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On-site solar PV generation and use: Self-consumption and self-sufficiency

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Research Article

Building Systems and Components

Abstract

As energy storage systems are typically not installed with residential solar photovoltaic (PV) systems, any "excess" solar energy exceeding the house load remains unharvested or is exported to the grid. This paper introduces an approach towards a system design for improved PV self-consumption and self-sufficiency. As a result, a polyvalent heat pump, offering heating, cooling and domestic hot water, is considered alongside water storage tanks and batteries. Our method of system analysis begins with annual hourly thermal loads for heating and cooling a typical Australian house in Geelong, Victoria. These hourly heating and cooling loads are determined using Transient System Simulation (TRNSYS) software. The house's annual hourly electricity consumption is analysed using smart meter data downloaded from the power supplier and PV generation data measured with a PV system controller. The results reveal that the proposed system could increase PV self-consumption and self-sufficiency to 41.96% and 86.34%, respectively, resulting in the annual imported energy being reduced by about 74%. The paper also provides sensitivity analyses for the hot and cold storage tank sizes, the coefficient of performance of the heat pump, solar PV and battery sizes. After establishing the limits of thermal storage size, a significant impact on self-efficiency can be realised through battery storage. This study demonstrates the feasibility of using a polyvalent heat pump together with water storage tanks and, ultimately, batteries to increase PV self-consumption and self-sufficiency. Future work will concentrate on determining a best-fit approach to system sizing embedded within the TRNSYS simulation tool.

Keywords

solar photovoltaic;
polyvalent heat pump;
energy storage;
self-consumption;
self-sufficiency

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1 Introduction

Rooftop solar photovoltaic (PV) systems are increasingly being installed in Australian households. Over 30% of Australian houses are reported to have rooftop solar PV systems (Australian Renewable Energy Agency 2022). Reasons for the widespread use of PV technology include the desire of residents to reduce their electricity bills (Li et al. 2021), low equipment prices (Khezri et al. 2020), and government policies and incentives (Chapman et al. 2016). For example, under the Solar Homes program, Victorian residents can claim a rebate of up to AUD 1,400 for the purchase of solar PV panels, plus the option of interest-free loans (Solar Victoria 2022). Similarly, a zero-interest loan of from AUD 2,000 to 15,000 can be used by Canberra residents to purchase rooftop solar panels, household battery storage systems, hot water heat pumps, etc., under the Sustainable Household Scheme (ACT Government 2022). It is expected that the installation of rooftop solar PV systems into Australian homes will continue to increase while government subsidies for renewable energy system installations continue.

However, the widespread installation of rooftop solar PV systems has created many problems. Firstly, the mismatch between peak PV generation and peak electricity consumption leads to a large excess PV generation being delivered to the electrical grid, which raises concerns that high reverse energy flows can lead to overvoltage on low-voltage lines, transformer fault currents, and substation transformer damage (Byrne et al. 2018). Secondly, Feed-in tariffs (FiTs) in Australia continue to decrease each year, because the electricity grid, designed to supply energy rather than receive it, is becoming overburdened. Electricity suppliers

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are beginning to restrict the export of PV-generated electricity to the grid by lowering feed-in tariffs or prohibiting feed-in entirely. As a result, households with rooftop PV systems may be unable to sell the electricity to the grid in the future. Thirdly, because PV generation and house electrical loads are not often simultaneous, PV self-consumption, which measures the proportion of total PV generation consumed locally, is relatively low (Bee et al. 2019; Horan et al. 2021). Therefore, finding strategies to increase PV self-consumption is increasingly important for households with rooftop PV systems.

Using electric batteries is a possible method to increase the self-consumption of rooftop PV systems (Ren et al. 2016). Integrating electric batteries into PV systems stores the excess PV-generated electricity during the day (Ke et al. 2015), and consumes it during periods with peak demand (Saez-de-Ibarra et al. 2016). However, a study conducted by Khezri et al. (2020) found that integrating electric batteries in solar PV houses is unattractive in NSW, Australia until the battery price decreases to $190/kWh, a quarter of the current market price. However, a heat pump coupled with water storage tanks is a promising approach to increase PV self-consumption (Wang et al. 2021). Combining rooftop PV systems with air-to-water heat pumps coupled with water storage tanks allows residential heating and cooling needs to be met by consuming PV-generated electricity, thereby increasing the self-consumption of rooftop PV and reducing the residential grid energy consumption (Battaglia et al. 2017). Arteconi et al. (2017) analysed the performance of industrial buildings using heat pumps in combination with a water storage tank for space cooling in a simulation, and the results showed that incorporating PV into this combined system can make thermal energy storage economically viable, regardless of the electricity tariffs.

Although thermal energy storage is less expensive, its stored energy can only meet residential thermal energy needs. Although electric batteries are expensive, combining thermal energy storage and electric batteries may be a better solution, as it will provide PV houses with a higher level of electrical and thermal energy self-sufficiency (Langer and Volling 2020). Many studies have examined the feasibility of using electric batteries or heat pumps coupled with water storage tanks in grid-connected solar PV houses to increase the PV self-consumption as well as to partially meet residential energy requirements. However, there are currently no studies that report the effectiveness of using an electric battery and heat pumps coupled with water storage tanks to increase rooftop PV self-consumption and PV self-consumption while fulfilling the heating, cooling, DHW and electrical demand of houses. Therefore, this paper aims to integrate electric batteries, a polyvalent heat pump with two water storage tanks, and a grid-connected solar PV house to meet the electrical and thermal energy needs of the house, while investigating the impact of such system integration on PV self-consumption and self-sufficiency. In this context, PV self-sufficiency refers to the proportion of the house load met by PV generation (Wang et al. 2022).

2 Literature review

This section reviews the existing literature related to the application of heat pumps with energy storage systems in solar PV houses, as they are the most prominent and effective approaches to increasing PV self-consumption and self-sufficiency.

2.1 PV-battery system

Several papers have presented the energy and cost performance of using electric batteries in grid-connected solar PV houses. For example, Ren et al. (2016) analysed the effect of using PV and batteries in houses on reducing peak electricity demand and annual grid electricity consumption. They also presented the bills savings of case study houses under different tariff structures. Horan et al. (2021) examined the energy and cost performance of applying PV battery systems in three case study houses. The authors discovered that a battery, regardless of size, requires a significantly large PV system to charge during wintertime. Beck et al. (2016) developed a mixed-integer linear optimization model to investigate how the PV self-consumption is affected by the temporal resolution of electrical load and PV generation profiles. The results demonstrated that the temporal resolution of load profile may contribute more than the resolution of PV generation for accurately estimating the PV self-consumption rate. Li et al. (2018) investigated the impact of battery storage on increasing PV self-consumption and peak shaving in grid-connected households in Kyushu, Japan. The authors concluded that increasing the battery size can raise the PV self-consumption, but the rate of its increase varies significantly across months and is greatly influenced by home loads and PV generation profiles.

Furthermore, the sizing of residential PV-battery system has gained a great deal of research attention. For example, Weniger et al. (2014) developed a simulation model with one-minute time intervals to analyse the sizing of residential PV battery systems. The study found that small-scale PV systems accompanied by a high self-consumption rate are considered the best, as revenues from feed-in tariffs will become less and less in the future. In order to reduce the total annual electricity bill of houses equipped with PV battery systems, a genetic algorithm-based method for optimal sizing of PV batteries was proposed and validated using the collected data (Li 2019). The author discovered that the house energy use pattern and, electricity and battery prices have a significant impact on the optimal sizing of PV battery systems.

