Transitioning from natural gas towards all electric solutions

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Abstract

As the world advances towards decarbonization, a solution is required for residential services dependent on fossil fuels. This paper investigates how replacing a conventional natural gas-driven space and hot water system with a solar PV-powered hot water heat pump in a house affects its energy consumption and carbon emissions. A typical Australian home is used as a case study; it was retrofitted with a 10 kW PV system and a hot water heat pump, and its gas and electricity use is measured. Two scenarios were created. The first involved grid supply, gas-ducted heating system and gas-boosted solar water heater. The second involved a 10 kW solar PV system, grid supply, hot water heat pump and fan coil units. The second scenario was simulated using TRNSYS and validated using actual measurements. Results indicate that all electrified services in the second scenario can match the natural gas demand of 5,138 kWh required in the first scenario. The annual electricity demand in the second scenario was 6,949 kWh, higher than the 4,393 kWh in the first scenario, but the inclusion of a 10 kW PV in the second scenario results in only 84% of the annual grid demand of the first. Furthermore, the annual carbon emissions of the second scenario are 42.31% less than the first falling from 3015 kg to 1739 kg. This study demonstrates the viability of electrifying and decarbonizing residential loads with a solar PV-powered hot water heat pump. Future research will concentrate on using other storage devices, such as batteries, to further increase the decarbonization level of the home.

Keywords: electrification, decarbonization, heat pump, solar PV, house

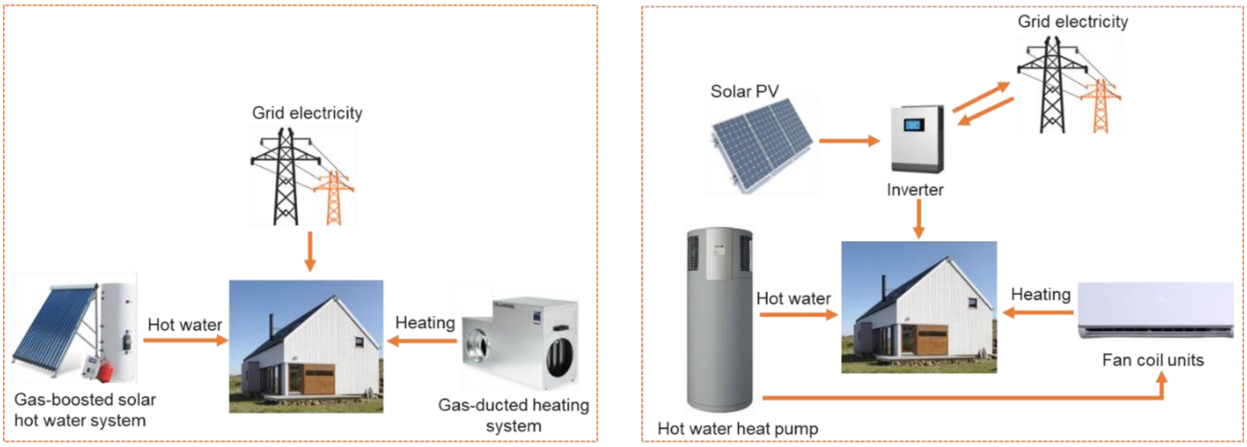
Introduction

As many nations have established goals to attain net-zero emissions by 2050, the residential sector, as one of the largest energy consumers and carbon emitters, must decarbonize. According to reports, 20% of carbon emissions in the United States originate from the residential sector [1]. Similar conditions exist in Australia, where the residential sector accounts for over 20% of the country's total carbon emissions, or more than 18 tonnes per household per year [2]. Particularly, space heating, space cooling, and domestic hot water (DHW) production account for approximately 65% of residential energy consumption in Australia [3]. Therefore, finding strategies to reduce both energy use and carbon emissions can make a significant contribution to global decarbonization.

Increasing global adoption of rooftop solar photovoltaic (PV) systems assists the residential sector in decarbonizing its energy use by reducing the consumption of grid electricity generated, at present, mainly by the combustion of fossil fuels. Once the electricity supply is decarbonized, other fossil-fuel-dependent residential building services, such as heating and DHW systems, can be decarbonized through electrification. Electrification with heat pumps eliminates direct carbon emissions and provide space conditioning and DHW for homes due to their exceptional heating and cooling capacities, ease of coupling with solar PV systems, and use of natural refrigerants [4, 5]. Therefore, this paper uses a typical Australian home as a case study to illustrate how coupling a hot water heat pump with a residential solar PV system for heating and DHW production can reduce grid electricity and natural gas consumption, resulting in lower carbon emissions.

