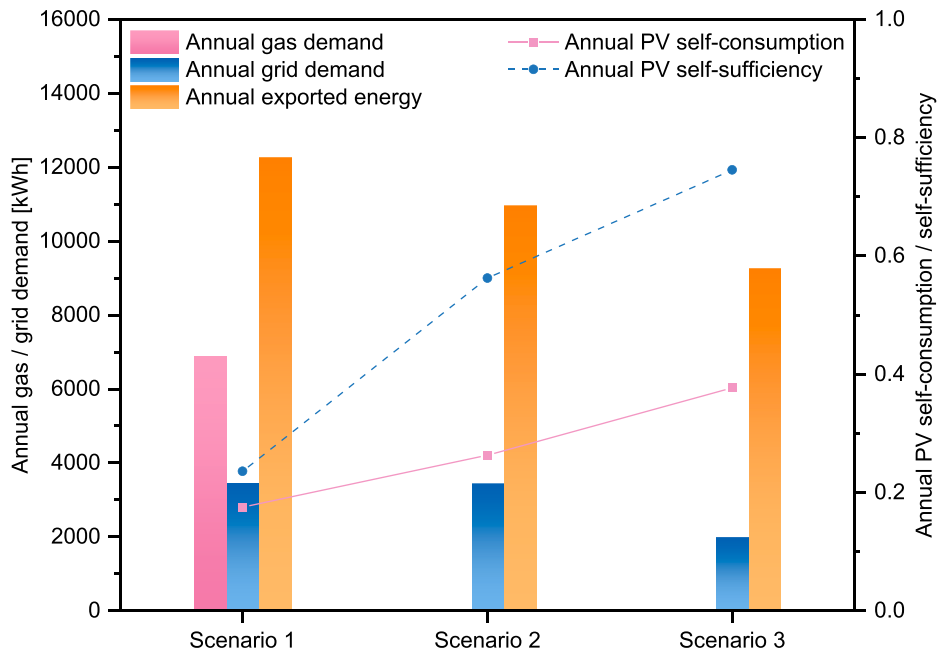


Fig. 7. Annual energy summary of the three scenarios.

gradual increase from Scenario 1 to 3. This is because using an air-source heat pump with water storage tanks and batteries allows excess PV energy to be stored as thermal and electrical energy for household needs. These findings demonstrate the potential of the proposed building services system to decarbonize and electrify house loads by increasing the utilisation of PV energy.

As shown in Fig. 8, PV generation and house energy loads can vary seasonally, so we focused on the hourly distribution of the grid and natural gas demand as well as the hourly exported energy of the three scenarios on 04 January in summer and 28 August in winter, when PV generation is at its highest. The results for these two days are presented in Figs. 9 and 10. In Fig. 9, when natural gas is used for heating DHW, Scenario 1 has slightly lower grid demand only at 0:00 and 20:00 than Scenario 2, and the building services in Scenario 2 are entirely powered by electricity. It is also significant that Scenario 3 has zero grid demand on this day after 19:00 because the 5 kWh batteries are discharged to satisfy the electrical demand of the house. Moreover, Scenario 3 has less exported energy than Scenarios 1 and 2 in the early morning before 9:00 a.m. because part of the excess PV energy is stored as heating and cooling energy via operating the air-source heat pump or is used to charge batteries.

Similar results can be found in Fig. 10. Scenario 1 requires a significant amount of natural gas to satisfy the home's space heating, and DHW needs on a winter day with peak PV generation. Due to not employing storage equipment to reserve excess PV energy, Scenario 1 generally has a greater grid demand and exported energy than Scenarios 2 and 3. The grid demand that occurs early in the morning and late at night in Scenario 2 is compensated by the 5 kWh batteries in Scenario 3. These energy performance results, summarized from these two days, highlight the importance of using heat pumps with water storage tanks and batteries to offset the natural gas needs in PV homes and alleviate the load on grid output and input.

5.3. Parametric study of component sizing on the energy performance of the proposed building services system

PV output thresholds determine the thermostats of the two water storage tanks, which significantly impact PV energy utilisation, as they determine how much PV energy can be stored by operating the air-source heat pump. Additionally, as stated in Section 4.2, each component of the proposed building services system in Scenario 3 was sized using the peak hourly or daily thermal and electrical demands of the house. These systems might therefore be either oversized, leading to energy redundancy, or undersized, leading to excessive demand for grid power. Thus, a parametric study is carried out in this section to ascertain the effect of changes in PV output threshold and component sizing on the energy performance of the proposed building services system.

To explore the effects of various PV output thresholds on the use of grid and PV energy in the proposed building services system, we adjust the thresholds to integers from 0 to 10, respectively, and the results are presented in Fig. 11. It shows that as the PV output threshold increases, annual house demand on the grid energy decreases progressively, reaching a minimum of 1795 kWh at the threshold of 2 kW before gradually rising. The observed trend is also reflected in the PV self-consumption and self-sufficiency, which attain their maximum values of 39 % and 77 %, respectively, at the 2 kW threshold. Therefore, it can be argued that the PV output threshold has a significant effect on the PV and grid energy demand of the system.