This paper focuses on the use of energy storage systems in grid-connected solar PV houses. In addition to the previously mentioned electric energy storage through batteries, hydrogen-based energy storage is now emerging as a new form of energy storage. While hydrogen energy storage may not currently be used in a single residential building, it is already widely used in the commercial sector or at the community level in combination with renewable energy generation. Therefore, it is necessary to review the literature related to the use of hydrogen energy storage in solar PV systems. Electrolysis of water through electricity generated from renewable sources, such as solar PV is an option for producing carbon-free and environmentally friendly hydrogen, which also promises to address the demand and supply imbalance associated with the intermittent or unstable nature of most renewable energy sources (Ozturk and Dincer 2021). Mobasseri et al. (2022) presented a schematic diagram of the multi-energy microgrids, showing the integration of facilities such as electricity grid, solar PV, battery storage, hydrogen energy storage, natural gas fuel cell and combined heat and power, etc. In particular, the gaseous hydrogen produced from water electrolysis can be compressed under high pressure and stored directly in storage tanks for use in fuel cell electric vehicles. While hydrogen energy storage is promising, its use in the commercial sector or at the community level may be more feasible. Izadi et al. (2022) investigated the impact of using hydrogen energy storage on reducing the carbon emissions of an off-grid office building with PV panels and wind turbines. The results show that the use of hydrogen storage can provide 39% of the electricity demand of the office building, thus increasing the total power supply from renewable sources from 49% to 88%. An energy management framework considering flexible demand, battery energy storage, and electric vehicles was developed aiming to achieve the maximum collective benefit of the energy community for prosumers (Tostado-Véliz et al. 2022b), which paves the way for the development of hydrogen energy storage in energy communities.

2.2 PV and heat pumps with water storage tanks

Numerous studies have looked into the impacts of combining heat pumps with water storage tanks to enhance the self-consumption and grid compatibility of rooftop PV systems, in addition to employing batteries to increase the PV self-consumption rate of houses. For instance, Sánchez et al. (2019) presented a heuristic control algorithm for operating a 1 kW input air-to-water heat pump with a 600 litre hot water storage tank in a typical Swiss house with the aim of increasing PV self-use and minimizing the cost of purchasing electricity and running the heat pump. Results demonstrated that the developed control program yielded a 49% cheaper operating cost and 5% higher PV self-consumption in the short term compared to other nonlinear programming solvers. Beck et al. (2017) created a mixed-integer linear programming model to determine the optimal operation, setup, and sizing of a cost-effective residential heat pump system in the context of PV self-consumption. The authors found that demand is the primary determinant of heat pump sizing. FiTs typically promote lower PV self-consumption, and small demand-driven PV systems can boost high self-consumption levels when FiTs are unavailable. Fischer et al. (2016) studied the impact of increased residential PV system installations and variable electricity prices on the optimal system sizing operation of heat pumps and thermal energy storage. They discovered that the residential thermal load profile strongly influences the system sizing. The existing sizing procedures are sufficient for sizing the heat pumps and thermal energy storage, except for some extreme cases such as the capacity of the PV system being too large or when the price of electricity fluctuates significantly. In these cases, a larger energy storage is required. By integrating heat pumps, water storage tanks, and PV with domestic heating and cooling systems, Li et al. (2021) proposed a rule-based control strategies using TRNSYS simulation and analysed the effect of this combined system on lowering house grid-based power demand and raising PV self-consumption. The authors discovered that in comparison with a traditional non-thermal storage system, the combined system reduces annual grid electricity usage by about 76% by including a 5 kW solar PV system. Moreover, the use of thermal energy storage raises the PV self-consumption from 27% to 56%. However, the heat pump used could only provide heating or cooling modes but not both at once. Nor did the authors consider using electric batteries to store excess PV energy.

2.3 PV, heat pumps with water storage tanks and batteries

Numerous studies have also focused on applying electric batteries and heat pumps in combination with water storage tanks in grid-connected solar PV houses. Battaglia et al. (2017) investigated the potential to increase PV self-consumption by applying electric batteries and heat pumps with water storage tanks in houses, but it only focused on the use of energy storage for residential electricity consumption, space heating, and domestic hot water (DHW) production, and neglected space cooling. Similarly, Williams et al. (2012)

demonstrated the effectiveness of using electric battery storage and heat pumps with water storage tanks to enhance PV self-consumption of houses, but the energy storage systems were used only to meet residential electrical and heating needs, without considering the use of heat pumps and thermal storage for DHW and cooling. Psimopoulos et al. (2016) showed how electric battery storage and heat pumps coupled with thermal energy storage have the potential to increase PV self-consumption and decrease grid-based energy consumption in residential PV systems. They discovered that for PV sizes ranging from 3.1 to 9.3 kW, using existing thermal energy storage could reduce final energy by 279 to 573 kWh annually. For the setups and module sizes studied, the grid-based energy reductions from utilizing electric batteries are significantly greater than those from adopting thermal storage. However, again, the energy storage systems in this study were only used for household electricity, space heating, and DHW use, but were not considered for space cooling.

The literature review shows that the use of electric batteries or heat pumps coupled with water storage tanks in grid-connected solar PV houses to increase PV self-consumption and manage residential energy requirements has been studied extensively. In this paper, a combined system is studied in which an electric battery and a polyvalent heat pump combined with water storage tanks buffer electrical and thermal energy by consuming PV power for providing electricity and DHW, heating and cooling for the house. A polyvalent heat pump can offer three modes: heating only, cooling only, or simultaneous heating and cooling in one system. In addition, the polyvalent heat pump is built with a DC compressor, so it can operate by directly consuming PV-generated electricity and battery storage.

3 A combined system for supplying electricity, DHW, heating and cooling

3.1 System configuration

The schematic of the proposed combined system is shown in Figure 1. This system includes a rooftop solar PV system, a hybrid inverter, a battery, a polyvalent heat pump, two water storage tanks, and some other auxiliary components such as water pumps, a fan coil unit, and hydronic conditioning systems etc. The detailed explanations for each component are as follows.

A hybrid inverter is one of the most important components in this design as it connects to the grid, the battery, and the household appliances and provides control. On the one hand, it can convert the DC output from the battery or the solar PV to AC and supply it to home appliances or the grid. On the other hand, it can convert the AC supply to 48V DC, charging the battery or operating DC appliances, such as the proposed polyvalent heat pump. The rooftop solar PV system is used to provide electricity for operating home appliances and the polyvalent heat pump as well as charging the battery.

Conventional heat pumps can offer heating only or cooling only mode, but cannot offer both simultaneous heating and cooling. As such, the idea of considering both thermodynamic outputs of heat pumps, namely, heating on the condenser side and cooling on the evaporator side, leads to a co-generation system, implying that both heating and cooling processes are achieved with the same energy input. This type of heat pump can be called the polyvalent heat pump, or a 3-in-1 heat pump. The polyvalent heat pump can achieve both heating and cooling simultaneously, or it can provide only heating or only cooling. It is important

