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THE IMPACT OF ELECTRICAL LOAD SHIFTING STRATEGIES ON STORAGE CAPACITY AND SERVICE PROVISION OF DOMESTIC HOT WATER SYSTEMS IN RESIDENTIAL BUILDINGS

D. Marini[1], R.A Buswell[1], C.J Hopfe[1]
[1]Building Energy Research Group, Loughborough University, UK

ABSTRACT

Domestic hot water can accounts for up to 25% of the total domestic energy consumption in the UK and is demand driven. In the UK there has been a trend to replace traditional tank systems with instantaneous supply of hot water through gas fired combination boilers, leaving the space occupied by the tank to be repurposed by the household. This space is likely to become more critical as the need for storage increases in order to participate in peak load shifting when space-heating and hot water is supplied by electricity rather than gas. The size of tank and hence the delivery of water at an appropriate temperature delivered when demand dictate is likely to become a point of tension in future systems. This paper introduces a notion of hot water 'service' that can be evaluated and used to compare the performance of different systems, along side more traditional metrics such as cost, power and tank size. The analysis compares several load shifting strategies through a TRNSYS model driven by high resolution hot water data (1sec) measured in a UK home. It is demonstrated that optimal tank size and the service the system can provide are very sensitive to the load shifting strategy applied.

INTRODUCTION

Domestic hot water tanks store thermal heat and can be utilised for balancing supply-demand mismatch in thermal systems. The objective is to charge the domestic hot water tank when the fuel price is the low, and make the heat available at peak times when the fuel is at its highest price and hence water heaters have been widely controlled through the direct load control method over the last few decades (Dolan et al., 1996; Nehrir et al., 1999; Elgazzar et al., 2009; Sepulveda et al., 2010). To be successful with peak load shifting, a suitable tank size needs to be chosen whilst considering energy consumption and an acceptable hot water supply temperature to service the hygiene activities of the users.

According to (Atikol, 2013), if demand side management programs are carefully designed, it would be possible to set the timers to operate the electric water heaters for once or twice a day to meet the daily demand of the household. Simulation by (Lacroix, 1999) identified the benefit of using large capacity tanks equipped with vertical heating element and a time clock for controlling bacterial contamination and managing loads. Phase change materials incorporated into domestic hot water systems have a significant effect on load shifting purpose, according to (Najafian et al., 2015). Based on modelling results (Oliveira et al., 2016) showed that the economical benefits of energy storage can be large for the consumer, and they increase with the increase of the storage capacity reducing the power consumption during peak hours. Field testing work has been carried out using time of use-tariffs and pseudo cost functions to optimize the domestic hot water heater costs and efficiency operation, (Kepplinger et al., 2016).

An analysis of price-based control systems in conjunction with energy storage (incorporating phase change materials) was carried out to test space heating for an experimental hut by (Barzin et al., 2015). The authors found that cost savings could achieve up to 63% depending on the electricity price. Direct control method of residential heaters was analysed by (Ericson, 2009) and found that power consumption can be reduced during disconnection period, however an increase of consumption was estimated due to the payback effect when heaters are reconnected. The authors suggested cycling control events to control new peak loads. It has been estimated that for a domestic hot water system with a storage tank of 120 litre (insulated with 17mm of polystyrene), and a pipe network (un-insulated) with average length of seven metres, the heat loss accounts about 23% (storage tank) and 8% (distribution pipe) of the total energy consumption, (Marini et al., 2015). According to (Armstrong et al., 2014), de-stratifying a storage tank to sterilise bacteria led to 19% reduction in effective hot water storage, meanwhile increasing the storage tank to compensate this loss would lead to about 11% increase in energy consumption. Authors suggest that policymakers and engineers should carefully consider system monitoring and design in order to prevent unsanitary hot water while ensuring economic operation.

Most of studies are focused mainly on different control methods to enhance load shifting implementing price signals or to explore the effect of water mass flow rate on tank thermal behaviour. Despite this, there is not a clear understanding how tank size, load shifting methods and system control can be integrated together as an integrated solution to improve system performance and optimize operation costs while satisfying users hot water needs. This paper explores this gap based on model simulation driven by real draw-off hot water profiles from a domestic dwelling. The authors identify how tank size and load shifting method effect the delivery temperature, system power consumption, heat loss and operation cost of a domestic electric water heater system.

METHODOLOGY

In this study, TRNSYS software (version 17) has been used to model a domestic electric hot water system with five storage tank capacities and four load shifting methods. The model implements four load shifting strategies for each tank size. The water draw-off profile in the model is based on real demand flow rates that have been measured at secondly timestep for a real dwelling, (Buswell et al., 2013). The dwelling considered in this case study is occupied by two adults (full time working 9 am -5 pm) and two children ages 11 and 14 (school schedules). The electric water heater storage tank unit provides hot water for users need and deliver hot water to following appliances: two showers, three taps, one kitchen sink and one bath tube. The system does not provide hot water for dishwasher and washing machine. The cold water temperature from mains has been measured as well so a measured value has been used in the simulation model. The Matlab software was used to analyse the output simulated results such as hot water services temperature, energy consumption/loss and operation costs.