Materials and method

A typical Australian house located in Geelong, Victoria, is used as a case study to demonstrate how the integration of a heat pump with a solar PV system can electrify and decarbonize a home. This house has experienced several retrofitting in terms of energy supply and building services. Specifically, a 3 kW and 7 kW solar PV system was installed in 2014 and 2019, respectively, bringing the total PV capacity to 10 kW. A PV system controller measures PV power generation at 15-minute intervals. Prior to the installation of a hot water heat pump in June 2022, DHW was provided by a gas-boosted solar hot water system. Space heating is provided by a conventional gas-ducted heating system, and there is no mechanical equipment for cooling the house. A smart metre installed in 2013 measures the electricity imported from and exported to the grid at half-hour intervals. Two different scenarios have been considered. In Scenario 1, the home is equipped with a gas-ducted heating system and a gas-boosted solar hot water system for space heating and DHW, respectively. Moreover, the electricity is sourced solely from the grid. Scenario 2 refers to a 10 kW solar PV system paired with the electricity grid to power the home. Additionally, DHW is provided by a hot water heat pump, which also supplies hot water to fan coil units for heating the house. A schematic diagram of the two scenarios is shown in Figure 1.



(a) Building services system for Scenario 1 (b) Building services system for Scenario

Figure 1. Schematic diagram of building service systems for the two scenarios

Smart meter data was downloaded from the electricity provider and PV generation data for 2021 was downloaded from the solar system support, indicating the hourly electricity use patterns and annual PV generation profile. Natural gas consumption was also measured for 2021 and from June 2022 to May 2023, with the latter being used entirely for heating the house. In addition, the electricity consumption of the heat pump was measured from June 2022 to May 2023 to represent the annual DHW load of the house. The electrical load on the grid and the natural gas load used for space and DHW heating in Scenario 1 have been obtained based on the collected data. To determine the electricity and natural gas loads for Scenario 2, we modelled the Scenario 2 using Transient System Simulation (TRNSYS). Specifically, the DHW load was first calculated using AS/NZS 4234:2021 and then validated by comparing the simulated power consumption of the heat pump with the measured power consumption. The simulated annual PV generation and house heating loads were validated by comparing them directly with the actual measurements.

Two parameters are introduced to depict the proportion of PV energy consumption relative to its total generation and the residential energy demand. The first, PV self-consumption, quantifies the percentage of total PV energy consumed locally. The second, PV self-sufficiency, assesses the proportion of a home's energy needs met by PV energy. In addition, the emission factors for one kWh of natural gas combustion and one kWh of grid electricity generation are 0.185 kg and 0.47 kg, respectively [6], which can be used to illustrate the difference in carbon emissions between these two scenarios.

Results

To investigate the energy performance of the two scenarios, a summary of the annual energy consumption was computed using the measured data for natural gas and electricity as well as the data obtained from the TRNSYS simulation; the results are depicted in Figure 2. The annual natural gas consumption for space and hot water heating in Scenario 1 is determined to be 5,138 kWh. Since there is no solar PV system, the annual electrical demand of 4,393 kWh is entirely supplied by the grid. In comparison, due to the electrification of all energy loads, the annual electricity demand of Scenario 2 reaches 6949 kWh, which is higher than that of Scenario 1. Interestingly, the annual grid consumption for Scenario 2 is lower than Scenario 1, with 3701 kWh, because the 10 kW solar PV system covers a portion of the electricity consumption, resulting in a PV self-sufficiency of 46.74%. Moreover, the PV self-consumption is found to be only 22.18% in Scenario 2. This is attributed to the significant PV generation as well as the time difference between the PV generation and house energy demand, leading to only 3248 kWh out of 14644 kWh being consumed locally. In summary, it can be argued that coupling hot water heat pumps to residential solar PV systems can effectively reduce the consumption of natural gas and grid electricity.

