Quantifying the energy and carbon effects of water saving

full technical report

Environment Agency

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Quantifying the energy and carbon effects of water saving

Final Report

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Summary

The overall CO_2 emissions from the UK water industry are relatively well known and understood. However, a recent Environment Agency Study (2008a) has demonstrated that the major greenhouse gas emissions associated with the supply-use-treatment cycle of water use in the domestic sector are during the 'use' phase of water with 89% of emissions attributable to water use in the home (with the remaining 11% attributable to utility companies). It is therefore important to understand the CO_2 emissions from specific water using activities and behaviours in the home, and this is what the current study addresses. Two approaches have been used in the current study. The first simple Water Energy Model (WEMlite) calculates hot water use or saving at the appliance and then divides by boiler efficiency to determine the fuel and therefore carbon used. However, in some instances this approach is too simplistic, because there are 'fixed' losses due to the hot water system (such as heat loss from the cylinder and pipe work), and during the heating season some of these heat losses could be considered to be useful gains. A second model (WEM, Water Energy model) incorporates these system losses and can therefore be used to evaluate improvements in cylinder and pipe insulation and plumbing design as well as the effects of changing volumes of water used.

Both models include an estimate of utility company CO_2 emissions and these can be added to each water-using component. To provide context, these emissions are set out in Figure 1 for a typical new build home. The proportion attributable to the utility company compared to domestic emissions is very close to the 11% calculated in the Environment Agency study (Environment Agency, 2008a).

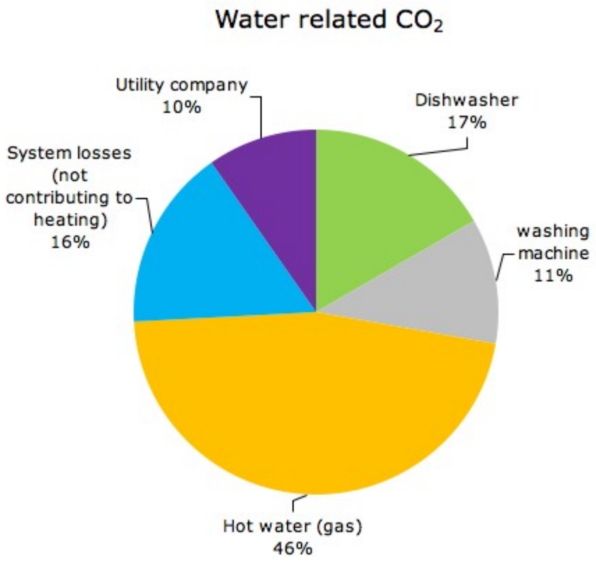

Figure 1. CO_2 emissions from water use incorporating both household and non-household emissions. New dwelling assumptions with gas boiler and dishwasher installed.

The output from the Water Energy model in terms of CO_2 emissions from a standard existing dwelling with a gas system boiler (78% efficiency), hot water cylinder (120 litres with 25mm foam insulation) and standard water use are shown in Figure 2.
As expected, appliances using hot water dominate. Also, since heating water using electricity results in higher CO_2 emissions than heating the same volume of water

using gas, the CO_2 emissions associated with white goods are proportionally higher than for the other hot water uses. It is therefore very important to consider the differences in CO_2 emissions between different fuel sources (i.e. the fuel factor) when calculating the impacts of measures (the CO_2 emissions from an identical water use in a home using entirely electrical heating will be approximately double that in a home in which a gas boiler provides hot water). It is also important to recognise that the results are very sensitive to assumptions about what we regard as standard water use.

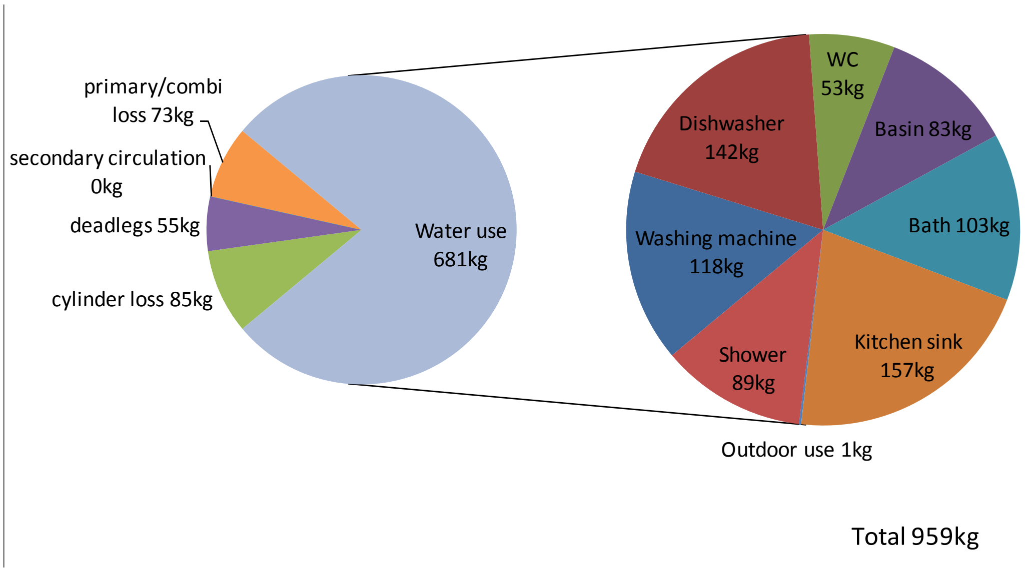

Figure 2. CO_2 emissions associated with the water use in existing houses with gas system boilers. Note that WC water use is relatively high and shower use relatively low compared with newer homes.

When considering new dwellings, we have assumed a different pattern of water use, reflecting the trend towards higher flow showers, more efficient white goods and the decrease in WC flush volumes. The CO_2 emissions associated with this water use are illustrated in Figure 3. Total emissions are similar to existing housing stock, because the improvement in boiler efficiency between old houses and new is largely cancelled out by the increase in hot water used for showering.

The CO_2 emission consequences of various modifications to the standard new dwelling have been investigated using the Water Energy model, including the effects of secondary circulation, electric water heating and the effect of meeting Code level 3 water use with and without rainwater harvesting. Finally, highly thermally efficient buildings have been investigated in order to establish the point at which the CO_2 emissions from hot water demand exceed those from space heating.

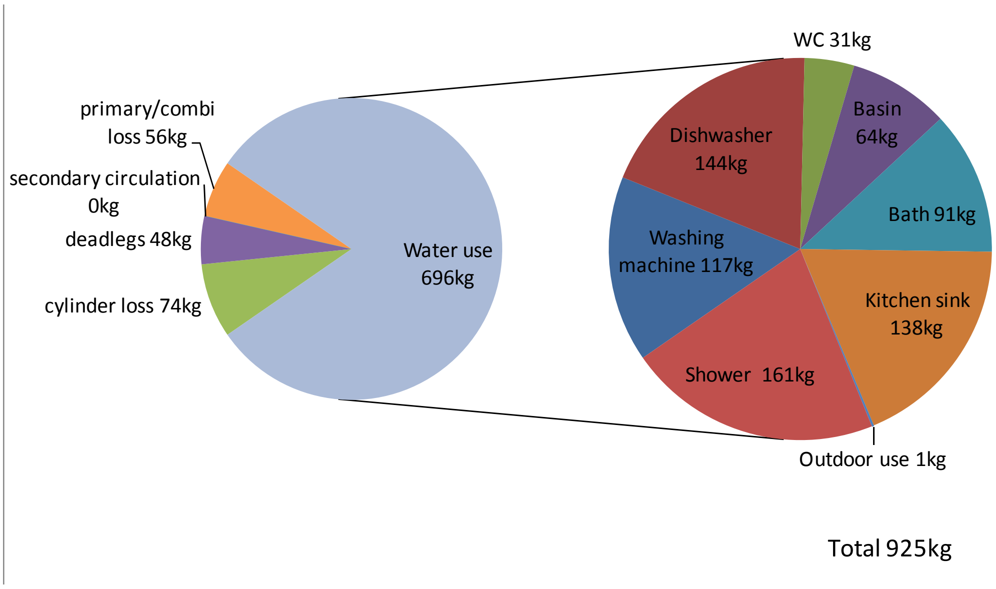

Figure 3. Water related CO_2 emissions in new houses. Note that increased shower frequency and duration has led to an increase in the emissions due to showering, but that the total CO_2 is marginally lower than in existing housing stock owing to the increase in boiler efficiency.

The Water Energy model indicates that optimised hot water system design in new houses (primary pipe work, boiler location, controls, cylinder sizing, insulation and hot water distribution) could provide significant CO_2 emission reduction, as well as water and cost savings. The model also indicates how commonly applied bad practice (e.g. long primary pipes, poorly insulated secondary circulation and long un-insulated dead legs) can lead to very significant losses. Whilst future research could quantify the impacts of regulatory improvements in this area, many of these measures result in cost effective savings and better performance and so should be implemented anyway.

If water efficiency measures are successful then the CO_2 emissions of white goods start to dominate the total CO_2 emissions. Typical water use pie charts used in messaging factor in average dishwasher ownership and so under-represent water and energy use for households that include them. The water use for all modern machines is low in relation to energy use and it is important that policy makers reach agreement on the relative importance of water and CO_2 in order to avoid conflicting messages. This is an important consideration for policy, labelling and incentives or regulations such as the Code for Sustainable Homes (CSH). If there is a trend towards building heat being supplied from low carbon sources such as district heat or solar thermal then the issue of hot fill for appliances or equivalent solutions should be revisited.

The financial cost of CO_2 emission savings from various measures has been quantified using marginal abatement costs (MAC). Initial results from this (Figure 4) indicate that financial and CO_2 benefits result from a range of water efficiency retrofits (such as dual flush retrofits and tap aerators) and provide a useful way of comparing measures in terms of their scope for total CO_2 saving.

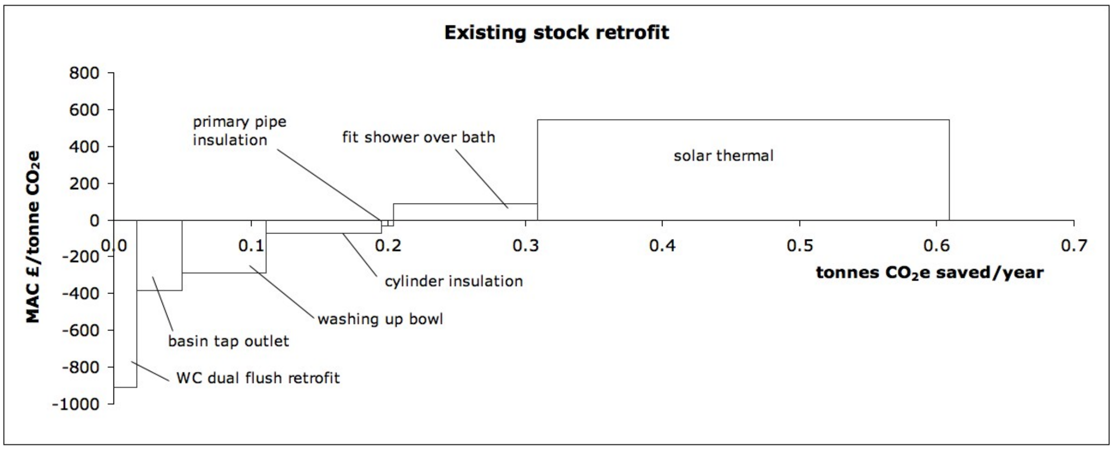

Figure 4. Marginal Abatement Cost Curve used to demonstrate the cost effectiveness of measures that save CO_2 for a single dwelling. Measures that save CO_2 as well as money are below the x axis.

Further discussion is required as to the best approach for calculating the financial costs of CO_2 emission reduction requirements. There is a huge disparity between the Shadow Price of Carbon currently used (£26 in 2008) and the marginal abatement costs for widely adopted measures such as solar water heating which have a reported marginal abatement cost between about 20 and 300[1] times that of the SPC.

Recommendations for new buildings

As new buildings become more energy efficient, CO_2 emissions from hot water start to exceed those from space heating (Figure 5). This effect is exaggerated by the fact that because the total space heating demand is lower, the usefulness of ‘losses’ from the hot water system decreases. As we move towards more energy efficient houses, a similar level of detail should be applied to hot water system design as to the building envelope and ventilation systems.

Hot water use in new homes is likely to be higher than in existing homes but there is considerable scope for savings by fitting water efficient showerheads, flow regulators or tap aerators. The current CSH water calculation method allows calculated savings in cold water (e.g. rain and greywater reuse) to offset increased hot water consumption (e.g. higher flow showers) and this can be shown to lead to a significant increase in CO_2 emissions. This study has demonstrated that it is entirely possible for CO_2 emissions from hot water use in newly built houses to be higher than that from existing housing stock, even when they comply with CSH level 3. Policy and regulation need to change in order to ensure that new buildings have lower CO_2 emissions than existing ones.

The way in which most current building energy models and energy standards consider hot water system losses is too simplistic for new build dwellings. The water-energy model developed for this project could be developed further to become a useful design tool for low carbon buildings. However we do not recommend micro-component modelling of water use as part of this since it is a behavioural variable rather than one that is suited to incorporating in plumbing system design models.

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[1] BRE (2001) reports a MAC of between £1,400 to £8,639 per tonne (discounting CO_2) for solar water heating. Our own optimistic figure was close to £500/t (CO_2 not discounted).

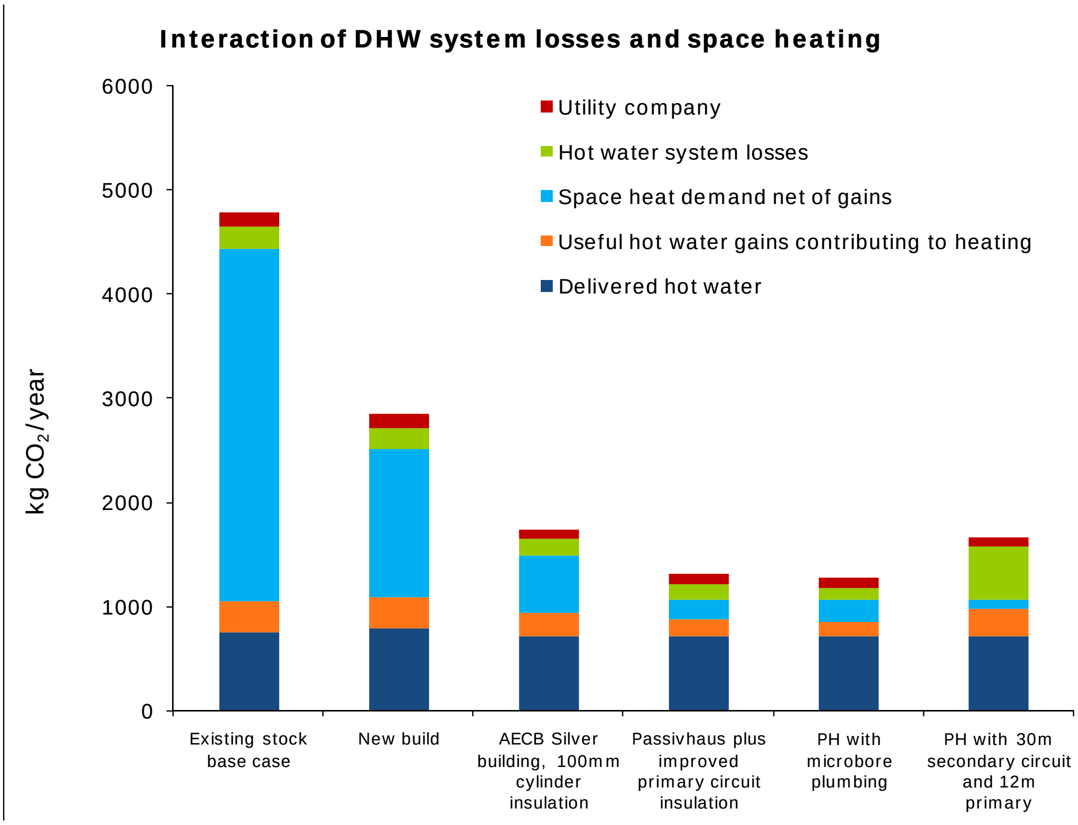

Figure 5. As the building envelope becomes more efficient, CO_2 emissions from hot water use exceed those from space heating. Hot water use remains constant for all scenarios. PH= Passivhaus. For explanations of building energy standards see page 43.

Recommendations for existing housing stock

From the perspective of the individual householder, the potential CO_2 and cost savings due to simple appliance retrofits are much lower than from behavioural changes such as using a bowl for washing dishes or taking a shorter shower. This is assumed to be in part due to the already low flow rates for gravity fed taps and showers and low power electric showers present in many existing homes, but also because behaviour has more impact on consumption than technology. However, when carried out across large numbers of houses as part of a renovation programme, significant CO_2 savings are achievable from water efficiency refurbishment or retrofit programmes, at a low financial cost, as illustrated by Marginal Abatement Cost Curves (discussed in section 6).

Adding an electric shower over a bath in existing households without showers can potentially save water but increase running costs and CO_2 emissions. A mixer shower (with pump if the existing head from a gravity system isn’t sufficient) with flow regulation provides a more carbon effective solution.

Water metering in existing homes reduces hot water use and therefore CO_2 emissions. The magnitude of this CO_2 saving is uncertain because the relative decrease in hot water use compared to cold is not known.

Recommendations for messages on water using behaviour

The simple model (WEMlite) developed in the current project (discussed in section 3) is sufficient when considering the impacts of simple behavioural change or appliance retrofits in existing households. This is particularly relevant when creating on-line calculators or simplified tools for providing consumer advice.

Summary statistics on water use that use arithmetic means as the ‘average’ are heavily skewed by high water users, and so most households are already using less water than ‘average’. This has implications for how water efficiency messages are targeted. Positive reinforcement of efficient behaviour is necessary for those who are already low water users, with high water users targeted with a different type of message. Messages that promote average behaviour (for example 35 litres for an average shower) could, if completely successful, result in total consumption remaining the same.

Recommendations for further research

There are large gaps in our understanding of micro-components of water use, particularly with regard to hot water use and how micro-component use differs between different households. Further analysis of existing datasets on hot water use is needed before commissioning new studies. Data on water use by taps is particularly scarce, and further monitoring studies need to take place at the level of the individual appliance, rather than at whole household level.

Shower sales are increasing, as is flow rate and frequency. This is of concern given the CO_2 emission consequences of hot water use. Further work is needed to define shower performance and to investigate other potential barriers to labelling and/or regulation of shower flow rates and energy use. Electric showers have low flow rates, but if the use of an electric shower displaces water use that would otherwise have been provided by a gas boiler, CO_2 emissions can increase. Currently electric showers are being promoted as a way of achieving CSH water credits because of their low cost and inherently low flow rate. It may (for example) be appropriate to consider labelling/regulation of showers in terms of energy use as opposed to a simple measure of their water use.

Preliminary calculations suggest that increasing hot water storage temperatures from those measured in previous studies to the 60°C recommended for legionella control would increase CO_2 emissions from hot water by around 5-10%[2]. Whilst the risks to human health should clearly remain a priority when setting regulations in this area, the impact on CO_2 emissions of an over-conservative approach suggest that further study in this area is justified.

Further research on losses from primary circulation of boilers is needed, as there is considerable scope for measures that lead to both CO_2 savings and better performance as perceived by the householder.

A number of social functions are embedded in water using behaviour, and research is needed in order to understand what influences behaviour and what causes people to

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[2] Although not modelled, this figure could be higher where solar thermal or heat pumps are installed.

change. We also know very little about how different social groups use water and the extent to which they are open to behavioural change messaging.

General findings

The heat loss due to cold water warming up in WC cisterns has been identified as ‘significant’ by a number of reports including a recent study of the life cycle impact of WCs. Our calculations and preliminary monitoring confirmed that the heat loss was significant. It is of a similar magnitude to the CO_2 emissions from water supply and wastewater treatment needed to supply water for WC flushing. However we calculate it to be around 20 kg CO_2 per year for a family of 4, so it is not a ‘significant’ heat loss in all but the best insulated buildings. However, cisterns could be insulated as standard during manufacture at little cost and this would help eliminate condensation and contribute to carbon savings.

Whilst in general water and CO_2 savings are complimentary, care must be taken when promoting water efficiency measures where the water is heated electrically (e.g. electric showers or dishwashers) as there are a number of situations where modest water savings could lead to significant increases in CO_2 emissions.

It is important to note that in the absence of regulatory pressure to prevent it, there is considerable scope for new build dwellings to have higher CO_2 emissions from hot water than existing dwellings.

A limitation of this work is that we know very little about the micro-components of hot water use in different households. WEM calculates CO_2 emissions from water use in an individual household according to assumptions about micro-component water use and water heating system, so results are very sensitive to changes in assumptions about water use; doubling the occupancy or showering more frequently will increase the emissions.

Contents

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The authors accept full responsibility for any remaining errors.

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Abbreviations and glossary

Abbreviations

AECB	Association for Environment Conscious Building. www.aecb.net
AIC	Average Incremental Cost. A measure of the life cycle cost of delivering a cubic metre of water.
BREDEM	The BRE domestic energy model. A model for calculating building heat requirements for domestic hot water and space heating.
CAPEX	Capital expenditure.
CHP	Combined heat and power.
CO_2 e	CO_2 equivalent of greenhouse gas emissions, typically expressed in kg.
COP	Coefficient of performance, e.g. of heat pumps. Units of heat supplied for a unit of electricity consumed.
CSH	Code for Sustainable Homes.
DHW	Domestic hot water, the hot water that comes out of the tap.
(D)WRMP	(Draft) water resource management plan.
GHG	Greenhouse gas.
LCA	Life cycle assessment.
MAC, MACC	Marginal abatement cost (curve). The financial cost (positive or negative) of avoiding an additional unit of pollution, in this case a tonne of CO_2.
OPEX	Operating expenditure.
PHPP	Passivhaus Planning Package, a building energy model for design and certification to Passivhaus and AECB energy standards.
RWH	Rainwater Harvesting
SAP	Standard Assessment Procedure, the UK Government's standard methodology for home energy rating.
SEDBUK	Seasonal Efficiency of Domestic Boilers in the UK. The average annual efficiency achieved in typical domestic conditions, making assumptions about pattern of usage, climate, control, and other influences.
SPC	Shadow price of carbon.
WEM, WEMlite	Water Energy Model (and simple version). The models arising out of the current study.

Glossary

AECB silver standard	Energy standard for low energy houses set in terms of annual heating energy consumption per m²
AECB water standards	A voluntary fittings-based water efficiency standard developed by the AECB to address concerns with the CSH.
Anglian100	A project set up in 1992 in which 100 domestic properties had water use monitored and recorded at all water using points at 15-minute intervals. ~60 of these properties are still being monitored.
Boiler cycling	This is when the boiler turns on and off (either due to a signal from the timer or a thermostat). Each time this occurs, the heat exchanger and water in the primary circuit cool down.
Boiler efficiency	The figures used in this report are based on SEDBUK methodology.
Combi boiler	Combination boiler. An oil or gas boiler that provides central heating and also delivers hot water on demand without the use of a separate hot water storage cylinder.
CSH Water calculator	Calculation to award CSH points for certain water saving measures.
Cylinder losses	Heat loss from a hot water storage cylinder.
Dead leg	A hot water pipe that cools down between uses. (terminology elsewhere is sometimes different, e.g. simply ‘leg’, with ‘dead leg’ referring to blanked off water pipes)
Direct feed system	Hot and cold water direct from mains (rather than gravity fed from a header tank which is filled from the mains). Also known as pressurised system.
DM measures	Demand management (water saving) measures.
EcoHomes	UK environmental rating scheme for homes, replaced by the CSH.
EN monthly method	A building heating energy model based on monthly climate data.
First Law of Thermodynamics	In this context is used to calculate the heat required to achieve a temperature change in water (kWh = 1.16 x volume (m^3) x temperature change (°C))
Fixed losses	Losses that do not vary significantly with variation in water use, e.g. losses from hot water storage, primary and dead leg losses.
Fuel factor (CO_2)	Factor for conversion between kWh and kg CO_2 emissions

Gravity plumbing system	A system in which the cold water feed to the hot water storage cylinder is from a header tank rather than direct from mains. Also known as vented, as the expansion from the cylinder is taken via a vent pipe back to the header tank.
ICE database	Inventory of Carbon and Energy database, Bath University
Identiflow®	A system for collecting and analysing water use data to estimate the water use by individual fittings using a single flow meter and data logger on the water meter to the house.
Microbore plumbing	Small bore pipe, typically 10mm diameter, used to reduce dead leg volumes in direct feed hot water systems.
Part G	Approved Document G of the England and Wales Building Regulations, Provision of Sanitary and Washing Facilities (soon to be updated to include water efficiency requirements).
Part L	Approved Document L of the England and Wales Building Regulations, Conservation of Fuel and Power.
PassivHaus, Passive House Standards	An advanced voluntary energy standard from Germany that forms the basis of the heat requirements of the higher levels of the CSH. UK certification is available through the AECB and the BRE.
Primary circulation	The hot water circuit between a boiler and hot water store.
Primary losses	Heat losses from the primary pipe work but also the heat lost as the water, primary circuit pipe and boiler cool down between boiler firings.
Secondary circulation	Hot water distribution system where hot water is pumped round an insulated loop with short pipes coming off it to feed taps etc. Used in commercial buildings, flats and larger dwellings to reduce dead legs.
System boiler	A boiler that heats a hot water storage cylinder, c.f combi boiler.
System losses	In this report, system losses refer to hot water storage, primary and distribution losses but not boiler flue losses. The same as fixed losses.
Trace heating	Self regulating electrical resistance heating of water pipes to maintain the hot water temperature or prevent freezing.
US EPA WaterSense®	US Environmental Protection Agency water efficiency program.
Useful gains	Heat losses (e.g. from the hot water system) that usefully contribute to space heating.
Utilisation factor	A factor that determines the proportion of gains that are useful, and is therefore dependent on the building heat loss and available gains.
Utility emissions	CO_2e emissions incurred in the delivery of mains water and the treatment of the resulting wastewater.