Model Description

Design Input Parameters

The domestic hot water model is equipped with a stratified tank unit, two immersion heaters (energy resources), two temperature thermostats which control temperature oscillations for respective heaters and pipe line which send hot water to draw-off points. Table 1 shows the input parameters that have been considered to model tank unit and have been defined considering common practice design values for domestic hot water systems. The tank capacity ranges from 100 to 500 litre in increments of 100(l). The height of tank range from 0.9(m) for tank 100(l) up to 1.7(m) for tank 500(l) with an increment of 0.2(m) for each increase of tank volume with 100(l). For the purpose of load shifting, the tank (copper material) was considered to be well insulated with 40(mm)polyurethane foam. The heat loss coefficient for the considered insulation was estimated to be 0.77(W/m^{2}K). The storage tank has two immersion electric heaters with capacities that range from 2(kW) up to 4(kW) for each element. It is considered that immersion heaters capacities increase by 0.5(kW) (each of them) when the storage tank capacity increases by 100(l). The lower element is considered to be located close to the bottom of the tank while the upper element is considered to be located about 2/3 of the tank height. For example, for tank capacity 100(l) and with a height 0.9(m) the lower element is located at height of 0.15m while the upper element at height 0.7(m). Temperature control thermostats are considered to be located about 0.05(m) above the heater elements to control the temperature oscillation in the tank unit. The pipe length is considered seven meter long (copper material, diameter 19(mm) and un-insulated) as an average length of the network. The ambient temperature is considered 20℃ for both tank and pipe.

System Operation and Control

Figure 1 shows the domestic water heater system as modelled with TRNSYS software. The thermal tank is modelled using TESS Library provided from TRNSYS package. It contains few storage tank models, however a study carried out by (Allard et al., 2011) suggests that Type534 tank model was the most accurate and has been used here.

The tank is a one-dimensional stratified model and has been divided into 25 constant volumes with 25 nodes (i.e the height of the tank is divided into 25 equal segments). The tank has only one inlet and one outlet port. At the beginning of the simulation, the model read the hot water demand profile (Type9a) and cold water temperature profile (Type9a-2). After the model reads the water mass flow it assume that the outlet flow rate at top of tank (outlet node) is equal to the inlet flow rate (outlet flow rate = inlet flow rate) at the bottom of tank (inlet node). The model calculates heat transfer through conduction and water temperature (nodal stratified levels) from one layer to another layer while the water flows from the bottom to the top of the tank (TRNSYS manual provide a full description).

The immersion heaters (Type1226-Elec-1 and Type1226-Elec-2) are heater elements that use electric power (converted into thermal energy) to heat up the volume of the water in the storage tank. The immersion heaters are located inside the storage tank unit at a specified high level (as specified in Table 1). The thermostats (aquastats) controller components (Type1052 and Type1052-2) control the water temperature of the storage tank (at specified node/high where they are located) and output ON/OFF control function (binary signal 1/0) signals. The water temperature setpoints are set at 55℃ and 50℃ for upper and lower thermostat respectively, while the dead band temperature difference (hysteresis control) is set at 2℃ for both thermostat controllers. The setpoint is assumed to be centred on the thermostat temperature dead bands, for example for the case of upper thermostat, the control signal is ON when temperature is less than setpoint - dead band/2 (54℃) and OFF when the setpoint is greater than setpoint + dead band/2 (56 ℃). Similarly for the lower thermostat, ON when temperature get lower than 49℃ and OFF when temperature is greater than 51℃. The component (Type-14h) employs a time dependent forcing function which has a behaviour characterized by a repeated pattern. In our case, this component create an ON/OFF

Table 1: Design input parameters for simulated tank units.

Design Parameter	Unit	Range Value	Increment Value*
Tank capacity	l	100 - 500	100
Tank height	m	0.9 - 1.7	0.2
Tank insulation thickness	mm	40	0
Tank heat loss coefficient	W/m^2 K	0.77	0
Number of heater elements	qty	2	0
Upper heater capacity	W	2000 - 4000	500
Lower heater capacity	W	2000 - 4000	500
Height of lower heater	m	0.15 - 0.35	0.05
Height of upper heater	m	0.7 - 1.12	0.1
Height of lower thermostat	m	0.2 - 0.4	0.05
Height of upper thermostat	m	0.75 - 1.17	0.05
Temperature setpoint for lower thermostat	℃	50	0
Temperature setpoint for upper thermostat	℃	55	0
Upper thermostat temperature dead band	℃	2	0
Lower thermostat temperature dead band	℃	2	0

* *The increment values refers the increment of input parameters as increasing them by one step*