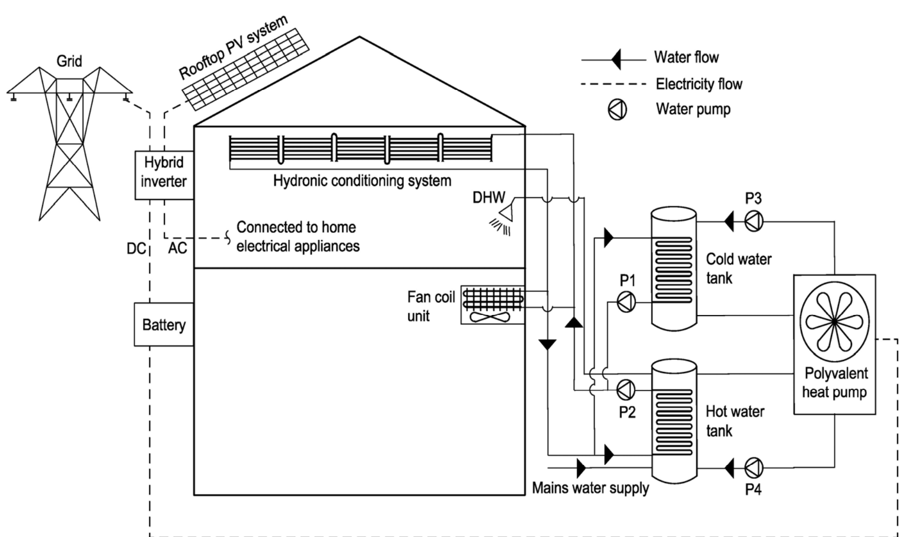

Fig. 1 Schematic of the proposed combined system

to note that when the polyvalent heat pump initially operates in both heating and cooling modes, it works as a water-to-water heat pump system to produce both hot and cold water. Eventually, when the water temperature in one of the tanks reaches the preset point, the polyvalent heat pump automatically switches to an air-to-water or a water-to-air heat pump system to continue heating the hot water or cooling the cold water. In addition, the polyvalent heat pump used in this work is designed and built with a 48V DC compressor, so it can operate directly from PV-generated electricity or battery storage. Hot and cold water are produced during the operation of the polyvalent heat pump and is stored into two storage tanks. The hot water can then be used for DHW or heating, while the cold water is used for cooling through a fan coil unit or a hydronic conditioning system.

3.2 Rules of energy flows for the solar PV house with a polyvalent heat pump, water storage tanks and batteries

It is assumed that the polyvalent heat pump can heat hot water to a maximum of 65 °C, and there is no available hot water storage when the hot water temperature falls below 40 °C. Once the hot water temperature drops below 55 °C, the polyvalent heat pump will be activated to heat the water to 60 °C. Here, PV energy is first to be consumed to operate the heat pump, followed by battery storage and grid power when PV output is insufficient. If there is still excess PV production after that, the polyvalent heat pump will continue to heat the hot water to 65 °C. Similarly, assuming that cold water can be cooled to a minimum of 5 °C by the polyvalent heat pump, there is no available cold water storage when the cold water temperature is above 25 °C. When the cold water temperature exceeds 15 °C, the polyvalent heat pump will begin to cool the water to 10 °C. Again, PV energy is first to be consumed to operate the heat pump, followed by battery storage and grid power when PV output is insufficient. If there is still excess PV output after that, the heat pump will continue to bring the cold water down to 5 °C. The set-point temperatures of the two water storage tanks are shown in Table 1.

Table 1 Setpoint temperatures of the two water storage tanks

	Hot water tank	Cold water tank
Maximum and minimum temperature setting	65 °C & 40 °C	25 °C & 5 °C
Secondary thermostats	55 °C & 60 °C	15 °C & 10 °C

Controls of a grid-connected solar PV house with an electric battery and a polyvalent heat pump with two water storage tanks are illustrated in Figure 2. This flowchart considers:

(1) When the secondary thermostats for the hot or cold-water tank are triggered, the polyvalent heat pump will operate until the secondary thermostats stops triggering.
(2) When the PV energy is greater than the house electrical load, the excess energy is used to operate the polyvalent heat pump to store heating and cooling energy into two water storage tanks.
(3) When there is excess PV energy during the operation of the polyvalent heat pump or after two water tanks are fully charged, it is used to charge the battery.
(4) When there is excess PV energy after the battery is fully charged, it is exported to the grid.
(5) If the PV energy is smaller than the house electrical load, the remaining required electricity is drawn from the battery.
(6) If there is still an electricity requirement after the battery is discharged, it will be met by importing the electricity from the grid.

3.3 Additional insights on the development of control program

The control program described in Section 3.2 was constructed in Excel Visual Basic for Applications with the expectation of obtaining a basic understanding of how energy flows between solar PV generation and a polyvalent heat pump together with thermal storage and a battery might be realized in accommodating the hourly energy loads of the house selected. The program allows the user to select and alter the solar PV array, heat pump, thermal storage, and battery sizes to explore interaction between these factors. It was decided, for learning purposes not necessarily accuracy, that a flexible yet quick tool be designed for an hourly annual analysis, yet allowing for solar PV, heat pump, thermal storage and battery size to be altered and studied in pursuit of meeting the hourly and peak loads of the particular house studied.

To achieve these goals, some assumptions have to be considered. It is well known that heat pumps have different COP values at different stages of their input and output temperatures under different environmental conditions. However, due to the limitations of developing the control program in Excel Visual Basic for Applications, the COP of the polyvalent heat pump in the three modes was assumed to be a constant value of 4. This caused the results to deviate from the actual operation of the heat pump. To address this issue, an analysis of showing how the heat pump COP affects the PV self-consumption, self-sufficiency and the annual imported energy is conducted and illustrated in Section 6.2.

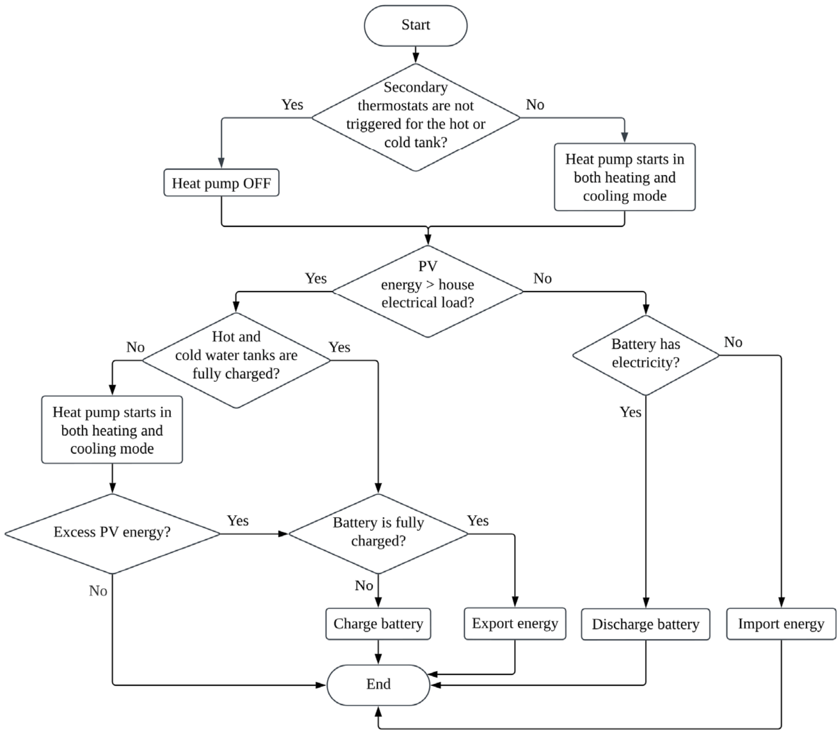

Fig. 2 Rules of energy flows for satisfying the building loads

4 Case study

A grid-connected solar PV house, located in Geelong, Australia, is used as a case study house in this paper. The house is a single storey building with three bedrooms. It is well insulated and double glazed, and the eaves are used to control sunlight exposure. The space heating is provided by a gas ducted system, and there is no equipment used for cooling. A hot water heat pump was installed in the home in June 2022 to supply DHW. Prior to that, a gas-boosted solar hot water system was used to meet home hot water demand.