The air-source heat pump prioritises its heating operation because of the annual requirement for DHW. Therefore, the effect of the difference in heat pump heating capacity on the energy efficiency of the proposed building services system needs to be examined. To do this, we first determine the optimal PV output threshold for the air-source heat pump with different heating capacities, using the lowest

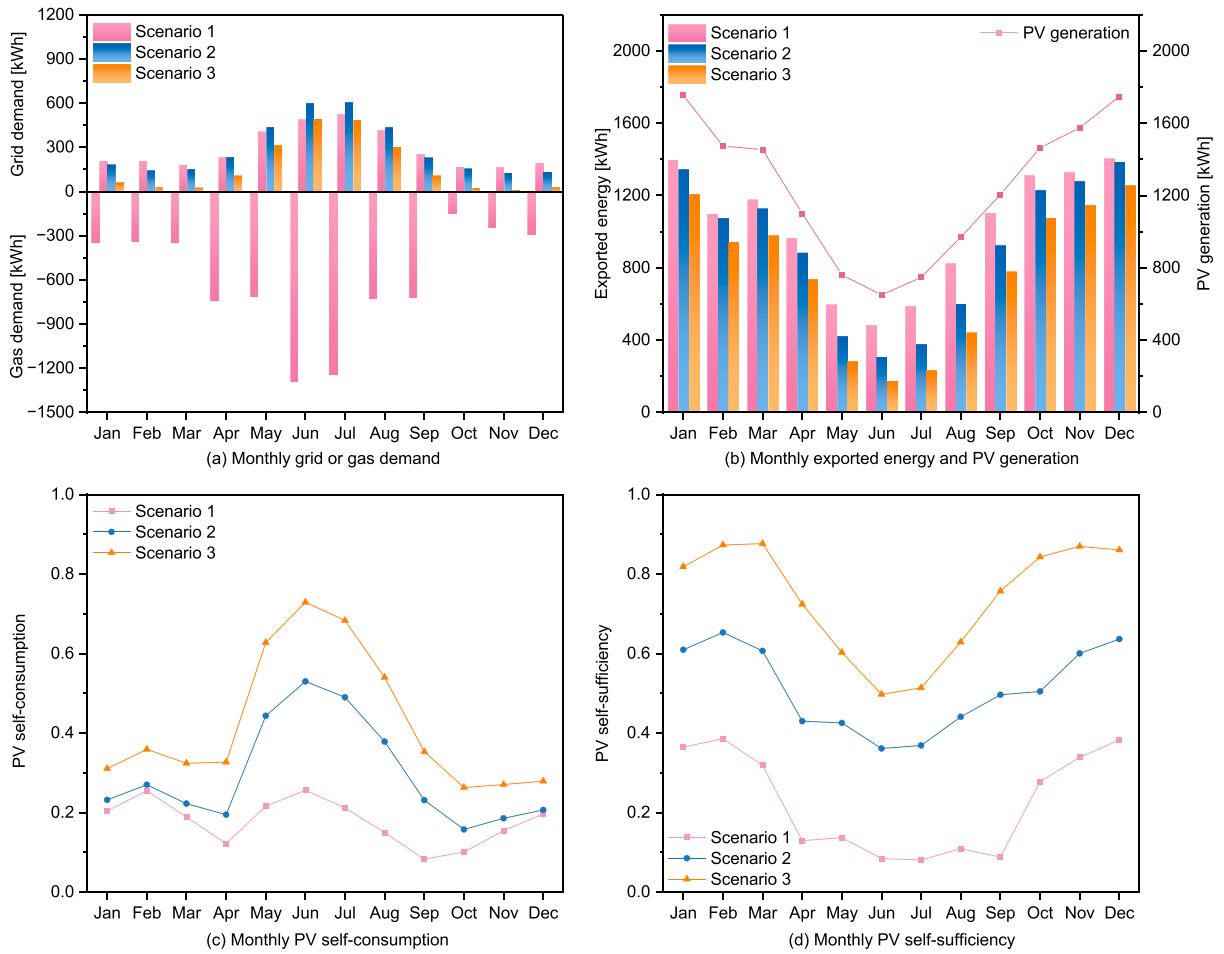


Fig. 8. Monthly energy summary of the three scenarios.