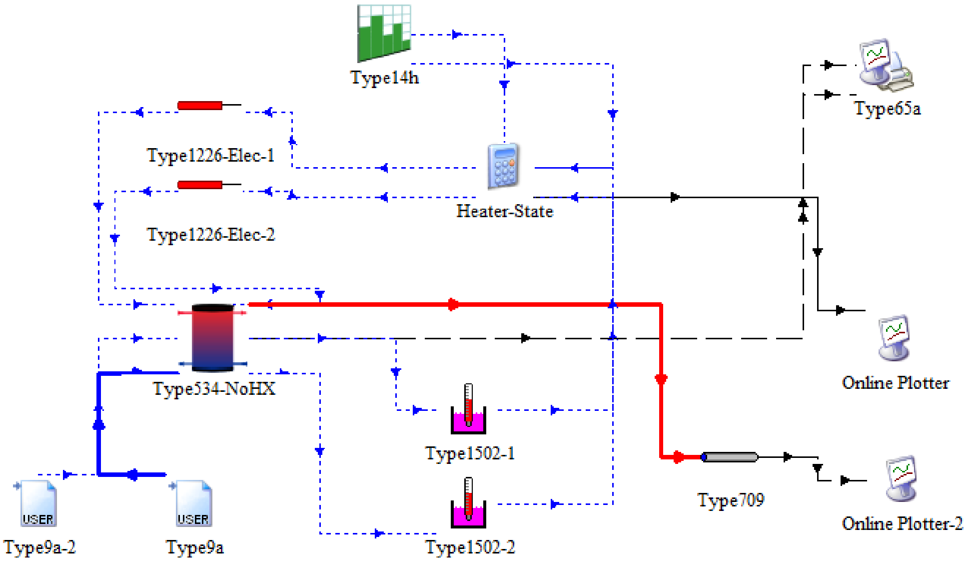

Figure 1: Modelled DHW system with TRNSYS.

signal (binary signal 1/0) for each hour of the day in order to model the load shifting profiles as defined in Table 2. The ”Heater State” receives binary signals (0/1) from Type-14 and (Type1052 and Type1052-2) components and uses two equations that produce two output signals for each of the power heater elements. The first equation multiplies the output signal from the upper thermostat (Type1052-1 with signal from (Type14h) to produce an ON/OFF signal for the upper heater element (Type1226-Elec-1), whilst the second equation multiplies the output signal from lower thermostat (Type1052-2) with the output signal from (Type14h) to produce an ON/OFF (1/0) binary signal for lower heater element (Type1226-Elec-2). Each of the heater elements will be able to switch ON only when the respective output binary signal from “Heater State” component is (1) and switched OFF when output binary signal from “Heater State” is (0). The component (Type 709) presents the hot water pipe line (red line) that deliver hot water from tank outlet to the point of use and it is the only component that extracts heat from the tank (no space heating modelled). The online plotters display variables while the simulation progress, meanwhile plotter (Type65a) record and stored selected variables in a separated output file.

Load Shifting Strategies

Due to high power peak demand in morning and evening hours, power supplier companies in the UK, offer to supply power at lower price rates at certain time periods (see section operation cost estimation) with the aim to shift high network power peak demands at OFF peak periods. Although the time of the designated hours can vary slightly from supplier to supplier and in different regions, the load shifting strategies are very similar. Table 2, shows load shifting methods and time periods when the heater elements are supposed to

Table 2: Load shifting methods and time periods for heater elements operation.

Load Shifting Method	Time period	Heaters Operation
No Load Shifting	00:00 - 24:00	ON
Peak Load Shifting	00:00 - 16:00	ON
	16:00 - 20:00	OFF
	20:00 - 24:00	ON
Economy10	23:00 - 06:00	ON
	06:00 - 12:00	OFF
	12:00 - 15:00	ON
	15:00 - 23:00	OFF
Economy7	23:00 - 06:00	ON
	06:00 - 23:00	OFF

switch ON/OFF in order to shift power demand. There are four load shifting methods identified:

- *No Load Shifting* - heater elements can operate continuously when there is a need for heat over the 24 hr period (business as usual).
- *Peak Load Shifting* - heater elements are forced to switch OFF (despite that there is need for heat) during evening peak hours demand (16:00-20:00) and allowed to switch ON for the rest of the hours.
- *Economy10* - heater elements are allowed to switch ON only seven hours during the night period (23:00-06:00) and only three hours during the day time period (12:00-15:00) and forced to switch OFF for the rest of the hours.
- *Economy7* - heater elements are allowed to switch ON only seven hours during night period (23:00-06:00) and forced to switch OFF for the rest hours.

There could be a “freedom” to define time periods for *Economy10* and *Economy7* when heater elements are able to operate (i.e. commence and finish one hour earlier or later), however the presented time periods in Table 2 are mostly suggested and applied as these are the hours when the power demand loads are at a lower level.

RESULTS

Hot water service, power and heat loss estimation

Heat loss from tank, or periods of multiple but very short draw-offs can cause the temperature of water in the tank to drop just below the cut-in temperature (i.e 54°C for upper element). Consequently, the heater elements may operate for only few seconds, rather than periods of greater than 1 minute in order to reach the cut-off 56°C setpoint and hence a simulation in minutely time-steps may overestimate the power consumption. To avoid this, simulations are carried out at secondly time-step here. As a consequence, computation time was long, so the simulations were run over just one month time period.

Figure 2 (top) shows the oscillation of the tank temperature and power consumption for tank capacity of 100(l) and *No Load Shifting* method during a one day period. Three temperature oscillations are shown: the tank outlet (red), tank average (black) and the tank bottom (blue). Similarly, the middle plot shows the temperature osculations and power consumption for the tank of 300(l) and the *Economy7* load shifting method. The bottom plot shows the water flow rate. In the evening (around 7:30pm) when there is a high water flow rate and long draw-off duration, it can be noted that the outlet temperature on the top plot drops at about 39°C whilst in middle plot for the same time period the temperature drops about 45°C. During that time period, about 60(l) of water is used shower or bath use), so a tank with capacity of 300(l) and *Economy7* can provide a higher temperature outlet as compared to the tank of 100(l) and *No Load Shifting* for the designed heater elements capacities.