1 Introduction

1.1 Context

Until recently, domestic water efficiency and domestic energy efficiency have rarely been linked in the same study. However, recent data has drawn attention to the importance of addressing this:

- A recent Environment Agency Study (2008a) has demonstrated that the major greenhouse gas emissions associated with the supply-use-treatment train of water for the domestic sector are during the ‘use’ phase of water with 89% of emissions attributable to hot water use in homes.
- The Code for Sustainable Homes (CSH) has mandatory requirements for both energy efficiency and water efficiency. Proposed revisions to Part G of Building Regulations are also likely to include water efficiency requirements for new dwellings based on a total household water use calculation tool such as that used in CSH. This complex water calculator allows appliances to be ‘traded off’ against each other in order to calculate a total household water use. It does not differentiate between hot and cold water use and could lead to conflicting requirements between the water and energy saving aspirations of the Code.
- Data from recent studies comparing micro-components of water use in new properties compared to old has demonstrated that as a proportion of total household water use, hot water use is increasing, whilst water used for toilet flushing is decreasing (MTP, 2008d). Decreases in total household water use may not therefore be mirrored by decreases in the energy use attributable to domestic water.
- As the thermal efficiency of new homes increases, the proportion of household energy required for domestic water heating (as opposed to domestic space heating) will increase (in houses built to Passive House Standards or CSH Code 4+ the energy required for water heating is greater than that for space heating).

It is therefore becoming increasingly important to ensure that water and energy efficiency are considered in tandem so that domestic water efficiency policies can complement energy efficiency policies as there is clearly the potential for them to conflict.

1.2 Report structure and outputs

Section 2 discusses the available micro-component data on water use and how this relates to the energy used. **Section 3** outlines the development of a simple model (WEMlite) of the influence of user behaviour on hot water use and carbon CO_2 savings. This model is designed to allow the impacts (financial, water and CO_2) of simple behavioural or appliance change to be quickly and easily calculated. **Section 4** discusses the development of a Water Energy model (WEM) to allow appliances which use water to be seen within the context of the total energy attributable to water, and also within the context of whole house energy use. The model is then used to investigate the impacts of various water use scenarios (such as the effect of water metering, water efficiency measures, Code for Sustainable Homes). There are an enormous number of permutations possible within this model and **section 5** considers some specific questions that have arisen, e.g. the relative importance of different appliances when the household heating source is low carbon, and the relative importance of domestic water heating energy in houses of different build qualities. **Section 6** then uses data from the previous sections to consider the cost effectiveness of CO_2 emission saving measures, as this is clearly of major importance to policy. This is expressed in terms of MAC (marginal abatement cost). **Section 7** discusses the implications of the findings for future research and policy. **Section 8** outlines the implications of the current study for the water resources carbon water footprint calculator. To improve readability, much of the detail is contained within the appendices.

Project outputs

- A detailed report on the findings and recommendations including technical and non technical summaries.
- A simple model (WEMlite) that allows the CO_2, water and financial impacts of behavioural interventions or appliance change to be investigated.
- A Water Energy model (WEM) that incorporates broader considerations of how domestic water use interacts with space heating within the home.
- A simple MAC spreadsheet for exploring the cost effectiveness of CO_2 abatement measures.
- The spreadsheets can be used to model a range of water use and heating scenarios to inform both future policies and communication campaigns.

2 Available data on water use

This section summarises the available data on micro-components of water use. Further detail is given in Appendix 6.

Relevance of cold water using appliances

The major energy and carbon impacts of domestic water use are related to hot water (Environment Agency, 2008a). However, cold water also has a carbon impact within the home. For example, a recent life cycle assessment (LCA) study for DEFRA concluded that the major impact in the life cycle of a WC was due to the heat loss involved when mains water comes in to the property at a low temperature, absorbs ambient heat while stored in the cistern and is then flushed away (Gandy *et al.*, 2008). In the standard UK dwelling with poor insulation and an uncomfortably cold bathroom, this additional heat loss is insignificant. This study also demonstrates the complexity of the relationship between water and energy, and the importance of a broad outlook. Theoretical calculations on the heat loss associated with water using appliances are incorporated into the models developed and discussed in sections 3 and 4 in order to demonstrate the (minor) extent to which cold water efficiency measures contribute to domestic energy efficiency.

With reference to specific cold water using micro-components, we have not examined the energy and CO_2 emission impacts of:

- pumps (e.g. mains pressure booster sets)
- outdoor water uses (e.g. pressure washers, pumping for garden purposes)
- water softeners or other water treatment systems
- food waste disposal units
- rain and greywater systems (although these are discussed in relation to calculations on the impacts of CSH).

Cold water to basin and kitchen sink taps is considered alongside hot taps in section 2.1.3, since much of the available data on these micro-components is not separated into hot and cold.

WC flush volumes and use frequencies are well documented and will not be discussed in detail here. The values chosen for existing stock dwellings are 9.4 litres/flush, and 11.52 uses/household/day (based on Chambers *et al.*, 2005).

Hot water appliances

Clearly, the major CO_2 emission impacts of water are associated with the hot water micro-components. Because of storage and distribution losses within the water heating system (such as heat loss from pipe work and the cylinder), the CO_2 impact is not simply related to the volume of water used. The importance of this is discussed in section 4 where the Water Energy model (WEM) is introduced.

Influence of boiler type on hot water use

It is widely predicted that properties with combi boilers use more hot water than properties with storage based water heating systems (system boilers), owing in part to the potential for a combi boiler to produce an unlimited volume of hot water. However, the lack of hot water storage results in reduced heat losses.

So far, there is little evidence on the effect of boiler type on hot water use, so it has not been incorporated into the models we have developed. Anglian100 data demonstrates a wide range of hot water uses across all boiler types, and the Energy Saving Trust (2008) demonstrates that whilst there was a difference between properties regarding where the hot water was used (combi boiler households had higher kitchen sink water use), the total volumes used were not significantly different. Evidence on this issue is discussed further in Appendix 6. WEM makes a provisional attempt at estimating the energy wasted when a combi fires up from cold and has to heat up the heat exchangers and water they contain, but further studies are needed in this area (discussed in Appendix 5.6). Similarly an issue with the cycling of the primary circuit of system boilers outside the space-heating season was identified as significant and a provisional algorithm has been included in the model pending further evaluation.

Trends in hot water use over time

The main historic data resource for existing homes is the Anglian100, shown in Table 1 and discussed in more detail in Appendix 6. The table suggests that increases in shower water use are being masked by the decrease in hot fill washing machines and the improved water efficiency of white goods. One would predict that since further efficiency gains in white goods are likely to be limited, total domestic hot water use will soon begin to increase due to the increase in showering. However, a notable feature of the Anglian100 data (not shown in the table below) is a large annual variability in hot water use even within an individual household, so the lack of standard deviation data for these figures makes it difficult to draw firm conclusions from them.

Appliance	**1992**	**2008**
Shower hot	2	14
Shower cold (i.e. electric)	7	19
Bath hot	32	32
Basin hot taps	18	22
Washing machine (hot fill)	9	5
Washing machine (cold fill)	69	38
Kitchen hot tap	Not available	30
Total (not including kitchen hot tap)	137	130

Table 1. Data from Anglian100 (MTP, 2008i), showing change in hot water use since 1992. All values in litres/household/day. Note that this data has been derived from graphs rather than numerical summaries of the data. Year-to-year variability is very high for baths and basins, but less so for other appliances (data not shown).

2.1.1 Baths

Detailed data for baths is given in Appendix 6.

The most reliable data source on bath use (Anglian100, MTP, 2008i) indicates that bath use was around 32 litres/household/day in 2008, although during the monitoring period (1992-2008) this has fluctuated between 28 and 58 litres. Without direct access to the data it is not possible to form a view on whether these fluctuations relate to frequency or volume. The prevailing view from behavioural survey data is that bath frequency is decreasing, but the range of frequencies quoted in different surveys is high (0.08-1.1/person/day). Identiflow® data suggests a frequency of 0.4/person/day.

Identiflow® data (MTP, 2008d) on bath volumes is 68.55 litres (new homes) and 73.3 litres (whole database), and there is considerable spread in the data. This is below the industry assumed volume of 80 litres.

The Energy Saving Trust (2008) demonstrates preliminary evidence in favour of the widely held view that houses with combi boilers have lower bath water use (hypothesised to be due to the limited flow rates of combi boilers meaning that baths take a long time to fill).

The impact of baths on CO_2 emissions depend upon the assumptions made about the households water heating system. We are not aware of any studies in which bath water use has been monitored together with data on boiler type and use patterns. The importance of assumptions regarding this can be evaluated using WEM (section 4) as and when data becomes available.

2.1.2 Showers

Detailed data for showers is given in Appendix 6.

Flow rate and volume
In many instances volumes and flow rates are estimated from the rated maximum flow of the appliance but there is little data on what shower settings people use in practice. In addition, differences in water pressure and plumbing system make it difficult to get robust data on this unless actual measurements are taken at the installed appliance. The difference in flow rates between shower types is large, but this data is often not available, which makes summary statistics unhelpful. Data on shower type and flow rate is obviously critical in order to understand the impact on CO_2 emissions of showers. Data on what is regarded as an acceptable flow rate for showers is discussed in detail in Appendix 6.4.3. In a study by Essex and Suffolk Water, 92% of people were satisfied with the flow rate of their electric shower (despite the fact that flow rate is limited by heat input and is rarely over 5 litres/minute). For mixer showers, aerated shower heads (which reduce flow rate) were generally acceptable (Critchley and Phipps, 2007), although the sample size was too small (n=9) to allow robust conclusions to be drawn.

Effects of shower type on temperature required
The amount of energy used in a shower event is related to the temperature increase required in the water, and the volume of water used. The water temperature required to maintain the thermal comfort of the user depends on a number of variables including: air temperature, relative humidity, radiant heat loss, air currents and water droplet size. The relative importance of these factors is poorly understood, but there is anecdotal evidence that aerating showers need higher water temperatures in order to maintain thermal comfort. Results from a simple experiment we have conducted to investigate this show the CO_2 cost of requiring a (slightly) higher water temperature are minor compared to the CO_2 benefits of using (a lot) less hot water (discussed in Appendix 6).

Duration

Very little raw data on actual shower durations is available. Limited Identiflow® data on shower duration is available for direct feed systems and suggests a median of 5 minutes, but Identiflow® will not give accurate durations on gravity fed systems (owing to the refilling of the header tank).

Whilst all data needs to be summarised in order to interpret it, it is important not to lose the underlying detail and variability, which in many cases may be more interesting than the summary statistics. For example, Identiflow® data (Waylen *et al.*, 2007) shows huge variability in shower durations (from 30 seconds to > 8 minutes). If this variability is genuine, it would suggest not only that survey data is of limited use, but also that 'average' duration is not a useful concept when considering how to influence behaviour, and more appreciation of what drives showering behaviour is necessary.

Frequency

Frequency data collected using different techniques (e.g. Identiflow® and household surveys) produce similar results. Both techniques suggest a mean frequency of around 0.6/person/day. However, as with shower duration, the differences in behaviour are huge and it is important to realise that regardless of the type of summary statistic used, the 'average' behaviour in this case actually only reflects what about a third of people do.

Interaction with bathing

The influence of showering on bath use and vice versa cannot be determined from the current data available, and there is no evidence from use frequency histograms that there is a correlation, let alone a causative relationship. As such we don't think it's appropriate to express this relationship as a ratio (which is the approach used in the CSH water calculator). It is likely that whilst there may be a minor influence of showering on bathing and vice versa, the other (social) factors affecting these behaviours are far more significant. Showers and baths should not be regarded as simple cleansing events as they have a range of functions (for example an Australian study listed 12 activities that people reported to do in the shower. Based on survey data; Energy Australia, 2006).

Interaction between flow rate and duration

Whilst it has been hypothesized that people spend longer in low flow showers, a robust relationship between flow rate and duration has not been observed in studies (discussed in Appendix 6.4.5) and there is no definitive evidence for or against this hypothesis.

Influence of shower type on energy use

Electric showers will always have low flow rates (maximum flow rate around 5 l/min) so are inherently water efficient compared to other shower types. However, the fuel factors for electricity and gas (Table 6) mean that there is potential conflict between water efficiency and energy efficiency. This is explored further in section 3.2. Ownership in 2008 is stated to be 38% of households (electric showers) and 42% (mixer showers). Showers from gravity plumbing systems also have limited flow rates, depending on pressure, and limits to the total volume of hot water available. Unfortunately, data on this type of plumbing systems is rarely available in studies, making analysis of the effect of shower type difficult, but the low water use by showers reported in existing households may be largely a consequence of old gravity plumbing systems and/or electric showers and lower shower ownership.

Differences in shower water use between new and old houses

The Identiflow® study comparing water use in new houses compared to old was not available for this study, but data from it is referred to in MTP (2008d). There is an apparent increase in the amount of water used by showers in new homes (from 31.97 litres/household/day to 73.6 litres/household/day). This is both frequency and volume related. Occupancy was not measured, so it is difficult to draw conclusions regarding changes in shower frequency per person. The exact nature of the comparison between new and old houses is not clear from the MTP report; there may be some demographic difference between the datasets, occupancy is not known, and it is not clear whether the data collected from old houses is recent, or old (the dataset appears to be from Chambers *et al.* (2005), which was collected in 2000-2002). Regardless of this, if a big increase in shower water use can be verified from other sources, it is of major importance for the Energy Saving Trust/Environment Agency domestic hot water strategy.

2.1.3 Taps

Detailed data for tap water use are given in Appendix 6.

The characteristics of tap events are known with even less certainty than showering and bathing events. The extent to which Identiflow® can robustly identify tap events is unclear and there is no differentiation between hot and cold tap events, or between kitchen sink and basin events. It is certainly unlikely to produce accurate data for properties with indirect plumbing systems (and this is further complicated by the fact that plumbing systems are often direct feed for cold water and indirect for hot). Unfortunately very little other data on tap use is available.

Average flow rates are stated to be 3.54 l/min for both kitchen and basin taps (Chambers *et al*., 2005), although given the frequency histograms this does not adequately describe the data. Duration of tap events is very uncertain; Chambers *et al.* (2005) is quoted as yielding a 40 second average duration, although in a more recent study, 70% of the tap durations were less than 20 seconds (Waylen et al, 2007). There is similar lack of certainty regarding the number of tap events per day. Total water use by taps is given by Chambers *et al.* (2005) as 87.17 litres/household/day (including cold taps). This compares with values on hot water use from Anglian100 of 35 litres/household/day for kitchen taps and 22 litres/household/day for basin taps (NB the figures for Anglian100 have been inferred from a graph, which also demonstrates the high variability in the data). The time resolution of the Anglian100 dataset (samples every 15 minutes) would not be sufficient to answer questions on individual tap events.

The characteristics of cold tap use (both kitchen and basin) are rarely reported. Figures available from the Anglian100 have been used in the current study (24 litres/household/day for the kitchen cold tap and 20 litres/household/day for basin cold taps, Berkshire, 2009).

Clearly users vary tap flow rate and duration to suit the task in hand, whether filling a vessel quickly or washing hands or rinsing a spoon under a gentle stream of warm water. In this way tap water use is more complex than water use by other appliances; a shower for example will typically be set at the preferred flow rate for the entire event and, unless the maximum flow rate is very high, this is likely to be a similar flow rate for all users. These compound uncertainties make even crude predictions of water saving due to reduced tap flow rate unwise. In order to generate more robust data on taps in the future, they should perhaps be considered as separate appliances (e.g. the function of a kitchen hot tap is very different to a kitchen cold tap, and different again to the functions of either hot or cold basin taps, and one might also expect differences between bathroom washbasin tap uses and tap uses in basins for downstairs WCs).

2.1.4 White goods

The water use (be it hot or cold) of white goods is difficult to determine from the literature for the following reasons:

- It is rarely made clear whether washing machines in the data set are hot or cold fill.
- Occupancy is a key variable with regard to the use of white goods (e.g. the dishwasher might be used every night, regardless of whether or not it is full), so expressing results in terms of volume per person needs to be accompanied by occupancy data.
- The water use of white goods has decreased considerably with advances in technology, but the age of white goods is rarely known in studies of whole house water consumption.

Washing machines

The most reliable data on washing machine use comes from the Anglian100 dataset (MTP 2008d), which gives a 2008 figure of 38 litres/household/day. It is expected that the future water efficiency improvements for washing machines are increasingly limited, so an increase in wash frequency will at some point lead to an increase in total water use (the point at which this occurs will depend upon the replacement rate of washing machines). As discussed in Appendix 6, use frequency is highly variable and an average use frequency is not a useful summary statistic.

Energy use by washing machines is estimated to be 216kWh/household/year (MTP, 2006a). The effect of different wash temperatures is discussed further in Appendix 6 and illustrated in Table 25.

Dishwashers

The prevailing view is that dishwashers are more water efficient than washing up by hand, but less energy efficient (MTP 2008a), and the extent to which this is the case is investigated in section 5.4.2. The implications of prioritising water over energy when choosing white goods are discussed in section 6.6. Dishwasher use frequency varies enormously, so the use of an average frequency is not appropriate when considering behaviour. Water efficiency improvements mean that statistics on replacement rates and age of machine are essential when interpreting data on volumes used. There will certainly be an interaction between dishwasher use and kitchen sink hot water use, but there is no good evidence in the literature on this (not referred to in sufficient detail in the Anglian100 data available, and tap data within Identiflow® is poor). For the purposes of modelling for the current study, we are suggesting that kitchen sink hot water use is reduced by 8 litres/person/day if a dishwasher is present, and the background to this assumption is discussed in Appendix 6.6. We have used figures of water use per cycle of 21.3 litres (existing households, taken from Chambers *et al.*, 2005) and 15 litres (new households, assuming a new dishwasher, manufacturer's data).

2.1.5 Future studies

Whilst the basic micro-component split between different appliances is known in very general terms, the data on showers, baths and taps is much less robust than that for more 'fixed use' appliances such as the WC and white goods. Summary statistics on flow rates, durations and frequency often seem very precise, but the variability of the raw data is a good indicator that we know very little detail about water using behaviour. There is enormous scope for academic research quantifying micro-component data in more detail and to higher degrees of accuracy. However, from the perspective of policy makers and regulators, some priority setting for this research is clearly needed. The decision was therefore taken to investigate the CO_2 and financial implications of hot water use (sections 3 and 4) prior to considering future studies, in order to frame discussion on future studies in terms of the potential for CO_2 emissions savings.

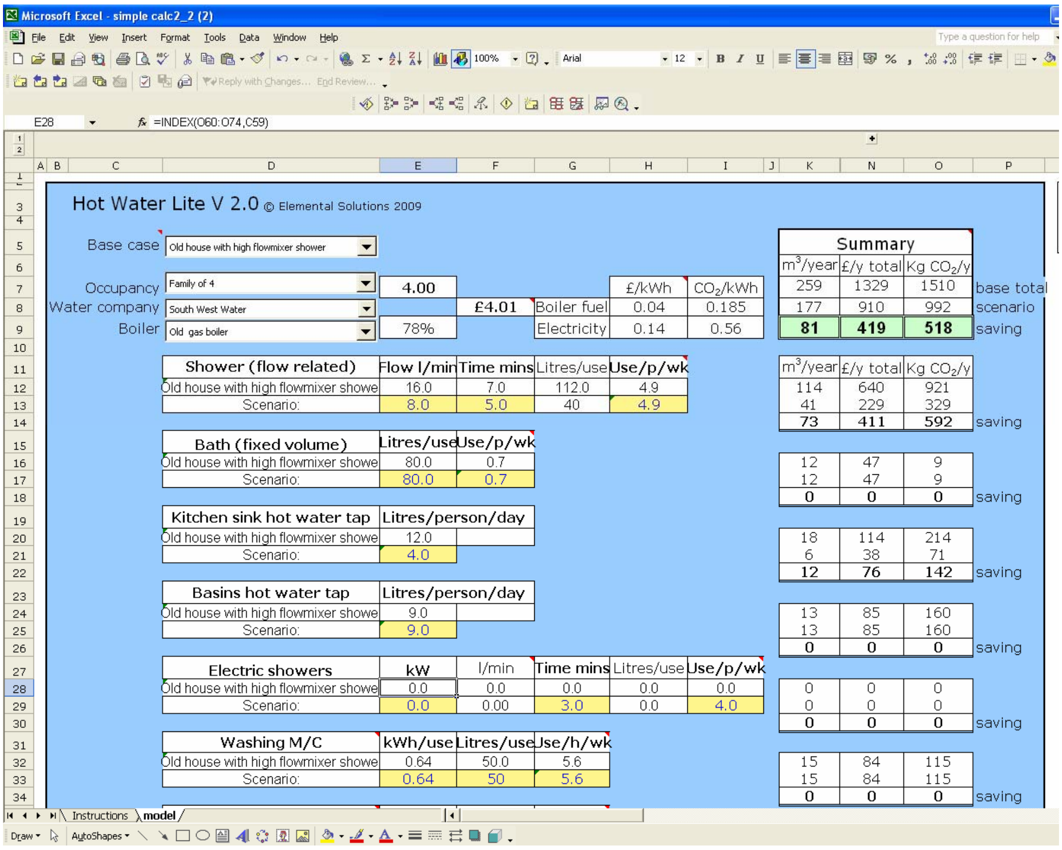
3 Quantifying the water, CO_2, energy and financial impacts of behaviours and appliances

The uncertainties and complexities of human behaviour are the most significant variable in micro-component models and trials. Whilst it is possible to specify fittings volumes and flow rates, the actual way in which appliances are used is much less certain. The WEMlite model described in this section (screenshot in Figure 6) is for calculating the impacts of different water use behaviours with regard to specific water use appliances, calculated without reference to system losses other than boiler efficiency. It has also been used to investigate the impacts of simple water efficient retrofits, and since the monetary costs of fuels and water are modifiable by the user, it can be used to investigate the impacts of price changes.

By contrast, the Water Energy model described in section 4 investigates the effect of changing details of the hot water system such as pipe lengths, storage volumes and insulation levels. The Water Energy model is therefore more appropriate when considering packages of measures, situations in which the energy source may change, and the way in which space heating and insulation assumptions impact on the CO_2 impacts of water use.

In the simple model described in this section, the heat requirement is determined from the First Law of Thermodynamics using the required temperature rise (mains water and delivered water temperatures specified by the user). This is converted into a CO_2 equivalent value by dividing by boiler efficiency and multiplying by a carbon factor for the chosen fuel. This model produces outputs expressed as totals and as annual savings; £'s, kg CO_2, and m^3 water. We expect the model to be primarily used for developing marketing messages, although it could equally be used as a tool for Energy Saving Trust/Environment Agency staff to answer specific consumer queries. This model generates simple answers to simple questions, and allows combinations of simple measures to be added together and quickly compared for different water companies, boiler types etc. For example, "If Mrs Smith has boiler W and currently spends X minutes in the shower every day, but in future spends Y minutes in the shower every day, the savings (water, CO_2, money) will be Z." The model can be used to consider a single fitting or a package of measures against a base case scenario.

If overall context is required (e.g. how does spending less time in the shower relate to overall domestic energy and water use?), then the more complex whole house model (discussed in section 4) allows this analysis to be carried out.



E28 =INDEX(O60:O74,C59)

Hot Water Lite V 2.0 © Elemental Solutions 2009

Base case: Old house with high flowmixer shower

				£/kWh	CO₂/kWh
Occupancy	Family of 4	4.00			
Water company	South West Water		£4.01	Boiler fuel 0.04	0.185
Boiler	Old gas boiler	78%		Electricity 0.14	0.56

Summary	m^3/year	£/y total	Kg CO_2/y	
	259	1329	1510	base total
	177	910	992	scenario
	81	419	518	saving

Shower (flow related)	Flow l/min	Time mins	Litres/use	Use/p/wk
Old house with high flowmixer showe	16.0	7.0	112.0	4.9
Scenario:	8.0	5.0	40	4.9

m^3/year	£/y total	Kg CO_2/y	
114	640	921	
41	229	329	
73	411	592	saving

Bath (fixed volume)	Litres/use	Use/p/wk
Old house with high flowmixer showe	80.0	0.7
Scenario:	80.0	0.7

12	47	9	
12	47	9	
0	0	0	saving

Kitchen sink hot water tap	Litres/person/day
Old house with high flowmixer showe	12.0
Scenario:	4.0

18	114	214	
6	38	71	
12	76	142	saving

Basins hot water tap	Litres/person/day
Old house with high flowmixer showe	9.0
Scenario:	9.0

13	85	160	
13	85	160	
0	0	0	saving

Electric showers	kW	l/min	Time mins	Litres/use	Use/p/wk
Old house with high flowmixer showe	0.0	0.0	0.0	0.0	0.0
Scenario:	0.0	0.00	3.0	0.0	4.0

0	0	0	
0	0	0	
0	0	0	saving

Washing M/C	kWh/use	Litres/use	Use/h/wk
Old house with high flowmixer showe	0.64	50.0	5.6
Scenario:	0.64	50	5.6

15	84	115	
15	84	115	
0	0	0	saving

Figure 6 Screenshot showing overall layout of model

3.1 Simple behavioural change

Indicative questions and answers are given in Table 2.

	Annual savings			
Question	**saving average(£)**	**kgCO₂**	**Water m3**	**Assumptions reference.**
Washing machines				
Do 3 loads a week instead of 4	21	21	3	1
Do 4 loads a week instead of 7	63	62	8	1
Do 7 loads a week instead of 12	105	103	13	
Dishwasher				
Do 7 loads a week instead of 14	156	270	8	2
Shower				
3 minutes instead of 6 in 10kW electric shower	183	541	23	3
5 minute electric shower per day instead of a bath	178	166	79	4
3 minute electric shower a day instead of 4 baths a week	93	69	44	4
3 minute shower at 6 litres/minute instead of 5 minutes at 9 l/min	155	328	39	5
3 minute shower at 6 litres/minute instead of a bath a day	378	849	90	5

Taps	£	CO_2	m^3	ref
wash up in a bowl instead of under a running tap	262	666	55	6
wash up in a bowl instead of the sink	26	67	5	7
rinse vegetables in a bowl instead of under a running cold tap	14	5	6	8
turn tap off whilst brushing teeth	100	33	44	9
put a spray head onto handwash basin hot tap	109	240	27	10

Table 2. The effects of simple water efficiency behaviour measures on savings in CO_2, water and money.