4.1 TRNSYS simulation

First of all, the thermal demand for heating and cooling of the case study house needs to be obtained for this work. There are a few methods available to achieve this. For example, Tostado-Véliz et al. (2021) derived a thermostatic model of a building, including the equivalent thermal resistance of the house and the air mass inside, by linearizing the differential equations and assuming a rectangular geometry of the building. The parameters considered in the model include the index for building elements, such as walls and windows, thickness, area, and thermal coefficient of each building element, the density of air, the dimension of the building and the roof angle of the building. However, some non-geometric parameters are not mentioned, such as the profiles of infiltration, ventilation, internal gains, heating, cooling, comfort and humidity of different building zones.

In this study, the Transient System Simulation (TRNSYS) program is used to simulate the house's annual hourly heating and cooling demand. TRNSYS is a dynamic simulation tool that is frequently utilized in the area of thermal processes, and it has the ability to model the heating and cooling of many types of buildings (Laxmi and KesavaRao 2020). It includes the weather data files for various specific locations that are required for the simulation, including temperature, pressure, wind speed, humidity, and solar intensity (Jani et al. 2020). In addition, TRNBuild, serving as an interface to the TRNSYS application, enables editing data pertaining to non-geometric features, such as infiltration, ventilation, internal gains, heating, cooling, comfort, and humidity profiles for various building zones.

First, the case study house model is drawn in TRNSYS3D, which is a plugin for SketchUp. The finished geometry can be found in Figure 3. This geometry is then sent directly to TRNSYS in which the materials properties of walls, floors, and windows and the regime types, such as profiles of infiltration, ventilation, cooling and heating, gain and loss, and humidity for each zone of the house is edited in TRNBuild.

The house model is divided into seven zones, including three bedrooms, lounge, living room, sitting room and study. Therefore, the total volume to be cooled or heated in the

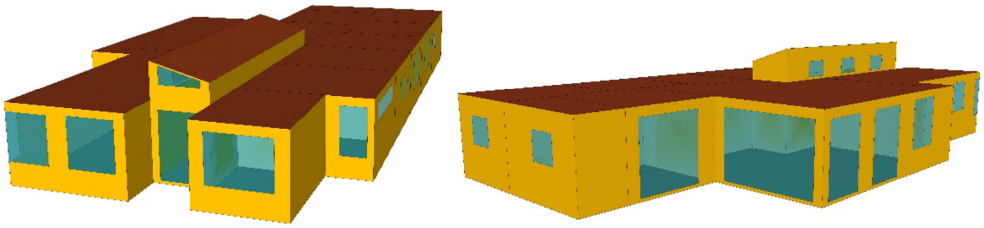

Fig. 3 (a) Southwest and (b) northeast views of the house

house is 471 m^3. The operating schedule and temperature settings of different zones of the house is shown in Table 2.

Table 2 Operating schedule and temperature setting of different zones of the house

	Bedrooms and associated spaces	Living areas and associated spaces
Operating schedule	21:00 – 7:00 occupied 7:00 – 21:00 unoccupied	21:00 – 7:00 unoccupied 7:00 – 21:00 occupied
Temperature setting in summer	25 °C when occupied 30 °C when unoccupied	25 °C when occupied 30 °C when unoccupied
Temperature setting in winter	20 °C when occupied 15 °C when unoccupied	20 °C when occupied 15 °C when unoccupied

As mentioned above, a hot water heat pump was installed in the house in June 2022 to meet the hot water demand. The electricity consumption of the heat pump has been monitored every minute since its installation by a Yokogawa power meter and recorded on a Secure Digital (SD) card. We extended the four months of power data collected to one year as the annual power consumption for the hot water heat pump. Additionally, a COP of 4 is assumed for this hot water heat pump. Therefore, the hourly DHW demand can be calculated based on the electricity consumption and the COP of the heat pump water heater.

4.2 Smart meter and solar PV data processing

In 2013, a smart meter was installed at the house, which records the amount of electricity imported from and fed into the grid in half-hourly intervals. A CSV file containing the last two years of smart meter data, recorded every 30 minutes, can be downloaded from the electricity provider (Powercor 2022). This house also has a 10-kW rooftop solar PV system, and a PV system controller records PV generation data every fifteen minutes.

The smart meter data measures imported energy as house electrical load minus harvested solar energy, and measures exported energy as harvested solar energy minus house electrical load. Since the imported and exported energy flow on the same wire, when one is positive, the other has a value of zero. The PV generation and smart meter data of the house in 2021 is used for the analysis in this work. The time interval used in this work is one hour. Thus, in each hour of the year, the electrical energy loads of the house can be calculated as follows:

$$E_i^{\mathrm{h}} = E_i^{\mathrm{s}} + E_i^{\mathrm{i}} - E_i^{\mathrm{e}} \tag{1}$$

where: E_i^{h} is the house electrical loads within ith hour. E_i^{s} is the harvested solar energy within ith hour. E_i^{i} is imported energy within ith hour, and E_i^{e} is the exported energy within ith hour.

This calculated E_i^{h} reflects the distinctive electricity consumption patterns of household appliances, because in this house, space heating is provided by a gas ducted system, and DHW is provided by a gas-boosted solar water heating system. This calculated E_i^{h} is taken as the base electrical load of the house.

4.3 A System sizing approach: key parameters

After importing the obtained annual hourly cooling, heating, DHW loads and PV generation data into Excel Visual Basic for Applications and running the proposed control program, several key parameters can be calculated, separately, using the following equations.

$$L_{\mathrm{total}} = \sum_0^t E_i^{\mathrm{h}} + \sum_0^t E_i^{\mathrm{hp}} \tag{2}$$

$$\mathrm{PV_c} = \sum_0^t \mathrm{PV}_i^{\mathrm{c}} \tag{3}$$

$$\mathrm{PV_{total}} = \sum_0^t \mathrm{PV}_i \tag{4}$$

$$\mathrm{SC} = \frac{\mathrm{PV_c}}{\mathrm{PV_{total}}} \tag{5}$$

$$\mathrm{SS} = \frac{\mathrm{PV_c}}{L_{\mathrm{total}}} \tag{6}$$

where: t represents a given period such as a day, a month or a year. L_{total} is the total electrical load of the house over a given period t, including the total base electrical load and the total electrical load for operating the polyvalent heat pump. PV_c is the total amount of PV energy consumed on site over a given period t. PV_{total} is the total amount of PV generation over a given time period t. SC is the PV self-consumption rate, and SS is the PV self-sufficiency rate.

5 Three different system sizing scenarios

The coordination of the proposed system considers the off-grid electrification of the house load through solar PV. Next, is the importance of utilising self-generated energy for thermal load requirements. This is achieved first by the polyvalent heat pump and water storage tanks, resulting in all DHW, heating and cooling loads being accommodated by conditioned water stored in tanks. Finally, the thermal load shift provides for electrical appliances to be operated primarily through battery storage. Building operation, including space heating, cooling and DHW heating, accounts for 65% of the total energy consumption of Australian households (Energy Consult 2022). Therefore, by considering thermal storage in the first place, the size of the battery can be significantly reduced. In addition, water storage tanks are cheaper and can last many more years than batteries. The concept of improved thermostatically controlled devices, such as proposed by Tostado-Véliz et al. (2022a) would add value to the above system being controlled effectively.

