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Benchmarking energy consumption and CO_2 emissions from rainwater-harvesting systems: an improved method by proxy

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Keywords

carbon; cost; energy; method; proxy; rainwater harvesting.

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Abstract

Life cycle analyses (LCAs) show the main operational energy contribution for rainwater-harvesting (RWH) systems come from ultravioletUV disinfection and pumping rainwater from tank to building. Simple methods of estimating pump energy consumption do not differentiate between pump start-up and pump-operating energy or include pump efficiency parameters. This paper outlines an improved method incorporating these parameters that indirectly estimates pump energy consumption and carbon dioxide (CO_2) emissions using system performance data. The improved method is applied to data from an office-based RWH system. Comparison of the simple and improved methods identified the former underestimates pump energy consumption and carbon emissions by 60%. Results of the improved method corresponded well to directly measured energy consumption and energy consumption represented 0.07% of an office building's total energy consumption. Consequently, the overall energy consumption associated with RWH systems is a very minor fraction of total building energy consumption.

Background

Globally, rainwater-harvesting (RWH) technologies are being more readily adopted, as the desire for buildings to become more adaptable and resilient to climate change and population growth increases (White 2010). In the United Kingdom, this is recognised by a target of 80 L per capita consumption (potable) under level 5–6 of the Code for Sustainable Homes (DCLG 2006), which potentially requires the installation of RWH. However, it has been suggested that RWH can actually have a negative impact on the environment, with particular reference to energy consumption and (carbon dioxide) CO_2 emissions (Parkes *et al*. 2010). Operationally, this is because of the energy required for ultraviolet (UV) disinfection and pumping water from an underground storage tank into a building (Thornton 2008). The latter is of greater importance as currently, most systems require a pump, whereas UV is optional. However, there is limited research on the quantification of this operational energy consumption. This is mainly because of the majority of RWH systems on the market not directly measuring energy consumption (Ward 2010). Additionally, previous indirect calculation methods have not distinguished between the energy consumed during pump start-up and operating phases. Research suggests such variables are often not considered in life cycle analyses (LCAs), perpetuating the gap in analysis of system configurations (Way *et al*. 2010). The following improved method addresses this gap, makes the distinction between pumping phases and has been developed for RWH systems where no pump energy-monitoring equipment is in place. The improved method is subsequently applied to an office-based RWH system and the results are presented.

Method

Derivation of the improved method

The energy use (E) of a pump is defined as (Dixon 2000; Roebuck 2008)

$$E(\text{kWh}) = P_R \times O_D \qquad (1) \qquad \boxed{2}$$

where P_R = pump rating (kW) and O_D = operating duration (h) and O_D is

$$O_D = \frac{V}{P_c} \qquad (2)$$

where V is the volume of rainwater pumped, i.e. consumed (m^3) and P_C is the pump capacity (m^3/h)

(Roebuck 2008). P_R and P_C can be obtained from pump specification documents. V can be estimated by calculating a demand value or derived from empirical data, where monitoring equipment is in place.

Previous studies (Dixon 2000; Roebuck 2008) have utilised these equations (the 'simple method') to calculate RWH system pump energy consumption in order to calculate system operating costs. However, these studies did not quantify CO_2 emissions. Additionally, they did not consider the efficiency of the pump, or incorporate parameters to distinguish between pump start-up and pump-operating energy consumption. In calculating total energy consumption, the differential energy consumption of these phases needs to be considered, as around 60% more energy can be consumed on start-up (Yago 2008). For example, a pump may consume 0.020 kWh for the first 60 s of operation (and pump only a small amount of water) and then revert to 0.01 kWh for the rest of the operating duration.

As most RWH systems are not able to measure energy consumption directly, but often measure harvested rainwater consumed (by being metered), it was decided to develop a method to estimate energy consumption using rainwater consumption data as a proxy. Consequently, the following improved method was developed based on Eqs (1) and (2) incorporating parameters for pump efficiency and start-up/operating energy. Additionally, the improved method was extended to include the estimation of CO_2 emissions.