General assumptions for all questions	
unit water and sewerage cost	£2.30
unit electricity cost	£0.14
unit gas cost	£0.04
marginal boiler efficiency	78%
CO_2e/kWh electric	0.56
CO_2e/kWh gas	0.19
Mains water temperature	13.4 C
Hot water temperature	55 C
Shower temperature	41 C
Bath temperature	44 C
Household occupancy	4

Table 3. General assumptions for the questions in Table 2. All can be changed by the user if required.

Specific assumptions for the questions in Table 2 (reference numbers refer to final column):

1. 50 litres and 0.64kWh/cycle, cold fill, 40C program. Cost is for electricity, water only and detergent assuming 20p/load for detergent (cost and dose is very variable). With the assumptions used, detergent costs are about the same as water and energy costs.
2. 21 litres and 1.3 kWh per cycle, 20p/load for detergent tablets (cost varies).
3. Family of four everyone has a shower a day.
4. Family of 4, gas boiler with incremental boiler efficiency of 78%. Electric shower 10kW. Everyone bathes once per day. Bath volume 80 litres per use at 44°C.
5. Family of 4, gas boiler with incremental boiler efficiency of 78%. a shower per day for everyone.
6. 10 litre bowl instead of 10 minutes at 6 litres/minute, 3 times a day.
7. 10 litres instead of 15 (Thames Water water saving tips), 3 times a day.
8. 10 litres instead of 40 litres (10 minutes at 4 litres/minute) 4 times per household per week.
9. 30 litres saved per person per day, 4 person household.
10. 50% saving assumed. Base case 22 litres hot water per household per day from Anglian100 scaled up to 4 person household.

3.2 Potential for water, CO_2 and price savings from water efficiency retrofit measures

There is considerable interest in the impact of water efficiency retrofit measures, and these have in the past had very variable effects in terms of the volume of water saved (Waterwise 2008b). Clearly it is worth considering the extent to which these measures also have benefits in terms of CO_2 emissions, and the potential cost savings, particularly given that these measures could be considered in tandem with energy efficiency retrofits (either as a widespread programme or for households in fuel poverty). In order to do this, Waterwise provided some standard assumptions, which were analysed with WEMlite and the results, are shown in Table 4.

Situation	Tech baseline	Behaviour baseline	Tech post intervention	Behaviour post intervention	Savings/year for occupancy of 2.4		
					m^3	£	CO_2
Shower retrofits							
Old house, with bath upgraded to shower over bath (model base scenario a)	80 litre per bath, no shower	0.5 uses per head per day	8.5 kW electric shower (over bath)	0.1 uses per head per day for baths, 0.7 uses per head per day for showers, 7 mins per use.	8	-14	-98
Old house, with bath no shower, bath replaced with mixer shower.	80 litre per bath	0.5 uses per head per day	Mixer shower replaces bath (8 litre/min)	0.7 uses per head, 7 mins per use	1	11	44
As above but lower flow shower and shorter duration	80 litre per bath	0.5 uses per head per day	Mixer shower replaces bath (6 litre/min)	0.7 uses per head, 5 mins per use	17	73	172
High flow shower replaced with aerating showerhead	Mixer shower @ 16 litres min	Suggested 0.7 uses per head per day @ 7 mins per use	Mixer shower (aerated/ water efficient) @ 6 litres/min	Hold behaviour constant	43	167	345
Average flow shower, long durations, shower time reduced	Mixer shower @ 12 litres min	Suggest 0.7 uses per day @ 15 mins a day	Hold tech constant	Suggested 0.7 uses per day @ 5 mins per day	73	286	592
WC retrofits							
Old home, high volume flush toilet, replaced with efficient model	10 litres per flush.	5 flushes per person per day	4.5 litres actual flush volume	Hold behaviour constant	24	58	26
Old home, old toilet, save a flush or hippo bag installed	9 litres per flush	5 flushes per person per day	Save-a-flush or hippo bag placed in cistern	1 litre saving per flush @ 5 flushes per day	4	10	5
White goods							
High use for washing up, behaviour changes	Washing using 16 litres a time	3 times per day per house	Washing up bowl used in sink: 9 litres per wash up:	3 times per day	8	37	93
Upgrading to a dishwasher	Washing using 16 litres a time	3 times a day	Dishwasher installed: eco setting used 10 litres & 1.05 kWh per event	1 dish washer use per day and one 16 litre bowl of water.	8	-6	-74
Upgrading an old washing machine	61 litres & 0.66 kWh per load at 40 °C for an old machine.	0.8 times per day per house	35 litres & 0.63 kWh for new machine on 40 °C eco setting	Behaviour constant.	3	9	8

Table 4. The effects of simple water efficiency retrofits on savings in CO_2, water and money.

Specific assumptions for Table 4:

1. Boiler efficiency 78%
2. Water charge £2.30/m^3
3. Occupancy 2.4
4. Washing machine used 0.8 times per household per day, energy and water data from MTP 'What if' tool for 1998 and 2006 machines on 40°C cycle.
5. Water use assumptions supplied by Waterwise for illustrative purposes, best estimates based on reported water company assumptions pending consultation. Detergent cost not included in scenarios.

Shower retrofits in homes that only have baths: Table 4 shows that even fitting a modest powered 8.5 kW electric shower over a bath can lead to increased CO_2 emissions and running costs if the energy source switches from gas. Clearly such calculations are sensitive to assumptions about shower and bath frequency and shower duration. Also it is assumed that the base case was a gas system boiler, and that this is retained for supplying other hot water needs. If this was not the case (e.g. in a household that turns the gas boiler off in the summer and boils a kettle for washing up etc) then the reduced storage heat losses could swing the balance in favour of the instantaneous electric shower. Such complexities are better modelled in the whole house model where changes in heating season duration and storage losses can be included.

If we consider the situation where 4 baths per week are replaced by 4 short 3 minute showers we see a water saving of around 33m^3 per year at standard 2.4 person occupancy and a modest cost saving of around £46 based on the assumptions above. However the CO_2 emissions rise by nearly 100kg a year and if the situation is moved to a cheaper water region, the cost saving is halved.

Installing a mixer shower instead of an electric one offers more robust savings so long as the flow rate can be regulated to 8 litres per minute or less and shower duration is assumed to be modest. Also demonstrated is the fact that even an increase in use frequency (typically associated with a shift from baths to showers) still allows a water, cost and CO_2 saving compared to a standard bath.

Shower head retrofits and modified shower behaviour: As would be expected, a decrease in shower flow rate leads to very significant water, energy and CO_2 saving without reducing shower duration. However such a saving may be best viewed as reduced wastage since the base case situation (of a longer than average shower duration in a high flow rate shower) would result in higher than typical hot water use equivalent to a bath a day. Simply decreasing shower duration (from 15 minutes to 5) for a standard flow rate shower (12l/min) has the largest savings (water, money, CO_2), emphasising the importance of behavioural change, regardless of policy drivers for retrofitting.

WC retrofits: As expected, WC retrofits result in small CO_2 savings, but should nevertheless be installed for their water efficiency benefits.

White goods: As expected, dishwashers can save water but will increase CO_2 emissions, and may also be more expensive to run (especially given that purchase cost is excluded from these figures). Clearly these results are very sensitive to assumptions about user behaviour. The issue is further complicated by the fact that people with dishwashers tend to hand-wash in a different way to people without dishwashers (ISIS 2007, illustrated in Table 24), and it is not clear the extent to which this represents a behavioural response to the type of items that are being washed by hand (e.g. just saucepans etc, no plates or glasses), compared to a behavioural difference that existed before the dishwasher was acquired (e.g. people who purchase dishwashers might be more likely to hand-wash under a running tap regardless of item). The dishwasher-kitchen sink interaction is also investigated using WEM in order to incorporated heat gains and losses, discussed in section 5.4.2.

The benefits of upgrading an old washing machine to a newer model are marginal, and given the embodied energy and purchase price, this is clearly not a measure that should be considered until the existing machine is being replaced anyway. It should be remembered that the differences between the most and least efficient new machines are much narrower thanks to energy labelling and that choosing white goods on their water consumption can lead to increases in CO_2 emissions, as discussed in Appendix 6.6.

Boiler replacement: The model could be used to examine the savings due to replacing an existing boiler with a newer condensing model, but this has not been undertaken since the primary purpose of such a measure would be for space heating and this would dominate any assumptions made regarding hot water savings.

3.3 Implications of future price forecasts on water saving

There are large differences between the cost of metered water and sewerage in different regions of the UK (e.g. Thames Water £1.48, South West Water £4.01, from OFWAT 2007). This disparity is much larger than any predicted price increases, in relative terms, over the next decade. The effect that water price increases will have on behaviour and water use is unknown, but will be affected by how households respond to the increased water metering.

There is a general expectation that the cost of energy will go up by more than the cost of water. Whether or not this will affect how much hot water people use (and therefore the CO_2 emissions associated with water use) is difficult to gauge, and will vary according to things such as social group, relative price increases compared to other commodities, prevailing social attitudes to water, penetration of smart metering and energy awareness, and many other factors. The rate at which electricity prices will increase relative to gas prices is also very uncertain.

Because of the magnitude of these uncertainties, a detailed analysis of the impact of future price forecasts on the relative impacts of water efficiency measures does not seem justified at this time. The simple water model that is one of the project outputs has user modifiable values for the price of water, electricity, gas and oil, so is therefore sufficiently adaptable to enable this analysis to be undertaken if specific hypotheses on price forecasts are available in the future.

3.4 Limitations of the simple model

The simple model only considers the *marginal* energy used to deliver water at a given temperature. The model does not calculate *fixed* losses (i.e. the ones that do not vary significantly with the volume of water used) such as hot water storage or secondary circulation. Gains that contribute to space heating or cooling are also ignored. These issues are all considered in the Water Energy model (WEM) described in section 4.

4 Development of the Water Energy Model

Whilst the simple model (WEMlite) described in section 3 allows the impact of various changes in appliances and behaviour to be investigated quickly and easily, it does not place this within the wider context of other energy uses within the home. The main energy use with which domestic water use interacts is space heating. Additionally, WEMlite cannot inform plumbing system design because it does not incorporate fixed losses. The model described in this section defines a fixed hot water use pattern (e.g. duration and frequency of showering) and the details of the hot water system (boiler efficiency, insulation, pipe lengths etc), and this allows us to calculate the total energy required with some degree of certainty. It is also possible to determine where the losses occur and to model performance for a number of use patterns.

There are various ways in which domestic hot water energy use can be calculated, and the approach taken in the current study has been to model it from the bottom up using available micro-component data. An enormous number of assumptions are necessary regarding water using behaviour, and it is difficult to calculate the implications of each of these assumptions being incorrect. A physics based model that models energy use for a given water use pattern will allow us to identify measures that will result in an energy saving for a given behaviour. This allows some priority setting in terms of where design and regulatory effort can best be focussed. The user of the model can easily change assumptions regarding water use.

4.1 Whole house scenarios

One of the aims of the project was to investigate the relative importance of energy use due to hot water in various scenarios. The basic scenarios indicated were:

- Existing housing stock
- Existing housing stock, with water meter installed
- Existing housing stock, with water meter and water efficient retrofits installed.
- New house with sensible water efficient specification, built to CSH level 3
- New house built to CSH level 3, with rainwater harvesting system

We added a further scenario that we regard as important:

- New house, in the absence of CSH or any sustainability drivers.

Generating these scenarios required some general assumptions (e.g. about occupancy, season and behaviour), and these assumptions are discussed in Appendix 2. Some specific assumptions related to each scenario were also necessary (summarised below, and discussed in more detail in Appendix 2).

4.2 Scenario description

Scenario	Description
Existing house	Existing house (pre 1990 build), representing basic housing stock. May have had various upgrades to boilers, bathroom etc, but not with water efficiency particularly in mind, or more or less than typical housing stock would be expected to have undergone.
Existing, metered	Existing house (as in scenario 1), but have opted to have a meter installed (but not a water enthusiast). Assume that installation of the meter is accompanied by an interest in water efficiency of the occupants, and some behavioural change from the baseline existing housing stock (but no appliance change).
Existing, metered, water efficiency measures	As metered scenario, but with cheap and simple water efficiency measures. Assume that the installation of the retrofit does not alter the behaviour of the occupants compared to the behavioural change in scenario 5. (e.g. they don’t spend longer in the shower because it’s low flow). Savings per household per day: Water efficient shower head (6.1 litres), tap inserts (10.8 litres, divided between kitchen and basin, hot and cold in proportion to their total use), WC modification (11.2 litres).
New house	New house (post 1990) build, but built before CSH water calculator, and not built with EcoHomes rating in mind, so ‘typical’ build spec.
CSH 3	New house built in 2008, with a water efficient specification that allows it to meet CSH level 3. No bath.
CSH 3 plus rainwater	New house built in 2008 to CSH level 3 but with rainwater harvesting allowing a higher flow shower.

Table 5. Basic assumptions for the various scenarios that have been modelled. Further detail and rationale for these assumptions is given in Appendix 2.

The water use by various micro-components within each of the scenarios is based on our best judgement from the information available to us, is summarised in section 2 and discussed in detail in Appendix 6. Inevitably some of the assumptions will not be applicable to all situations. However, different scenarios can be tested as and when more robust data becomes available on any element and the model is designed to be transparent and easily modified so that alterations can be made to more fundamental parameters if required.

4.3 Water Energy Model development

A full description of the methodology is given in Appendix 3. The model adds to the simple model by incorporating a number of factors that relate to the total energy used by water in the household, including consideration of how this relates to the total temperature balance in the house. Except for embodied carbon in water, all calculations are performed in terms of energy and converted into CO_2 emissions at the last stage of calculation where this is required. Fuel factors can be varied but the DEFRA figures are used in this report (Table 6).

Fuel	Fuel prices p/kWh	kgCO_2/kWh net CV	kgCO_2/kWh gross CV
Gas	4.03	0.206	0.185
Electricity (day)	13.95	0.562	0.562
Electricity (night)	8.27	0.562	0.562
Oil	6.09	0.258	0.245
Coal	2.77	0.313	0.296
LPG	5.93	0.225	0.214

Table 6. Fuel factors used in the model. (from DEFRA, 2008)

Electric showers are assumed to operate at full rated power and so a flow rate is calculated based on this and the energy use is calculated from the power and duration independent of water temperatures. White goods energy use is calculated from the energy rating, cold fill is assumed.

The model considers heat loss from storage, pipes and at point of use, in some detail. The useful utilisation of hot water losses in the heating season is calculated based on an algorithm derived from SAP and PHPP (PHPP 2007).

As both the WC LCA report (Gandy *et al.*, 2008) and PHPP consider space heating losses to cold water to be significant, this has also been calculated based on best available estimates of the temperature rise of cold water in WC cisterns and pipes. Cold water warmed in pipes that is then mixed with hot water (for example in a shower or bath) is not counted as a loss as less hot water is required.

4.4 Results from the Water Energy model

This section describes the CO_2 emissions impacts of water use under the various conditions we have been asked to investigate. There are obviously an enormous number of possible permutations given the variety of heating systems, and since the model is one of the project outputs, specific areas of interest can be investigated further by Energy Saving Trust/Environment Agency in the future.

Standard assumptions

- Occupancy 2.4 person
- Building floor area 84 m^2
- System boiler with 12m primary pipe work and 120 litre cylinder with 25mm foam insulation.
- Hot water storage temperature 55°C[3]
- Cold water feed 13°C
- Mains water embodied carbon 0.75 kg CO_2e/m^3
- 28m of 15mm hot water pipe work.
- Outdoor water use 5 litres/person/day

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[3] Lower than recommended in plumbing guidelines, but based on actual recorded values (e.g. Energy Saving Trust, 2008)

4.4.1 Note on CO_2 and energy

The model results have been presented in terms of CO_2 rather than kWh and gas heating has been assumed (unless otherwise stated). Using CO_2 rather than kWh means that the higher carbon emissions of electrical heating (for example in white goods), is factored in. However the CO_2 split by fittings is very dependent on fuel choice and this needs to be remembered when considering the results and how to use the model. Figure 7 demonstrates the importance of the carbon emissions of the fuel source. This illustrates a new dwelling, with water use identical in each case. In the top pie charts where the hot water system is gas, total CO_2 emissions from hot water are 925kg, and the white goods result in a high proportion of the total emissions (despite being a small proportion of water use), owing to the fact that they rely on electrical heating. The pie charts for a dwelling with electrically heated water are shown in the middle; the total CO_2 emissions are much higher than for a house with gas heating, and white goods are of lesser importance here because the larger hot water volumes needed for other appliances dominate. In the final pie charts in Figure 7, water heating is by a low carbon source (in this case biomass[4]) so the total CO_2 emissions from hot water are low and the washing machine and dishwasher are responsible for more than half of the emissions.

Note that whilst dishwasher use is assumed to remain constant in all three scenarios, the net CO_2 emissions differ depending on the space heating fuel source because some of the heat from the dishwasher is assumed to contribute to space heating. Consequently if the building is heated by gas or biomass, some of these fuels are in effect replaced by electric heating, with correspondingly higher emissions.

In each case, CO_2 emissions attributable to the water supply/treatment/disposal process that occur outside the home (i.e. utility company emissions) are included within these figures, so they represent total emissions from water use.

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[4] There is considerable controversy as to the correct CO_2 factor to use for various forms of biomass heating. The authors have used the DEFRA figure to illustrate the effect of a low carbon heat source but are not implying that biofuels can be considered to be zero carbon or that widespread use for space heating is the most sensible use of this limited resource.

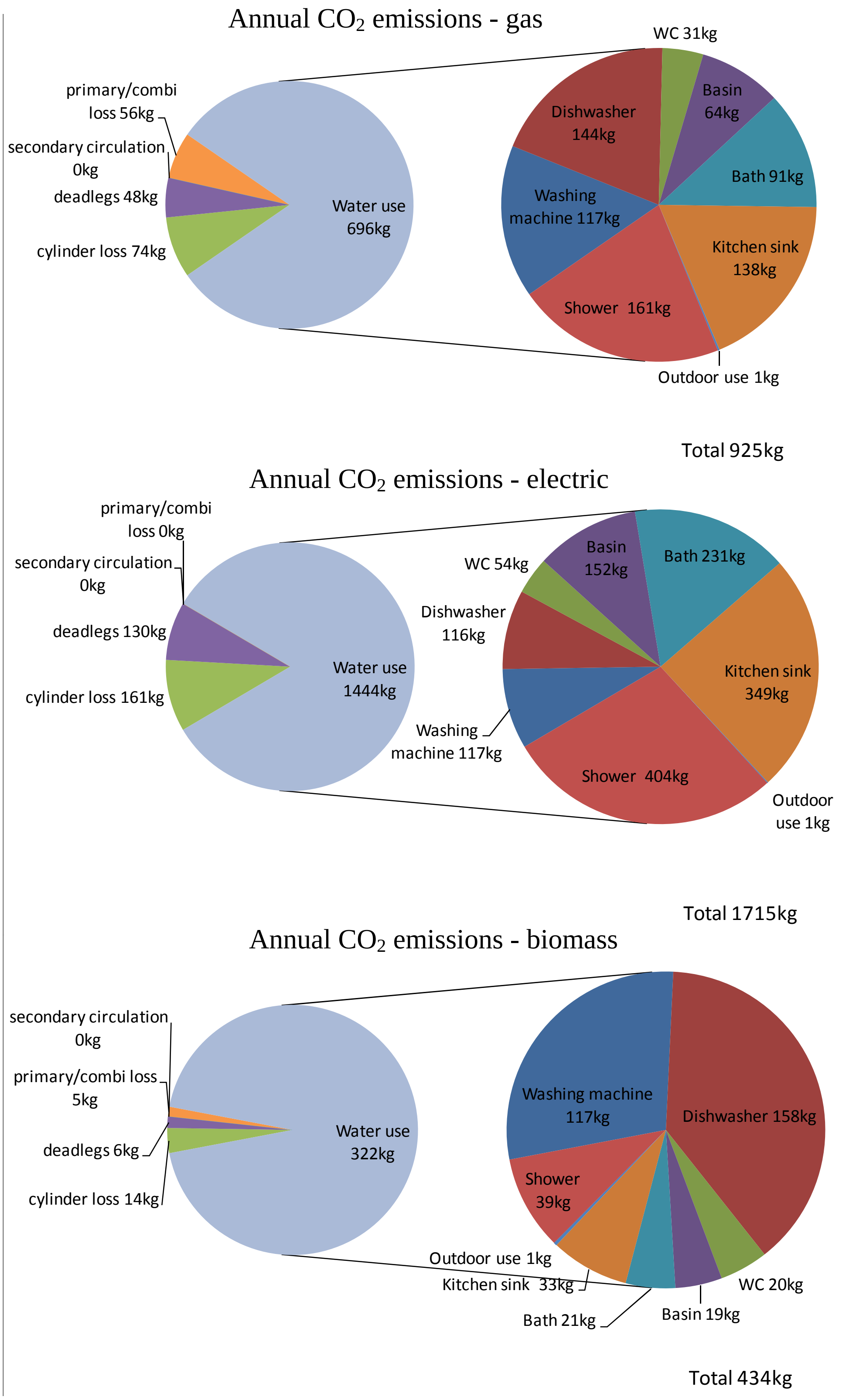

Figure 7. CO_2 emissions split for new dwelling with gas, electric or biomass hot water heating (auxiliary electricity for pumps and fans excluded). The water use is the same in each, but the fuel factor means that both the proportions of CO_2 emissions attributable to each appliance, and the total CO_2 emissions are very different. Note that whilst dishwasher use is identical, some of the heat loss from the appliance is taken as a useful gain for space heating. The CO_2 cost of the heating this displaces differs between the three scenarios, see text for details.

4.4.2 Existing housing stock

The basic water use assumptions for this scenario are given in Table 7 and discussed in detail in Appendix 2.

Device	**vol/use**	**freq/p/d**
Toilet	9.4	4.66
Kitchen taps	59[5]	Taps taken as volume/day, 40% cold
Basin taps hot	42	Taps taken as volume/day, 30% cold
Bath	70.00	0.21
Washing machine	50.00	0.34
Shower	25.70	0.59
Dishwasher	21.30	0.29

Table 7. Water use assumptions for existing stock dwellings. Based largely on 2008 data from Anglian100. Details regarding assumptions in Appendix 2.1.

The baseline hot water system in existing stock was assumed to be:

- Boiler efficiency 78% (i.e. fairly new model but not condensing)
- Cylinder volume 120 litres with 25mm foam insulation

Figure 8 shows the water use in this property. This is broadly similar to commonly assumed micro-component splits from other sources. Shower water use is lower than in new houses (due both to lower shower frequency and flow rates), and WC use is high, both are highly dependent on the age of the bathroom suite within the property.

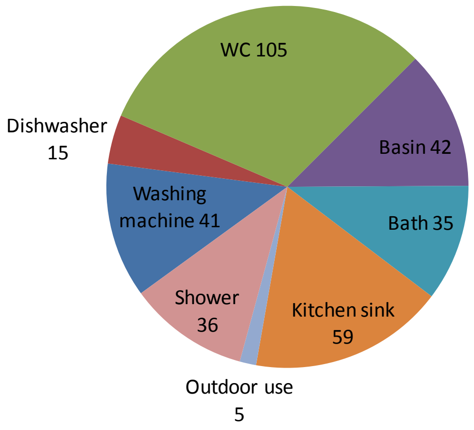

Figure 8. Water use (litres/household/day) assumed in existing properties. Water use data as in Table 7, but expressed for a standard 2.4 occupancy. Total water use 338 litres/household/day.

Figure 9 shows the output from the model in terms of CO_2 emissions for this standard existing dwelling. As expected, hot water using appliances dominate, but the high water use for WC flushing results in 53kg of CO_2 emissions per year. Around 50% of these emissions are due to utility company emissions and 50% due to heat loss as the WC water warms up.

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[5] Data on volume/use and use frequency is uncertain, but more accurate figures for volume/day are available. Consequently tap use is grouped to total daily use per household.

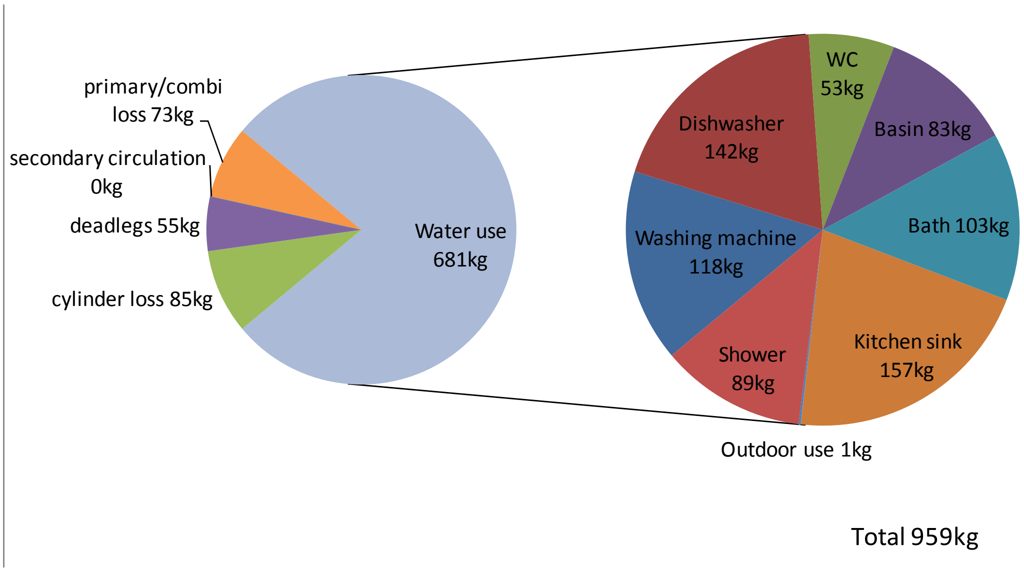

Figure 9. CO_2 split for existing stock with gas system boiler and hot water cylinder.

4.4.3 Existing housing stock with modifications

Having established the baseline impacts of the CO_2 emissions associated with water in existing dwellings, the next stage is to modify some of the water using appliances to see what effect this has. The standard assumptions on hot water system type (78% efficient gas boiler, 120 litre cylinder with 25mm foam insulation) are retained.

Figure 10 demonstrates the effects of various modifications on the annual CO_2 emissions due to water heating for a typical existing dwelling. Water metering is assumed to result in a 12% decrease in water use by all appliances. Justification for this assumption is given in Appendix 2.