Three different scenarios are designed in this paper to analyse the impact of using electric batteries and a polyvalent heat pump with water storage tanks on the PV self-consumption, self-sufficiency, and grid energy consumption of the house. Scenario 1 refers to a house with a 10 kW solar PV system and a polyvalent heat pump that produces cold and hot water for space heating, cooling, and DHW. It is worth noting that no storage system is used in Scenario 1. Scenario 2 refers to a house with a 10 kW solar PV system, a polyvalent heat pump, and two water storage tanks. Scenario 3 refers to the house with a 10 kW solar PV system, a polyvalent heat pump coupled with two water storage tanks, and a 5 kWh battery. The battery technology considered in this paper is a lithium-ion battery and it is assumed that the battery can reach a 100% state of charge and 0% state of complete discharge. The input capacity of the polyvalent heat pump for the three scenarios is determined based on the peak hourly heating, cooling, and DHW load of the house, and the size of two water tanks in Scenarios 2 and 3 are determined based on the peak daily heating, cooling and DHW load of the house. Additionally, the two water tanks and the battery are assumed to be fully charged at the initial stage. The capacities of relevant systems in the three scenarios are listed in Table 3.

Table 3 Sizing of each system component in three scenarios

Scenarios	PV system (kW)	Polyvalent heat pump: Input capacity (kW)	Polyvalent heat pump: COP	Tank size (m^2): Hot water tank	Tank size (m^2): Cold water tank	Battery size (kWh)
Scenario 1	10	2.8	4	—	—	—
Scenario 2	10	2.8	4	2.6	2.0	—
Scenario 3	10	2.8	4	2.6	2.0	5

In order to show the difference in the consumption of the house on the grid and PV energy, the annual imported energy, annual PV self-consumption and annual PV self-sufficiency for the three scenarios were collected after running the control program and plotted in Figure 4. It can be seen that using a polyvalent heat pump in combination with water storage tanks reduces annual imported energy by around 28%, from 3380 kWh in Scenario 1 to 2429 kWh in Scenario 2. After adding a 5 kWh battery in Scenario 3, this value is decreased to 892 kWh, which is around 74% less than the value in Scenario 1. Moreover, Figure 4 shows that the annual PV self-consumption, which measures the proportion of total yearly PV output consumed by house loads, rises from 23.25% in Scenario 1 to 29.56% in Scenario 2 and finally to 40.24% in Scenario 3. On the other hand, annual PV self-sufficiency, which refers to the percentage of the annual house load met by PV energy, rises from 49.70% in Scenario 1 to 63.61% in Scenario 2 and then to 86.63% in Scenario 3. The significant change in these values can be attributed to the fact that more PV energy is consumed through a battery and the polyvalent heat pump coupled with water storage tanks.

It has been found that the annual PV self-consumption and self-sufficiency can be increased by using batteries and heat pumps with water storage tanks. To figure out how the use of thermal and electric battery storage affects the

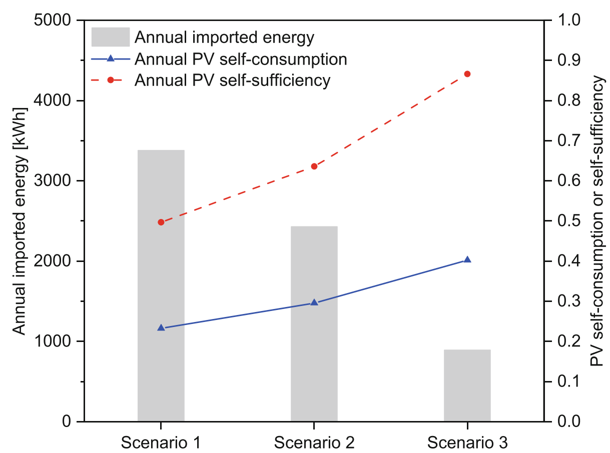

Fig. 4 Annual imported energy, PV self-consumption, and PV self-sufficiency with different service system scenarios

consumption of PV and grid energy of the house each month, we plot the monthly PV self-consumption and self-sufficiency for the three scenarios in Figure 5. Scenario 3 has the highest PV self-consumption and self-sufficiency every month of the year. This is because the use of batteries and water storage tanks allows more PV energy to be stored during the day and used at night or during peak load periods. Furthermore, in each scenario, monthly PV self-sufficiency is higher in summer than in winter, while the opposite is true for monthly PV self-consumption, with higher values in winter than in summer. This is because PV generation is greater in summer than in winter. In summer, more of the house load can be met by PV energy, leading to higher PV self-sufficiency, while in winter, higher PV self-consumption is due to the fact that most of the limited PV energy is consumed during daylight hours.

These facts can also be supported by the results shown in Figure 6, which depicts the monthly imported and exported energy for the three scenarios. It is obvious that for each of the three scenarios, the monthly energy imports from spring to autumn are larger than those in winter, while the monthly energy exports are lower than those in winter. This effect can be explained by several reasons, including high nighttime energy demand and the limited PV generation in winter. Furthermore, it is evident that in Scenario 2 with thermal energy storage, monthly grid energy imports are lower than in Scenario 1. When a 5 kWh battery is included, Scenario 3 imports less energy than Scenario 2 does for each month of the year. These effects are due to the battery and the polyvalent heat pump coupled with water storage tanks that enable excess PV output during the day to be stored as electrical or thermal energy, reducing the amount of PV output to the grid and partially offsetting the household's grid energy demand. Therefore, it can be argued that using a battery and a polyvalent heat pump coupled with water storage tanks has a substantial impact on reducing the house grid energy demand as well as minimizing the burden of exporting PV energy to the grid.

To figure out how the daily PV self-consumption and self-sufficiency are distributed, we use the data for the three scenarios in February 2021 as an example of a month, and the results are plotted in Figure 7. It can be noticed that Scenario 3 has the highest daily PV self-consumption and self-sufficiency rates due to the use of water storage tanks and batteries, allowing excess PV energy to be stored during the day and consumed during peak hours. In addition,