To accommodate the additions outlined previously, E becomes E_2 and the improved method is defined as

$$E_2 = E_{PST} + E_{POT} \tag{3}$$

where E_{PST} is the total energy consumed on pump start-up (kWh) and E_{POT} (kWh) is the total energy consumed during operation. Thus

$$E_{PST} = E_{PS} + (E_{PS} \cdot S_F) \tag{4}$$

where

$$E_{PS} = P_R \cdot O_{DS} \tag{5}$$

S_F is the start-up energy factor (% extra energy used on start-up) and O_{DS} is the start-up operating duration (h) and

$$E_{POT} = P_R \cdot O_{DO} \tag{6}$$

where O_{DO} is the operating duration:

$$O_{DO} = V_1 / P_C \tag{7}$$

where

$$V_1 = V \cdot O_V \tag{8}$$

V_1 is the volume of water pumped during operation (and subsequently, V_2 is the volume pumped during start-up). O_v is the percentage of water consumed that is pumped during operation (1-S_V), obtained from the pump manufacturer and

$$O_{DS} = V_2 / P_C \tag{9}$$

where

$$V_2 = V \cdot P_S \cdot S_V \tag{10}$$

S_V is the percentage of volume consumed pumped on start-up and

$$P_S = \frac{V}{((H_C \cdot H_2) - (H_C \cdot H_1))} \tag{11}$$

where P_S is the number of pump start-ups, H_C = header tank capacity (m^3), H_1 = float switch on level (%) and H_2 = float switch off level (%). The latter two parameters indicate changes in the volume of water in the header tank. H_1 and H_2 are illustrated in Fig. 1 and can be obtained from RWH system manuals or specifications.

A pump is never 100% efficient and therefore the pump efficiency (P_E) must be included to estimate total energy consumption (E_{TOT}). P_E is defined as

$$P_E = P_R / P_I \tag{12}$$

where P_I = pump input power (kW), which can also be obtained from pump specification documents.

Thus, the final equation for estimating RWH system pump total energy consumption (E_{TOT}) is

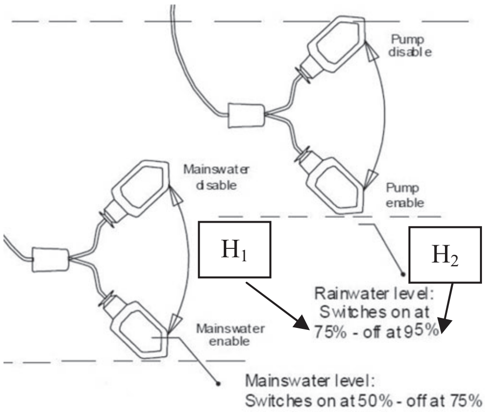


Fig. 1. Float switch levels in the rainwater-harvesting (RWH) system header tank (Ward 2010).

$$E_{TOT} = E_2 + (E_2 \cdot (1 - P_E)) \tag{13}$$

Consequently, the carbon dioxide emission (E_{CO2}) can be estimated from:

$$E_{CO_2} = E_{TOT} \cdot E_C \tag{14}$$

where E_C is the CO_2 emitted (in kg) from electricity derived from the combustion of coal, that being 1.04 kg/kWh (CDIAC 2010). Other CO_2 equivalent values for this factor could be used, depending on the electricity source or the unit of comparison.

Case study

In order to test the method, rainwater consumption data and RWH system parameters for the Innovation Centre on the University of Exeter's Streatham campus were utilised. The Innovation Centre is a new-build office building and a RWH system located within the building is used to flush toilets in order to reduce mains water consumption (Ward *et al.* 2010). The RWH system consists of catchment, conveyance, storage and redistribution sections. The catchment and conveyance section consists of a south-facing roof catchment (1500 m^2) that has both aluminium and Bitumastic-felt-membrane sections and powder-coated aluminium rainwater goods (guttering and downpipes). The storage and redistribution section consists of a glass-reinforced plastic (GRP) underground storage tank (25 m^3), a control system, two GRP header tanks (0.8 m^3 each) and associated medium-density-polyethylene (MDPE) and copper pipework. There is also a three-tiered filtration system, consisting of a 440-µm pre-tank coarse debris filter, a 180-µm in-tank floating suction filter and a 35-µm inline backwashing filter. The system has a stainless steel submersible 1.1 kW pump (P_C of 3.39 m^3/h). There is no UV disinfection fitted to the system, and therefore, the primary source of energy consumption is the pump unit within the underground storage tank.