When water efficient retrofits are also implemented (assumptions in Table 5, results in third stacked bar in Figure 10), further decreases in CO_2 emissions result. The benefits of simple energy efficiency measures (extra cylinder and pipe insulation) are illustrated in the fourth stacked bar; actual domestic hot water used remains constant but the hot water system losses and gains decrease. The final stacked bar in Figure 10 shows the potential additional benefit of simple behavioural change (3 minute daily shower per person at 5.8 l/min, no baths). With reduced bathing, kitchen sink and dish washer use become dominant and it is likely that an energy aware householder could make further significant savings in these areas although we have no evidence on which to base any modeling.

Whilst an inefficient way to heat the dwelling, we can see that for poorly insulated dwellings, over half of the hot water system losses can usefully contribute to space heating throughout the year.

Definitions of terms used in the stacked bar charts.

Delivered hot water (expressed in kg CO_2/year)
This is the heat energy delivered at the fitting including boiler efficiency losses but excluding all other losses. All electricity use for the dishwasher and washing machine are included.

= (Heat x fuel factor/boiler efficiency) + (kWh electricity x fuel factor)

Utility company (expressed in kg CO_2/year)
This is the amount of CO_2 generated by the utility company associated with the total volume of water used.

Utilisation factor
This is the proportion of system losses that usefully contribute to space heating and depends on the heating season length and the space heat demand of the building.

Useful hot water gains contributing to heating (expressed in kg CO_2/year)
These contribute to heating the house.
Useful hot water gains = total heat losses from cylinder, dead legs, primary and secondary pipes, warm water cooling and cold water warming x *utilisation factor*

Space heat demand net of gains (expressed in kg CO_2/year)
This is the annual space-heating requirement after subtracting the useful gains from the hot water system and losses to cold water warming (e.g. WC cistern).

Where space heat demand net of gains = heat demand - useful hot water gains

Hot water system losses (expressed in kg CO_2/year)
These are the hot water system losses that do not contribute to useful space heating

Hot water system losses = total heat losses from cylinder, dead legs, primary and secondary pipes x (1-utilisation factor).

Note that this doesn’t include cold water warming and warm water cooling. These are irrelevant when the house does not need heating, and do not require energy input over and above that needed for delivered hot water. The losses that are included, e.g. cylinder heat loss, do require additional boiler input and so are counted here.

Boiler efficiency
Boiler efficiency is factored in to each of the above and is not reported as a separate loss.

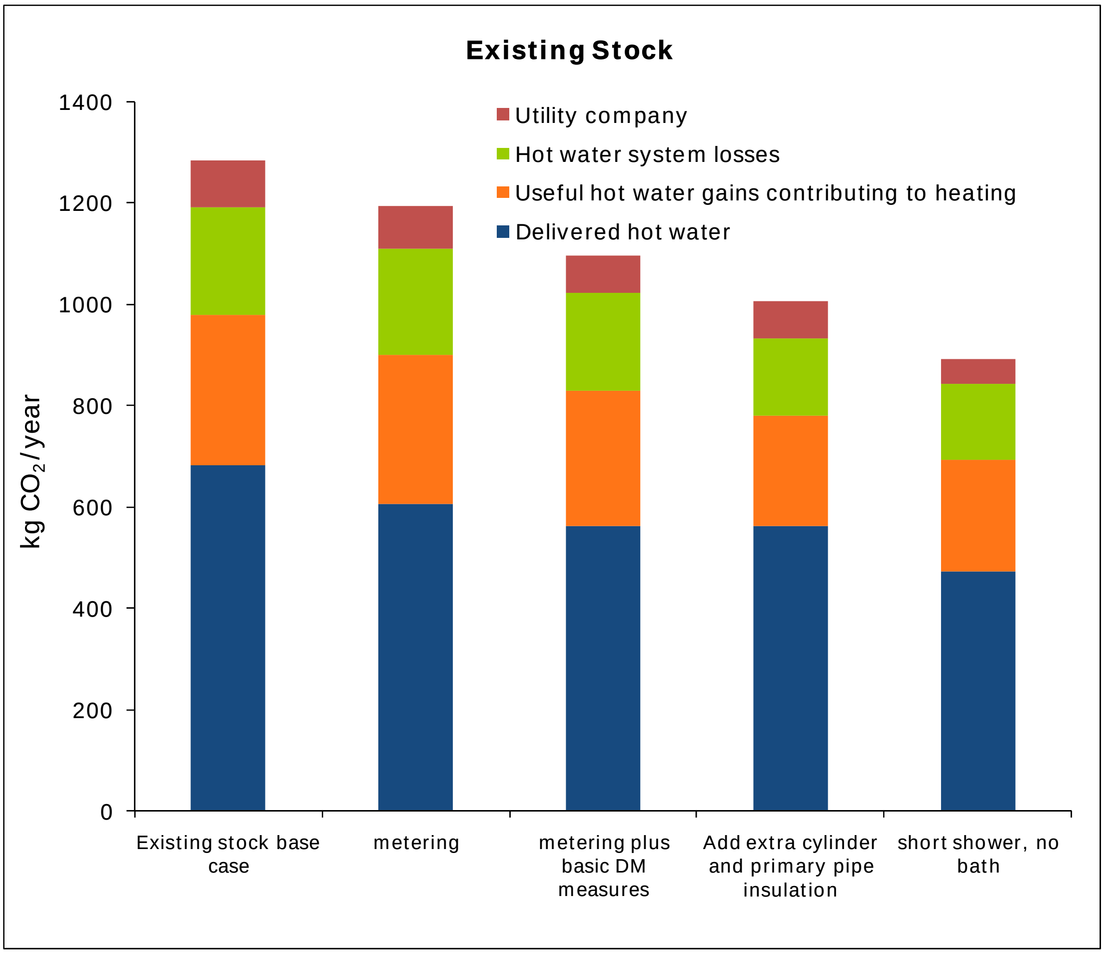

Figure 10. CO_2 emissions for existing stock assuming a range of options. Measures are cumulative.

4.4.4 New dwellings to 2006 Building Regulations

The water use in new dwellings is shown in Figure 11. The difference between new dwellings and old dwellings (compare Figure 11 and Figure 8) reflects a trend towards increased showering, an increase in shower flow rates, more efficient white goods and the decrease in WC flush volumes.

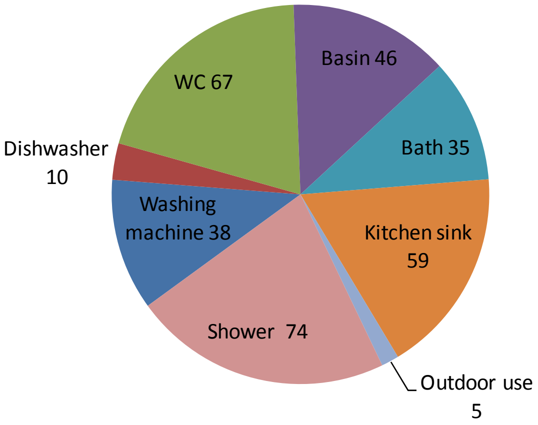

Figure 11. Water use in new dwellings, showing an increase in hot water use and a reduction in WC use. Total water use 334 litres/household/day. Water use data as in Table 8, but expressed for a standard occupancy of 2.4. Assumptions discussed in Appendix 2.2.

The CO_2 emissions associated with this water use are illustrated in Figure 12. The main difference between existing stock and new stock (i.e. between Figure 9 and Figure 12) is the increase in CO_2 emissions due to showering. Total CO_2 emissions are marginally lower than in existing housing stock; 925kg compared to 959kg (largely because the increase in showering is offset by improved gas boiler efficiency in new homes). However, the assumptions on water use in new homes are based on very limited data, particularly for showers, which show a big difference compared to existing dwellings. The result is therefore highly sensitive to this assumption and better data is needed.

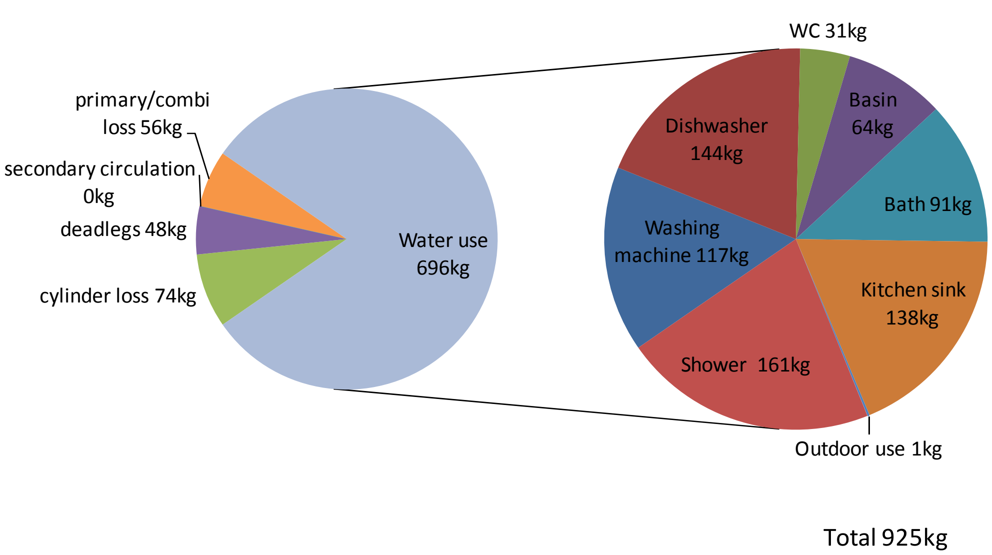

Figure 12. CO_2 emissions from water use in new homes.

Device	vol / use	freq / p / d
Toilet	6.00	4.66
Kitchen taps	59	Taps taken as fixed event, 40% cold
Basin taps	42	Taps taken as fixed event, 48% cold
Bath	70	0.21
Washing machine	46	0.34
Shower	41.12	0.75
Dishwasher	15	0.29

Table 8. Water use assumptions for new buildings. Discussed in Appendix 2.2.

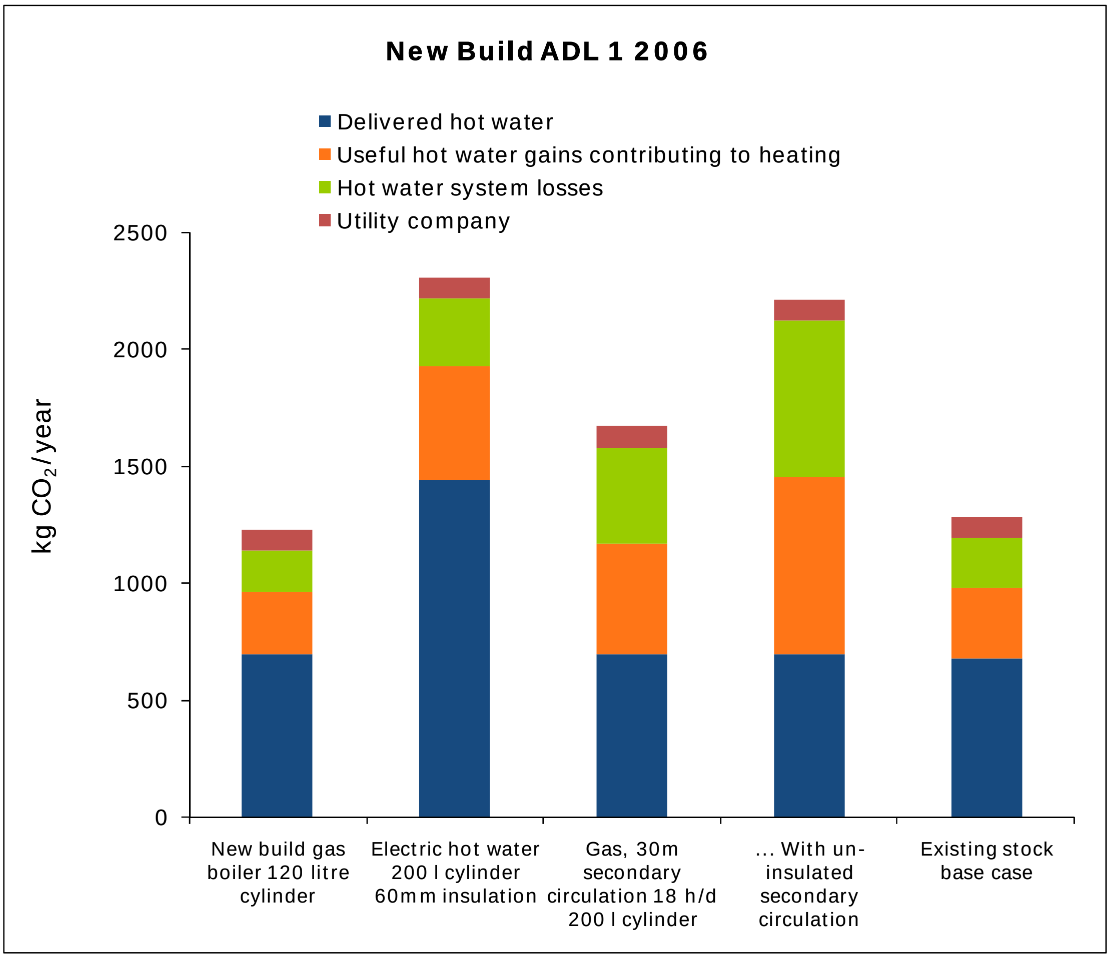

Figure 13. Calculated CO_2 emissions for new build (compliant with Approved Document L1 of 2006 Building Regulations). The graph shows the obvious impact of fuel choice and potential losses due to secondary circulation. Water use is the same in each situation, except in the final stacked bar which is the existing housing stock for comparison (and water use is lower in terms of litres, but very similar in terms of CO_2 emissions).

The first bar in Figure 13 shows the base case new build dwelling from Figure 12. The second bar illustrates the effect of switching to electric hot water (off peak storage at 60°C with a 200 litre cylinder and 60mm foam insulation)[6]; and largely reflects the higher fuel factor of electricity.

Whilst more likely to be installed on larger dwellings, secondary circulation was modelled for the same dwelling in order to illustrate the magnitude of the additional CO_2 emissions (third stacked bar in Figure 13). At this level of building insulation, just over half of the losses are thought to contribute to space heating. The effect of not insulating the secondary circulation in the same system is shown in the next stacked bar. Existing housing stock (as in Figure 10) is included for comparison. It is important to note that in the absence of regulatory, or other, pressure to prevent it, there is considerable scope for new build dwellings to have higher CO_2 emissions from hot water than existing dwellings.

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[6] The cylinder difference is based on the assumption that it is designed to be heated using off peak electricity, and is therefore larger and better insulated than the cylinder for a conventional gas system boiler might be.

4.5 New-build energy and water efficient dwellings

The project brief required us to investigate the CO_2 impacts of water within the context of the Code for Sustainable Homes (CSH). This raises two major complications:

Issues relating to the reliability of the water calculator. The approach taken was to use the CSH water calculator to demonstrate compliance, but not to predict actual water use. Appliance specification is detailed in Appendix 2, code compliance is illustrated in Table 9 and assumptions on resulting water use are detailed in Table 10 and illustrated in Figure 14. It should be noted that there is no bath in this scenario, as it is difficult to see how it is possible to meet Code level 3 without either unusable low flow rates at some appliances or by offsetting water use with a rainwater harvesting system. *NB: The water calculator is under review, and the version used in the current study is based on the April 2008 Technical Guide.*

The space heating requirements of houses at different code levels. This is important because the space heating requirements of the building will affect the amount of losses from the hot water system that can reasonably be regarded as providing ‘useful’ space heating, i.e. the utilisation factor. CSH does not clearly define space-heating demands (in kWh/m^2) and focuses on carbon emissions instead. This means that ‘low carbon’ technologies can be offset against a lower standard of thermal efficiency, and makes it very difficult to work out the relationship between space heating and water heating. Consequently the decision was taken to use Passivhaus and AECB energy standards. The annual space heat demand in new build energy efficient dwellings was assumed to be 40-45kWh/m^2 (before gains due to domestic hot water). This is equivalent to AECB silver standard. Note that this level of thermal efficiency will not necessarily be met by even CSH level 5 houses, but will be met at CSH level 6. The relationship between standards is discussed in the box on page 43.

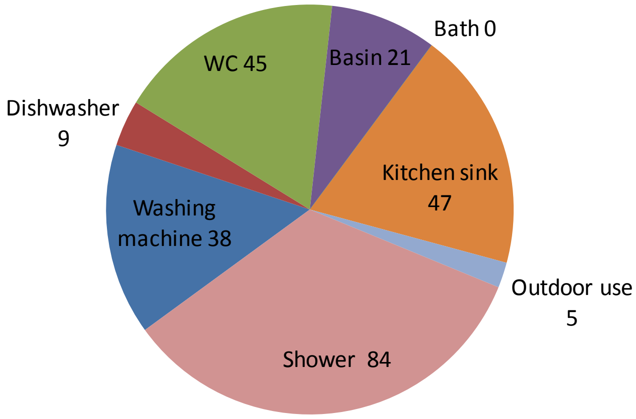


Figure 14. Water use (litres/household/day) in a household complying with CSH level 3 for water fittings. Estimated water use 249 litres/household/day. Same figures as in Table 10, but expressed for a standard occupancy of 2.4.

Energy standards and CSH levels

The Code for Sustainable Homes follows current building regulations in setting energy standards in terms of a percentage reduction in carbon emissions. The emissions are predicted using SAP, based on the BRE domestic energy model. This includes energy used for heating, hot water, fans and pumps, and lighting.

Part L of the Building Regulations: level of carbon emissions forms the base for CSH levels, and is derived from a "reference model" – the proposed design built to set standards of insulation and heating efficiency.

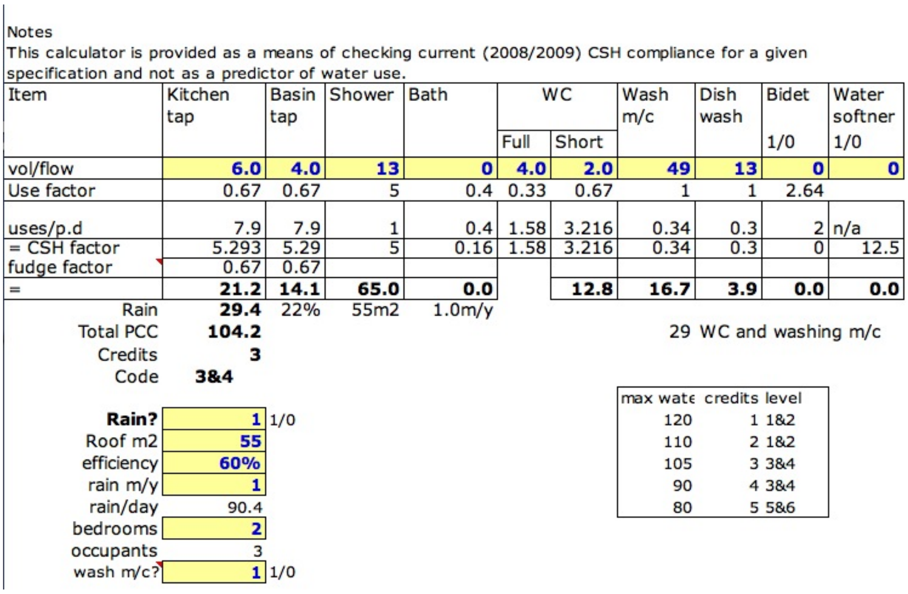
CSH levels 3&4: these levels of the Code require the calculated carbon emissions to be 25% and 44% lower than the Building Regulations level. Reductions of this order in heating energy use are achievable by increased insulation. The total includes hot water, but hot water consumption is fixed in SAP and water efficiency measures are ignored, so level 4 generally requires solar hot water.

CSH level 5 requires a reduction of 100% in building services carbon emissions. This cannot be achieved purely through efficiency so renewables are required, such as biomass heating. This tends to make extra insulation a pointless additional cost in terms of code compliance. Renewable electricity generation is also required.

CSH level 6 adds household electricity use to the equation, requiring further renewable electricity generation to make the house "zero-carbon". The level 6 standard also includes a requirement for insulation levels based on the total heat loss per m^2.

Passivhaus is an energy standard for low energy buildings being adopted across Europe. It just covers heating, and sets an absolute heating energy standard, at 15kWh/(m^2.year). This is not zero-carbon, but does represent around an 80% cut in carbon emissions for heating. The heating energy is calculated in a program similar to SAP, but with climate data specific to a location, so different levels of insulation are needed for different climates. The CSH level 6 heat loss is approximately that required for Passivhaus.

AECB Silver The AECB has adopted the Passivhaus standard, and has extended the methodology to a lesser standard considered easier to adopt now as a stepping stone to Passivhaus. This standard uses a heating energy limit of 40kWh/(m^2.year).



Notes

This calculator is provided as a means of checking current (2008/2009) CSH compliance for a given specification and not as a predictor of water use.

Item	Kitchen tap	Basin tap	Shower	Bath	WC		Wash m/c	Dish wash	Bidet	Water softner
					Full	Short			1/0	1/0
vol/flow	**6.0**	**4.0**	**13**	**0**	**4.0**	**2.0**	**49**	**13**	**0**	**0**
Use factor	0.67	0.67	5	0.4	0.33	0.67	1	1	2.64	
uses/p.d	7.9	7.9	1	0.4	1.58	3.216	0.34	0.3	2	n/a
= CSH factor	5.293	5.29	5	0.16	1.58	3.216	0.34	0.3	0	12.5
fudge factor	0.67	0.67								
=	**21.2**	**14.1**	**65.0**	**0.0**		**12.8**	**16.7**	**3.9**	**0.0**	**0.0**

Rain	**29.4**	22%	55m2	1.0m/y
Total PCC	**104.2**			
Credits	**3**			
Code	**3&4**			

29 WC and washing m/c

max wate	credits	level
120	1	1&2
110	2	1&2
105	3	3&4
90	4	3&4
80	5	5&6

Rain?	**1**	1/0
Roof m2	**55**	
efficiency	**60%**	
rain m/y	**1**	
rain/day	90.4	
bedrooms	**2**	
occupants	3	
wash m/c?	**1**	1/0

Table 9. Implementation of CSH Water Calculator to demonstrate compliance with Code Level 3 (rainwater and higher flow shower option) but not used for actual water use prediction.

Device	**vol / use**	**freq / p / d**	
Toilet	4.0	4.66	
Kitchen taps	47.2	Taps taken as fixed event, 40% cold	20% reduction assumed
Basin taps	21.0	Taps taken as fixed event, 48% cold	50% reduction assumed
Bath	none		No bath
Washing machine	46	0.34	
Shower	35	1	
Dishwasher	13	0.29	

Table 10. Water use assumptions with appliances that meet CSH level 3.

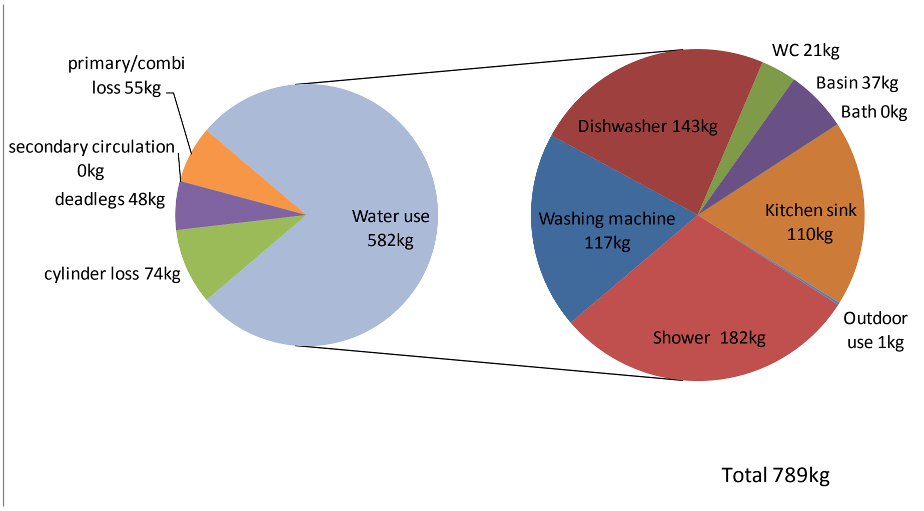


Figure 15. CO_2 emissions associated with water use in an energy efficient dwelling with an annual space heating demand of 40-45kWh/m^2. Water use is compliant with CSH level 3. Gas boiler assumed.

The micro-component split of CO_2 emissions resulting from water use are illustrated in Figure 15. As in the other scenarios modelled, the impact of white goods is high owing to them using electrically heated water. The contribution from showering is also large (owing to the high shower water use). This scenario is also illustrated in Figure 16, alongside some potential modifications to the water system in the dwelling. If a home is to comply with Code level 3 water use but a higher flow shower is required (say, 13 l/min), a rainwater harvesting system could be installed. The CO_2 emissions impact of this is illustrated in the second stacked bar of Figure 16 (rainwater system had plan roof area 55m^2, rainfall 1000 mm/y, system efficiency 60%, rainwater used for WC and washing machine). Note that while the building complies with CSH level 3 water use, the installation of rainwater harvesting has resulted in this dwelling having CO_2 emissions as high as existing housing stock or new housing stock with just basic regulatory compliance (compare the second stacked bar in Figure 16 with the first and last stacked bars in Figure 13).

If a house complying with Code level 5 water use was required (still with no bath) this could be achieved using the same appliances, with a rainwater harvesting system, and reducing the shower flow rate to 7 litres/minute (data not shown).

The CO_2 emissions from the operation of a rainwater system (i.e. pumping energy) have been assumed to be the same as those due to mains water supply (and so have been incorporated into the utility company part of the stacked bar in Figure 16). This is a crude and rather optimistic assumption; the CO_2 emissions will be higher in most instances, but are not modelled in detail here. The wider environmental considerations relating to rainwater are considered in section 5.3.

The right hand stacked bar in Figure 16 shows the effect of complying with the AECB water standards rather than using the CSH water calculator. The hot water system losses are reduced owing to the requirement for short dead legs, and the delivered hot water use is also lower owing to a 5.8 litre/minute shower. All other water uses are assumed to be constant.