Although the same flow rate, the water temperature drop in the tanks will be different. The larger the storage tank the lower the temperature drop as more energy has been stored whilst the opposite happen for small tank. For long draw-offs and high flow rates, the temperature of the water in the tank drop quiet lower and it will take more time for heater elements to recover and heat-up the water temperature in tank. The only way to provide a higher temperature for 100(l) tank could be to increase the capacity of the heater elements. The plots present results for the first simulation day. In order to heat up the water storage from 20°C to 55°C for the 100(l) tank, it takes about one hour, whilst for the 300(l) tank it takes about one and half hour (for considered heater capacities presented in Table1).

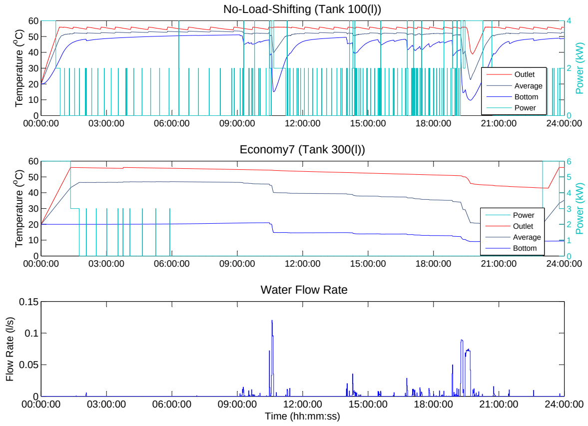

Figure 2: Tank temperature oscillations and power consumption for two cases: tank 100(l) and No Load Shifting (top plot); tank 300(l) and Economy7 (middle plot) as considering the hot water usage profile (bottom plot).

In order to estimate the level of *‘service’* that the hot water system provides, a measurable metric is applied, ϕ, given as,

$$\phi = \frac{d^{\theta}}{d^{total}},$$

where d^{θ} is the total volume of hot water drawn where

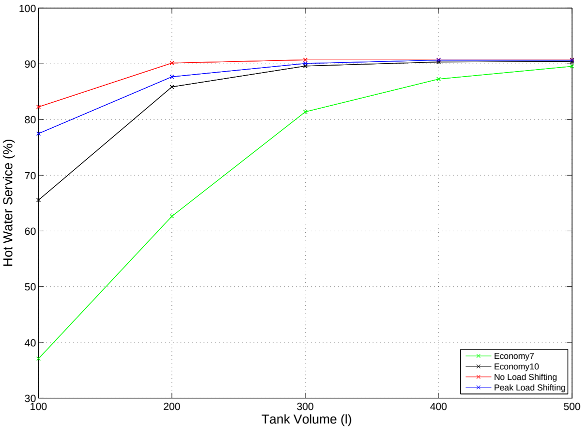

Figure 3: Comparison of hot water services considering a minimum supply temperature ($T > 45$°C).

the temperature at the outlet is at or above the temperature threshold θ and d^{total} is the total volume draw of water. The useful temperature might depend on activity or task (dishwashing/showering, etc.). The threshold temperature θ is taken to be 45°C for this study. Figure 3 compares the variation of hot water services for different load shifting and tank sizes, considering a minimum supply temperature of 45°C . It can be noted that for the considered storage 300(l) tank or larger, and the (*Economy7*) method, the hot water service supplied over considered temperature is over 80% whilst for the other load shifting methods is about 90%. The considered temperature is an averaged value as it depends on the mixed water mass flow rates (tank outlet and mains) and on the water mains temperature in order to provide a supply temperature at a draw-off point around 37°C comfortable for human skin.

Figure 4 shows how the hot water supply temperature (estimated at the pipe outlet) is influenced by the tank size and load shifting method. The hot water service estimated with above formula (in percentage) at the ordinate axes represents the percentage of the hot water volume that has been supplied over a certain temperature. For example, in the case of *Economy7* for a tank size of 100(l), only about 45% of the total hot water use have been supplied at a temperature greater than 37°C while only about 21% is supplied over 51°C . Increasing the size of the tank the percentage of hot water supplied over a certain temperature increases, but for *Economy7* the tank size should be at least over 300(l) in order to have some acceptable limits to deliver hot water over a certain temperature. For other load shifting methods, the trends of hot water services are similar in progressive (higher percentage) order as compared with *Economy7*. As can be noted from all plots, none of the load shifting methods and tank sizes has a percentage of hot water service over 95%. This is because for short draw-offs, the hot water supplied from tank has not been able to reach the pipe outlet and is cooled down in the pipe. A part of the tank size and load shifting method, another parameter that can influence the hot water service are the considered design heating temperature setpoints. Higher threshold temperatures will provide a higher percentage of hot water service, however this will be associated with higher heat loss and power consumption. Parameters such as tank size, water flow rate and dead band thermostat control temperature can influence the frequency and duration of the heaters operation. Figure 5 shows power consumption rate and tank outlet temperature for a 200(l) storage capacity with four load shifting methods during one day period. For this tank size, the heater elements are considered to have a capacity of 2.5(kW) each, so the maximum power load is 5(kW) when both heaters operate simultaneously. For *No Load Shifting* and *Peak Load Shifting* methods as can be seen from the two bottom plots, the frequency (when operating only one heater element) dominates the frequency when both element operate simultaneously. For *Economy7* and *Economy10* as shown in the two top plots, the frequency when both heaters operate simultaneously is higher, however the power demand is shifted at off peak hours when the power demand in the grid is at a lower level (i.e night or early afternoon hours). The outlet temperature for *Economy7* drop to about 35°C , so if a household use about 140 l/day (as that specific day) considering the tank capacity 200(l) and *Economy7* the user might not get the adequate hot water service. For other load shifting methods the outlet temperature do not drop below 50°C .

