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Using storage electric water heaters to improve grid stability and reduced energy costs

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E_{Neg}	Energy consumed under negative real time price conditions (kWh)
E_{DR}	Energy consumed under price index demand response (kWh)
E_{CL}	Energy consumed under controlled load timer (kWh)
E_{EH}	Energy consumed under emergency heating (kWh)
E_{San}	Energy consumed under Legionella sanitation and standby (kWh)
E_{FR}	Energy reserve to raise electrical network frequency (kWh)
E_{FL}	Energy reserve to lower electrical network frequency (kWh)
$E_{Total\ DR}$	Energy consumed by heater under demand response (kWh)
C_{Neg}	Income from energy consumption at negative real time price conditions ($)
C_{DR}	Cost of energy consumption under price index demand response ($)
C_{CL}	Cost of energy consumption under control load timer control ($)
C_{EH}	Cost of energy consumption under emergency heating ($)
C_{San}	Cost of energy consumption under Legionella sanitation and standby ($)
C_{FR}	Income from reserves provided to raise electrical network frequency ($)
C_{FL}	Income from reserves provided to lower electrical network frequency ($)
C_{DRNet}	Cost of energy consumed under demand responds ($)
C_{Total}	Total cost of the water heating energy consumption ($)

Introduction

Global electrical distribution networks are rapidly evolving from centralized generation to fragmented and variable distributed power generation [1, 2]. The environmental credentials and financial appeal of renewable generation, and its rapid deployment is leading to a reduction of the reliance on fossil fuel and nuclear energy to generate electricity. Historical technical and financial limitations which supressed the uptake of renewable energy are being replaced with realistic targets and plans of 100% renewable energy [3]. Energy storage and demand management are now substantial limiting factors that hinder further uptake of renewable energy.

Frequency control on a network has historically been managed utilizing the large rotational inertia of fossil/nuclear power generators. As renewable energy replaces fossil/nuclear electrical generation, the requirement for frequency control is increasing [4]. Frequency control countermeasures are predominantly undertaken utilising fast response energy supply/demand devices such as batteries, solar PV acting as virtual inertia or wind turbines acting as synthetic inertia [5]. Whilst studies such as that by Basit, Dilshad [6] detail extensive frequency control using power electronic based solutions and energy storage, solutions that consider demand management tend to be overlooked. Daly, Qazi [7] analysed the impact of frequency response reserves in electric water heaters at a network level where an increase of 5.7% in frequency response reserves was identified.

Voltage control through demand control is not necessarily new, with crude time of use tariffs set to encourage users to predictably increase demand when network demand is minimal [8]. A more sophisticated study of water heaters operating under voltage demand response (DR) using a combination of fuzzy logic control (FLC) and particle swarm optimisation (PSO) demonstrated consumer cost savings of 56% [9]. Two significant limitations in this study were the omission of real-time spot prices and thermal stratification of the water heater. Numerous other studies have also analysed the DR potential of electric water heaters [10-13], however detailed modelling of the thermal stratification within the water heater has again been limited. This suggests further savings could be obtained with higher resolutions of price and water heater operating conditions.

The challenge that this manuscript addresses is to change the control of electric water heaters from crude "off peak" control to sophisticated DR. To achive this, the heater design and control complexity increase from one simulation to the next. The aim of this is to replace local automated control such as controlled load (off peak), minimum thermal supply and sanitation control with DR to access lower purchased electricity prices and the financial benefits of frequency reserves. It is demonstrated that a symbiotic relationship can be formed between network operator and consumers using water heaters as decentralized energy storage to stabilize electrical network voltage and frequency.