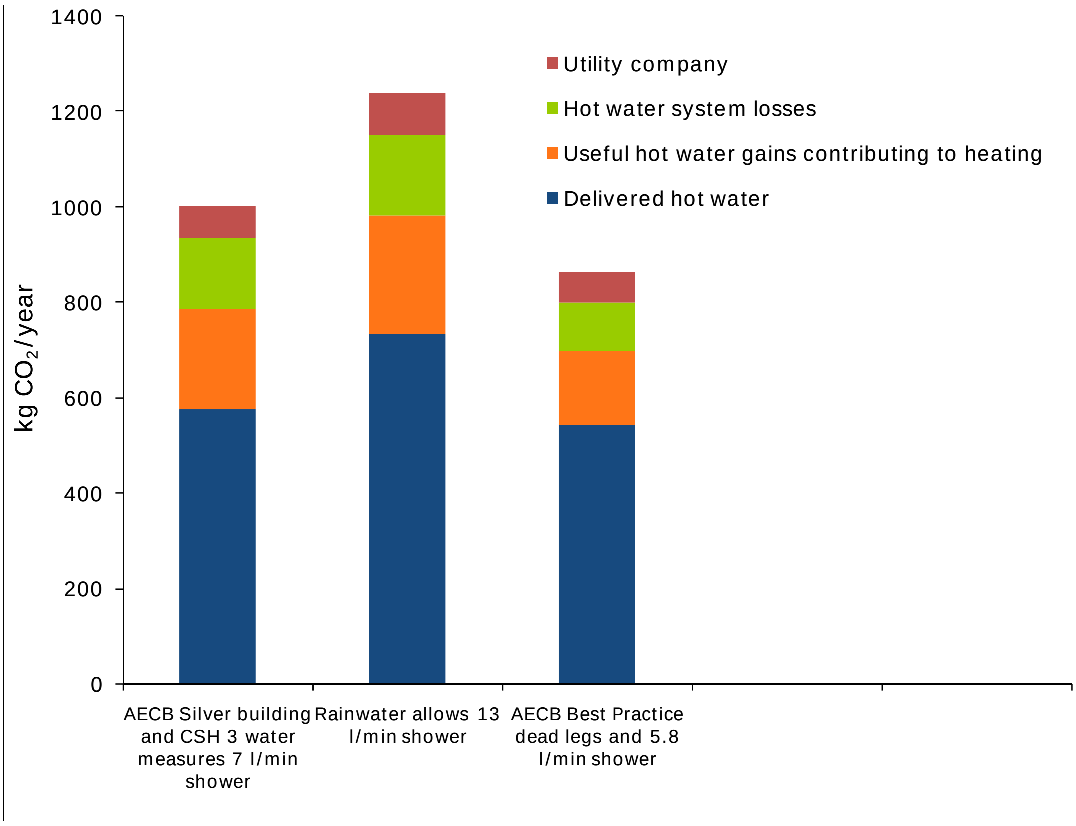


Figure 16. Modifications to an energy and water efficient dwelling, complying with AECB silver standard (energy) and CSH level 3 (water). Total emissions are lower than for standard new dwellings. Assuming sufficient roof area and rainfall, rainwater allows a higher flow shower for a given code level leading to higher emissions (second stacked bar) and therefore results in similar emissions to existing housing stock. The final bar illustrates compliance with the AECB Best Practice water standard. Compare the CO2 emissions with those in Figure 13.

4.5.1 Contribution of hot water to CO_2 emissions in highly thermally efficient dwellings (Passivhaus or Code 6 building envelope)

In existing dwellings and typical new build dwellings, the CO_2 emissions associated with space heating far exceed those due to water use. However, as the building envelope improves in efficiency and less space heating is needed, the hot water demand starts to dominate the CO_2 emissions. The effect is exaggerated because the utilisation factor for the hot water system losses is reduced as the heat demand reduces (i.e. less of the waste heat is useful, because the building needs less heating).

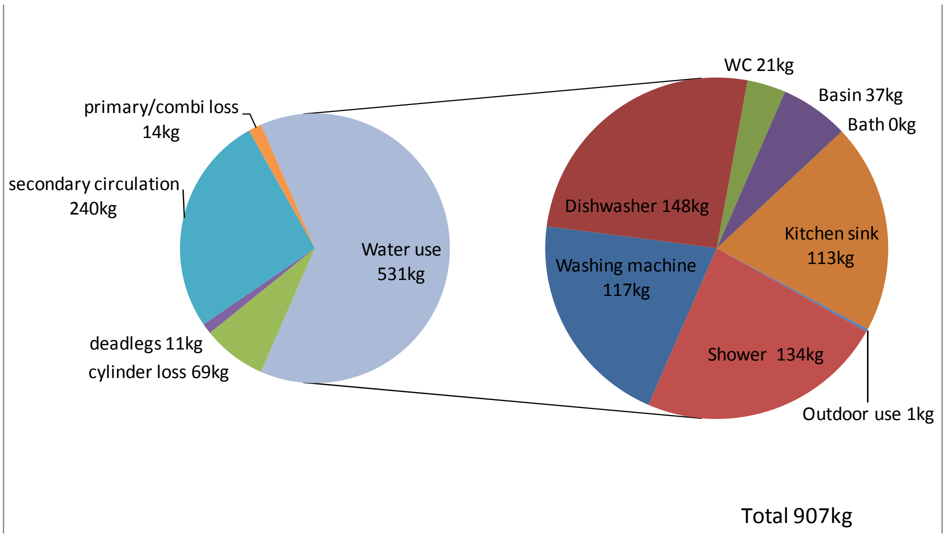


Figure 17. Even a well-insulated secondary circulation circuit (30m total length) will result in significant heat loss.

In Germany, where highly thermally efficient buildings to Passivhaus standard are more common, it is also common to specify a secondary circulation (where hot water is pumped around a loop throughout the house, and appliances are fed by short spurs from this loop) for hot water. These systems are used to ensure that hot water is almost instantly available (i.e. to eliminate the dead legs). It would seem from our model that secondary circulations represent a very significant potential inefficiency, as illustrated in Figure 17 (the left hand pie chart demonstrates that whilst the CO_2 emissions from dead legs have decreased, the pumped circulation results in 240kg of CO_2).

Figure 18 shows a Passivhaus level of building envelope efficiency (which would also be achieved at CSH level 6[7]) with three possible hot water system designs. The water use for each scenario is identical but the first assumes an optimised design[8] with microbore pipes to minimise hot water dead legs without secondary circulation. Additionally the hot water cylinder is 250 litres with 100mm of foam insulation allowing for solar input but also a single boiler firing per day. The larger cylinder leads to increased cylinder losses but the model suggests that this is offset by the reduced firing frequency. The boiler is located close to the cylinder to further reduce primary losses. This cycling effect is discussed in section 5.6 and is not to be confused

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[7] As described in the text box on page 43, space heating demand is not clearly specified at CSH levels, hence the use of Passivhaus terminology.

[8] Based on the AECB Best Practice water standard.

with the more commonly discussed boiler cycling in space heating mode, which is not thought to lead to such significant losses.

The second scenario on the graph uses secondary circulation with good insulation and the primary pipe work is increased to 12m to reflect typical UK practice with the boiler downstairs and the cylinder in an airing cupboard upstairs. The final scenario is the same as the second except for a smaller 120 litre cylinder (2 boiler firings per day) and more typical 12mm thick pipe insulation on the secondary circulation line. The secondary circulation is assumed to run for 18 hours per day.

Note that because this part of the study is investigating plumbing system design, water use has been assumed to be constant in each scenario; whilst we might expect hot water use to change with plumbing system design, there is no robust evidence on this.

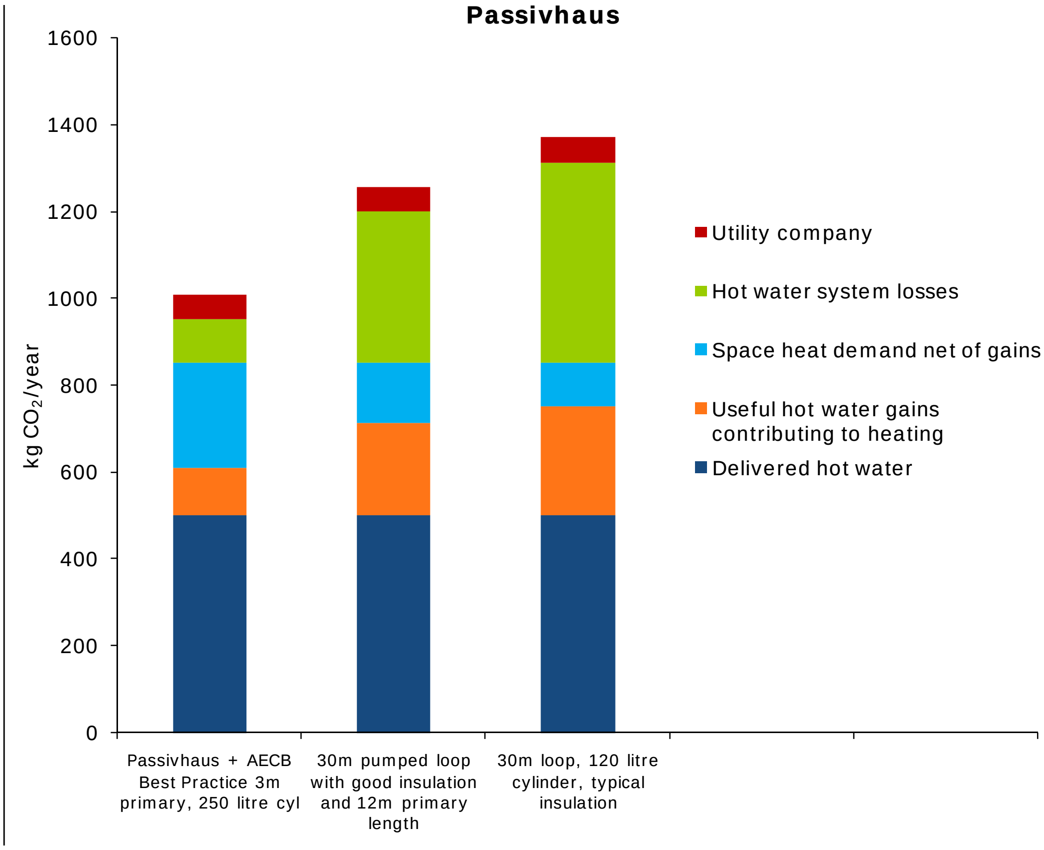

Figure 18. Three different approaches to plumbing system design in a very well insulated house (thermal efficiency similar to that achieved at CSH level 6). A short primary loop is the most efficient configuration.

4.6 Limitations and implications of findings

WEM is a model intended for design as opposed to accurate prediction of large-scale savings for a given measure. This distinction is important, given the enormous variable that human behaviour introduces. For example we can calculate the energy lost when a hot water dead leg cools off (regardless of whether the cold water drawn off is used or wasted). This calculation can be quite precise with consideration of the heat capacity of the pipe and other factors. The final model can predict the volume of water that must be run off before hot water is delivered and this can be tested against reality and the model refined. As we have shown, such a model can provide useful design guidance and identifies a number of priorities for future regulations. However we cannot use such a model to predict exactly how much hot water would be saved if dead legs were reduced by regulation unless we know how people will interact with their plumbing systems. For example if a dead leg takes a minute or more to run off some users will do something else whilst the water is left to run hot, whilst others will make do with the cool water rather than wait or waste the water. However, good plumbing system design can offer improved performance (in terms of short wait times for hot water) together with lower CO_2 emissions than standard plumbing.

Summary of findings from use of WEM

Metering and water efficient retrofits both contribute to decreased CO_2 emissions from water use in existing housing, as illustrated in Figure 10. These findings are clearly very sensitive to the assumptions made about how metering affects different micro-components of water use. Figure 10 also demonstrates that the scope for CO_2 emissions reductions due to behavioural change is significant.

In the absence of any sustainable water use ‘drivers’, the difference in CO_2 emissions due to hot water use are very similar in new dwellings compared to old (Figure 10 compared to Figure 13). Whilst boiler efficiency has increased, this has been offset by the increase in hot water use (predominantly shower). This finding is clearly very sensitive to assumptions made about hot water use in new homes.

In standard new build dwellings, the additional CO_2 emissions from installing secondary circulation (as might occur in luxury dwellings with en-suite bathrooms) are large (Figure 13) and are an obvious target for regulation on optimising plumbing system design.

Water related CO_2 emissions in a dwelling complying with CSH level 3 water use are illustrated in Figure 16, and are lower than in existing dwellings. However, achieving the same Code level using rainwater harvesting to allow a higher flow rate shower, results in water related CO_2 emissions being just as high as in existing poor quality housing stock.

Finally we have used the model to demonstrate the importance of plumbing system design in high efficiency dwellings where the CO_2 emission implications of domestic hot water are greater than the space-heating requirement (Figure 18).

5 Additional findings related to the CO_2 emission implications of water use

The number of permutations of boiler type, house type, fuel type etc that could be studied using the whole house model are enormous. The Water-Energy model developed as part of this project allows permutations to be investigated as and when they seem relevant. However, whilst undertaking this study a number of important questions have arisen and are discussed in this section.

5.1 The relative importance of hot water and space heating in buildings of different standards

When considering the influence of building standards we have used the AECB Silver and Passivhaus standards as they have clearly defined heating demands. The heat loss parameter limit for CSH level 6 means that the heating demand for this level will be approximately the same as Passivhaus. The relationship between these standards is discussed in the box on page 43.

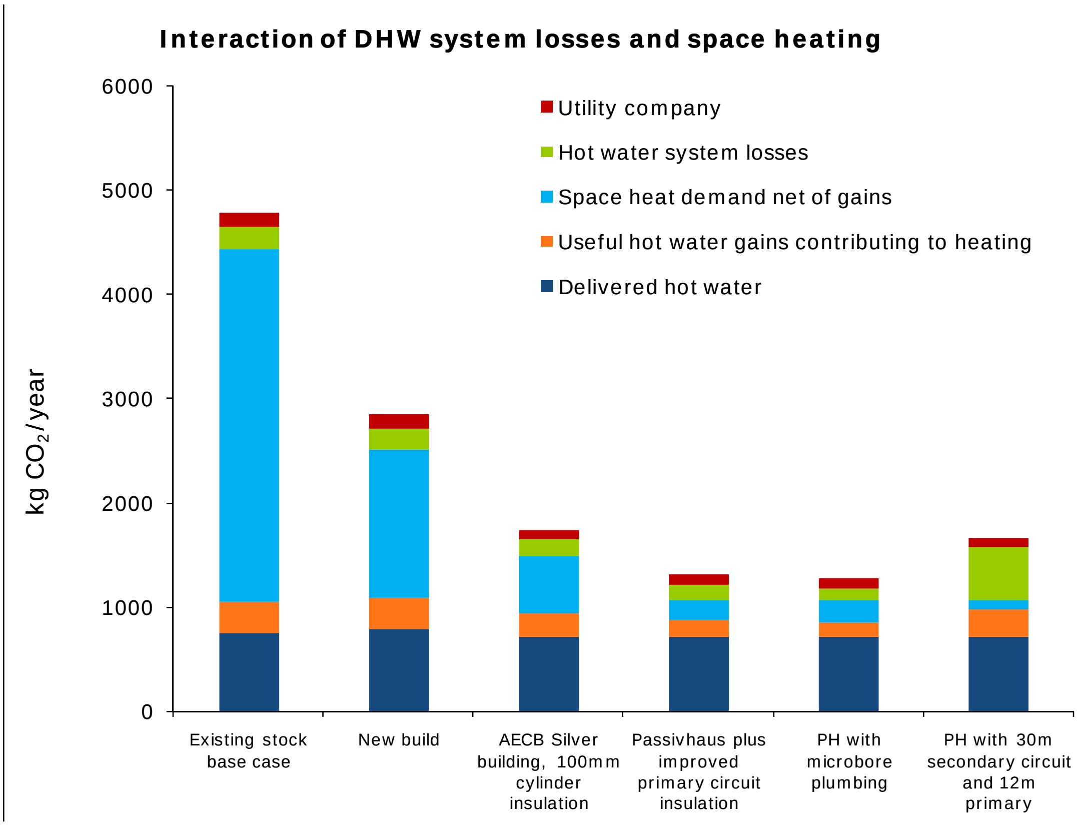

Figure 19. As the building envelope becomes more efficient, CO_2 emissions from hot water use exceed those from space heating. Hot water use remains constant for all scenarios. PH= Passivhaus. The relationship between PH and CSH is discussed on page 43.

Figure 19 shows that in existing dwellings, space heating dominates the energy demand. This is still the case in a standard new build dwelling (compliant with Part L of Building Regulations), as illustrated in the second bar in Figure 19. As buildings improve to Passivhaus levels of thermal performance, the CO_2 emissions from hot water use will start to exceed those due to space heating.

The model shows that as the heating requirement falls, the proportion of losses that are actually useful for space heating also falls. If hot water system losses are increased slightly, for example by adding secondary circulation to reduce dead legs, then hot water related energy use completely swamps space heating requirements with system losses becoming significantly higher than the target space-heating demand (final stacked bar in Figure 19).

This shows that hot water system design deserves a similar level of attention to detail as afforded to building envelope design and ventilation systems in new buildings.

5.2 Dead legs

The model uses a very simplistic calculation for heat loss due to dead legs cooling, based on the method used in PHPP 2007. This assumes that all dead legs cool down three times per day per person. In practice some dead legs such as showers and baths will not be used this often but others such as the kitchen tap may be used more. The current model does not differentiate between pipe runs to different fittings although this could be done, in conjunction with modelling the diurnal hot water demand. The current model also ignores the water run to waste when this is too cold to use. A more detailed model would be interesting from an academic perspective, but variations in behaviour mean that from a policy perspective it may be sufficient to identify that the heat loss due to dead legs is significant and then focus on reducing this loss within practical limits rather than calculating it more accurately. The US EPA WaterSense standard (EPA, 2008) and AECB Water Standards (AECB, 2009) set maximum volumes for hot water dead legs in order to minimise this loss and so reduce the importance of an accurate model to calculate the loss. Without such a requirement it is possible for very significant heat and water loss to occur. The trend towards more en suite bathrooms means that the length of pipe runs will increase and the frequency of use for each fitting will reduce. This reduces the chance of the water in the pipe remaining hot for the next user and so increases the wasteful heat loss. Additionally reduced flow rates for water saving will lead to a longer wait times for hot water.

There are a number of ways to reduce the dead leg problem. Optimised pipe sizing with minimised pipe runs is the best solution in terms of cost and energy loss and lower flow rates allow smaller pipes for the same pressure loss. However for larger dwellings with spread out plumbing fittings the dead legs may large enough to cause user dissatisfaction leading to the specification of secondary circulation. Modelling this in WEM demonstrates the significant impact of secondary circulation on hot water system losses. Electric trace heating will have a similar effect, (potentially worse, owing to the use of electricity as the heat source rather than gas), and so both should be avoided if at all possible. This could require regulatory intervention.

The authors know of at least one supposedly low carbon renovation where un-insulated secondary circulation was installed on the reasoning that the heat loss would contribute to space heating. The model clearly illustrates the fallacy of this approach.

5.3 Rainwater harvesting systems and greywater recycling

Rainwater harvesting (RWH) and greywater recycling systems are increasingly specified under the Code for Sustainable Homes, as the water calculator allows water from these systems to be ‘traded off’ against mains water, thereby allowing higher mains water use by other appliances (e.g. showers). This has been demonstrated in the scenarios above, where a RWH system in a CSH level 3 house allowed the shower flow to be increased from 7 litres/minute to 13 litres/minute and meant that the resulting CO_2 emissions were as high as for dwellings not achieving any code level, and similar to those in existing housing stock. This trading off has a carbon impact which can be investigated using the model, and is also discussed by Hassell (2008).

Regardless of the trading off issue, the environmental impacts of RWH systems are higher than mains. This has been explored in a number of studies (Crettaz *et al.* 1999, Hallman *et al.* 2003, Thornton 2008). Whilst it is possible to criticise the assumptions made within all of these studies, at a simple level, the energy cost of pumping alone is higher than the total impact of the equivalent volume of mains water (pumping costs for RWH range from 1-3kWh/m^3, total energy cost for mains water 0.56kWh/m^3, from WaterUK 2008).

Whilst it could be argued that renewable energy generation in CSH level 6 houses means that extra energy use is effectively CO_2 neutral and therefore justifiable, this is clearly not the case; minimising energy use in all buildings is crucial, and excess electricity from renewables should supply the national grid to be used where it is most needed. LCA studies of RWH systems have also demonstrated that systems are worse for all other environmental parameters used within LCA studies (e.g. photoxidant formation, eutrophication, acidification, ozone depletion, toxicity, resource depletion), so even if the CO_2 neutral electricity generation argument is accepted, these systems are less environmentally sustainable than mains water supplies. These wider impacts are related to the increased amount of infrastructure required, and their magnitude depends upon the assumptions made regarding the fuel source required to produce the additional infrastructure (e.g. it would not necessarily be the case if the RWH system was produced in a country with a 100% renewable fuel mix).

The only argument left in favour of RWH systems is therefore the fact that regardless of other environmental costs, they should be encouraged on the basis that they displace the use of potable quality water. In order to accept this argument as valid, two requirements must be met:

1. The amount of water supplied by a RWH system must be significant
2. The alternative ways of supplying this water must have a higher environmental impact

There is a close correlation between water catchments which are already over-abstracted (as evidenced by Environment Agency work on catchment abstraction management strategy (CAMS) maps, Environment Agency 2008b), and areas of low rainfall. It is therefore difficult to see how RWH systems can contribute in areas where extra water supply is needed. In a study of the potential for water neutrality in the Thames Gateway (Environment Agency, 2007), RWH was not regarded as one of the favoured options, on the basis of it meeting insufficient demand (36 litres/household/day with an average roof area of 50m^2) relative to the installation costs. With regard to the relative environmental impact of different water supply measures, the water resources carbon footprint calculator (Environment Agency, 2008a) can be used to demonstrate that RWH has a higher impact in addition to having a low potential volume of water supplied.

It is also worth noting that an extensive examination of the financial cost effectiveness of RWH systems (Roebuck, 2007) in which 3840 scenarios were modelled (including hydraulic related variables such as tank size, roof area, rainfall, and economic factors such as system cost, net present value, discount rate and discount period) demonstrates that under no circumstances did RWH systems work out as more cost effective than mains (AIC, average incremental cost was on average 7.6 times higher than mains). This is despite assuming a basic cost for a domestic system of just £1000, on the assumption of bulk purchasing.

The CO_2 emissions resulting from the energy consumed by RWH systems have not been modelled in any detail in WEM because the amount of energy is low compared to the CO_2 consequences of the trade off against shower use made possible, and is also highly dependent on assumptions made regarding water use.

We have not included greywater recycling for toilet flushing in any of the scenarios. Greywater recycling schemes currently have a lower level of acceptability than rainwater systems, due to poor aesthetic water quality (cloudiness), cost, lack of choice of systems and concern over their environmental impact. Unlike rainwater systems, the supply (greywater) is available on a daily basis, so the storage volumes necessary for greywater systems are much lower and storage is typically in a tank in the house, in some cases concealed above a WC cistern (e.g. in a system manufactured by Ecoplay). Additionally, water quality concerns associated with greywater mean that it is undesirable to store it for longer than 24 hours. We are not aware of any detailed work on the environmental impacts of greywater recycling schemes, but it is expected to be higher than mains water owing to the infrastructure required at household level, the need for pumping, and in some systems the need for disinfection. It is entirely possible that whilst environmentally worse than mains water, greywater systems may have a lower impact than rainwater systems. How much of total WC flushing demand they meet in practice is also unclear. The argument that greywater systems contribute to space heating (if the greywater is stored within the thermal envelope of the building) could be tested using the WEM, but is academic compared to the practical concerns posed by greywater systems.

5.4 White goods

5.4.1 Washing machines

Modelling in WEM has demonstrated that the carbon impact of wet white goods is very dominant especially if water is heated by a low carbon energy source such as solar or biomass. Lower temperature detergents and improvements in machine design have potential to deliver further savings although water efficiency is thought to be close to the limit for current technologies. Indeed what little variation that is shown on labels may be less than the variation in actual water use. When discussing washing machines, the publication *Especially Economical Household Appliances 2007/08* (Klaus 2008) states:

"For these units, we no longer publish a list showing the individual washing machines with the lowest power and water consumption, as in previous years. The reason is that models with extremely low water consumption in some cases show unsatisfactory rinsing properties."

With regards the accuracy of Energy Label claims, *Which?* has previously found energy labels to be rather optimistic. A more recent study for the MTP found that the samples tested largely conformed to the requirements of the EU

Energy label with regards to the claimed consumption. However Figure 20 shows that some manufacturers appear to be claiming an energy consumption at the upper limit of the A rating. Whilst the measured consumption falls within the allowable 15% tolerance, the measured value would put the machines in the lower B category. Interestingly machines with an unofficial A+ rating had measured consumption much closer to the claimed value.

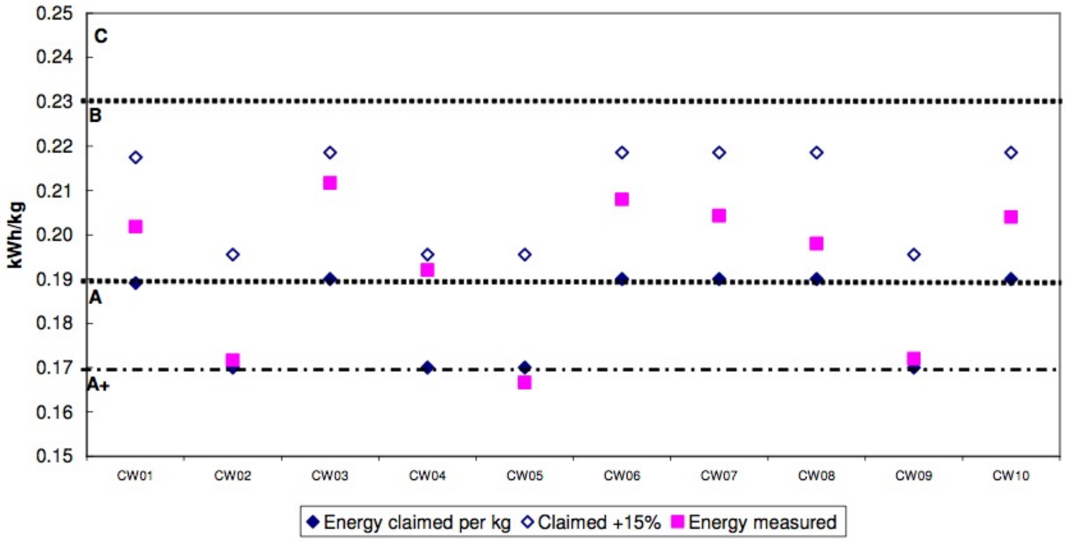

Figure 20. Measured versus claimed energy consumption for washing machines. (MTP 2006a)

5.4.2 Interaction between dishwasher and kitchen sink water use

It is widely assumed that use of a dishwasher decreases the amount of hot water used at the kitchen sink. The scenarios modelled in section 4.4 using WEM have not incorporated such a correction, as the magnitude of the decrease in water use is very unclear. Instead, the approach taken was to model this separately both using WEMlite (results in section 3.2) and WEM (discussed here). Differences in results between the two models are expected because WEMlite does not take into account the potential for useful heat gains from the dishwasher (drain water is discharged at a high temperature, and this could be regarded as useful heat that contributes to heating the house). The assumption we used (evidence discussed in Appendix 6.6) was that dishwasher use results in 19.2 litres/household/day less hot water at the kitchen sink. This differs from the assumptions suggested by Waterwise (2009), and so it is useful to consider how sensitive the results are to these differences.