Figure 6 shows how the tank size and load shifting impacts the energy consumption and the heat loss. The power consumption factor (left plot) shows how the power consumption increases by increasing the tank size for each load shifting method. For comparison purposes, the 100(l) tank and the *No Load Shifting* method are taken as reference point where the power consumption and the heat loss factors are considered equal to 1. Increasing the tank size to 200(l) and *No Load Shifting*, the power factor increases to 1.1 meaning 10% higher power consumption. For other load shifting methods, for example considering (*Economy7*) and a tank volume of 100(l) the power consumption factor of about 0.55 means that the power consumption accounts for around 55% of the total power consumption as compared to the *No Load Shifting* method. Meanwhile increasing the tank volume from 100(l) to 200(l) for (*Economy7*) the power factor increases from 0.55 to about 0.85, e.g. the consumption increases by around 30%. In a similar way the heat loss factor can be interpreted (right plot). For example, increasing the tank volume from 100(l) to 500(l) and considering the (*No Load Shifting*) method, the heat loss factor increases from 1 to about 3 meaning that the heat loss increases by around 300%. For (*Economy10 and Economy7*) load shifting methods the heat losses are lower however when increasing the tank volume the trend of the heat loss factors is very similar for all load shifting methods. Figure 7 shows the total energy

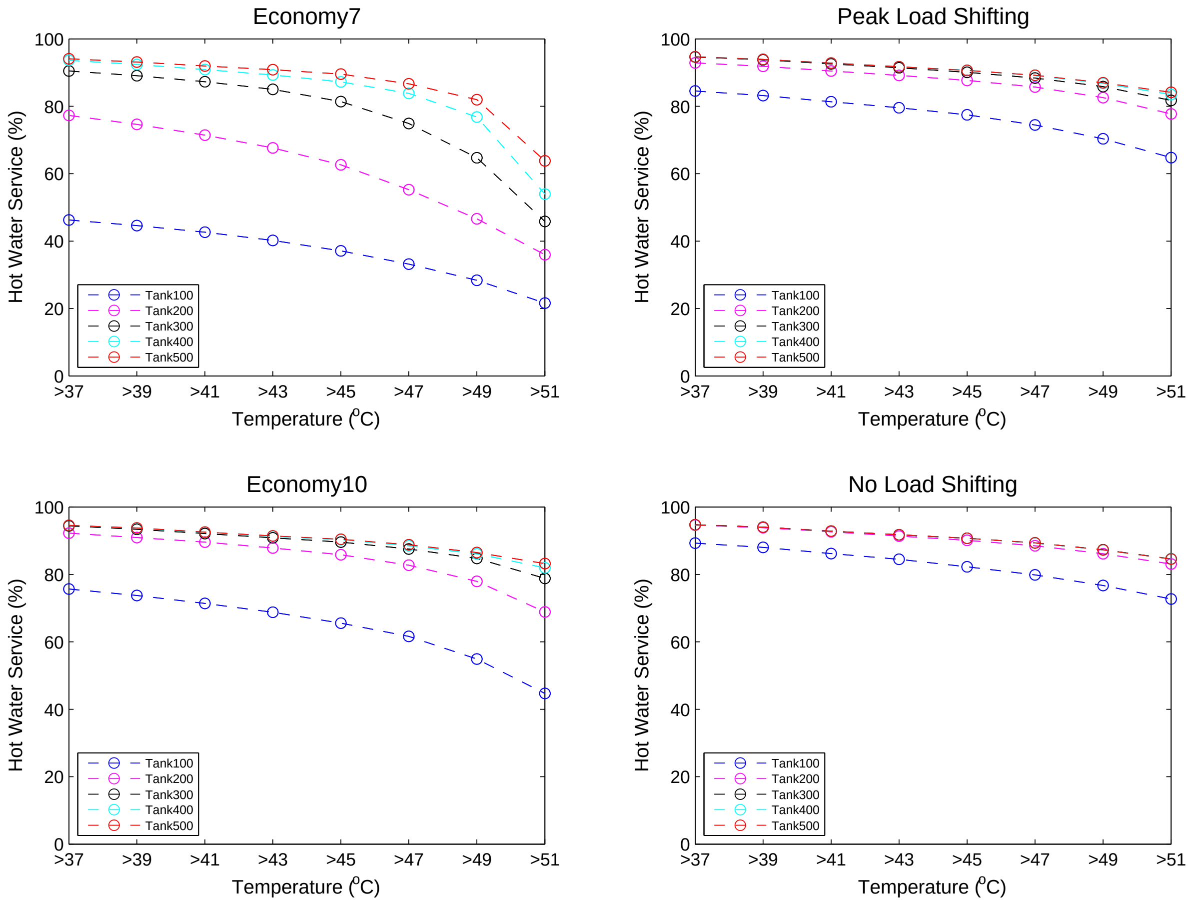

Figure 4: Hot water supply temperature (pipe outlet) as depended on the tank size and load shifting methods.