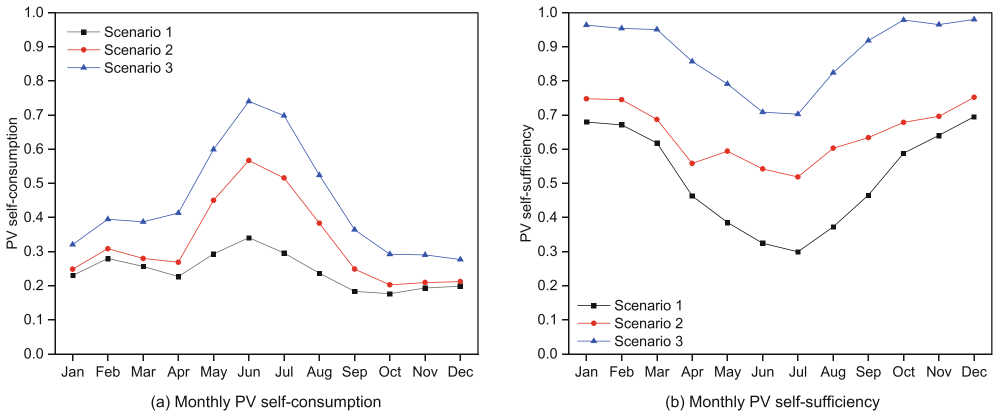

Fig. 5 Monthly PV self-consumption and self-sufficiency for the three scenarios

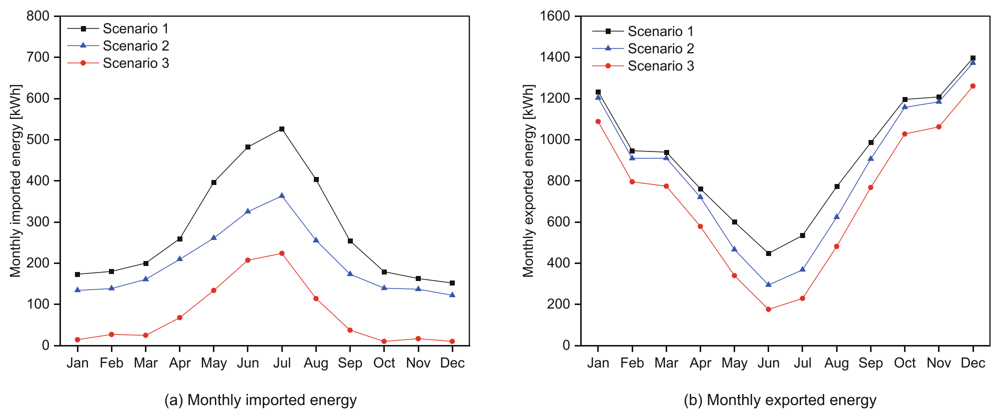

Fig. 6 Monthly imported and exported energy for the three scenarios

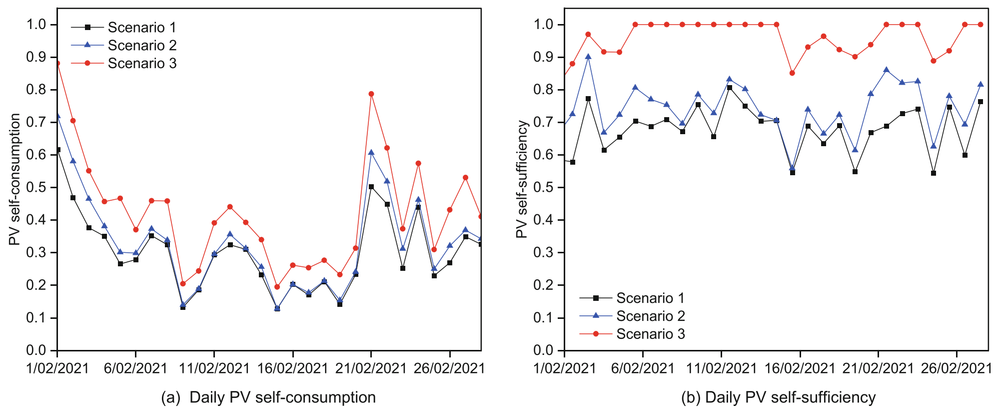

Fig. 7 Daily PV self-consumption and daily PV self-sufficiency for the three scenarios in February 2021

the batteries have a greater impact on increasing PV self-consumption and self-sufficiency rates for several days than using a polyvalent heat pump with water storage tanks. This can be explained by the fact that the thermal energy stored in the two storage tanks can only be used for space heating, cooling or DHW use, while the electricity stored in the batteries can be consumed by all household appliances as well as by heat pumps to produce hot and cold water.

To further illustrate the effects of using a battery and a polyvalent heat pump coupled with water storage tanks on the reduction of house grid energy consumption, the annual hourly imported energy for the three scenarios was collected and presented in Figure 8. It is discovered that the large portion of the imported energy that occurs from late afternoon to early morning in Scenario 1 is greatly reduced in Scenarios 2 and 3. In addition, the peak hourly imported energy occurring at 19:00 in Scenario 1 is greatly diminished and shifted to 8:00 a.m. in Scenario 3. Additionally, Scenario 3 has a smoother imported energy curve than Scenarios 1 and 2. These significant effects result from the load shifting caused by the battery and the polyvalent heat pump with water storage tanks to match the home energy demand with PV output.

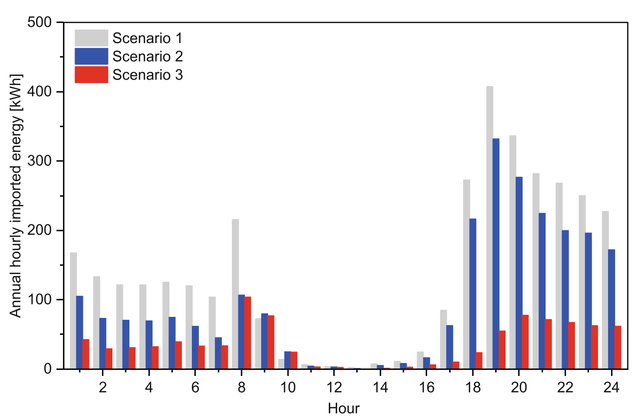

Fig. 8 The annual imported energy for each hour of a year

6 System components impact on PV self-consumption and self-sufficiency

The sizes of several system components, including hot and cold tanks, solar PV arrays, electric batteries and the heat pump COP, are varied to analyse their impact on annual PV self-consumption and self-sufficiency as well as the annual grid energy consumption of the house.

6.1 Hot and cold water tank size

The sizes of the hot and cold tanks are varied to analyse their effects on the annual PV self-consumption, annual PV self-sufficiency, and annual energy imports of the house, and the results are shown in Figure 9. When the hot tank size is fixed, the annual PV self-consumption and annual PV self-sufficiency, as well as the annual imported energy, remain almost stable when increasing the cold tank size. This is because the cooling load only occurs in summer. Due to the daily demand for DHW, the polyvalent heat pump can operate in simultaneous heating and cooling modes, producing hot and cold water with the same electrical input. Therefore, increasing the size of the cold water tank does not really affect the grid or the PV energy consumption. The figure also shows that increasing the hot tank size leads to more annual PV self-consumption and self-sufficiency, and results in a decrease in annual imported energy, but the increase or decrease is not significant. This is because the COP of the polyvalent heat pump is considered to be a constant value of 4, which enables the heat pump to operate effectively at all times and results in its relatively low power consumption. Another reason is that when the size of the hot tank increases, the stored heating energy is not used efficiently and becomes redundant.

Figure 10, which depicts the temperature of the hot and cold water tanks in relation to the hot water tank size,

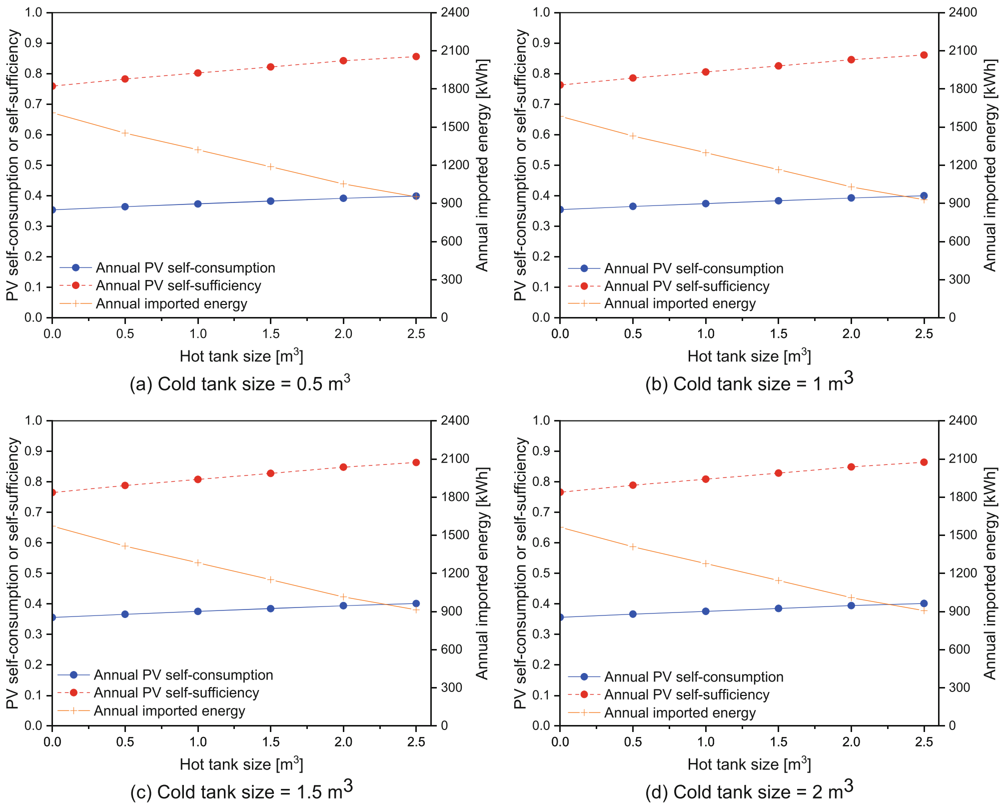

Fig. 9 Annual PV self-consumption, annual PV self-sufficiency, and annual imported energy as functions of hot and cold tank sizes (PV system size = 10 kW, battery capacity = 5 kWh, and polyvalent heat pump input capacity = 2.8 kW)