Method

In this manuscript the following dynamic inputs are used in TRNSYS [14] simulations for the calendar year 2018 with a simulation time step of 1 minute: -

- Recorded climatic conditions from Adelaide, South Australia at a frequency of 1 minute [15].
- Heated water thermal load as derived from South Australia Power Network (SAPN) using data from 81 houses with water heaters on a controlled load. The daily average SAPN recorded electrical consumption was converted to an average daily thermal consumption using a TRNSYS reference water heater simulation.
- Recorded electrical network 5 minute real time (spot) price and frequency response ancillary services (FCAS) prices from Australian Energy Market Operator (AEMO) [16]

A graphical example of the TRNSYS simulation is shown in **Fig. 1**.

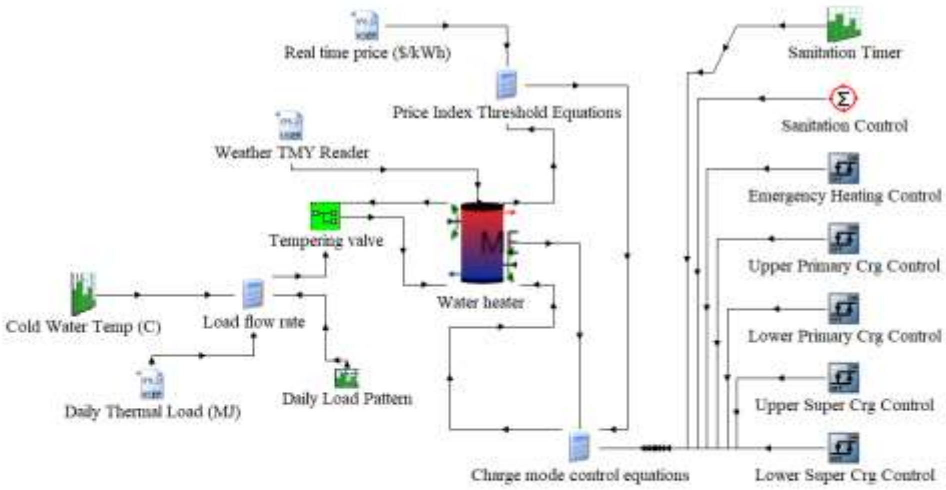

Fig. 1 Example of TRNSYS schematic of a domestic hot water system.

All simulations were conducted in modelled water heaters with constant values shown in Table 1.

Table 1 Water heater geometric and thermal performance parameters

Heater parameter	Value
Tank storage volume (L)	315
Tank heat loss at Δ T = 55 K [17] (kWh/day)	2.5

(U = 0.68 W/m^{2}K)	
Tank inner diameter (m)	0.54
Heater element size/s (kW)	3.6
Thermostat dead band (K)	8

Note: the tank heat loss is calculated at each node and time step.

Simulation *A* is the baseline that all subsequent simulations are compared to, and consists of a popular off peak storage electric water heater operating over the 2018 calendar year with a thermostat temperature of 60°C.

Demand response of the water heater was subject to the real time spot price which is reflective of the abundance of electricity on the grid. To determine if the current spot price is conducive to water heating, a price index was utilized that compared the current price to historical prices [18]. The real time price index was then set to a threshold which can either be static or dynamic. The static price index in Simulation B was set to 0.5 which indicated a spot price of ½ the historical average. If the price index was ≤ 0.5 then the water heater would consume energy until the thermostat set point is reached. Additional controls were included to ensure minimum thermal supply (emergency heating) and Legionella sanitation was maintained.

Further demand response controls were included in simulations C & D whereby the price index threshold was dynamic (see Fig. 2). In this case the water heater state of charge (SOC) was used to dynamically adjust the price index response threshold. Simulation C utilised a linear price index threshold whereas Simulation D used a 4th order polynominal price index threshold.