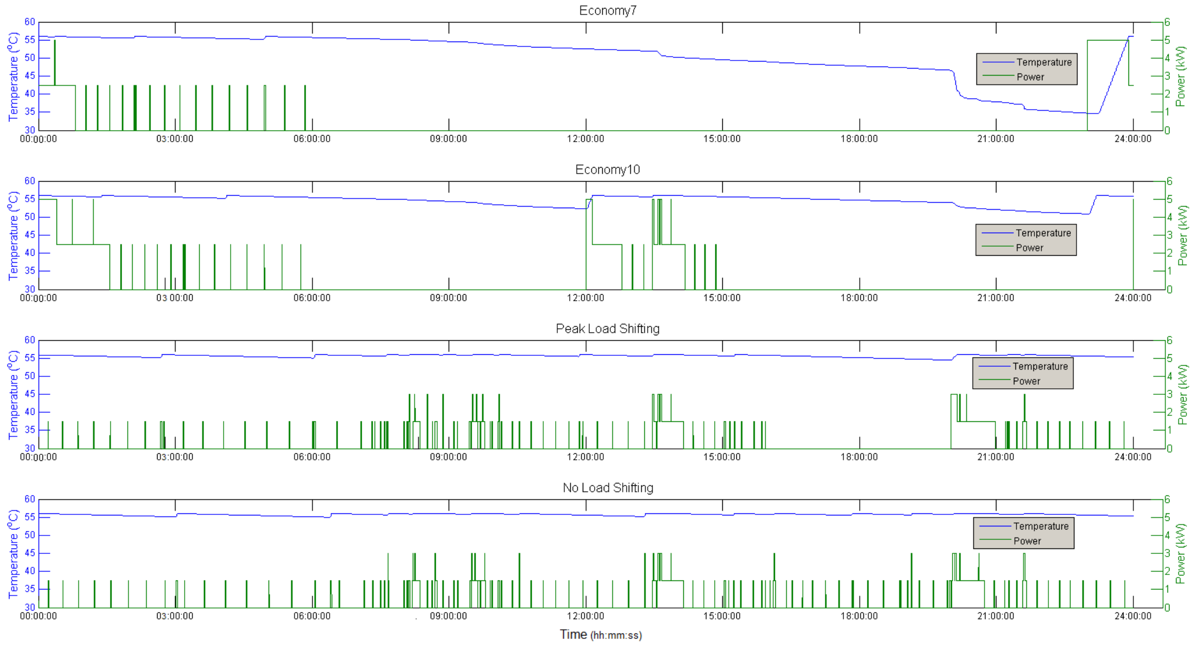

Figure 5: Power loads and temperature oscillations for tank storage 200(l) and four load shifting methods.

consumption and energy loss during a one month period for each considered load shifting method and storage tank capacity. The energy consumption (top plot) ranges from about 130 kWh for tank 100(l) and *Economy7*) up to about 300 kWh for tank 500(l) and *No Load Shifting*). The energy loss (bottom plot) ranges from about 6 kWh to 50 kWh accounting for 5% to 17% of the total energy consumption. A small tank size for example 100(l) has a lower consumption and heat loss but also provided a lower hot water service