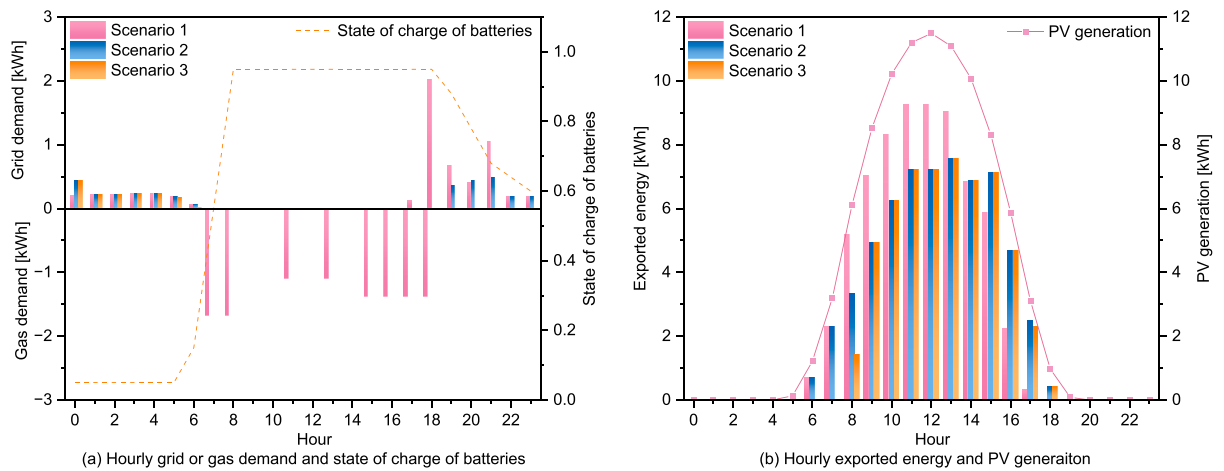


Fig. 9. Hourly energy summary of the three scenarios on the day (04 January) with peak PV generation in summer.

annual grid demand as the criterion. Then, the corresponding PV self-consumption and self-sufficiency are recorded at each threshold, and the results are plotted in Fig. 12. It demonstrates that the annual grid demand for the proposed building services system is lowest at the 2 kW threshold when the heating capacity of the air-source heat pump is between 2.5 kW and 6 kW. The optimal threshold

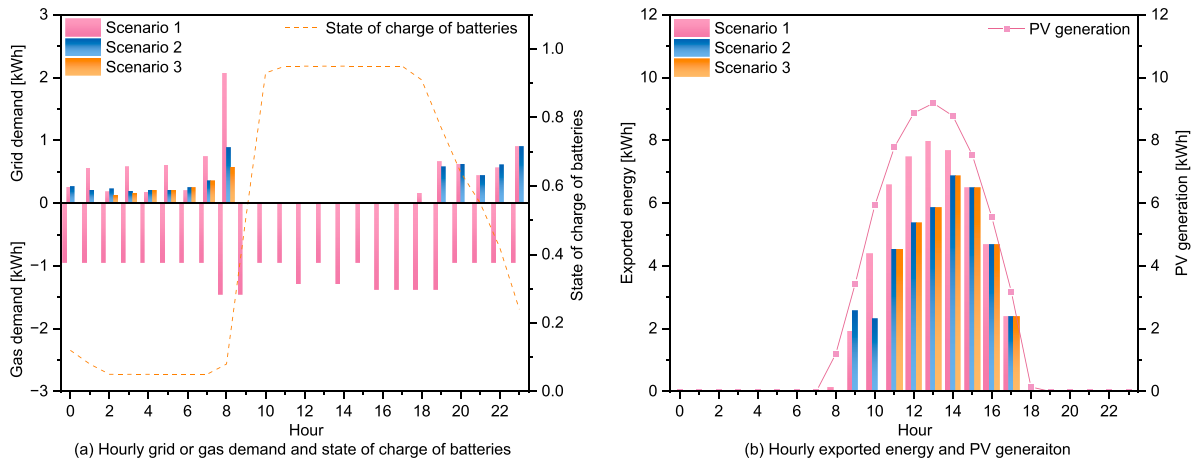


Fig. 10. Hourly energy summary of the three scenarios on the day (28 August) with peak PV generation in winter.

