Domestic hot water systems as energy storage for excess PV. A thermal model and performance analysis.

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Introduction

Domestic hot water systems are one of the most energy-consuming applications in households worldwide [1]. Among the different technologies, domestic electric water heaters (DEWH) have become increasingly popular, reaching more than half of market penetration in Australia [2]. On the other hand, the increasing uptake of distributed PV (D-PV) generation has produced several new challenges to the grid, such as voltage issues or PV curtailment [3]. The possibility of controlling and optimising DEWH charging period schedules is a promising alternative to allocate excess PV generation, increasing the household self-consumption, with potential economic, network and environmental benefits. In Australia, DEWH systems can be controlled by energy providers to limit the heating periods outside the network peak demand, typically during nighttime [2]. Therefore, in order to use hot tanks as energy storage for excess D-PV, new control strategies to control DEWH systems are required.

Previous studies have analysed the hot water draw (HWD) patterns [4], control strategies to shift aggregated DEWH system from peak hours, as well as optimization algorithms to minimise electricity costs based on day-ahead forecasts and hot water draw profiles (HWDP) [2]. The maximization of PV self-consumption using DEWH as thermal batteries and have also been studied, and optimisation algorithms are proposed [5]. However, there is limited understanding of the thermal losses associated with these systems and how the possible modifications in the heating control and consumption patterns can affect them. Better understanding of the thermal behaviour of hot water tanks would allow to develop more efficient and reliable control algorithms, identifying the best heating periods to reduce losses as well as minimise the risk of hot water shortage.

The main goal of this work is to characterise the hot water tank behaviour and assess its performance under different real-world conditions, such as typical hot water consumption patterns and control loads. A DEWH thermal model was developed for this purpose, and results for typical Australian households are presented and discussed.

Numerical Model

An integrated Python-TRNSYS solution is developed, as shown in Figure 1. This approach takes advantage of the flexibility of the Python language with the capabilities and speed of TRNSYS. A domestic hot water system layout is generated in TRNSYS 18 [6], as shown in the orange box in Figure 1. The Python algorithm (green box in Figure 1) is split into three sections: (i) defining the simulation conditions, (ii) updating and running the TRNSYS simulation based on the created layout, and (iii) post-processing and analysis. The problem is entirely defined by two types of constraints: design parameters and time-series profiles. Design parameters, such as tank volume, heater nominal power, and maximum temperature, are fixed during the simulation. The time-series profiles required are weather variables, hot water draw profiles (HWDP) and control signal (defining the time when the tank circuit is open and can be charged). They are created in the Python script and called by TRNSYS as plain text files.

The performance of the system depends on two main factors:

- the household HWDP, which define the timing and amount of energy extracted from the tank,

- the control load schedule, which defines the time when the tank can be heated (i.e., when the tank circuit is on.

Six different HWDPs were tested based on consumption patterns identified in Australian households by previous publications [1]: 'morning and evening only', 'morning and evening with day time', 'evenly distributed through the day', 'morning dominant', 'evening dominant', and 'late night'. On the other hand, five different control load schedules are included in the analysis. Three control load schedules defined by NSW-based distribution network service provider (DNSP) Ausgrid are considered [7]. Control load 1 (CL1) turns the circuit on only during nighttime (typically between 10pm and 7am). Control load 2 (CL2) allows charging the whole day, except by the evening peak (5pm and 10pm). A new control load, CL3, introduced early in 2023, which is similar to CL1 but includes an additional solar window (an additional 5:45 hours in the middle of the day). Finally, a default 24-hrs general supply (GS) and an exclusive solar soak (SS) schedules between 9 am and 3 pm are included as additional realistic cases.