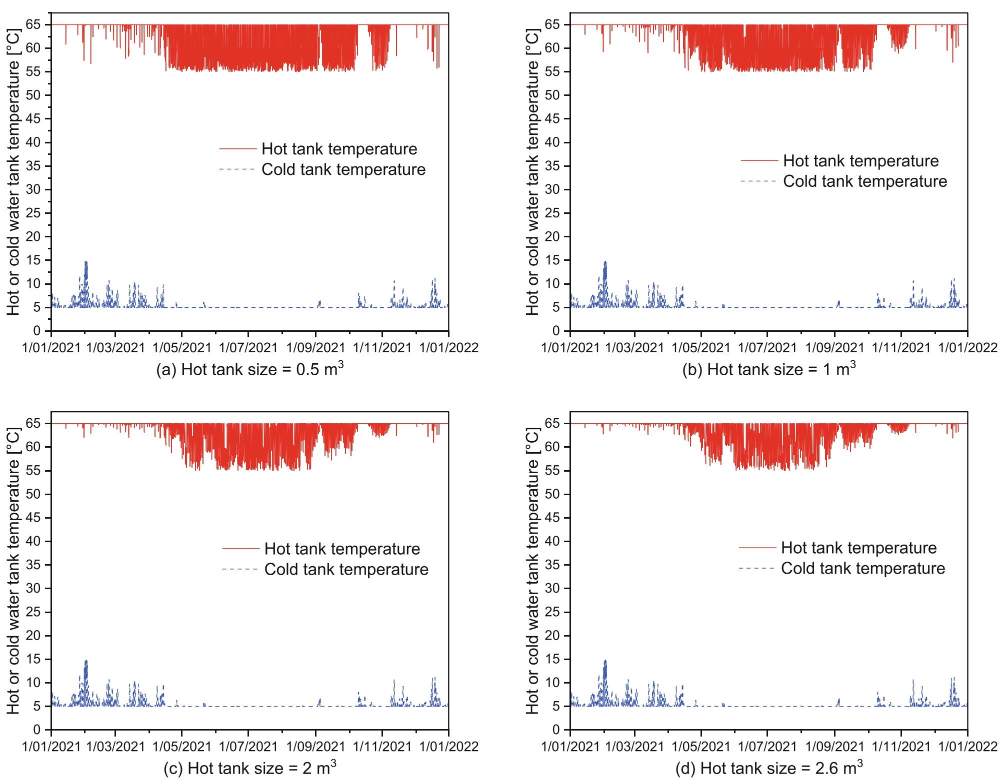

Fig. 10 Hot and cold tank temperature as a function of hot tank size (PV system size = 10 kW, battery capacity = 5 kWh, polyvalent heat pump input capacity = 2.8 kW, cold tank size = 2.0 m^3)

illustrates similar results. As seen in the graph, the frequency with which the hot water tank temperature approaches the maximum temperature of 65 °C increases as the size of the hot water tank increases. This indicates that a continuous increase in the size of the hot water tank to consume PV energy becomes less useful, i.e., the increase in annual PV self-consumption and self-sufficiency becomes progressively slower as the size of the hot water tank increases. It can also be observed that the hot tank temperature drops below 60 °C far more frequently in the winter than at other times of the year for the four various tank sizes. This is attributed to the house having higher heating and DHW demand in winter, which causes hot water consumption to be higher than in other seasons. Additionally, the limited PV generation in winter restricts the operating time of the polyvalent heat pump. According to the control strategy, when the PV generation is insufficient in winter, the polyvalent heat pump will only be turned on when the hot tank temperature drops below 55 °C and heats the hot water to 60 °C by consuming grid energy. Therefore, in summary, the size of the tank should take into account both the home cooling, heating, and domestic hot water loads, as well as the seasonal characteristics of PV power generation.

6.2 Heat pump COP

The polyvalent heat pump in this work can provide three modes, i.e., heating only, cooling only, and both simultaneous heating and cooling modes. The COP of the heat pump is varied with changes in the ambient conditions and the temperature of the heat source and sink. Due to the limitations of developing control programs in Excel Visual Basic for Applications, the COP value of the polyvalent heat pump in all three modes is assumed to be a constant value of 4. In order to reduce the impact of the assumption of the heat pump COP on the final results of this work, we analysed how the annual PV self-consumption, annual PV self-sufficiency, and annual energy imports vary with the change of the heat pump COP, and the results are illustrated in Figure 11. As the COP value decreases from the initially assumed value of 4, there is a gradually increasing trend of annual PV self-consumption and annual imported energy. This is due to the fact that as the heat pump's COP decreases, it needs to operate for longer periods to maintain the same level of thermal output. As a result, the heat pump consumes more PV power during the day, contributing to the increased annual PV self-consumption. Similarly, the heat pump must draw more energy from batteries or the electricity grid at night or during periods of low PV power to maintain the same thermal output, resulting in more annual grid energy consumption.

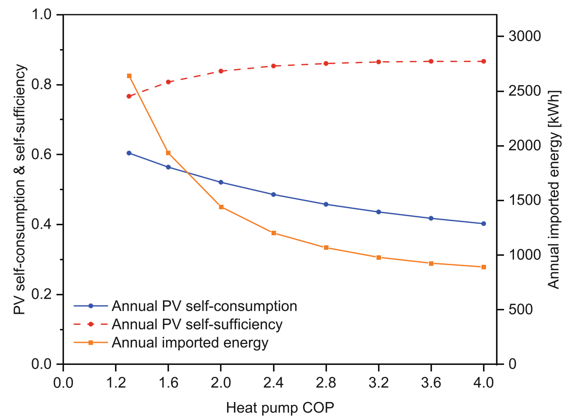

Fig. 11 Annual PV self-consumption, annual PV self-sufficiency, and annual imported energy as a function of heat pump COP (PV system size = 10 kW, battery capacity = 5 kWh, polyvalent heat pump input capacity = 2.8 kW, hot tank size = 2.6 m^3, cold tank size = 2.0 m^3)

On the other hand, the graph shows that the annual PV self-sufficiency remains almost constant when the COP value of the heat pump is higher than 2.4, and only when its value continues to decrease from 2.4, the annual PV self-sufficiency slowly decreases. This is because when the COP value of the heat pump is very low, the hot or cold water produced by the heat pump through the consumption of PV energy during the day is not enough to meet the house energy demand. The heat pump has to operate by consuming more grid energy during nighttime, resulting in reduced annual PV self-sufficiency. In addition, it is important to note that based on the input power of the heat pump and the existing size of the two water storage tanks, the COP of the heat pump needs to be at least 1.3, as shown in the figure, to meet the annual heating, cooling and DHW loads of the house. Thus, it can be found that the heat pump COP does have an impact on annual PV self-consumption and self-sufficiency as well as on the annual grid energy consumption of the house. Future research will focus on simulating the polyvalent heat pump in TRNSYS to explore more precisely the impact of changes in heat pump performance on PV and grid energy consumption at different ambient temperatures, heat sources, and sink temperatures.