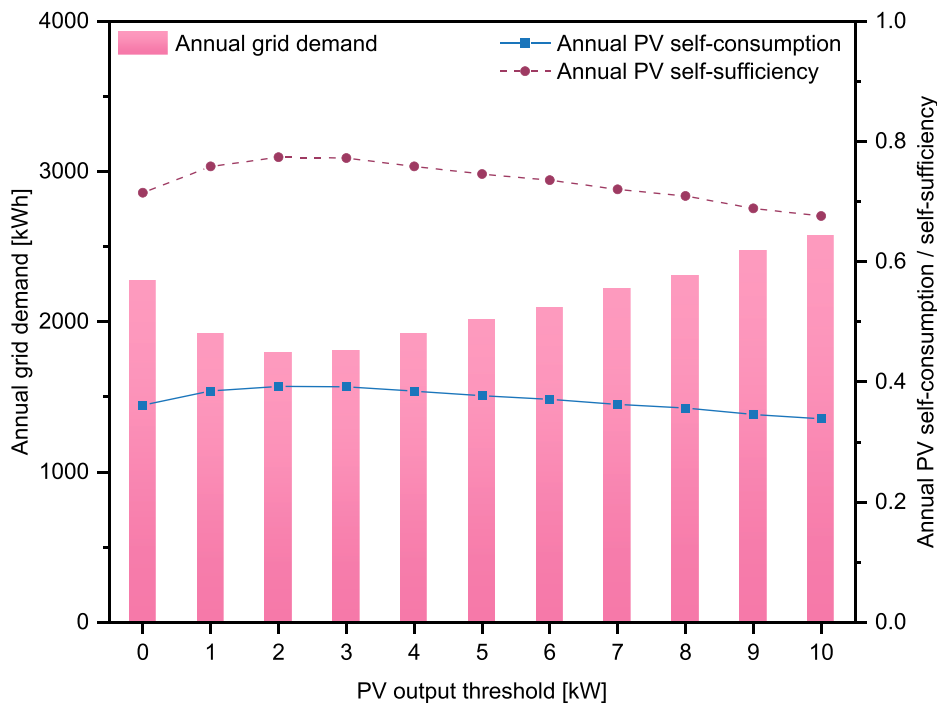


Fig. 11. The impact of PV output thresholds on the energy performance of the proposed building services system (heating and cooling capacity of the air-source heat pump = 5 and 7 kW, respectively, PV size = 10 kW, and battery capacity = 5 kWh).

increases to 3 kW between 6.5 and 7 kW of heating capacity. Furthermore, a gradual decrease in the annual grid demand is seen as the heating capacity rises. The lowest point is researched at the heating capacity of 5 kW, when the annual PV self-consumption and self-sufficiency also find their highest values of 39 % and 77 %, respectively. In light of the fact that the air-source heat pump with a heating capacity of 5 kW prevails over all others in terms of annual grid demand, PV self-consumption and self-sufficiency, the threshold of 2 kW and a heating capacity of 5 kW is used in the subsequent analysis.

The sizes of two water storage tanks are also varied to find out their impact on the system energy performance, and the results are illustrated in Fig. 13. It can be observed that increasing the size of the hot water tank results in an increase in annual PV self-consumption and self-sufficiency, as well as a decrease in annual grid demand, but this trend is diminishing. This is primarily because, as the size of the hot water tank increases, the stored heating energy exceeds the daily heating demand and becomes redundant. In addition, we observe that increasing the size of the cold water tank has a negligible effect on the system's energy efficiency. This is due to the following explanations: First, according to the control strategies, the heat pump operation is prioritised to

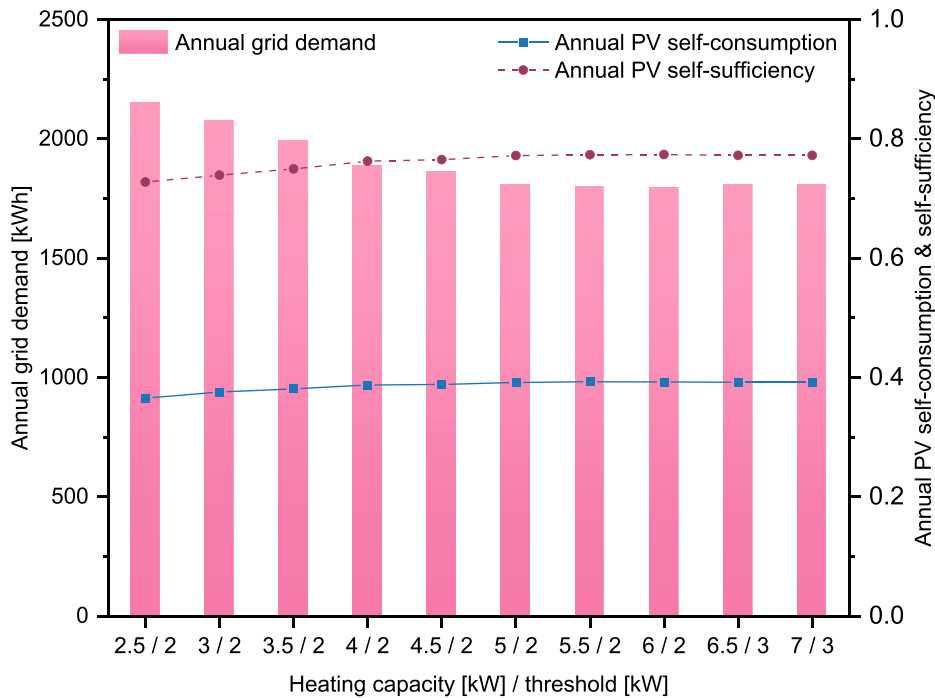


Fig. 12. The impact of heating capacity of the air-source heat pump on the energy performance of the proposed building services system (cooling capacity of the air-source heat pump = 7 kW, PV size = 10 kW, and battery capacity = 5 kWh).

satisfy the hot water demand of the house. Thereby, an increase in the cold tank size has a minimal effect on the heat pump's energy consumption. Second, since most of the cooling demand occurs during the daytime in the summer when solar irradiance is substantial and PV generation is abundant, the heat pump consumes a negligible amount of PV energy relative to its total generation. Therefore, it can be said that the variation in the hot tank size has a greater impact on the energy performance of the proposed system than the variation in the cold tank size. Considering the effectiveness of increasing the hot and cold tank sizes on reducing the annual grid demand, we select 1 m^3 and 0.5 m^3 as the size of the hot and cold tanks for the proposed building services system, respectively, and use them for further analysis.