System specification information required for parameterisation within the application of the improved method was gathered and is summarised in Table 1. P_C was derived using the pump rating (P_R) in conjunction with the data taken from Roebuck (2008). These values are summarised in Table 2. The other requirement of the improved method is the availability of information on the volume of rainwater pumped (i.e. supplied/consumed). Although this can be estimated, a more accurate energy/emission calculation is facilitated by utilising empirical data. Data on water supplied and consumed was collected from the Innovation Centre and used to estimate total pump energy consumption and carbon emissions.

Table 1 Parameters and their values used to estimate pump energy consumption

Parameter	Unit	Value
P_R (pump rating)[a]	kW	1.1
P_I (pump input power)[a]	kW	1.62
P_C (pump capacity)[b]	m^3/h	3.39
H_C (header capacity)[a]	m^3	0.8
H_1 (float switch on level)[a]	%	75 (0.75)
H_2 (float switch off level)[a]	%	95 (0.95)
S_F (start-up factor)[b]	%	0.6
S_V (start-up volume)[c]	m^3	0.001 (0.1% of 1 m^3)
O_V (operating volume)[c]	m^3	0.99 (1-S_V)
P_E[d]	%	68 (0.68)

[a] From system specification.
[b] From literature.
[c] Estimated.
[d] Calculated.

Table 2 Pump ratings and capacities (modified from Roebuck 2008)

Height of building (m)	10	20	30
Power rating (kW)		Capacity (m^3/h)	
0.8	3.60	3.00	1.80
1.0	3.78	3.30	2.70
1.1	3.84	3.39	2.91
1.2	3.90	3.48	3.12
1.4	4.02	3.60	3.30

Table 3 Rainwater volumes supplied by the Innovation Centre rainwater-harvesting (RWH) system

Month	Volume (m^3)
January	25.02
February	29.89
March	38.84
April	2.77
May	14.25
June	38.16
Total volume supplied	148.93 m^3