6.3 PV-battery system capacity

Figure 12 illustrates the annual PV self-consumption, annual self-sufficiency, and annual imported energy of the house as functions of PV and battery sizes. Four different PV system sizes, including 2.5 kW, 5 kW, 7.5 kW, and 10 kW, are studied, and the PV generation rises proportionally to its size. It has been discovered that, for every PV system size, the annual amount of energy imported falls as battery

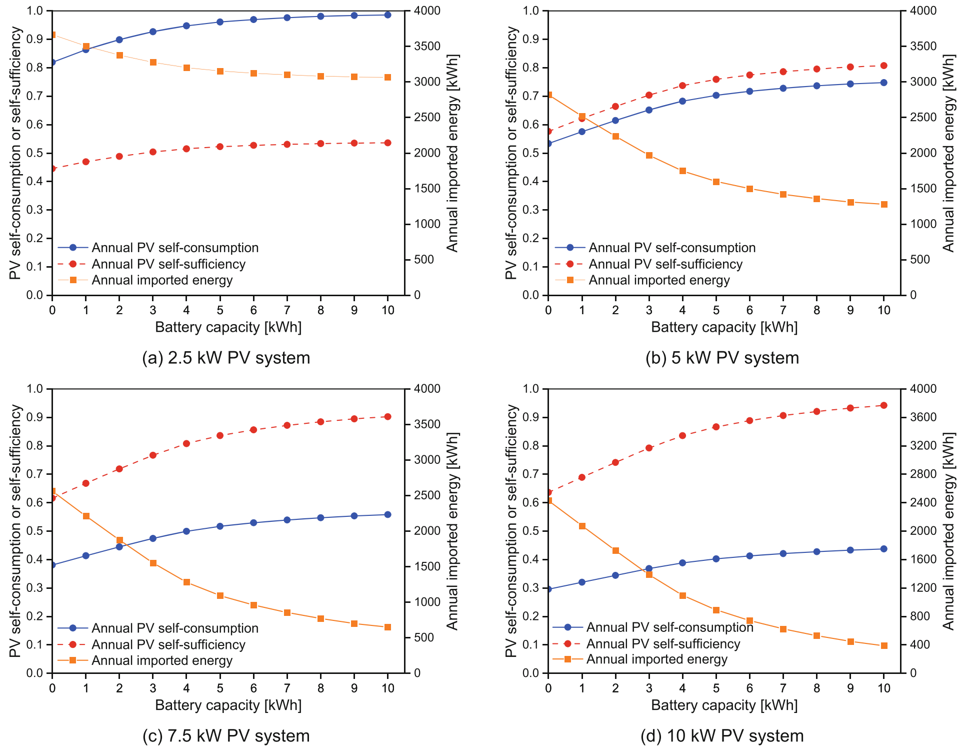

Fig. 12 Annual PV self-consumption, annual PV self-sufficiency, and annual imported energy as functions of PV and battery sizes (Hot tank size = 2.6 m^3, cold tank size = 2.0 m^3, and polyvalent heat pump input capacity = 2.8 kW)

capacity rises, and the annual PV self-consumption and self-sufficiency rise. However, the increasing trend is constrained by PV generation because the amount of electricity generated by PV is influenced by the seasons. In particular, PV generation is adequate in the summer, and any excess energy can be used to charge the battery. The PV generation is not sufficient to satisfy the daily household load during the winter due to shorter days, lower solar altitude and greater night-time energy demand, so the battery cannot be charged effectively. It can also be found that under a fixed battery capacity, such as 5 kWh, increasing the PV system size leads to an increase in annual PV self-sufficiency, from 52.25% for 2.5 kW PV to 86.63% for 10 kW PV, but the annual PV self-consumption decrease dramatically, from 96.09% for 2.5 kW PV system to 40.24% for 10 kW PV system. This is because the increase in PV system size can reduce the amount of energy imported from the grid, but it is small compared to the increased amount of energy exported to the grid. Therefore, it is noted that when installing PV systems and batteries, it is necessary to consider the characteristics of PV generation and house electricity demand in order to determine the best size combination of PV and battery systems.

7 Conclusion

This paper is about utilizing PV-generated solar energy through a polyvalent heat pump combined with water storage tanks and batteries. The performance of a mechanical system depends on the energy that can be stored. Conventional systems do not offer this but utilize fossil fuels and electricity during the day and nighttime hours. While we could store electrical energy in a large battery to operate mechanical systems at night, this is not economically feasible nor efficient use of electrical energy. Figure 4 Scenario 1 illustrates an instantaneous DHW and conditioning system, which consumes more grid energy than the other two scenarios with thermal and battery storage. The discovery is to utilize a mechanical system (heat pump) that can provide for thermal storage by consuming PV energy during daylight hours. Thermal storage allows us to separate conditioning loads from electrical (appliance) loads.

This paper explores how the use of thermal and battery storage can increase PV self-consumption and self-sufficiency while fulfilling the house's electricity, heating, cooling, and DHW needs. The results revealed that by using appropriate control strategies and component sizes i.e., heat pump, storage tank capacity and battery, the proposed combined system could increase the PV self-consumption and self-sufficiency to 40.24% and 86.63%, respectively. Compared to Scenario 1 without energy storage, the annual imported energy of the house is reduced by almost 74% in Scenario 3 with water storage tanks and a battery. It was also discovered that increasing the battery capacity led to an increase in PV self-sufficiency and self-consumption, but the trend is limited due to the constrained PV generation in winter. Therefore, there are limitations to costly battery sizing that depend upon solar PV array sizes. Increasing the PV system size resulted in an increase in PV self-sufficiency. Note, a decrease in PV self-consumption is due to a great deal of PV energy being exported to the grid. Furthermore, the increase in hot tank size could contribute to an increase in PV self-consumption and self-sufficiency, but the trend is limited as the COP of the polyvalent heat pump is assumed to be a constant value, and the amount of heating energy storage is not used effectively and becomes redundant.

Results from the control program also demonstrated that there is perhaps no such thing as "an optimum" in the selection of components to a service system of the type that we are advocating here. In other words, there may be several "best fits" of a system that are suitable to an owner's costs, the spatial accommodation of equipment, or the fact that certain factors have already been determined before the analysis (such as a 10 kW PV array). There is no such thing as "an optimum" for everyone, as this definition rests on the interpretation of the individual.

Another interesting point to make in this study is the size of the solar PV array and the low self-consumption achieved by the project. However, it may be interesting to consider that different battery technologies or electric vehicles may apply this excess PV power. In addition, electric vehicles may provide additional battery requirements for our houses at night. All these considerations will be part of a much more complete sizing and energy use model for our houses in the future.

Finally, the control program and the calculation process of the house's electrical energy consumption in this study were implemented in Visual Basic for Applications. To obtain more accurate and comprehensive results, future work can be done by simulating the proposed combined system using shorter time intervals in the TRNSYS program, in which using the cold water tank to store heating energy in winter, the water temperature stratification of the two storage tanks, the performance mapping of the polyvalent heat pump can be analysed in more detail.

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