Fig. 14 illustrates the energy efficiency of the proposed building services system for various battery capacities. Evidently, increasing the battery capacity can have a significant effect on annual grid demand, PV self-consumption, and self-sufficiency, as excess PV energy generated during the day is stored and consumed at night or during peak load periods. This demonstrates the viability of using batteries to increase PV energy utilisation; however, their cost effectiveness is also worth considering, as will be discussed in the following section of the paper.

5.4. Payback period and carbon emissions results based on energy demand

Components are resized for scenarios 2 and 3, as described in Section 5.3. Specifically, the air-source heat pump has a heating capacity of 5 kW and a cooling capacity of 7 kW. The hot and cold tanks are sized at 1 and 0.5 m^3 , respectively, and the battery capacity for Scenario 3 is kept at 5 kWh. The initial costs of these components are then obtained from direct online searches or interviews with suppliers, and the results are plotted in Fig. 15-(a). It can be found that among all components, the 5 kWh battery has the highest cost, followed by the air source heat pump and the two fan coil units used for the two thermal zones of the house. The cost of the auxiliary components includes the cost of water pumps, plumbing costs, etc.

In addition, the cumulative NPV for Scenarios 2 and 3 over 25 years is calculated based on the annual reduction in natural gas and grid demand and the annual exported energy for Scenarios 2 and 3 compared to Scenario 1, and the results are depicted in Fig. 15-(b). As can be seen, the investment in Scenario 2 can be recovered after 8 years, while the payback period for Scenario 3 requires 9 years, which can be attributed to the high cost of batteries. It also demonstrates that the cumulative NPV of Scenario 3 is initially 50 % less than that of Scenario 2; however, by the end of year 13, the cumulative NPV of Scenario 3 begins to surpass the value of Scenario 2 and reaches 120 % of that of Scenario 2 by the end of year 25. This demonstrates that the investment in batteries is gradually yielding benefits.

As shown in Fig. 7, the annual grid demand for scenarios 1, 2, and 3 is 3475 kWh, 3468 kWh, and 2018 kWh, respectively, and only scenario 1 uses natural gas for space and DHW heating, resulting in an annual natural gas consumption of 6915 kWh. Thus, the annual carbon emissions of three Scenarios are computed using the natural gas and grid consumption as well as the carbon emission factors, and the results are displayed in Table 5. It can be found that the electrification of the heating and DHW of the case solar house by using an air source heat pump with storage tanks results in a 44 % reduction in carbon emissions per year for Scenario 2 compared to