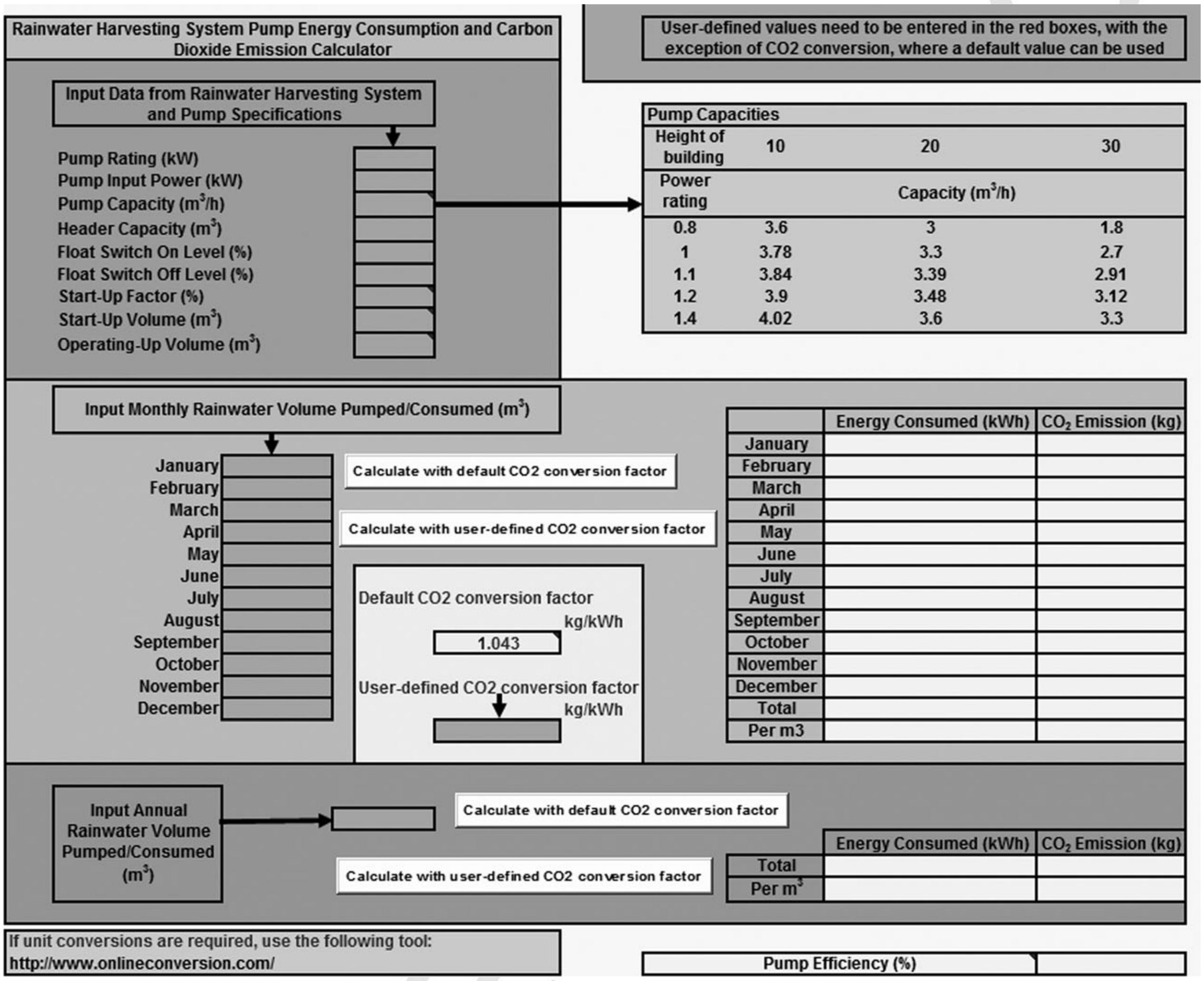
Results

Innovation centre data

The monthly rainwater volumes supplied by the Innovation Centre RWH system for a 6-month period are summarised in Table 3. These were used in the above mentioned equations to estimate energy consumption and associated carbon emissions. The results were expressed as energy required and carbon emissions per unit (m^3) of harvested rainwater pumped.

Simple and improved method comparison

A simple spreadsheet tool (Fig. 2) was developed using the improved method equations outlined above, in order



Pump Capacities

Height of building	10	20	30
Power rating	Capacity (m³/h)		
0.8	3.6	3	1.8
1	3.78	3.3	2.7
1.1	3.84	3.39	2.91
1.2	3.9	3.48	3.12
1.4	4.02	3.6	3.3

Default CO2 conversion factor kg/kWh: 1.043

	Energy Consumed (kWh)	CO_2 Emission (kg)
January		
February		
March		
April		
May		
June		
July		
August		
September		
October		
November		
December		
Total		
Per m3		

	Energy Consumed (kWh)	CO_2 Emission (kg)
Total		
Per m³		

If unit conversions are required, use the following tool:
http://www.onlineconversion.com/

Fig. 2. The RWH system pump energy and carbon tool interface (Ward 2010).

to estimate the energy consumption and operational CO_2 emissions associated with the rainwater used within the Innovation Centre building. The tool is divided into three sections: the first is for inputting pump parameter data and the following two sections allow monthly or annual rainwater consumed values to be entered. Within these sections, there is the option to use a default CO_2 emission conversion factor or to enter a user-defined factor. Additionally, values were estimated using the simple method (i.e. Eqs (1) and (2)) to allow a comparison. These results are summarised in Table 4. As can be seen, the improved method increases the estimated pump total energy consumption from 0.32 kWh/m^3 to 0.54 kWh/m^3 and CO_2 emissions from 0.34 kgCO_2e/m^3 to 0.56 kgCO_2e/m^3. This indicates that compared with the improved method, the simple method potentially underestimates total pump energy consumption and carbon emissions by 60%. This highlights the significance of the contribution of pump start-up energy consumption and pump efficiency and the importance of their inclusion in estimating pump total energy consumption and CO_2 emissions. The improved method therefore provides a new way of

Table 4 Results of the improved method compared with the simple method

Month	V (m^3)	E (kWh) ^{SM}	E_{CO2} (kg) ^{SM}	E_{TOT} (kWh) ^{IM}	E_{CO2} (kg) ^{IM}
January	25.02	8.12	8	13.40	13.97
February	29.89	9.70	10	16.00	16.69
March	38.84	12.60	13	20.80	21.69
April	2.77	0.90	1	1.48	1.55
May	14.25	4.62	5	7.63	7.96
June	38.16	12.38	13	20.43	21.31
Total	148.93	48.33	5	79.75	83.17
Per m^3	1	0.32	0.34	0.54	0.56

SM, simple method; IM, improved method; V, volume of rainwater pumped; E, energy use, E_{CO2}, carbon dioxide emission; E_{TOT}, total energy consumption.