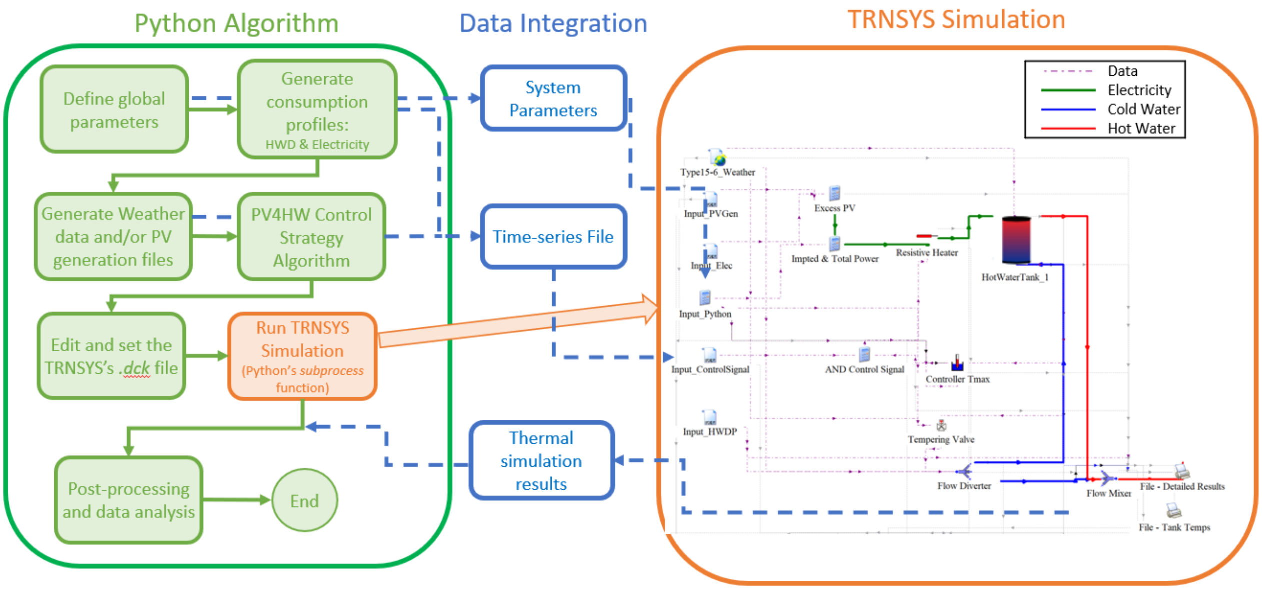


Figure 1. A general schematic of the Python/TRNSYS integrated algorithm. Python components are shown in green, the TRNSYS layout is in orange, and interconnecting data components are in blue.

Two main parameters are used to analyse the hot water tank performance. The storage efficiency (η_{stg}) is the ratio between the thermal energy delivered by the tank and the electricity consumed by the electric heater. This term is used to measure the losses within DEWH, and a higher storage efficiency refers to smaller losses in DEWH. In addition, the state of charge (SOC) is used as a parameter to summarise the overall behaviour of the tank and its energy availability. In particular, the minimum SOC can be used as a parameter to quantify the system's reliability to provide hot water at any point in time. These parameters are defined as:

$$\eta_{stg} = \frac{E_{HWD,year}}{E_{heater,year}} \tag{1}$$

$$SOC = \frac{Q_{u,tank}}{Q_{max}} = \frac{\sum_{i=1}^{N_{nodes}} (T_i - T_{cons})^+}{(T_{max} - T_{cons})} \tag{2}$$

Where $E_{HWD,year}$ is the annual thermal energy delivered by the hot tank, $E_{heater,year}$ is the annual electricity consumed by the electric heater, $Q_{u,tank}$ is the useful thermal energy stored in the tank, Q_{max} is the maximum possible energy to be stored if the whole tank is at its maximum temperature, T_i are the temperatures on the nodes, and T_{cons} is the assumed consumption temperature. N_{nodes} is the number of nodes considered in the stratified tank.

Results

A base case DEHW system is tested under different HWDP and control load combinations. The base case considers a 4-people household in Sydney with an average daily consumption of 200 (L/d), a 315L tank, a 3.6kW electric heater, a consumption temperature assumed at 45°C, and a maximum temperature in the tank of 65°C. Figure 2 shows the storage efficiency for the six HWDPs and five control loads tested for Sydney. The type of control load has a stronger influence over the storage efficiency than the type of HWDP. The two schedules with better storage efficiency are CL1 and solar soak, with average efficiencies of 71% each analysed over six different HWDP. It is also seen that the longer the circuit is on, the lower the efficiency. This happens because when a circuit is on for a longer time, it allows more charging that keeps the tank hotter, resulting in higher thermal losses to the environment.