This was tested in our base case scenario of water use in the existing housing stock, with occupancy of 2.4, and gas boiler efficiency of 78%. Kitchen sink washing up water assumed to be entirely hot water (i.e. used at the stored hot water temperature). Water and energy use assumptions used are given in Table 11.

	Assumption (Waterwise)	**Assumption (ES)**
Use frequency (per day)	1	0.7
Energy use per cycle (kWh)	1.05	1.1
Water use per cycle (litres)	10	21.3
Decrease in hot water at sink	32 litres/day less	19.2 litres/day less

Table 11. Differences in assumptions modelled for the effect of a dishwasher on kitchen sink hot water use.

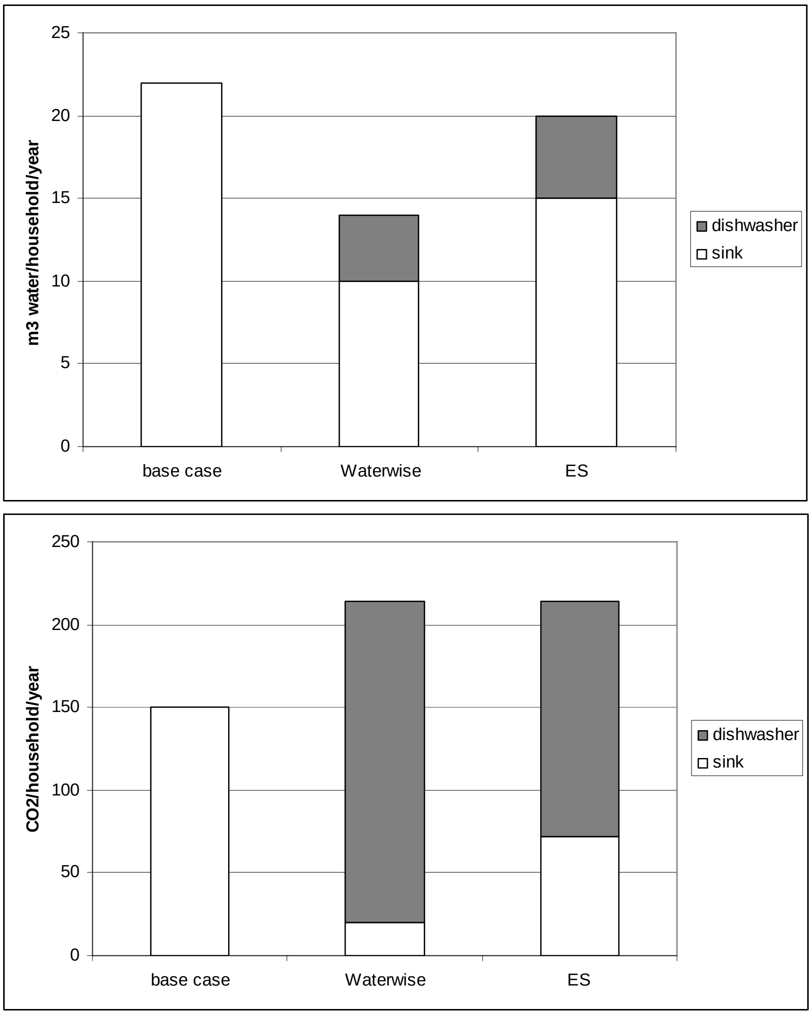

Figure 21. The effect on water use and CO_2 emissions of dishwasher ownership, using different assumptions about the effect on kitchen sink hot water use. NB: the fact that the model reports identical CO_2 emissions for both Waterwise and ES assumptions is entirely due to chance!

Figure 21 shows that with both sets of assumptions, whilst dishwasher use results in water savings compared to the base case, the CO_2 emissions go up by around 50% (from 150kg to 214kg). We have limited confidence in the validity of both sets of assumptions and therefore the precision of the answer, but the general principle of dishwashers increasing CO_2 emissions is logical and confirms the findings in section 3.2.

5.5 The impact of hot water storage temperature on CO_2 emissions

Hot water storage cylinders are recommended to be kept at 60°C, based on the risk of legionella. The temperature of hot water required at the appliance varies (e.g. shower 40°C, bath 44°C, kitchen sink 55°C). We therefore mix cold water with the hot water from the cylinder in order to get the desired temperature. This therefore begs the question of what effect hot water cylinder temperature has on CO_2 emissions (because higher storage temperatures will result in higher heat losses).

In a recent study (Energy Saving Trust, 2008) of 120 houses, water storage temperatures were considerably lower than the widely assumed 60°C (52.9°C ±1.5°C for system boilers, 49.5 ± 2.0°C for combi boilers). If these values are representative of the wider housing stock, it does raise an important question about legionella.

A preliminary calculation using the Water Energy model indicates that increasing the storage temperatures reported in the study (Energy Saving Trust, 2008) to the recommended temperature of 60°C would increase CO_2 emissions from hot water by around 5-10%.

The risk of contracting legionella from domestic water supplies is unclear. Whilst there are no reported cases of legionella being caught from domestic showerheads, this does not necessarily prove that the risk is small. The most common consequence of legionella is pneumonia and since the medical treatment for community acquired pneumonia is the same regardless of the underlying bacterial infection causing it, the bacteria responsible is not routinely identified.

Whilst the risks to human health should clearly remain a priority when setting regulations in this area, the impact on CO_2 emissions of an over-conservative approach suggest that further study in this area is required:

- further study on the microbiological aspects of legionella in domestic hot water systems, including the relative risks of direct hot water systems and gravity systems (where header tanks are prone to contamination).
- risk analysis, based on the Energy Saving Trust (2008) finding that most hot water systems do not comply with storage temperature recommendations, yet we do not appear to have a widespread problem with people contracting legionella from their domestic hot water systems
- quantifying the CO_2 impacts of the various regimes regarded as appropriate for legionella control to ascertain how to minimise health risk whilst minimising CO_2 emissions. This is particularly pertinent for systems heated by solar thermal or heat pumps (in which COP falls considerably with rising temperature) and fossil fuelled heat top up is used.

5.6 Primary circuit heat loss

The primary circuit of a hot water system consists of the pipes to and from a boiler and hot water store, and the heat exchanger within the boiler itself. The model accounts for primary circuit heat loss in three categories: the heat lost from the distribution pipes whilst heated water is flowing through them (known as transmission loss), the “cooling down” loss of pipes and contents between boiler firings, and the same cooling down losses for the boiler heat exchanger. This approach reflects the modern fully pumped system, as opposed to the old gravity circulation system where transmission heat loss was the only factor. The pipe work cool-down losses were estimated reasonably accurately for a given pipe length and diameter, the boiler losses were estimated given typical data for a modern domestic boiler, and will vary considerably with boiler design. All three elements were found to be significant, the exact proportions depending on pipe length, amount of insulation and number of boiler firings per day. Data from actual dwellings (Bell, 2009) showed that primary heat loss was dependent on the length of timed hot water heating periods. Also the heat loss appeared significantly higher than transmission loss alone.

The number of firings per day was estimated on the basis of maintaining the cylinder at a set temperature at the cylinder thermostat location, assumed to be at one third of the height of the cylinder. So after drawing off one third of the total cylinder volume of hot water the boiler will fire.

As with other losses, the cool down losses are discounted when they are contributing to heating.

The conclusions from investigating this in WEM are:

- Insulation alone will not eliminate primary circuit losses
- Short primary connections are important to reduce both the transmission losses and the cool-down losses
- Number of boiler firings has a large impact, as it leads to cool down losses in both the primary circuit and the boiler
- A larger hot water cylinder offers a benefit in reducing the number of boiler firings. This would be amplified if a more sophisticated control were used, firing the boiler when a high level sensor indicates a minimum reserve level of stored hot water remains, and turning the boiler off when a lower level sensor indicates the cylinder is fully heated.

Further practical research is needed to validate the model in this area, as it would appear to have major implications for boiler hot water system efficiency and design priorities.

Combi boiler loss

In order to base the modelling of combis on the same footing as system boilers, the model uses the same cool-down heat loss approach. For combis the number of firings is based on the number of draw-offs, as quantified for hot water dead legs.

In general this resulted in combi boilers having lower CO_2 emissions than system boilers though with the most efficient cylinder set-up the results were comparable, and well within any errors introduced by the assumptions in the model. The model did not include “keep-warm” facilities in combi boilers as they are not found in all boilers, and their use is optional. In effect, the keep-warm facility is typically a thermal store like a small hot water cylinder, and a continuous heat loss is incurred whether or not hot water is used.

Modelling combi losses as a cool-down heat loss, rather than a reduced percentage efficiency for hot water generation, suggested that combi losses were independent of water efficiency as these only affected gas use when the boiler was firing at operating temperature, and had no impact on the cool down losses. Therefore efficiency measures would only save energy at the maximum boiler efficiency rating, and not an average hot-water use efficiency rating (this latter rating would actually go down as hot water flow rates reduce).

Again, further research is needed to validate this approach to modelling combi energy use for hot water.

6 Cost effectiveness of carbon saving

6.1 Methods for valuing carbon

The original brief called for a quantification of the value of carbon savings due to proposed measures. The DEFRA methodology uses the concept of a shadow price of carbon (SPC) to attribute a cost to carbon emissions. Whilst setting a carbon cost is fraught with problems, this appears to be the only way to factor in carbon when evaluating potential investments that do not specifically set out to reduce carbon emissions. For example when choosing between two water supply options where the more expensive option has lower life cycle carbon emissions, including a carbon cost could be argued to more fully represent the true costs from a global perspective. In this example, factoring in a carbon cost may (or may not) swing the economic argument in favour of the greener option.

However for the purpose of evaluating and ranking household energy efficiency measures, which are being specifically selected to reduce emissions, the issue of a carbon price can be at least temporarily avoided by considering the cost effectiveness of measures in pounds (£) per tonne of CO_2 not emitted. The cost of measures can then be compared with the current SPC but any measures with a negative or neutral cost can be identified as cost effective regardless of the current price of carbon.

After reviewing the literature we recommend using Marginal Abatement Cost or MAC. This is the energy equivalent of the concept of AIC that is used in the water industry (p/m^3) which allows a direct comparison between efficiency and supply side measures.

Whilst the MAC calculation does not require a carbon cost to be assumed, the cost of measures can be compared with a shadow, social or market price of carbon. Also, if a total mitigation target (household, regional national or global) is set, then a MAC curve can be used to suggest a carbon price, i.e. the maximum we would need to pay per tonne mitigated in order to achieve the required mitigation goal.

Method

The marginal abatement cost is calculated by dividing the net present cost of the proposed measure by the annual carbon saving. Some analysts discount the carbon as well as the costs and savings (BRE 2001) but others do not. After consultation with the authors of the Carbon Trust’s MAC curve Tool (AEA Technology 2009) we have chosen not to discount the carbon but care must be taken when comparing values calculated with the carbon discounted, (or a different discount rate or basis period).

For a simple measure with a single capital cost (e.g. no maintenance) and constant annual savings in money and carbon:

$$MAC = \frac{NPV_{measure}}{C.n}$$

Where NPV is the net present value of the measure, C is the CO_2e saved per year and n is the lifetime of the measure in years.

We have used a 10% discount rate based on the Carbon Trust's recommendations and a default 10-year basis period. Some measures justify a longer basis period, which reduces the MAC. For this analysis the cost saving used has been that experienced by the householder in reduced fuel and water bills. An alternative approach, in line with AIC methodology, would be to consider the much lower marginal cost saving for the utility company. This makes sense where the utilities are comparing demand side and supply side investment.

6.2 Initial results for marginal abatement costs

In MAC graphs, bars below the x-axis represent measures that have a financial payback as well as a CO_2 saving. The width of the bar along the x-axis represents the total potential of CO_2 saved by the measure, so this allows us to consider the relative importance of measures (e.g. some may save very small amounts of CO_2, so are a lower priority than measures of similar financial cost but with high CO_2 saving potential). The area of the bar is total tonnes saved multiplied by cost per tonne saved so is equal to the total cost assumed for the measure.

MAC curves should never be considered as absolute and there are many assumptions that can be changed which will alter the results considerably. However they are a very useful tool for identifying 'win win' solutions, technologies to avoid and areas where further work could improve cost effectiveness. The examples given in this report should be used as a starting point for more detailed analysis and discussion.

An additional issue with any cost effectiveness analysis is that measures interact. For example adding insulation to an un-insulated hot water cylinder will be more cost effective than adding additional insulation to one that already has a little. Improving boiler efficiency or adding solar water heating will reduce the cost effectiveness of efficiency measures. Perhaps the most interesting paradox is where a dwelling is heated by biomass and so the heat is considered to be carbon zero. In this case any carbon cost analysis shows no savings from efficiency measures. However if we apply a MAC curve analysis at the national or global level we realise that whilst a woodstove appears to be a cheap way for a single dwelling to achieve zero carbon heating, the total yield (x-axis) is too small for this to provide a UK wide solution.

A less extreme consideration is whether to use gas as a base case fuel or electricity. Again the issue is one of future availability. All such considerations are beyond the scope of this report but need to be considered when evaluating national strategy.

6.2.1 Existing housing stock

Figure 22 shows the MAC for some commonly considered modifications related to water use in existing housing stock. Dual flush retrofits have financial benefits but minor CO_2 benefits. Measures relating to hot water use (e.g. basin tap aerators or sprays saving an assumed 40% of wash basin hot water use, and use of a washing up bowl[9] saving 40% of kitchen sink water use) obviously save more CO_2 and have cost savings. The cost of installing a shower will depend on the need for additional tiling and whether a low cost curtain or proper glass screen are installed but then a shower could be said to add value to the property and be a desirable addition regardless of

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[9] A high quality stainless steel bowl was assumed, as this is more likely to be retained than a greasy plastic one.

cost or CO_2 savings. Calculations in section 3.2 show that fitting an electric shower (rather than a gas heated one) could increase CO_2 emissions, depending on assumptions about behaviour.

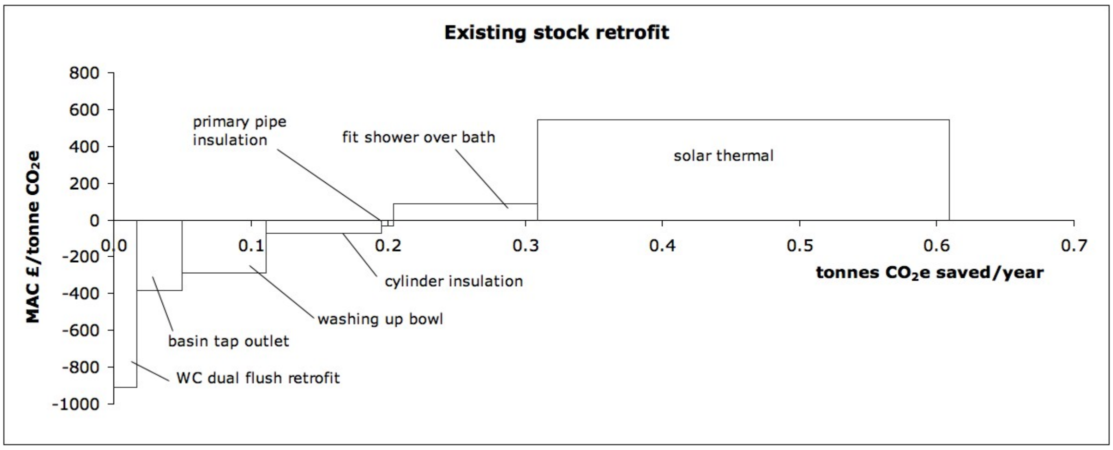

Figure 22. Marginal abatement costs for some common water related retrofits to existing housing stock.

	Measure	Cost	Water saved m^3/y	Fuel saved kwh/y	CO_2 saved $kgCO_2$/y
	6 l/min mixer shower installed over bath				
base	4 baths/week, no shower available		132	4008	1105
scenario	1 bath, 5 x 5 min showers	£500	125	3473	1000
	saving		7	535	105
	Stainless steel washing up bowl				
base	Washing up in sink		125	3473	1000
scenario	Stainless steel bowl saves 40%	£25	116	3178	939
	saving		9	295	61
	Dual flush WC retrofit				
base	9 litre		116	3178	939
scenario	7.5 effective flush	£25	104	3136	922
	saving		12	42	17
	Cylinder insulation upgrade				
base	12mm equivalent ins’		104	3136	922
scenario	50mm equivalent insulation	£50	104	2683	838
	saving		0	453	84
	insulated primary pipe work				
base	No insulation, 12m pipe length		104	2683	838
scenario	Good insulation added	£10	104	2635	829
	saving		0	48	9
	Add basin spray inserts to taps				
base	Normal taps		104	2635	829
scenario	60% of base	£10	97	2479	796
	saving		7	156	33

Table 12. Assumptions to calculate MAC for existing stock retrofit scenario.

6.2.2 New build dwellings with high specification plumbing

Figure 23 shows the MAC for a new build with better than usual plumbing system design in which cylinder insulation is increased to 100mm and micro-bore plumbing is used to minimise hot water dead legs. A high quality 6 litre/minute showerhead (compared to a standard 12 litre/minute one) demonstrates both financial and CO_2 savings. In practice low flow showerheads are available for the same cost as standard ones but an over-cost has been assumed to allow for premium quality. In this example the cost of solar water heating has been split between the over-cost of a higher specification cylinder and the rest of the system.

Since nominally very low flush WCs (4/2 litre dual flush) are now available for the same price as medium specification standard WCs, we have assumed that some additional savings may be possible if a slightly more expensive model could guarantee an actual flush volume of 4 litres whilst also including an insulated cistern to avoid condensation and provide a very modest additional carbon saving due to reduced heat loss[10]. Whilst hypothetical, it is given as an example to show the sort of (modest) carbon savings compared with an assumed 6 litre (actual flush) base case.

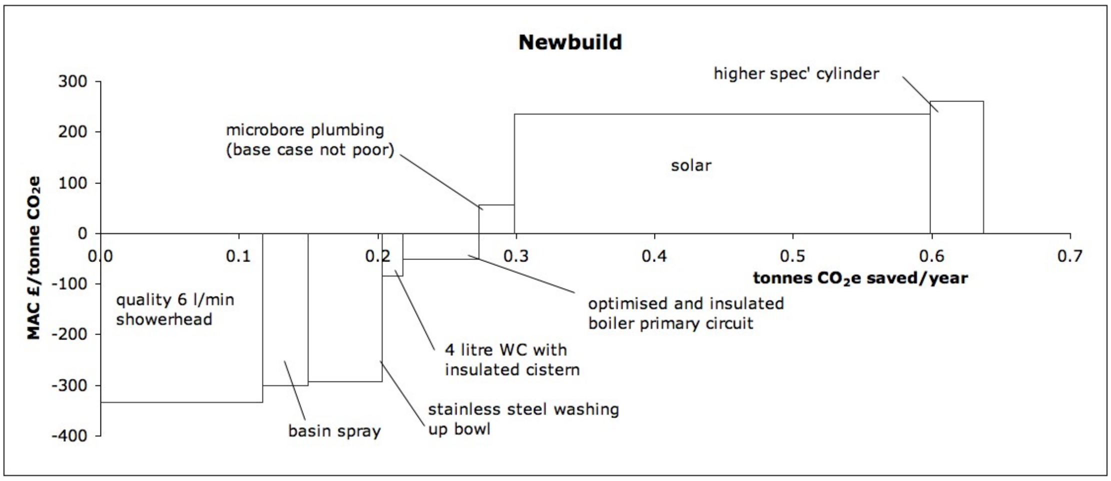

Figure 23. Marginal abatement costs for a new build property with improved plumbing system design and water efficient specification. See Table 13 for main assumptions.

	Notes	Cost	Water saved	Fuel saved	CO_2 saved
	Watersaver shower	Cost	m^3/y	kWh/y	$kgCO_2$/y
base	12 litre per minute showerhead		39.4	1150	234
scenario	replace with high quality 6 litre/minute head	£30	19.7	575	117
	saving		19.7	575	117
	washing up bowl				
base	Washing up in sink		21.5	593	132
scenario	Stainless steel weashing up bowl	£25	12.9	356	79
	saving		8.6	237	53

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[10] The WC water was assumed to warm by 2 °C rather than 4 °C in the base case.

	Notes	Cost	Water saved	Fuel saved	CO_2 saved
	Microbore radial plumbing to reduce deadlegs				
base	standard 15mm pipes		3.6	2887	884
scenario	extra 10mm pipes	£100	0	2747	858
	saving		3.6	140	26
	Cylinder upgrade				
base	120 litres, 25mm insulation		0	2887	884
scenario	250 litres, 100mm insulation	£150	0	2681	846
	saving		0	206	38
	Optimised primary pipe work				
base	standard length and insulation		0	2887	884
scenario	short plus insulation	£50	0	2586	829
	saving		0	301	55
	Basin spray tap				
base	Normal tap at mains pressure		16.8	343	81
scenario	Spray or aerator assumed to save 40%	£10	10.1	206	48
	saving		6.7	137	33
	WC with toilet cosy!				
base	6 litre actual flush standard WC		24.5	64	32
scenario	Assumed best practice 4 litre actual flush + insulation	£150	16.3	21	17
	saving		8.2	43	15

Table 13. Assumptions used to calculate MAC in the new build scenario.

6.3 Reflections on the value of carbon

Whilst the absolute numbers should be treated with extreme caution, the examples for both existing housing stock and new build show that the CO_2 savings from the combination of water efficiency measures that have a payback (i.e. a negative MAC) are similar in magnitude to those from a solar hot water system (which is much less cost effective). However, once the ‘win win’ measures that save both money and CO_2 have already been carried out, further CO_2 savings at the household level[11] probably do require more expensive measures such as solar water heating.

Interestingly, the MAC curves produced by Vattenfall (Vattenfall 2007) only show measures costing up to about €40/tonne, about 10% of our optimistic costing for solar hot water heating. By comparison BRE (2001) calculated the abatement cost for domestic solar water heating to be in the range £1,400 to £8,639. With the 2008 DEFRA price for the shadow price of carbon at £26/tonne (rising at 2% a year) we clearly have a wide disparity in how carbon and carbon mitigation measures are valued.

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[11] As opposed to from district CHP or decarbonised grid electricity at a grand scale.

Another way of considering what might be an acceptable cost to mitigate CO_2 at the household level with regard to hot water comes from considering the cost of warming a cubic metre of water by 28°C (from 13 to 41°C) for showering and other warm water use:

Gas required	= 1.16 x 28°C x 1 m^3 / 90% boiler efficiency	= 36 kWh
CO_2 emissions	= 36 kWh x 0.185 kg/kWh	= 6.7 kg

Assuming an average water and sewage cost of £2.30/m^3 a gas price of 4p/kWh then the cost to the householder is £3.74/m^3 of hot water used.

If householders had to pay a carbon tax either directly or included in fuel prices, what would the cost be? If the SPC was £26/tonne, the carbon costs incurred to the householder using 1m^3 of warm water would be 6.7kg x £26/1000 = 16 pence or about 4% of the total cost.

Water and sewage	£2.30
Gas	£1.44
CO_2 emissions @ £26/t	£0.17 (4.5% of the total)

The alternative way of looking at the same data would be to consider it in terms of the financial cost per tonne of CO_2. In a household with 1 tonne of CO_2 emissions attributable to domestic hot water (such as the household scenarios explored in section 4), the price (water and gas) would be £587. This again makes the SPC of £26 seem too low to have any impact on decisions.

7 Implications for future research

Research into the micro-components of water use

There are large gaps in our understanding of the micro-components of water use, particularly with regard to hot water use. Many micro-component studies to date have significant limitations, but such studies are difficult and expensive to carry out. Because both WEM and WEMlite calculate CO_2 emissions from the 'bottom up' (i.e. from the water use of individual micro-components, rather than 'top down' from total UK domestic water use), the results are sensitive to the assumptions made about water use in the particular household under consideration.

Guidance on study design has come from Waterwise (2008a) and UKWIR (2000), and is discussed in Appendix 4. An almost limitless number of future studies are possible and would be interesting from an academic perspective, but we would suggest that prioritising according to the CO_2 emissions savings potential of the research output, is a sensible approach.

We have identified a number of areas where there is considerable scope for reductions in the CO_2 emissions from domestic hot water use. In many cases, these interventions would result in improved performance (as perceived by the householder), together with CO_2 emission reductions and financial savings.

Research into the CO_2 emission consequences of showers

Sales data indicates that shower sales are increasing, together with a trend towards higher flow rate showers. Whilst sales of electric showers (which are low flow) are also increasing, the CO_2 consequences of these are high if hot water would otherwise be provided by a gas boiler (discussed in section 3.2). A potential response would be either clear water efficiency labelling for showers and/or regulation on a maximum flow rate or energy use for showers. Research on the potential barriers to such measures will be necessary. This is likely to include defining what constitutes 'acceptable' shower performance, as discussed in Appendix 6.

Research on hot water storage temperatures

As discussed in section 5.5, the fact that measured hot water cylinder storage temperatures in Energy Saving Trust (2008) are so far below recommended temperatures may be regarded as a legionella concern. However, the lack of evidence that people contract legionella from their domestic hot water systems, together with the CO_2 consequences of increasing storage temperatures (estimates from WEM indicate that a 5-10% increase in CO_2 emissions from domestic hot water would result) indicate that further work is needed in this area. The effect on heat pump COPs is even more significant.