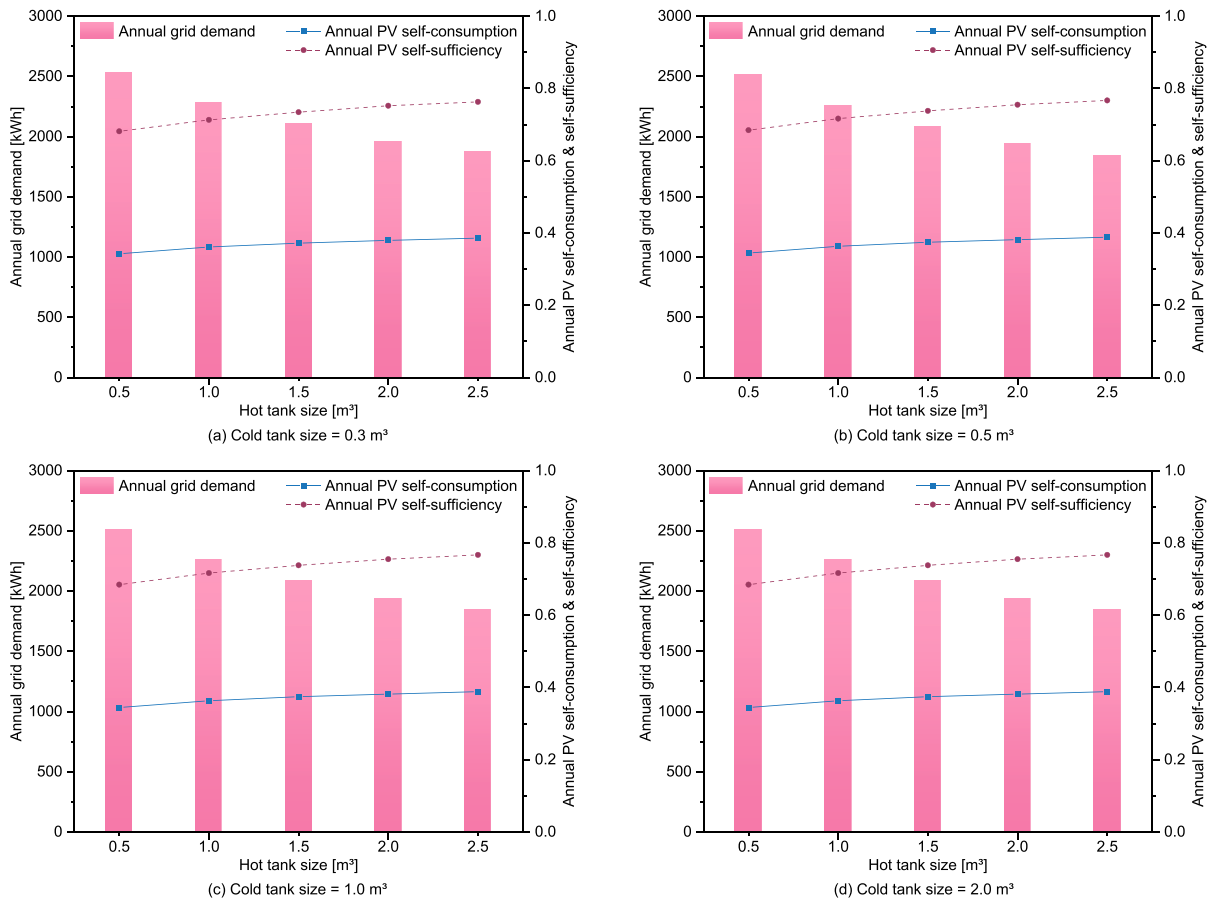


Fig. 13. The impact of hot and cold tank sizes on the energy performance of the proposed building services system (heating and cooling capacity of the air source heat pump = 5 and 7 kW, respectively, threshold = 2 kW, PV size = 10 kW, and battery capacity = 5 kWh).

Scenario 1. In Scenario 3, including 5 kWh of batteries to store excess PV energy reduces grid electricity demand of 1450 kWh, resulting in an additional 33 % reduction in carbon emissions. Thus, it can be argued that the proposed building services system can have a significant impact on the decarbonization of solar houses.

The efficacy of the proposed building services system in reducing the utilisation of fossil fuels and grid electricity has been established. When considering the broader community context, adopting the proposed building services system by a more significant number of property owners has the potential to substantially decrease the community's reliance on conventional fossil fuel-based systems. Such transition would yield significant environmental benefits, primarily through reducing fossil fuel usage and associated carbon emissions, thereby mitigating the growing threat of global climate change. Furthermore, the payback period of the proposed system will be reduced even further when subtracting the capital cost of the conventional building services system (details of which will be further discussed in the next section), which enhances the sustainability and acceptability of the proposed system at the economic level. This is especially crucial for certain cities around the world that wish to implement novel energy management initiatives while facing budget constraints. Ultimately, the increasing application of the proposed system within communities can contribute to the development of a community-based household energy management system. In particular, the surplus of PV energy generated by a household can benefit neighbouring consumers within the community, promoting localised energy exchanges that aim to achieve collective advantages [46]. Community-based battery hubs can be seen as an example. Surplus PV power generated by households can be effectively stored within a centralised battery hub built in a community, enabling the redistribution of stored energy to homes that do not possess PV systems. This approach effectively addresses the issue of grid overload by exporting PV power while concurrently diminishing the community's reliance on grid-based power usage.

6. Discussion

The findings of this study indicate that the proposed building services system has the potential to save fossil fuels and increase PV energy utilisation for solar houses. Compared to Scenario 1, using the conventional building services system, Scenario 3, with the proposed building services system, has a significant reduction in annual grid energy consumption and annual carbon reduction due to the concept of electrifying building loads and using energy storage systems. The effect of tank size variation on the energy performance