Table 5 Energy cost associated with Innovation Centre RWH system pumping

Month	E_{TOT} (kWh)	Cost (£)
January	13.4	1.4
February	16.0	1.7
March	20.8	2.2
April	79.75	8.29
May	1.5	0.2
June	7.6	0.8
January	20.4	2.1
Per m^3	0.54	0.06

E_{TOT}, total energy consumption.

benchmarking the impact of RWH systems at a range of scales.

Cost of RWH pumping energy consumption

The first quarterly electricity bill (January to April 2009) for the Innovation Centre was obtained from the building management team (Dyer 2010). This enabled the per unit (kWh) electricity cost to be identified (10.42p) and the cost of the pumping energy was quantified using the improved methods and is summarised in Table 5.

The quarterly total electricity consumption was 71 513 kWh (January to April), resulting in the proportion attributable to the RWH pump being 0.07%. This is perhaps not surprising given the quantity of electrical equipment (lights, personal computers, servers, etc.) present in most offices, but it does highlight that the energy consumption of the RWH system is marginal compared with the building's overall consumption.

Comparison with other studies

In order to place these results in context, they were compared to the results of other studies. The figure estimated in the present study (0.54 kWh/m^3) compared very well to that measured by Gardner *et al.* (2008; 'M' on Fig. 2), which was 0.54 kWh/m^3 (albeit from a domestic property rather than an office building). An older empirical study (Brewer *et al.* 2001) identified the energy consumption to be significantly higher than this at 7.1 kWh/m^3, although this installation was subject to numerous technical faults. The difference between this earlier study and the more recent ones could be attributable to improved implementation reducing the number of pump start-ups required or an improvement in pump efficiency. A more recent study (Parkes *et al.* 2010) identified the full LCA energy consumption of RWH as being 1.16 kWh/m^3 (0.63 kgCO$_2$e/m^3). In comparison, the report identified mains water distribution system (WDS) energy consumption (for water delivery only) was 0.6 kWh/m^3 (0.33 kgCO$_2$e/m^3). However, this study did not consider 'future' systems, such as gravity systems or those with more energy-efficient pumps, which will reduce the pumping energy requirement (Ward 2010; Way *et al.* 2010).

Figure 2 summarises the full findings of the described studies. The cost value for the WDS refers to distribution (i.e. pumping) only to ensure a valid comparison with the pumping (operating) aspect of RWH represented in this paper. Figure 3 indicates that all per unit values are higher for the improved method than the simple method. Additionally, per unit RWH *pumping* energy consumption and its associated cost is lower than for the WDS, but carbon emissions are higher for RWH than the WDS. However, as different methodologies were used in calculating the figures (such as different CO$_2$ equivalent values), caution should be used in making generalisations from the CO$_2$ emission comparison. The above mentioned comparisons indicate that the energy consumption for pumping rainwater and for WDS is comparable and RWH systems appear unlikely to consume any additional energy. On the contrary, they offer considerable water-saving potential and reduction in energy required to treat the volume of potable water saved.

Conclusions and further work

An improved method for estimating the energy and CO$_2$ impact of RWH system pumps by proxy has been demonstrated, providing a way of benchmarking system impacts.

(1) Application to a RWH system pump in an office building yielded energy consumption and CO$_2$ emission values per unit (m^3) of consumed harvested rainwater of 0.54 kWh/m^3 and 0.56 kgCO$_2$e/m^3, respectively.