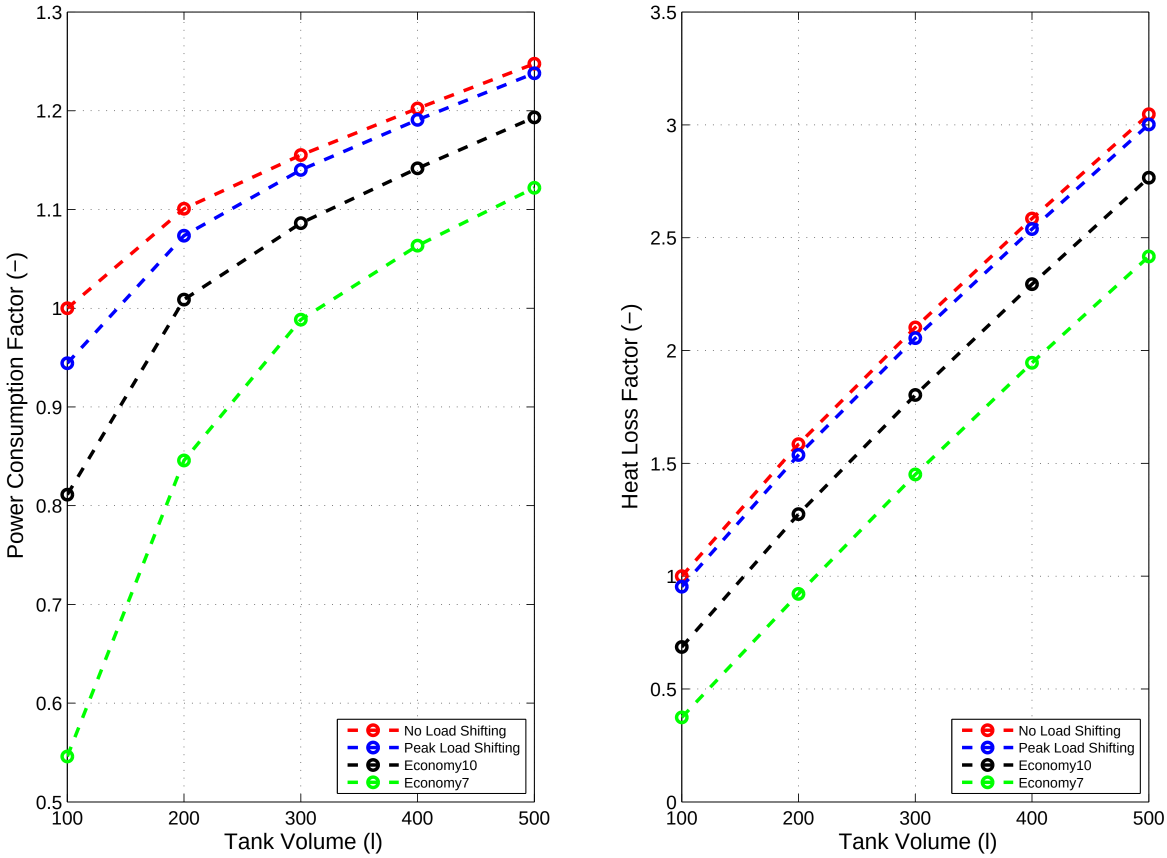

Figure 6: Impact of tank size and load shifting on power consumption and heat loss.

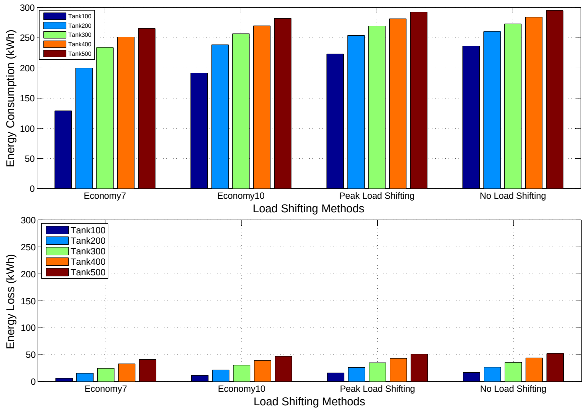

Figure 7: Energy consumption and loss for one month period.

(see Figure 4) as compared with other tank sizes.

Costs Estimation

The supplier companies in the UK offer power at different price rates which also can vary from region to region. Despite this, the differences are very small and have no significant impact on the overall estimated costs. Table 3 presents standard power rates applied from British Gas (British Gas supplier - power price rates., 2016) for the domestic sector. The supplier offers three tariffs method: single rate (the same price over a 24 hours period); two rates (night/day)tariff where for night hours (22:00-08:00) the rates are almost 70% lower compared to the day tariff; and OFF peak tariffs where the price during the peak hours period (16:00-20:00) is about 40% higher as compared with the price of the remaining hours. The operation costs and potential reductions estimated in Table 4 are calculated based on estimated power consumption and power tariffs presented in Table 3. Although the system is controlled to operate according to load shifting time periods defined in Table 2, the power consumption has been aggregated based on the time periods defined in Table 3. The aggregated values for these time periods were multiplied with the respective power rates (see Table 3) to estimate operation costs. For example, for *No Load Shifting* method, the power consumption estimated during all day (24 hr period) is multiplied with respective price (single rate tariff) to estimate the operation cost (all power consumption is multiplied with single tariff). For *Peak Load Shifting* method, the aggregated power consumption for the two operation periods it is multiplied with respective price (OFF peak tariff). For *Economy7 and Economy10* load shifting methods the power consumption aggregated for respective operation time periods are multiplied with respective power prices (Two rates tariffs) to estimate operation costs. Figure 8 shows the estimated costs for each load shifting and tank size calculated based on defined price rates. It can be seen that (*Economy7*) has the lowest operational cost and this is because all power consumed from this load shifting method falls into the cheapest price rate. The highest operational

Table 3: Standard domestic power rate electricity charges.*

Tariff Method	Time period	Price (£/kWh)
Single rate	00:00 - 24:00	0.122
Two rates tariffs	08:00 - 22:00	0.174
	22:00 - 08:00	0.06
Off peak tariffs	16:00 - 20:00	0.172
	20:00 - 16:00	0.106

* *British Gas supplier with effect from March, 2016*

Table 4: Potential cost reduction (%) when implementing: Peak Load Shifting; Economy10 and Economy7 vs. No Load Shifting method.

Tank Size (l)	Load Shifting Method		
	Peak LSh*	Economy10	Economy7
100	-18.9	-19.2	-73.2
200	-15.7	-13.0	-62.3
300	-14.0	-12.3	-58.0
400	-14.4	-12.5	-56.6
500	-14.2	-12.7	-55.9

* *Peak Load Shifting*

cost results from (*No Load Shifting*) for which the single rate price tariff was considered. Table 4 shows potential cost reductions that can be achieved when the user (e.g. the householder) chooses to apply any of the load shifting methods versus *No Load Shifting*. Considering different tank volumes, the potential savings for (*Peak Load Shifting*) and (*Economy10*) ranges from 13% to 19% whilst for (*Economy7*) reductions range from 56% to 73%.