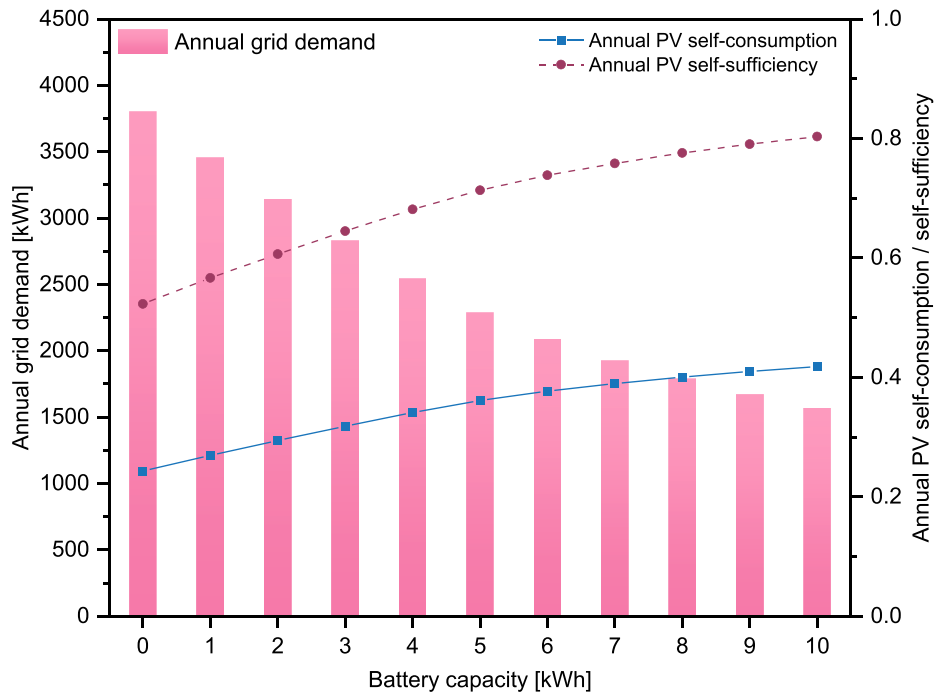


Fig. 14. The impact of battery capacity on the energy performance of the proposed building services system (heating and cooling capacity of the air source heat pump = 5 and 7 kW, respectively, threshold = 2 kW, hot tank size = 1 m³, cold tank size = 0.5 m³, and PV size = 10 kW).

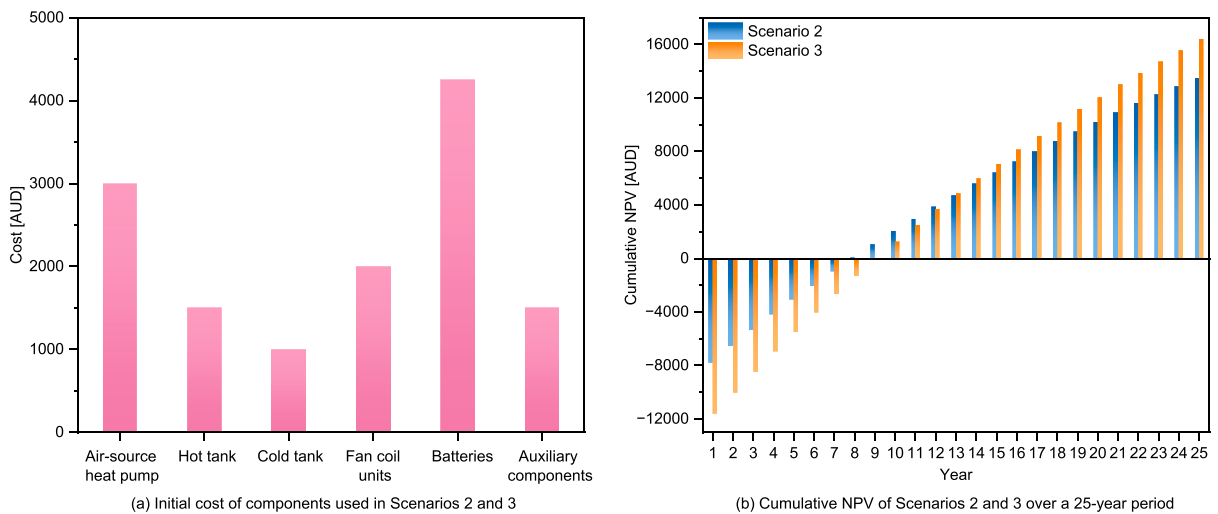


Fig. 15. Initial cost of components and cumulative NPV of Scenarios 2 and 3.

Table 5
Annual carbon emissions of the three scenarios.

Scenarios	Annual gas demand (kWh)	Annual grid demand (kWh)	Annual carbon emission (kg)	Percentage reduction in annual carbon emissions compared to Scenario 1
Scenario 1	6915	3475	2913	–
Scenario 2	0	3468	1630	44 %
Scenario 3	0	2018	948	67 %

of the proposed building services system has been analysed in both our work and the previously cited study by Li et al. [17]. However, it is necessary to mention that Li et al. [17] did not include batteries in the system design, and they did not examine the impact of hot and cold water tank sizes on the energy performance of the system separately, making it unclear to the reader the difference between the hot and cold water tanks in terms of affecting the system performance. In contrast, we found out that increasing the size of the hot water tank raises annual PV self-consumption and self-sufficiency and cuts down annual grid demand, whereas changes in the cold water tank size have little impact on the energy efficiency of the system.