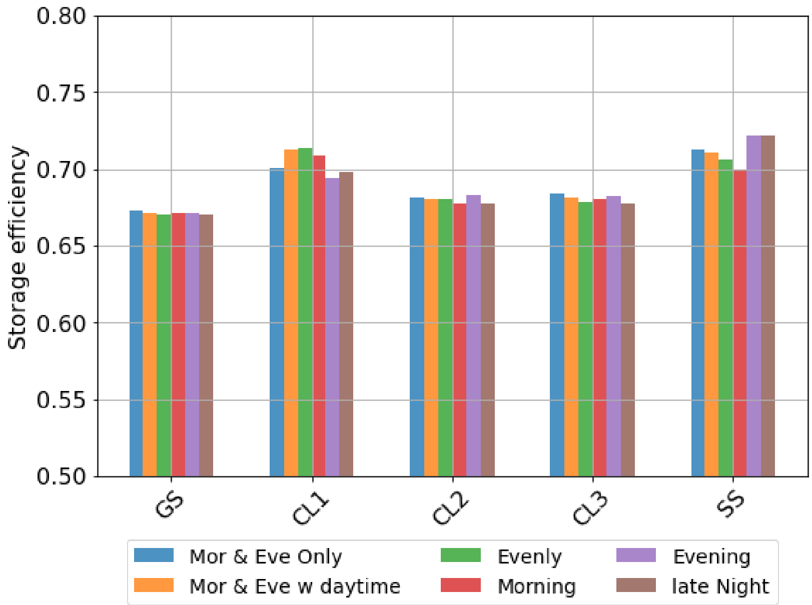
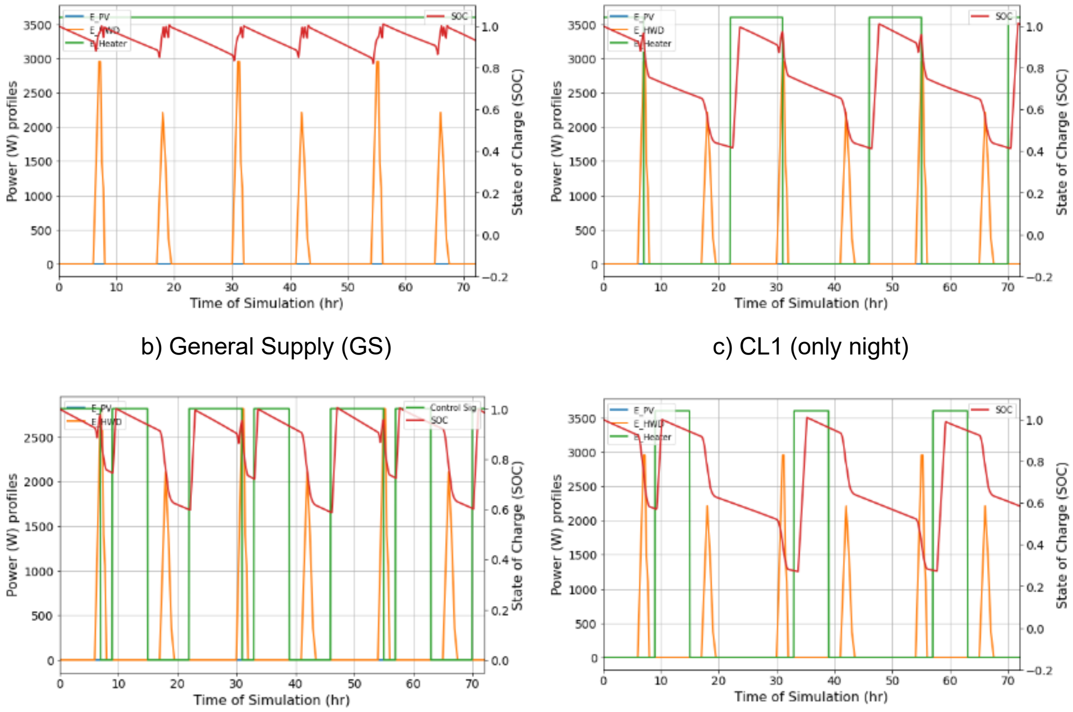


Figure 2. Storage efficiency for base case scenario with different control loads and HWDPs.

The influence of control load on the tank behaviour is more evident once in the detailed results shown in Figures 3. In this figure, the first three days of simulation for selected cases are presented for the same HWDP (morning and evening only) and different control load schedules. In each subplot, the control load signal (Boolean) is shown in green, the thermal power extracted from the tank at a given time (which represents the HWDP) is in orange, and the SOC is presented in red. For GS (subplot a), the tank always has a SOC between 0.8 and 1.0 because the heater is always turned on when the thermostat indicates so. On the other extreme, for the solar soak schedule (subplot d), the tank is discharged deeper, and the average SOC is lower (around 0.6), reducing, on average, the losses and, therefore, the electricity consumption.



b) General Supply (GS) c) CL1 (only night)

d) CL3 (CL1+SS) e) Only solar soak (SS)

Figure 2. Detailed results for first three days of simulation with HWDP=1 and different control loads. In orange the HWD profile, in green and the control load signal, and in red the State of Charge (SOC).

Conclusions

A novel approach is presented to simulate the hot water tank behaviour as part of a domestic hot water heating system. This integrated Python/TRNSYS solution takes advantage of both worlds, allowing accurate and quick results provided by TRNSYS with the flexibility and extended analysis capabilities provided by Python.

The results show that the hot tank efficiency is affected more by the control load than the hot household behaviour (i.e., HWDP), with average annual efficiencies between 67-72%. These results are meaningful insights for the control algorithm development and open the possibility for thermal models-based control algorithms with the potential to improve their efficiency, accuracy, and reliability.

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