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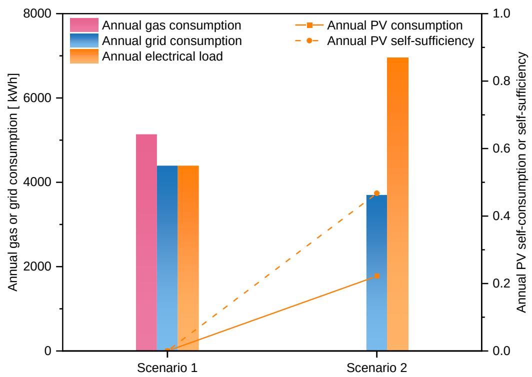

Figure 2. Annual energy summary of the two scenarios

To further illustrate the effect of integrating a heat pump with a residential solar PV system on reducing grid electricity and natural gas consumption, we calculated and depicted the monthly energy loads for both scenarios in Figure 3.

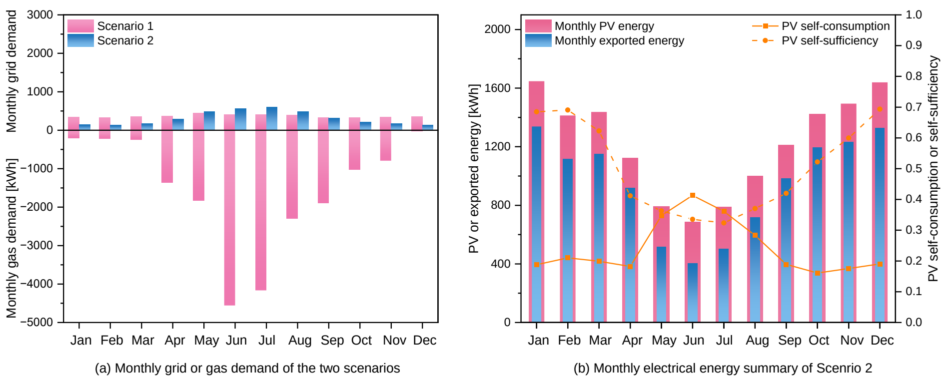

Figure 3. Monthly energy summary of the two scenarios

As shown in Figure 3-(a), Scenario 1 requires a substantial amount of natural gas, particularly during the winter months, for space and hot water heating, and similarly, Scenario 2 uses more electricity during the winter months than during other seasons. Additionally, the grid demand for Scenario 2 is higher in winter months than for Scenario 1 and lower at other times. This is due, first, to the electrified house loads that lead to an increase in the electrical loads for Scenario 2 and secondly, because PV generation is subject to seasonal variations in solar radiation, which is reflected in Figure 3-(b) by the fact that PV generation is significantly lower in winter months than in other months. Overall, the integration of hot water heat pumps with solar PV systems demonstrates significant potential in electrifying house loads. Furthermore, the significant amount of exported energy shown in Figure 3-(b) for each month suggests introducing battery storage to further increase the decarbonization level of the house.

As shown in Figure 2, the annual grid demand for Scenarios 1 and 2 are 4393 kWh and 3701 kWh, respectively, and Scenario 1 requires additionally 5138 kWh of natural gas for space and hot water heating. So, the annual carbon emissions of the two scenarios are calculated using their annual grid electricity and natural gas consumption and their associated carbon emission factors [7], and summarized in Table 1. Coupling heat pumps with residential solar PV systems reduce the annual carbon emissions of the house by approximately 42.31% from 3015 kg to 1739 kg. Therefore, it is arguable that integrating hot water heat pumps with solar PV systems can have considerable effects on the decarbonization of houses.

Table 1. Annual carbon emissions of the two scenarios

Scenarios	Annual gas demand (kWh)	Annual grid demand (kWh)	Annual carbon emission (kg)
Scenario 1	5138	4393	3015 kg
Scenario 2	0	3701	1739 kg

Conclusion

This paper employs a typical Australian residence as a case study to demonstrate the effects of replacing conventional grid and natural gas building services with solar PV heat pumps to electrify and decarbonize the home. Using actual measurements and TRNSYS simulations to collect electricity and natural gas data, the results indicate that the second, all electric, scenario eliminates the 5138 kWh natural gas demand required of the first scenario. Although the annual electricity demand of 6949 kWh in the second scenario is higher than the 4393 kWh in the first scenario, its annual grid demand is approximately 16% lower because of the 10 kW solar PV system. Furthermore, the carbon emissions of the second scenario are reduced from 3015 kg to 1739 kg, a reduction of about 42.31%. This study shows that it is feasible to electrify and decarbonize the house load using a solar PV-powered hot water heat pump. Moreover, in the second scenario a significant amount of energy was exported to the grid suggesting future research, for example, into the use of batteries.

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