Research in existing housing stock

Anglian100 data remains the largest and most useful dataset for calculation of CO_2 emissions from hot water use and access to this would strengthen the conclusions on CO_2 emissions savings discussed in section 4. It is not clear how representative this dataset is of existing housing stock in general, but as discussed in Appendix 5, it is likely that further analysis of this dataset would in many ways be more useful than carrying out any new micro-component studies on existing houses. Maintaining and extending the scope of this project (e.g. to ensure that it has a representative cross-section of household types) should be considered.

Boiler cycling

Primary losses from boilers were found to be highly significant in WEM. This finding and the need for more research on boiler primary circulation is discussed in section 5.6. There is considerable scope for such research leading to large CO_2 savings in conjunction with better boiler performance as perceived by the householder if findings were incorporated into regulatory standards. Any revision to SEDBUK should address both user convenience (minimal wait for hot water) and the energy cost of proposed solutions such as combi boiler keep warm facilities, small insulated stores or flue gas economisers.

Research into behaviour

The largest potential for CO_2 emission savings related to domestic water use in existing houses is in behavioural change and therefore understanding what affects behaviour is critically important. The current behavioural trend is towards higher flow showers, and increases in shower frequency, which is a cause for concern in terms of CO_2 emissions. Many micro-component studies to date have attempted to ‘tidy up’ the data in order to produce a single summary statistic such as an average water use or shower duration. However, if we want to understand behaviour, it is the variability in the data that is actually the useful information. Understanding how a sector of the population behaves and what influences them will enable more efficient targeting of messages. In particular it should be remembered that attempts to educate people in a logical way do not necessarily lead to behavioural change, because we have an enormous amount of social function built around water use (Hand *et al.,* 2006). It is impossible to predict how external influences will shape water use in the future (e.g. if the popular press decides that spas and hot tubs are fashionable, or if the cost of energy doubles). Future studies may not even involve measuring water use at all; asking people how they behave and why they behave in that way are also important study techniques. For example an Australian survey of shower behaviour (Energy Australia, 2006) considered shower water use in the context of 12 different activities that people undertake in the shower.

The effectiveness of water efficient retrofits has been demonstrated in previous studies to be highly variable (Waterwise 2008b). Given the influence of behaviour on water use, particularly hot water using appliances, this will always be the case. The current WRc study (CP359, using Identiflow® to measure the effectiveness of water efficiency devices) will further understanding of the effectiveness of retrofits, and future studies in this area should incorporate surveying techniques that allow behavioural influences to be identified.

Research into plumbing system design for new houses

A striking feature of the outputs from WEM (in section 4) is that new houses have similar CO_2 emissions from water use compared to existing dwellings, despite increases in boiler efficiency. This is partly due to different assumptions about water use. However, as detailed in section 5, there is a need for background research on plumbing system design for new houses as there is scope for significant CO_2 emission savings together with performance improvements. Many of these measures are easy to implement in new installations, but are too time consuming and/or expensive to be realistic options in existing housing stock.

As the thermal performance standards of new houses improve, the relative importance of domestic hot water use compared to space heating increases significantly. The way in which most current building energy models and energy standards consider hot water system losses is too simplistic for new build dwellings. As we move towards more energy efficient houses, a similar level of detail should be applied to hot water system design as to the building envelope and ventilation systems. WEM indicates that optimised hot water system design (primary pipe work, boiler position, controls, tank sizing and insulation and hot water distribution) could provide significant and cost effective carbon and cost savings. The model also indicates how commonly applied bad design (long primary pipes, poorly insulated secondary circulation and long un-insulated dead legs) can lead to very significant losses. Klein (2008) and others in the USA have developed a large body of work in this area. Quantification of the savings achieved by a more sophisticated approach to plumbing system design would strengthen the case for regulatory intervention in this area.

Research on effects of water metering

The water efficiency benefits of water metering are well established and there is already a UK wide commitment to increase meter penetration. However, there is very little data on how much the decrease in total water use by a metered household is split between hot water and cold water and therefore the extent to which CO_2 savings result from metering (the limited evidence is discussed in Appendix 2.5). In the current study, a simplistic assumption was necessary (total decrease 12% affecting hot and cold uses equally). Since low water users are more likely to request a water meter, savings in groups other than optants (e.g. compulsory metering, or change of occupancy, COM) may be quite different, both in total and in the hot/cold split. It may also depend on a number of other factors including existing water use, social group, appliances, and approach to a metering programme. Accurate quantification of the CO_2 emissions reductions from metering could inform policy on the timescale over which the metering programme is pursued, but study design is complicated (for example a study of hot water use in optants would be of no help in predicting future savings in areas about to embark on compulsory metering).

Research into greywater heat recovery

WEM can easily be adapted to estimate the potential effectiveness of greywater heat recovery. Such research must consider the practical issues, which have to date presented a technical barrier to the uptake of cost effective solutions at the domestic scale.

8 Implications for the water resources carbon footprint calculator

The report on GHG emissions associated with water supply and demand management options, and the accompanying model (Environment Agency, 2008) represents the first attempt to compare the carbon costs of various options when considering water supply and demand management. Results are expressed in terms of the total CO_2e emitted through the life-cycle and as a financial value using the Shadow Price of Carbon (SPC), the DEFRA approved method for valuing greenhouse gas emissions in government appraisals. This is for use in all policy and project appraisals across government with significant effects on carbon emissions.

The study, as part of a broader project on energy efficiency and carbon emission reductions across the water and wastewater sector, provides an evidence base for water supply and demand management options. The model was developed for high-level carbon cost appraisal in advance of more detailed study. It can be tailored to suit regional and scheme specific data as appropriate.

Data sources underpinning the model
A major variable in determining CO_2e factors is the fuel mix of the country in which any product that is part of the CAPEX originates from. It is therefore important to determine whether figures used to calculate embodied carbon from embodied energy are relevant to the country concerned. The carbon intensity of a given countries fuel mix will also change over time. As stated below, the CAPEX is less significant on the demand side of the model, so this is primarily a supply side issue.

In most instances manufacturing energy data is unavailable, and has been stated as a percentage of the embodied energy cost (values ranging from 20% to 200%). This is a reasonable approach if the percentage has been taken from a similar manufacturing process (Basson, 2009), but there are no references to verify whether or not this is the case.

The data source for most of the material CO_2 emission factors is the Inventory of Carbon and Energy (ICE) database from Bath University (Hammond & Jones, 2008). Carbon emissions associated with energy use are sourced from published DEFRA emission factors, although the model only considers electricity and diesel fuel sources.

Academic debate is ongoing around the values within the ICE database (Basson, 2009 Elghali, 2009). This centres around the fact that the ICE database solely deals with embodied energy with no consideration given to the carbon equivalence of other greenhouse gases. However, this carbon equivalence is included in figures from some of the other data sources, so the error introduced will vary between materials. Additionally, the figures from the ICE database are averages of a large range of studies with different system boundaries, fuel mixes and local factors which will affect the CO_2 emission factors. Whilst the ICE database is undoubtedly a useful resource, site specific data should be used in preference if available, or a comparative check should be made against a situation with similar parameters and system boundaries to the system under study.

Demand side measures

- For the vast majority of products, the 'use' phase of a product comprises the largest portion of the total energy cost, and so lack of precision in the embodied carbon costs have little impact on the overall result. This has been demonstrated in detail for some water using appliances (e.g. the LCA of WC's, Gandy *et al.*, 2008), and will be even more true of appliances using hot water.
- Calculations for the carbon benefits of water efficiency measures take a simplistic account of whether hot water or cold water is being saved, and this calculation is embedded within the model rather than being clearly visible to the user. A simple correction factor, clearly labelled and adjustable by the user could be applied to the model, which would serve to establish the relative importance of hot and cold water efficiency measures. Some recommendations for future updates to these correction factors are indicated in Table 14.

Measure	Default saving per home (%)	Comment
Metering	10	This is a reasonable assumption, and can expect water companies to have their own regionally specific data. Further research is needed regarding which micro-components are reduced in order to incorporate a hot water correction into this saving.
Toilet – hippo	10	Waterwise (2008) emphasises the enormous variability of effectiveness of this measure and the importance of incorporating half life into the calculation. A regionally specific value should be used, based on assumptions of cistern age and predicted uptake of the measure
Toilet – Cistern Displacement Device	7	Await findings from ongoing WRc study (CP359) for volume saved, and reduce CO2 savings to take account of the fact that cold water is saved rather than hot.
Toilet – low flush	8	Consider using data from WRc CP337 to represent actual water savings from new low flush toilets
Shower retrofit	8	Await findings from ongoing WRc study (CP359) for volume saved, and make hot water correction.
Bath (small)	6	We are not aware of any evidence regarding whether or not small baths lead to lower water use, neither are there any trials ongoing on this subject.
Tap retrofit	11.6	Await findings from ongoing WRc study (CP359) for volume saved, and make hot water correction.
White Goods	4	The carbon footprint of white goods relative to other hot water uses is critically dependent on assumptions regarding hot water fuel source. As demonstrated in the whole house model, the carbon impact of white goods is very high when a low carbon fuel source is specified for domestic hot water.

Table 14. Suggestions regarding specific water savings within the water resources carbon footprint calculator.

Supply side measures

The supply side of the model does not fall within the project brief. However, having examined this side of the model briefly, certain key elements are apparent:

- For most supply side measures, the CAPEX is a much higher proportion of the total than for demand side measures, so data assumptions on embodied energy are more important than on for demand side measures.
- The OPEX for almost all supply side measures is largely related to pumping. Results will therefore be particularly sensitive to changes in the fuel source (which isn’t easily selectable within the model) and pump efficiency. Pumping requirements also differ massively between installations, so detailed studies are best considered on a case by case basis. However it should be noted that in assessing the emissions associated with generic supply options reported in the model, the details of 68 schemes planned for the South East of England were evaluated.
- The CAPEX for reservoir construction is predominantly related to concrete. The emissions factor for concrete is largely dependent on the cement content of the mix. This can vary by +/- 50% depending on the concrete specification, and it is unclear which concrete specification has been used. Data on this is taken from the British Cement Association. The value is similar to that within the ICE database, although this figure has been reported by the database authors to be an error (Jones, 2009, but direction of error not reported).
- Given the importance of CAPEX on the supply side of the model, in future it is important to establish what material wastage rates are in water supply construction projects and to what extent the civil engineering calculations used to calculate the structures involved in supply side measures reflect what is built in practice.

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1 Appendix 1- Energy and CO_2 impacts of water supply and sewage treatment

The aim of the current project was to further understanding about the CO_2 emissions associated with the domestic use of water. In order to calculate the total impact, the external emissions (abstraction, treatment, conveyance, disposal) have been included. The CO_2 impacts for mains water supply and sewage treatment vary across the UK (Figure 24).

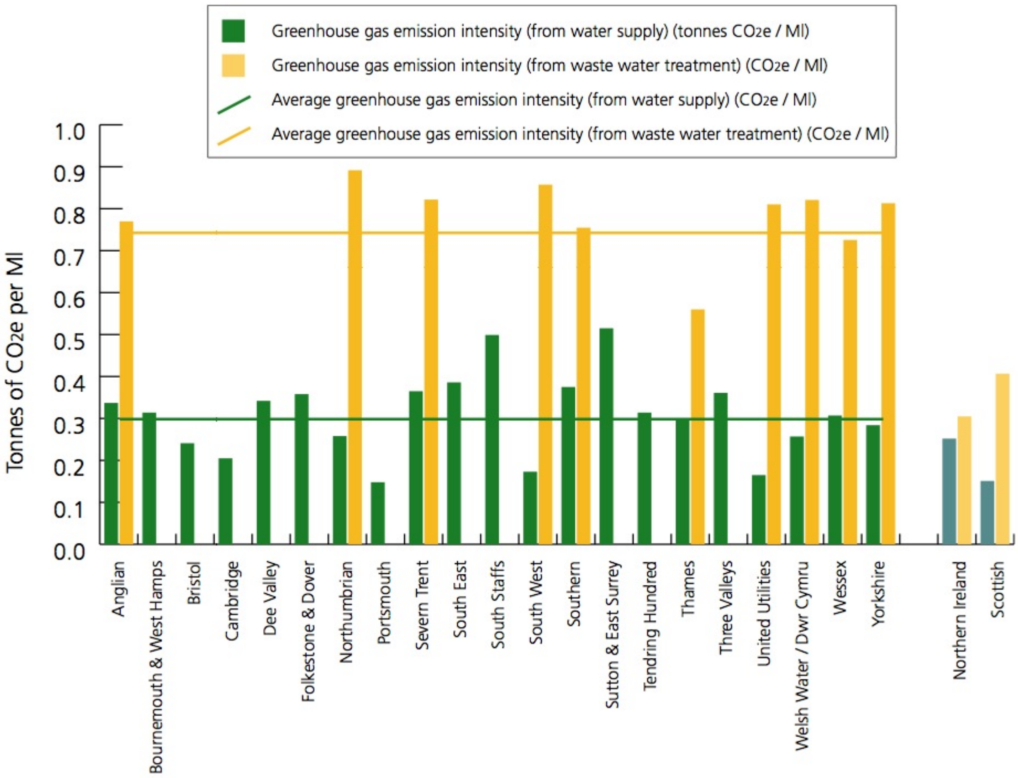


Figure 24. Greenhouse gas emissions by water company, Water UK (2008).

The most recent data are from Water UK's 2007/2008 Sustainability indicators report:

Reported values, Water UK 2008:		
A	Water into supply	17640 Ml/d
B	Total loss from network	4372 Ml/d
C	Total energy use	8290 GW.h/y
D	Total GHG emissions	4.93 Mt CO_2e
E	Tonnes CO_2e/Ml water supply	0.276
F	Tonnes CO_2e/Ml sewage treatment	0.693
Calculated values:		
E+F	supply & sewage	**0.969** kg CO_2e/m^3
And from A, B, D	Total CO_2/(supply-leakage)	**1.02** kg CO_2e/ m^3
from A, B, C	Total kWh/(supply-leakage)	1.71 kWh/m^3

Table 15. Data from Water UK which suggests an average value of about 1kg CO_2e/m^3 useful water supplied.

For comparison the Environment Agency Water Carbon Footprint Calculator (Environment Agency, 2008) uses a slightly lower figure of 0.747 kg/m^3.

The quoted figures include energy to run offices, transport etc. Anecdotal evidence reported in MTP (2008j) suggests that about 70% of this energy is for pumping, so a reduction in water use will result in a significant but not proportionate, reduction in energy use since not all energy use is not volume related.

The Environment Agency figure of 0.75kg/m^3 has been incorporated into the modelling carried out throughout the current project. Since this represents around 10% of the total carbon emissions due to water in the home, an exact figure is not required for the purposes of the models used in this report.

2 Appendix 2 – water use assumptions

In order to model the CO_2 impacts of modifying appliances in section 4, a number of assumptions on water use were required.

General assumptions on water use

- Water use behaviour is based on 2007/2008, and based on‘typical’ people (i.e. not water enthusiasts). There is limited evidence on the ways in which different social groups use water, this is not the subject of the current study
- We have not investigated the effects of occupancy on micro-component use, although we recognise that increasing occupancy leads to decreases in individual use, and that this effect varies between micro-components
- Whilst water use in showers, baths and external water use has a seasonal component (Anglian Water, 2007), we have not incorporated this.
- We have not investigated the effect of day of week, holidays etc on water use, although we recognise that weekend water use differs from week day water use in many ways.

Water using appliance ownership assumptions

Water use data is generally based on an ‘average’ household, according to a percentage of the population that owns an appliance. However, this can skew data on total use volumes unless ownership is close to 100%. For the purposes of this study we are assuming 100% ownership of WC, kitchen sink, hand basins and washing machine. Ownership is lower for shower, bath and dishwasher and we are using assumptions based on current MTP data. Both models generated in the current study model a single household, so the influence of appliance ownership can be investigated.

2.1 Assumptions for existing housing stock

Data for basic scenario of usual housing stock				
Device	ownership	frequency	vol/use	litres/property/day
toilet	1.00	11.52	9.40	108.29
kitchen tap hot	1.00			35.00
kitchen tap cold	1.00			24.00
basin tap hot	1.00			22.00
basin tap cold	1.00			20.00
bath	0.88	0.52	70.00	32.00
Washing machine	0.94	0.81	50.00	38.00
shower	0.85	1.46	25.70	32.00
Dishwasher	0.37	0.71	21.30	5.60
				Total 316.88

Table 16. Data used for the basic scenario of existing housing stock, based on an occupancy of 2.4. Data is colour coded according to their source. Red: CP187. Blue: Anglian100. Black: assumed. Green: calculated from other columns.

Approach

These assumptions are based on a composite of several datasets, and therefore have limitations. However, no complete datasets were available. Anglian100 data is used in preference to WRc Identiflow® where available. Using the latter source is problematic given a) the lack of subdivision of the ‘internal tap’ category, b) the discrepancy between water use attributed to baths compared to Anglian100 and c) the fact that Identiflow® data is derived from whole house data rather than collected at the level of the appliance. These problems are particularly important given that the current study is largely concerned with hot water using micro-components.

2.2 Assumptions for new housing stock

Appliance ownership assumptions are taken from MTP (2008d). Bath ownership decreases, and shower ownership increases compared to the existing housing stock. Dishwasher and washing machine ownership has increased. The issue of the effect of dishwasher ownership on kitchen sink use is discussed in Appendix 6.6.

Frequency WC use has remained the same. Volume per use has been decreased to 6 litres, the maximum allowed under the Water Regulations. Whilst more water efficient WC's are available, and the true flush volume may well be lower in some households, evidence from MTP (2008d) suggests that the range of WC flush volumes remains large. This may partly reflect half:full flush ratios and merits further investigation.

Kitchen and basin water use are unchanged from existing housing stock. We are not aware of robust data as to whether or not this assumption is reasonable, and we have concerns about arbitrarily subdividing the 'internal tap' category presented in MTP (2008d) in order to generate this data.

Bath frequency and volume per use are unchanged. Whilst MTP (2008d) indicates an increase in bathing frequency, and a marginal decrease in volume compared to old homes, we note that the water use attributed to baths is considerably higher in the dataset from Chambers *et al*., (2005), against which the new house data is compared, than in the Anglian100.

Washing machine and dishwasher use frequencies are the same as in existing housing stock (as we regard this to be a variable more related to occupant behaviour than to house type). Washing machine volume is decreased to 46 litres (MTP, 2008a), on the assumption that new houses will have new washing machines. Dishwasher volume is decreased to 15 litres, for the same reason.

The major difference between new housing stock and existing is the increase in shower frequency and volume. The magnitudes of the increases we have used are based on MTP (2008d). We are concerned that by doing this we are in effect confusing three variables; a) appliance ownership, b) house age, c) year in which data was acquired, and then applying these increases to a composite dataset. This is not a satisfactory approach, and future studies are needed on new houses.

Limitations and unresolved issues

- The most significant area of uncertainty is with regard to shower frequency and volume and better data is needed on this.
- There will be demographic differences between the inhabitants of existing housing stock compared to new houses.
- It is difficult to separate the genuine difference between a new house and existing stock from any underlying behavioural change in water use over time. Whilst we did not have access to WRc source data on this, it would appear that

> the comparison is between existing housing stock data that has been collected primarily between 2000-02, with new house data from 2007-2008.

We accept that many of these assumptions limit the validity of the model outputs, but since different water use data can easily be inserted into the model these limits are testable.

2.3 Assumptions for water use at CSH level 3

The project brief called for investigating the water and energy impacts of meeting various levels of the Code for Sustainable Homes. The water calculator that is used to calculate whether or not a particular appliance specification meets a given code level is currently under review, owing to a number of flaws. We have therefore generated what we regard to be a ‘sensible’ water efficient appliance specification, but also allows the Code to be met. In order to do this it has been necessary to not have a bath in the scenario. If a bath was required, a ‘trade off’ would have been necessary that would require another appliance to have an unusable specification (e.g. a 1.7 litre/minute kitchen tap). NB. The water calculator is **not** intended to predict water use. We have therefore estimated from what we know about water using behaviour what the actual water use is likely to be (in most cases we expect water use to be much lower than figures generated by the calculator).

Appliances

WC	4/2 litres
Shower	7 litres/min
Washing machine	46 litres
Dishwasher	13 litres
Kitchen sink	6 litres/min
Basin taps	4 litres/min

Assumptions regarding actual water use in this scenario

All use frequencies and ownership assumptions are the same as in the new house scenario, with the exception of there being no bath. Basin tap use assumed to be reduced by 50% using low flow fitting. Shower use assumed to be 5 minutes/day per occupant. Kitchen sink tap use assumed to be reduced by 20% due to aerator.

Limitations

No allowance has been made for any change in behaviour that might result from use of low water use fittings. Whilst very low water use fittings might interact with behaviour, the fittings chosen in this scenario represent an optimum response allowing good performance together with water efficiency.

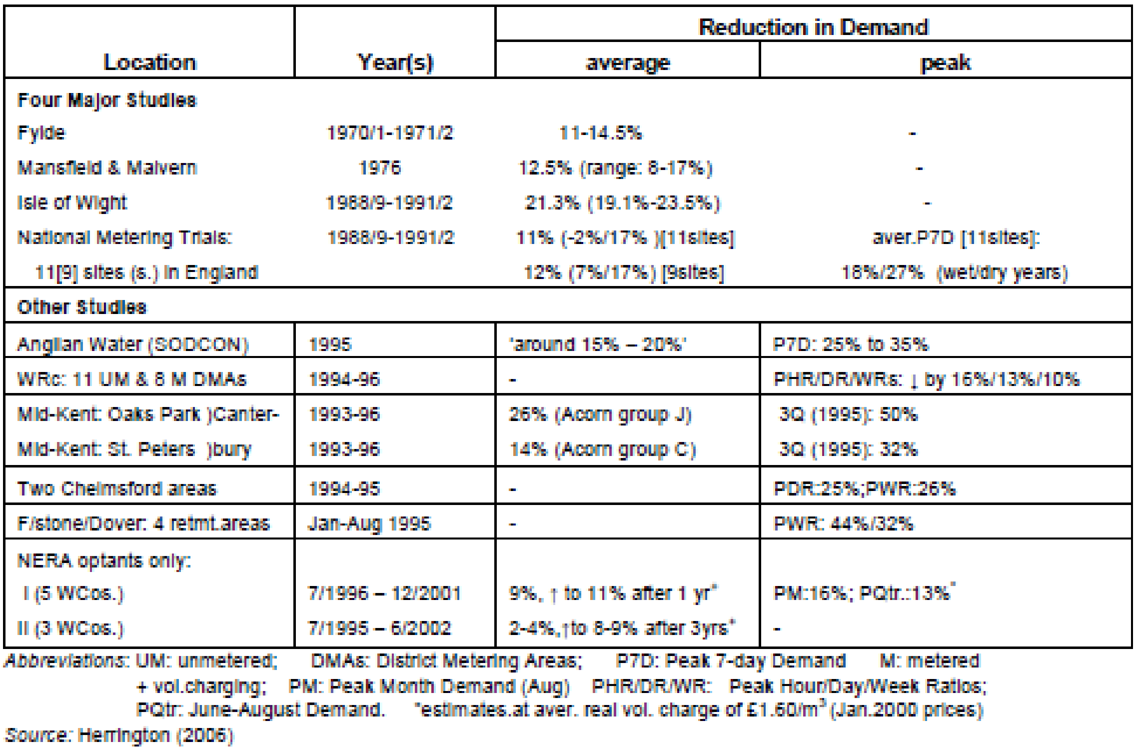
2.4 Assumptions for CSH level 3 with rainwater

Appliance specification is the same as for the standard CSH level 3 scenario, but the addition of rainwater harvesting allows the shower flow to increase to 13 litres/minute. Roof area assumed to be 55m^2, rainfall 1 metre/year, efficiency (roof and filter factor combined) 60%. Rainwater used for WC and washing machine, no outdoor use.

There are a number of ways in which CSH levels can be reached, but given the fact that the water calculator is under review, we have chosen not to explore alternative appliance specifications. These could be investigated at a later date by Energy Saving Trust/Environment Agency using the model, if required.

2.5 Assumptions for the impact of metering in existing housing stock

The impact of water metering has been extensively reviewed by Herrington (2007) and is summarised in Table 17.



Location	Year(s)	Reduction in Demand	
		average	peak
Four Major Studies			
Fylde	1970/1-1971/2	11-14.5%	-
Mansfield & Malvern	1976	12.5% (range: 8-17%)	-
Isle of Wight	1988/9-1991/2	21.3% (19.1%-23.5%)	-
National Metering Trials:	1988/9-1991/2	11% (-2%/17%)[11sites]	aver.P7D [11sites]:
11[9] sites (s.) in England		12% (7%/17%) [9sites]	18%/27% (wet/dry years)
Other Studies			
Anglian Water (SODCON)	1995	'around 15% – 20%'	P7D: 25% to 35%
WRc: 11 UM & 8 M DMAs	1994-96	-	PHR/DR/WRs: ↓ by 16%/13%/10%
Mid-Kent: Oaks Park)Canter-	1993-96	26% (Acorn group J)	3Q (1995): 50%
Mid-Kent: St. Peters)bury	1993-96	14% (Acorn group C)	3Q (1995): 32%
Two Chelmsford areas	1994-95	-	PDR:25%;PWR:26%
F/stone/Dover: 4 retmt.areas	Jan-Aug 1995	-	PWR: 44%/32%
NERA optants only:			
I (5 WCos.)	7/1996 – 12/2001	9%, ↑ to 11% after 1 yr*	PM:16%; PQtr.:13%*
II (3 WCos.)	7/1995 – 6/2002	2-4%,↑to 8-9% after 3yrs*	-

Abbreviations: UM: unmetered; DMAs: District Metering Areas; P7D: Peak 7-day Demand M: metered + vol.charging; PM: Peak Month Demand (Aug) PHR/DR/WR: Peak Hour/Day/Week Ratios; PQtr: June-August Demand. *estimates.at aver. real vol. charge of £1.60/m^3 (Jan.2000 prices)

Source: Herrington (2006)

Table 17. Summary of studies on the impact of water metering on household demand. Data from Herrington (2006).