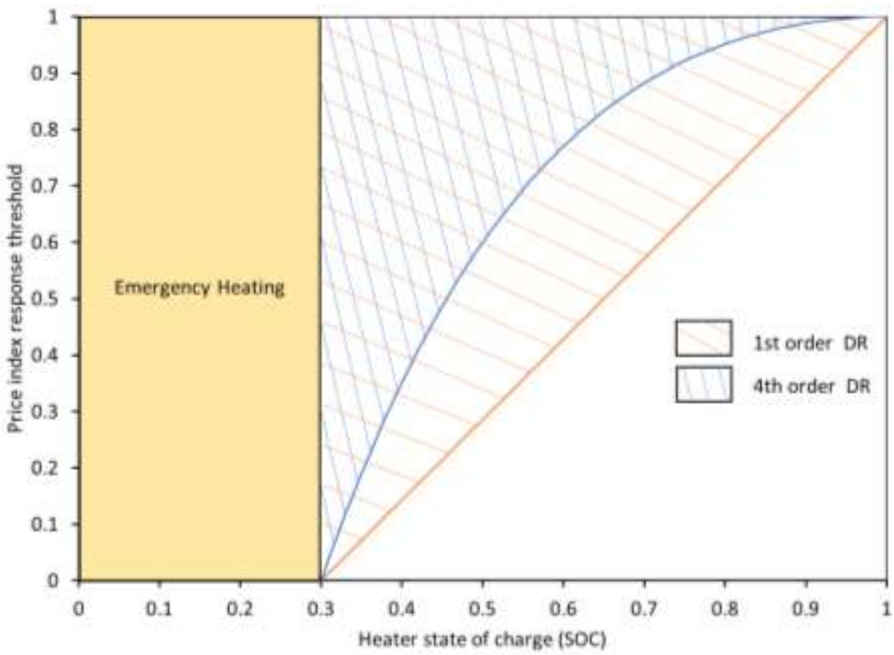

Fig. 2 Dynamic price index response threshold (demand response can operate in hatched area) as a function of heater state of charge.

The frequency reserves that could be obtained through demand response of water heaters was quantified in simulations B to D by assessing the energy consumption at any point in time and then assigning the corresponding raise or lower frequency reserve price. Frequency responses as directed by AEMO were simulated by either activating or ceasing water heater energy consumption.

Results and discussion

Annual energy consumptions and purchased energy costs are shown in Fig. 3 and Fig. 4 respecively.

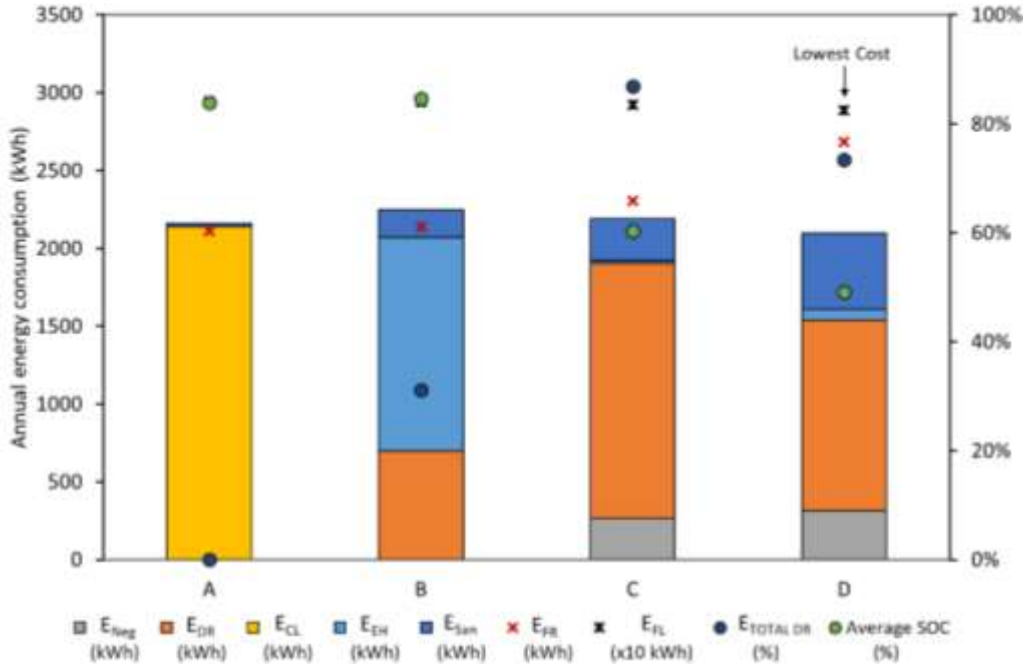

Fig. 3 Annual energy consumption of water heaters under various demand response algorithms.