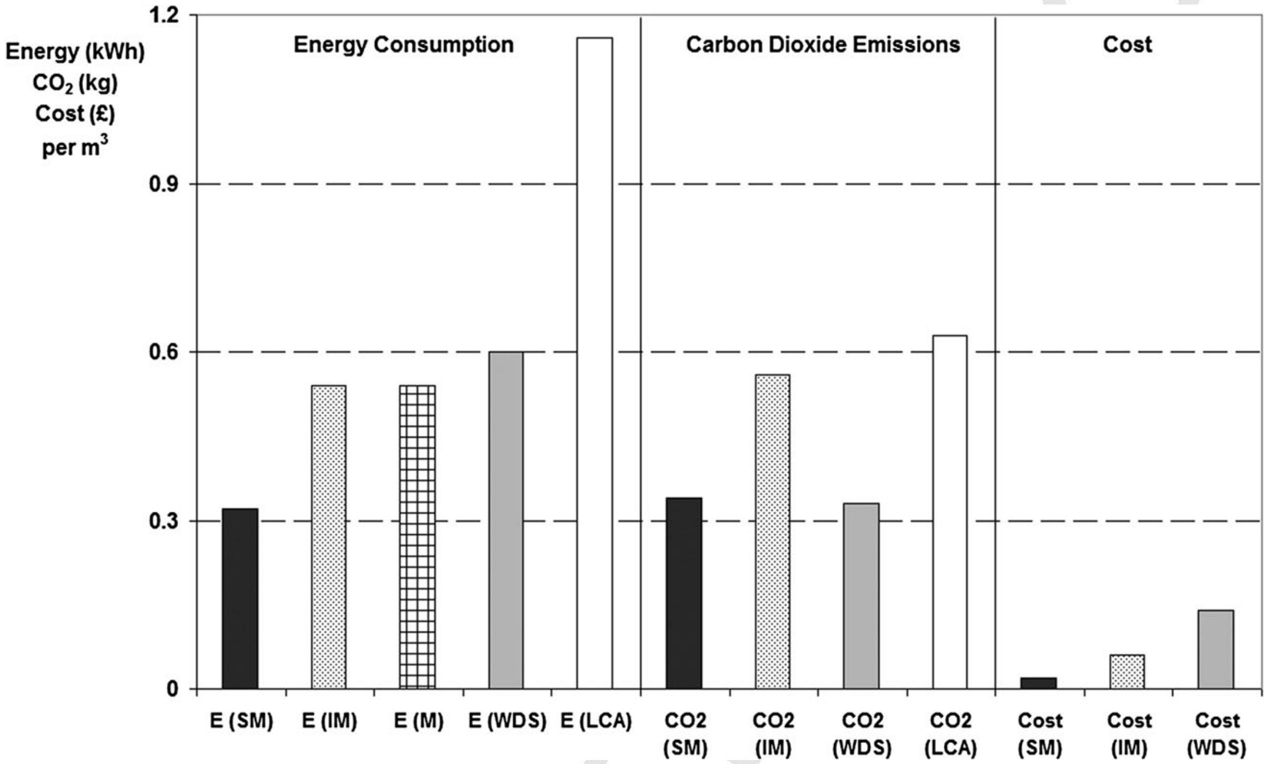
(2) Comparison with previously used simple methods identified these underestimated energy consumption and carbon emissions by 60%, by not representing the full pumping regime and pump efficiency.

(3) The improved method estimate compared well with empirical data and energy consumption was shown to be less than that of the WDS for a unit pumped.

(4) It was also identified that the energy consumed by the RWH system pump represented 0.07% of an office building's total energy consumption.

(5) Although the improved method shows an increased contribution of carbon emissions, overall, the energy consumption associated with RWH systems appears to be a very minor fraction of total building energy consumption.

(6) The water-saving benefits offered by RWH systems are significant and should not be ignored.



7 **Fig. 3.** Comparison of results of the improved method with other studies. All values are for RWH with the exception of those labelled WDS. E, energy consumed; CO_2, carbon dioxide emitted; Cost, cost of energy used; IM, improved method; LCA, full RWH embedded and operational impact; M, measured; SM, simple method; WDS, mains water.

Further research is currently being undertaken to parameterise UV disinfection systems within the model and to perform a sensitivity analysis of all the parameters represented in the model. Although new, emerging RWH system designs will ultimately reduce and optimise energy consumption, conventional systems are likely to be in use for a number of years. Therefore, increased understanding of their energy consumption is required, which is facilitated by the development of the method outlined.

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