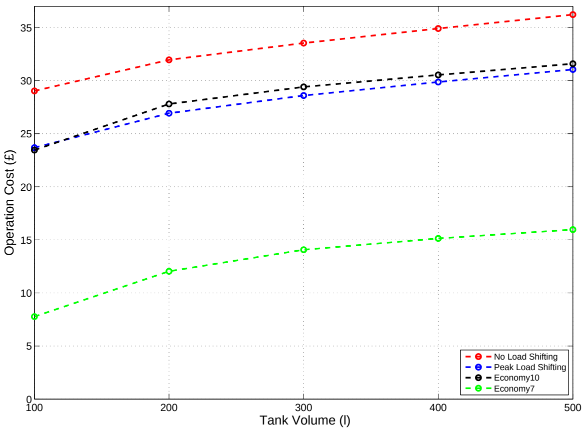

Figure 8: Estimated costs for each load shifting and tank volume.

The price of storage tanks varies between manufactures and type of cylinders. However, based on the RM manufacturer (RM Cylinder Manufacturer. Cylinders price rates, 2017), the price of a direct copper cylinders range from £150 for 120(l) up to £660 for 450(l) storage capacity. The same manufacturer provides cylinders that suit for (*Economy7*) purpose with two immersion heaters, capacity 210(l) costing about £309. Replacing a normal cylinder 120(l) with one of 210(l) designed for load shifting it can cost about £120 more, however considering the potential reduction of operation cost the payback period is approximately after six month time for (*Economy7*) and about two years for (*Economy10*) or (*Peak Load shifting*) methods.

At first, the (*Economy7*) seems the most convenient method to reduce the operational costs considerably (even for a large tank volume). However caution needs to be paid because the hot water production is not the only thing that consumes power in the home. Other equipment consumes power during daytime periods when the power price is high and that might change the overall potential cost reduction feasibilities.

CONCLUSIONS

A domestic hot water system has been modelled in TRNSYS using measured water demand profiles. The impact of four load shifting strategies on the system performance and cost was evaluated using a new measure of 'service' defined by using the outlet supply temperature to delineate between water supplied at a useful temperature and water below this. The key findings are:

- **Hot Water Service**[1]**:** For a storage tank of 100(l), the hot water service provided over 45°C varies from 38% (*Economy7*) up to 83% (*No Load Shifting*) when considering different load shifting methods. Increasing the tank size from 200(l) to 300(l) the hot water service increases and ranges between 63%-90% and 82%-91%, respectively. For a 500(l) tank the range is less than 2% difference (90%-92%) for all considered load shifting methods. It was estimated that about 5%-6% (assuming a minimum pipe outlet temperature of 37°C) of hot water service is lost in the pipe network (heat loss distribution) as short draw-offs can not reach the pipe outlet and the water is cooled down inside the pipe.
- **Power Consumption:** The power consumption for a 100(l) tank size and the *Economy7* load shifting method decreases by about 45% (*5% Peak Load Shifting* and *18% Economy10*) when compared with *No Load Shifting*. This is however associated with providing a lower hot water service as shown above. Increasing the tank size from 100(l) to 500(l), the power consumption increases by about 25% for *No Load shifting* and up to 60% for *Economy7*. This is however associated with increasing (different proportions) of the provided hot water service.
- **Heat Loss:** Increasing the tank size from 100(l) to 500(l) the relative increase of heat loss accounts for about up to 30% for all load shifting methods. The heat loss is an important factor which influences the power consumption. However, for a well insulated tank with 40mm polyurethane

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[1] hot water service - refer the ratio of hot water volume supplied over certain temperature divided by the total volume of hot water use

foam, a U-value of 0.77 W/m^{2}K has been estimated and the heat loss ranges from 5% to 17% (depending on the tank size and the load shifting) of the total amount of heat supplied into the tank.

- **Costs:** Potential reductions of operation cost can be achieved for each load shifting method. For example with *Peak Load Shifting* and *Economy10* depending on the tank size the cost reduction ranges from 13% to 19% as compared with *No Load Shifting*. Meanwhile for *Economy7* where heater elements are allowed to operate only during night hours (low price tariffs) the costs saving ranges from 55% to 73%. Installing a larger storage tank capacity example 200(l) which is designed for load shifting purpose might cost double of the price as compared to 100(l) normal tank, however the payback period range from six month to two years due to lower operation costs depending on the load shifting method implemented.

If a householder use about 140 l/day of hot water, has installed a storage tank of 300(l) and implement *Economy7* load shifting method, the provided hot water service ($T > 45℃$) can be over 80% whilst the operational cost reduces to about 58% compared with *No Load Shifting* method. In summary, the tank size and the load shifting methods have a significant impact on the hot water service, power consumption, heat loss and operational costs. A good hot water service can be provided whilst reducing the operational costs in the same time by considering load shifting methods and different tank sizes. Future work will investigate further how different hot water demand profiles from other dwellings (including washing machines/dishwasher) might influence the above findings. It will also be interesting to consider as well the energy demand for space heating (i.e provided by a heat pump system) and investigate how the system can satisfy the energy demand while reducing operation cost through optimal sizing/control and considering load shifting strategies.

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