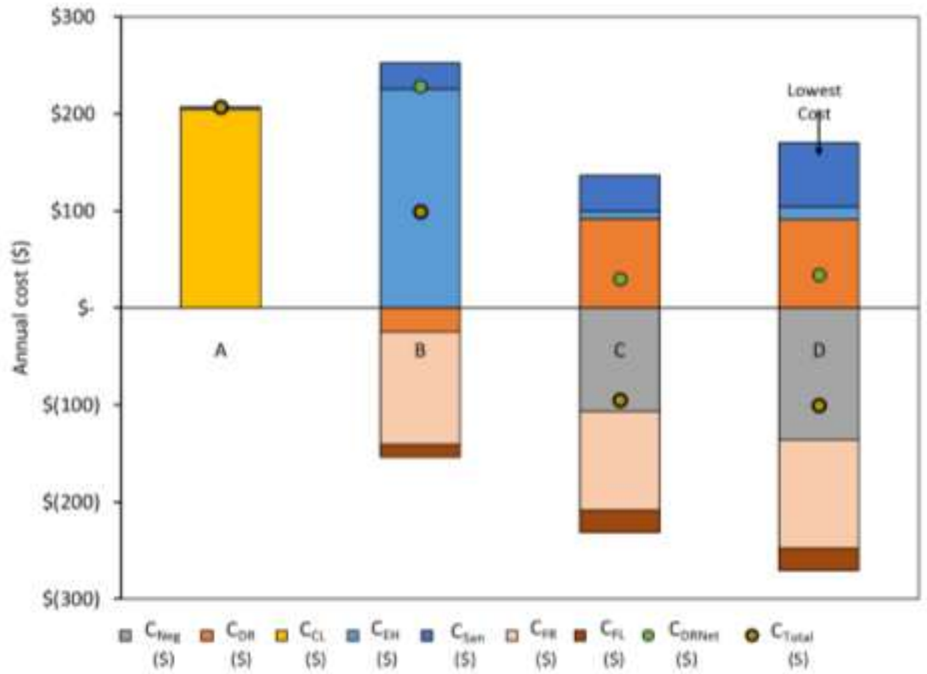

Fig. 4 Annual cost of purchased energy of water heaters under various demand response algorithms.

The benefit of heating in periods of negative spot price is obvious and coupled with the financial returns of FCAS reserves the purchased energy savings are substantial. Whilst the energy consumed by all simulations was similar, the cost of purchased energy significantly changed from $207 for the baseline case to -$101 for simulation D representing a 149% reduction in purchased costs (turning a wholesale energy expense into an income).

It needs to be noted here that the costs are calculated from the wholesale spot and frequency reserve prices. Historically the fluctuating wholesale prices have not been passed to retail customers where time of use tariffs are used. However, the emergence of new business models where the spot price is reflected more accurately in the retail price will encourage consumer engagement in demand response [19].

The impact of emergency heating at times of high energy costs as seen in Simulation B demonstrates that static price index thresholds are inferior to dynamic price index thresholds. Of interest is that there is minimal financial difference between the first and forth order dynamic price index controls as seen in Simulations C & D. In the short term, where the frequency of negative spot prices is predicted to increase [20], arguably the 4th order dynamic control in Simulation D would be preferable. However in the longer term, the expected decrease in the volatility of spot prices (due to increased grid scale energy storage and demand management) may result in the first order control in simulation C being preferable because of reduced need for sanitation heating, and higher demand response control.

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