It has been determined that the proposed building services system has a 9 year payback period, which seems lengthy given the high initial investment for all system components. The payback period is determined by the system cost and savings from reduced natural gas and grid electricity demand relative to Scenario 1 as well as revenue from the sale of excess PV energy to the grid. It is essential to note that building services systems are a necessity in homes and that the payback period for conventional fossil fuel-based building services system, even with a PV system installed in the home, is either non-existent or in the far future. This is because their home thermal energy requirements are predominantly satisfied by purchased natural gas and grid electricity. In addition, excess PV power during the day is wasted because it cannot be stored, and the current diminishing returns from selling electricity to the grid further reduce the profitability of PV energy. The payback period becomes more attractive if we subtract the cost of the conventional fossil fuel-based building services system from the original cost of the proposed building services system, reflecting the promising future of the proposed building services system.

Furthermore, the proposed building services system incorporates an air-source heat pump. In practical application, activating the heat pump results in a transient substantial current load. According to the control strategies of using PV batteries, batteries need to be discharged when the instantaneous PV power generation fails to satisfy electrical loads. This circumstance places a significant demand on batteries with limited capacity, accelerating the depletion of their stored power. In such case, to guarantee the PV self-sufficiency and self-consumption ratio in houses, it becomes imperative to enhance the battery capacity proportionally, leading to an increase in the capital cost associated with the battery, along with a corresponding extension of the payback period [47]. Therefore, these considerations must be taken into account when determining the battery capacity for using the proposed building services system in our houses. Furthermore, the implementation of a 48 V compressor with direct current (DC) inverter technology in air source heat pumps presents a potentially viable resolution to the issue of surge current during heat pump start-up [48]. This is due to the fact that the DC inverter 48 V compressor initiates operation at a reduced power level and subsequently ramps up gradually, in comparison to conventional compressors that rely on 220–240 V alternating current (AC) power. Additionally, 48 V DC air source heat pumps can be directly connected to PV systems and batteries, eliminating direct conversion losses between DC and AC power and further realizing efficient energy use.

7. Conclusion

This research examined the energy, economic, and environmental consequences associated with replacing a conventional fossil fuel-based building services system with a proposed system incorporating air source heat pumps, water storage tanks, and batteries within PV homes. This was achieved through the modelling of three scenarios in TRNSYS. The primary novelty of this study is in the comprehensive fulfilment of both electrical and thermal demands within the homes through the proposed system. Furthermore, using empirical data on PV generation and employing an actual case study on household power demand enhances the reality and legitimacy of this work. As compared to Scenario 1 with the conventional system, this study has shown that due to the ability to electrify house loads by consuming more daily PV power, Scenario 3 using the proposed system can help offset the full 6915 kWh of annual natural gas demand and 42 % of annual grid demand, from 3475 kWh to 2018 kWh. Consequently, the annual PV self-consumption and self-sufficiency increased from 18 % to 24 %–38 % and 75 %, respectively.

Another interesting finding from the parametric study is that the 2 kW PV output threshold results in the greatest system performance, with the annual grid demand reaching the lowest value of 1795 kWh. While variations in heat pump capacity and cold tank size have a negligible effect on system performance, increasing the hot tank size from 0.5 m³ to 2.5 m³ reduces the annual grid demand from 2535 kWh to 1876 kWh while maintaining the cold tank size at 0.3 m³. Certainty, battery capacity can affect PV energy utilisation significantly since more excess PV energy can be stored directly and consumed when needed. Findings from the economic analysis demonstrate that the proposed building services system requires a payback period of 9 years, which may become more attractive given the non-existent payback period of the conventional building services system. Finally, the proposed building services system reduced annual carbon emissions by 67 %, from 2913 kg to 948 kg.

This study demonstrates the possibility of using the proposed building services to meet all the electrical, heating, cooling and DHW loads of houses via solar PV systems, resulting in the electrification and decarbonization of dwellings. In addition, it also provides a great solution to residents and policymakers regarding the current issues of high network voltage caused by the substantial injection of excess PV energy from buildings to the grid. However, one limitation of this work is that it only examined the proposed building services system under a single climate zone. Therefore, future research will explore the differences in implementing the proposed building services system under various climatic conditions.

CRediT authorship contribution statement

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

Data availability

Data will be made available on request.

Appendix A. Components and types used in the TRNSYS

Table A.1
Components and types used in the TRNSYS

Component	Type name	Component	Type name
Multi-zone building	Type 56	Batteries	Type 47a
Weather data processor	Type 15-2	Water pumps	Type 114
Air-source heat pump	Type 941	Tee piece	Type 11h
Water storage tanks	Type 158	ON/OFF differential controller	Type 165
Solar PV array	Type 103b	Heating coil	Type 753e
Inverter	Type 48b	Cooling coil	Type 508c
Mixing valves	Type 649	Fan	Type 146
Diverting valves	Type 647	Controlled flow diverter	Type 11f
Air flow mixer	Type 148b	House base electrical/DHW load	Type 9e

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