Impact of metering on micro-components

It could by hypothesised that 'easy' behavioural changes like turning the tap off whilst brushing teeth, and more careful outdoor water use would mean that a decrease in water use due to metering was biased towards cold water micro-components rather than hot. However, this appears not to be the case. Limited data on this is available from behavioural surveys carried out by water companies. In almost every instance, reported behaviour for showers, baths and taps shows lower use frequencies in metered properties than un-metered (e.g. Table 22). Volumes of water saved cannot be accurately determined from behavioural surveys, but the general principle that use frequency of hot water appliances is lower in metered households is demonstrated.

Whilst it is widely accepted that water use per person is lower in metered households than non-metered, it is obvious that low water users are more likely to request a water meter, so it is not surprising that there is a behavioural difference between the two groups. This argument would not apply to metering done for other reasons (e.g. compulsory metering, or change of occupancy, COM), and this limits the relevance of carrying out further studies on existing metered customers in order to make predictions about the CO_2 impacts of compulsory metering. It has also been hypothesised (Environment Agency, 2008c) that the mentality of 'paying for what you use' could lead to higher water use, because the householder regards this as a legitimate benefit of metering.

For the current study we have chosen to use a 12% decrease in water use to all micro-components, hot and cold. We accept that decreases will vary between micro-components, but no data was available on which to base an alternative decision. Neither is there data on whether any decrease is due to decreased event frequency, duration, or volume (most likely to be a combination of all three), so we have applied it to the total water use for each micro-component.

Influencing factors we have not considered

- No adjustment has been made for the season of the year, although there is evidence from Anglian100 and Southern Water that showering and bathing have seasonal differences.
- No adjustment for difference in social grade between metered and unmetered
- No distinction made between compulsory metering, change of ownership, or optant metering
- No adjustment has been made for potentially different appliance ownership in metered compared to un-metered properties. Whilst such a difference might exist, the distinction is further complicated by the social grade differences between metered and un-metered.
- Supply pipe leakage is often identified in conjunction with meter installation. The fixing of supply pipes is generally regarded to result in additional 10% water saving, over and above the fitting of the meter itself (Herrington, 2007). These savings have not been included in our assumptions.
- There is no numerical data on whether or not savings due to metering decline over time. Whilst there is anecdotal evidence that this is the case, it is not clear the extent to which this is a genuine effect independent from the gradual trend towards increasing water use seen in all households.

Future data sources for the impact of metering on micro-component water use

More definitive data on could be obtained from the Anglian100 data, and in a statistical analysis and micro-component modelling report (Anglian Water, 2007) it is stated that "most micro-components had strong meter effects".

2.6 Assumptions for the impact of water efficiency measures on existing metered households

The main data source for the assumptions we have made is Waterwise (2008b) which summarises more than 20 water efficiency retrofit trials. Results were highly variable and many were assumed rather than measured. The range of water efficiency retrofits available is discussed in Environment Agency (2007b), and the economics of water efficiency are discussed in Environment Agency (2003).

The approach taken to extracting data from the Waterwise evidence base has been only to include studies in metered houses where water saved was measured either at the level of the customers water meter or by flow loggers on a selection of appliances. A median value for water saving was used for each device.

Final assumptions used for impact of water efficiency retrofits:

- A cistern displacement device, or dual flush retrofit is installed and gives an 11.2 litre/household/day water saving.
- A water efficient shower head is installed in households with showers that are suitable for retrofit and results in a 6.1 litre/household/day saving.
- Tap inserts are installed throughout, with a total water saving of 10.8 litres/household/day. These savings are apportioned between the different appliances (kitchen and basin, hot and cold) according to the relative initial water consumptions in the existing housing stock scenario.

General assumptions

- We have not looked at the interaction between retrofitting and behaviour change, on the assumption that a household with enough enthusiasm for water saving to have opted for a meter and will have undergone some behavioural change. This is typical of the type of household likely to have water efficiency measures installed by a water company.
- We are not incorporating any ‘half life’ calculation whereby the impact of the water efficiency measure decreases over time.

Future data

We expect the current WRc Identiflow® project (CP359) to yield useful data regarding the water efficiency benefits of retrofitting water efficiency measures. These can be incorporated into the models in the future by Energy Saving Trust/Environment Agency.

3 Appendix 3 - development of the Water Energy house model (WEM)

3.1 Introduction

The spreadsheet provides a model for water and energy use within a dwelling. The primary input is the water use data which is standardised into litres/day/household for each end use. The temperature at which the water is delivered and the percentage splits into hot and cold give the energy demand of delivered hot water.

The initial model assumes a hot water cylinder system, heated by a boiler or electrically, or a combi boiler. Fuels modelled are natural gas, LPG, oil, coal and wood.

The hot water energy systems are modelled in reasonable detail to cover heat losses from distribution pipe work, hot water cylinder & boiler primary circuits. These heat losses contribute to space heating, and are combined with the heating effect of hot water in use (e.g. from showers) and the cooling of cold water storage (e.g. in WC cisterns). The net offset to heating energy depends on the heating demand of the house – a well insulated house will not use as much of the waste heat as a poorly insulated one. So a range of house insulation standards are included to derive the utilisation factor.

The net heat demand on the boiler is then calculated, taking the delivered hot water energy and the losses minus the fraction that provides useful space heating. Then a simple boiler model takes seasonal efficiency and fuel type to calculate CO_2 emissions. Emissions associated with direct electrical water heating are calculated separately, though any hot water in-use gains associated are offset against boiler use.

Further elements are the water treatment CO_2 emissions and secondary pump power. Electric consumption of the boiler is not included.

Outputs

The primary output is the total energy use and CO_2 emissions associated with water use in the house over the year. This is broken down into delivered hot water, with use categories as described in the water use data (e.g. WC, shower, bath etc), and other losses in the system. These losses are reduced by the net useful heating they provide, as the system losses are generally specific to the system design rather than the water consumption. Where there are specific heat gains associated with end uses (e.g. showers warming the bathroom) these factors are included in the use category CO_2 emissions.

3.2 Details of model

Water use

Initial examples follow the micro-component model of daily frequencies per person and per-use volumes. All volumes are converted to household per day figures, to allow use of other monitored data as this is gathered.

Delivered energy

The use figures are split into hot and cold for basins and sinks, and assigned standard delivery temperatures for other uses. Some temperatures are set as mains cold, and stored hot, others depend on use (e.g. showers). The combination of volumes and temperatures provides kWh/day demand figures. There is also an estimation of direct impact on space heating from the water use. Examples are the warming of water in WC cisterns, adding to space heating load, and the heating of bathrooms caused by running showers or baths. These figures are preliminary estimates and further research is needed.

A total kWh/day figure for hot water is derived, and this is converted back to a litres/day figure at a particular delivery temperature. This allows a cross check with BREDEM, PHPP and the Energy Saving Trust (2008).

Direct electric heating is separated, and in the micro-component model electric showers are rated by kW, which is converted to a flow rate at the specified shower delivery temperature and cold water supply temperature. Data for washing machines and dishwashers is included, though here the water heating energy use is appliance specific and not directly related to water consumption.

Hot water storage and delivery

This covers the hot water storage in the cylinder and distribution via pipes, i.e. up to the point of delivery. It deals in heat loss from these elements, which depends on system design and not actual water use. All heat loss figures are given as kWh/yr for the household.

The cylinder model initially uses the algorithms used in SAP to generate heat loss figures for cylinders of different sizes and insulation thicknesses. This is adjusted to take into account varying storage temperatures and room temperatures.

A range of hot water distribution methods are considered: the usual branching network found in most UK houses; a pumped secondary circulation loop, and a radial microbore system. For each a table of typical pipe lengths and diameters is used. This may be varied to suit specific house designs, to vary according to house size, or to illustrate a range of compact to dispersed hot water systems.

The heat loss from most pipe work is due to what is known as the dead leg – the length of pipe which remains full of hot water after the tap is turned off. In some instances water consumption is increased as this cold dead leg volume is drawn off initially, e.g. when wanting hot water at the kitchen or shower, whereas it normally isn’t wasted filling a bath. However the hot water left in the pipe is always left to cool down, which it does in a matter of minutes in an un-insulated pipe.

Therefore the heat loss in a pipe is a function of water volume, and of pipe heat capacity, given that this both heats up and cools down. This is calculated from the pipe dimensions and pipe lengths. The heat loss per tap opening is then multiplied by an estimate of the number of tap openings[12] – simply taken here as 3 times per person per day. This is the figure used in PHPP (2007).

The microbore radial system is essentially the same, but with smaller pipes, and hence less water and pipe work to cool down.

For the continuous secondary circulation loop (used in larger dwelling to reduce the wait for hot water), heat loss is calculated by estimating the average water temperature, given the cylinder temperature, the pipe heat loss per m, the length of pipe loop, and the hours run per day. Short runs from the loop to individual taps are dealt with as per normal deadlegs.

Boiler

This section deals with the heating circuit. This is the boiler and the pipe work connecting boiler to cylinder.

The total hot water energy demand is derived from the point of use demand plus the cylinder and pipe work losses. This gives an average boiler load which gives an estimate of the boiler run-time needed to heat the water. The boiler flow temperature is used to derive an average water temperature in the primary circuits and the boiler run-time estimate used to estimate the 24hr average water temperature in the pipe. Then the pipe length plus heat loss per metre per degree give the heat loss of the primary pipe work.

Further losses come from the cool-down of the water and pipe work once the cylinder is reheated; this is calculated as for supply dead legs. A similar calculation is made for the boiler itself, which also contains water which cools down after use; an estimate of boiler thermal capacity is used. The number of reheats is estimated assuming that the cylinder thermostat is one third from the base of the cylinder, so the re-heat cycle occurs after one third of the cylinder volume has been used, rounded up to a whole number of firings per day.

This figure has been compared with the option of standard figures as used in SAP. For combi boilers the primary pipe work loss doesn't apply, but the boiler loss does. Here the boiler fires more frequently, and the same "3 x occupancy" figure used for draw-off (see above) is applied to boiler firings.

Now the total annual heat demand at the boiler can be calculated, the boiler efficiency allowed for and the carbon density of the fuel used to give the CO_2 emissions associated with heating the hot water. However some of these heat losses are useful, they go towards heating the house. If they weren't there the boiler would have to provide that heat anyway. This has tended to be ignored in poorly insulated houses, as the amount of heat would be less than the heat loss from predicted draughts etc. However with super insulated airtight houses such as Passivhaus, high CSH levels or small flats with little external envelope, then this can be a significant amount of heat, in fact so much that it can't all be used, so there is already consideration of the

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[12] More precisely this is an estimate of the number of times the pipe cools down per day, i.e. the number of grouped use events.

utilisation of waste heat in SAP and PHPP with simple algorithms derived from more complicated dynamic thermal models.

Pumps

Some energy use is due to pumps, but this has only been considered for secondary circulation. This is based on run times and typical pump watt ratings. Pump energy use is all converted to heat within the building, so gains would be subject to utilisation for space heating and would offset some heating CO_2 emissions. Though the pump energy use is electrical, and generally has higher CO_2 emissions per kWh.

Utilisation of losses

To calculate the utilisation factor for waste heat some idea of the heat demand of the house is needed. The model takes four cases, existing houses, current building regulations standard, AECB Silver standard and Passivhaus standard. In each case there is an estimate of typical gross heat demand and useful gains (solar, electrical and people) over the heating season. This gives a utilisation factor for making use of the waste heat which gives the useful contribution the waste heat makes to heating the house. When the hot water losses for the duration of the heating season are added a new utilisation factor is derived and a new heating contribution, so the increase is the hot water contribution, and the marginal utilisation of hot water losses derived by dividing this by the total hot water losses. For the annual utilisation this is then multiplied by the heating season proportion of the year.

The calculations show that in older houses or those of building regulations standard, the hot water losses are useful throughout the heating season. In AECB Silver Standard houses 5% is not useful and in Passivhaus 25% is not useful, in round terms.

The figure for heat losses includes all those discussed above; cylinder, distribution pipe work, primary pipe work. It also includes an element for direct heat loss from water after point of delivery. This is the loss that leads to shower water cooling as it passes through the air, or the bath just getting colder. These losses are calculated based on an estimate of the temperature drop of the total volume of water delivered to the particular end use. The temperature drop is based on some preliminary experiments by ourselves (Figure 26) and other research where it is available (Critchley & Phipps, 2007). However some more work is needed on determining how much of this heat loss is in the form of converting water from liquid to vapour which leaves the building still as vapour in the extract air from the bathroom, so the energy is not in fact recovered.

The model currently assumes that 50% of the energy used by the dishwasher is lost down the drain and 50% becomes an internal gain (before applying utilisation factors), based on the fact that dishwashers dry the contents with some heat. Washing machines are assumed to provide no heat to the building, in part because of the lower wash temperatures and in part because they finish on a cold rinse. Whilst these two assumptions are the result of much discussion and some calculations, they should be considered as no more than an educated guess.

Losses to cold water

Another area of interaction between the water used and the heating is the warming up of cold water. The principle issue here is the water stored in the WC cistern – it has the time to warm up, and no one cares what temperature it is used at (Gandy *et al*., 2008). Preliminary experiments were used to calculate values for this (Figure 25). Most other water uses, where cold water may warm up in the pipes, are for baths and showers where cold and hot water are mixed to a particular temperature so the energy lost in cooling the house is effectively regained as slightly less hot water is needed. These hot and cold water cooling and warming may account for 10-20% of hot water energy use, but one is negative and one is positive, so the net effect is less than this.

Figure 25. A datalogger with temperature probe in a WC cistern was used to obtain data on losses to cold water. Note the condensation up to the water-line on the surface of the cistern.

Final output

The various heat losses from the water systems are factored by the utilisation factor to give the net energy requirement from the boiler, and the total CO_2 emissions resulting from the water use in the house are derived, once those resulting from direct electrical heating, and pumps etc, are added. Thus the change in CO_2 emissions from changing the water use data – e.g. changing type of shower – can be seen, with all the various factors taken account of. Also, the results are presented with the various energy use elements listed along with the associated CO_2 emissions, so that the distribution of emissions can be illustrated. The output can be simplified by grouping components such as delivered hot water or total system losses depending on what is being demonstrated.

Source of algorithms used

The water use is taken as an input, and a variety of assumptions and data sets are used. The model relies on the first law of thermodynamics for most calculations concerning energy, but there is some latitude in the temperatures used. This is for supply temperatures, boiler temperatures, and storage temperature, which are based on standard heating design engineer data, but merit some experimental confirmation.

The utilisation factors are based on the algorithm used for the PHPP annual method, which is like the SAP method – the EN monthly method would be excessive for this purpose.

Utilisation factor, η_G, the percentage of heat gains that provide a useful contribution towards heating is calculated as follows, where Q_F is heat gain and Q_L is heat loss:

$$\eta_G = \frac{1 - \left(\frac{Q_F}{Q_L}\right)^5}{1 - \left(\frac{Q_F}{Q_L}\right)^6}$$

Figure 26. Space heating gains from the bath were calculated from experiments. Surface temperature (infrared thermometer) and room temperature were both measured. Bath temperature was measured (probe suspended in the water by Delyth the Duck)

4 Appendix 4 – water efficiency study design

In an attempt to standardise the way in which water efficiency studies are carried out and to improve the quality and usability of data, several water industry guidance documents exist:

- UK Water Industry Research (UKWIR). Quantification of the Savings, Costs and Benefits of Water Efficiency and the Effects for Charging (report by Entec, 2000)
- Waterwise. Water efficiency audit programmes: A Best Practice Guide. (2008)

Rather than add to these documents (which are clear and comprehensive) we have highlighted a specific issue which is almost universally ignored in water efficiency studies; that of statistical power.

Sample size and implications of statistical power

A key point emerging from this review is the importance of understanding how big a sample needs to be in order to produce a useful result. The general approach in the past has been to study as many households or appliances as there is budget or equipment to do. This has led to a lot of small studies producing inconclusive or inconsistent results. It is recommended that a more statistical approach to determining study size is taken in the future, involving a ‘statistical power’ calculation. The sample size necessary for a given study is dependent on four factors:

- The variability of the data
- The size of the effect being studied

These factors can be considered as the signal:noise ratio

- The type I error rate
- The type II error rate

These factors are set at the study design stage, and are in effect a statement of how definitive the answer needs to be.

Variability of the data: If there is a high degree of natural variability in the data, a larger sample size will be needed in order to detect the effect of an intervention. This is the ‘noise’ in a signal:noise ratio. When carrying out studies it is usually easier to reduce the variability of the data (e.g. by only studying the effect of a water efficient shower head on showering behaviour in a particular subset of the population) than it is to increase the sample size. Initial considerations of the number of likely confounding variables are necessary, together with the feasibility of either reducing the magnitude of these confounding variables (preferable), or measuring them if they cannot be removed (in order to allow some assessment of whether the confounding variable could in fact be responsible for the effects observed). In many studies the best way of reducing variability or background noise is to make more specific measurements (so for example to log the flow, duration and use frequency of the shower when studying showering behaviour, rather than expecting to be able to get this data from total household water use).

The size of the effect being studied: Large effects are obviously easier to detect than small ones. So in the above example of showering behaviour, if the water efficient shower has a flow rate that is 1 litre/minute lower than the shower it is replacing, more samples will be needed than if the water efficient shower head has a flow rate 5 litres/minute lower than the one it is replacing.

Type I error rate: This is the risk of finding an effect when in fact none exists (i.e. getting a false positive). For example, finding that a water efficient shower results in lower water use, when in fact it doesn’t.

Type II error rate: This is the risk of not finding an effect when in fact one does exist (i.e. getting a false negative). For example, not finding an effect of water efficient shower heads on water use, when in fact there is one.

It is not possible to set absolute rules on necessary sample sizes, because these factors will vary from one study to the next and according to study design (e.g. paired sampling, use of a control group etc).

The natural variability in water use between households is high, and a large sample population would be needed in order to discern an effect of (for example) a water efficient shower head if one chose to construct a study as two separate groups of households (one group with the intervention, and one control group). The alternative is to study the effect of appliance change within an individual household, rather than seeking to compare households. However, examination of Figure 27 (from Anglian100 data) below demonstrates that even within an individual property, hot water use varies considerably on an annual basis, so it may still be difficult to achieve statistically robust results.

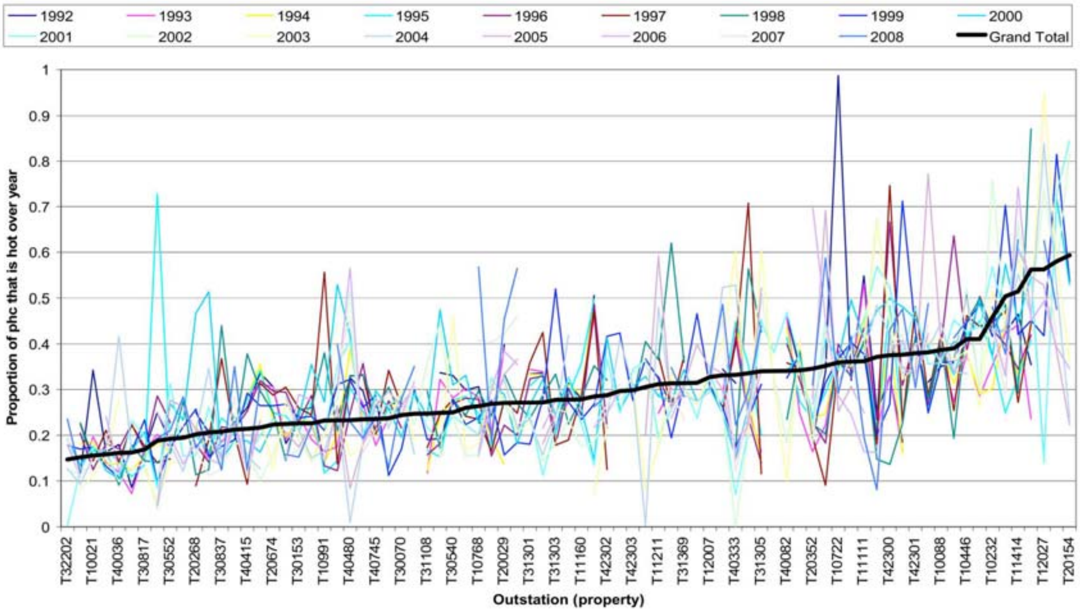

Figure 27. Hot water use at the various properties in the Anglian100 dataset.

Considerations of the variability and its influence on sample size also illuminate the fact that it is absolutely vital to collect occupancy data. Whilst it is accepted that this is difficult to do, there are very few studies where the effect of occupancy will not be significant; not measuring occupancy is in effect introducing an enormous variable into the study design that will usually dwarf the effect that you are trying to measure. This omission can render a study worthless in terms of being able to reach robust conclusions (and statistical power calculations can be used to demonstrate this).

General concerns on data analysis within existing micro-component studies

There are a number of concerning elements in the way in which data has been expressed in many studies to date:

- Inappropriate summary statistics, particularly the use of arithmetic means when medians would provide a useful summary. Errors and deviations are rarely reported.
- Exclusion of outliers in the data. In instances where the mean is strongly influenced by a small number of what are stated to be ‘obviously erroneous’ data points, it is usually more appropriate to use a median than to censor the data by excluding outliers.
- Attempts to provide summary statistics where data is too variable to warrant it; in some instances the variability in a value is of more important than its average (e.g. where there is a behavioural influence on the variable). This is particularly the case with use frequency.
- Correlations between two variables are assumed to be causal, without consideration of other (unmeasured) variables that may influence the relationship.
- Lack of clarity regarding whether data for a particular appliance is expressed as a total volume (with the total water use of that individual or property also stated), or expressed as a proportion (with no regard for the total water use).
- Lack of appreciation of the influence of occupancy on individual water use (dividing a household water use by an average occupancy is not a satisfactory approach).
- Use of a high number of statistical tests on a single data set without any apparent use of corrections (e.g. Bonferroni) for multiple comparisons[13].

Problems stemming from interpreting the results of ‘single issue’ studies

The studies that have produced the most convincing data on water use have either involved very intensive monitoring (e.g. Anglian100) or been focussed on particular appliances. The focussed approach has the advantage of allowing a particular situation (e.g. shower use) to be studied in more detail. However, single issue studies are not without their disadvantages; it is almost inevitable in such studies that some variables that influence the data will not be measured. For example, the use of one appliance may interact with use of another (the most obvious example being bath and shower use), which can limit wider applicability of the results of a single study.

Insufficient appreciation of alternative explanations for results

Unfortunately, there are many examples of where the most important variables are not actually measured. The most obvious example of this in the past has been occupancy (a ‘known unknown’), and this is usually now measured. Whilst we cannot deal with the ‘unknown unknowns’, we can at least postulate what some of these might be. An Identiflow® study for Essex and Suffolk Water (Creasey & Bujnowicz, 2006), is a good example of where influencing variables were not measured, and erroneous conclusions could be drawn. The study was designed to measure the difference between hot water use in households with direct plumbing compared to indirect plumbing systems. It was hypothesised that households with direct plumbing systems would use more hot water, owing to the volume available not being limited by the size

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[13] For example with a significance level of p=0.05, a significant result is likely to occur on 1 in 20 occasions purely due to chance.

of the hot water tank. However, the opposite was found to be true. Several other variables that could explain this result were subsequently measured, and the result was then attributed to supply pressure differences between the two groups of properties. It is entirely possible that these other variables would not have been measured if the initial results had confirmed the study hypothesis (in which case the ‘right’ result would have been obtained for entirely spurious reasons).

Similarly, taking single elements of datasets from a range of studies can inadvertently lead to the limitations of a study technique being magnified. An example of this is the use of isolated pieces of Identiflow® data in the CSH water calculator. The Identiflow® technique is thought to over-estimate frequency of bathing, as it can be difficult to differentiate between a brief bath event (e.g. for topping up a bath that is cooling down, or for rinsing a bath) from a kitchen sink event. The calculator uses bath volume data from a different source, so results in a much higher water use due to bathing than would have resulted if the calculations had all come from a single dataset.

Consequently, it is important to continually compare data from studies that use different techniques, as they will all have their limitations; if similar answers can be obtained independently, by people asking the same question in different ways, then it is reasonable to have more confidence in the data.

Problems with specific data gathering techniques

Identiflow®. This tool has reliability issues when studying hot water using micro-components and it should be recognised that since the actual measure is of total household water use at any given time, it is a prediction of a micro-component water use rather than an actual measure. Specific issues include:

- It seems unreliable for any appliance fed by an indirect plumbing system, and it is not clear how much of the dataset this applies to. The specific issue of indirect plumbing has been explored in a recent study (referred to in Waterwise, 2008) with regard to shower use, but not with regard to other appliances.
- Potential for mis-classification of events by the analyst.
- No distinction between wash basin and kitchen sink use, or between hot and cold.
- The dataset now encompasses data collected over a long time period, during which significant changes in appliances and behaviour will have occurred. The year in which data was acquired is rarely available in the study reports.

Anglian100. Since this data is actually collected at the level of the micro-component it constitutes genuine appliance data. However, since logging occurs every 15 minutes, it does not have sufficient resolution for short duration events. It has not been possible to ascertain how much of a problem this represents, but it will differ between appliances (e.g. important for taps, less important for baths).

5 Appendix 5 – potential for new study designs

In general, the evidence base on the water consumption of ‘fixed function’ appliances (white goods, WC) is good, but is much less so for appliances where the function is variable (taps, showers, baths). One can always argue that more data is needed, but this leads to an almost infinite number of future studies. Given that the primary focus of the current study is to investigate the CO_2 emissions impact of domestic water use, one approach is to prioritise these in terms of potential for CO_2 emissions reduction.

However, it could also be argued that if a marginal abatement cost (MAC), as considered in section 6 demonstrates both cost and CO_2 emission savings for a given measure, it should be adopted anyway, and lack of knowledge about the exact magnitude of the benefit should not delay action.

Scope for re-analysis of the Anglian100 dataset

As discussed in section 0, it is highly likely that re-analysis of existing data could be a better approach than completely new studies. The obvious example of this is the Anglian100 dataset. Some examples of questions that could potentially be answered from this dataset and the value of knowing the answers are given in the table below.

Question	**Implication of knowing the answer**
How variable is shower flow rate within an individual property and how does it compare to the maximum flow rate of the appliance? How does this vary between shower types?	Understanding whether a water efficient shower head will result in water savings. Are people routinely using the maximum flow available, or are they already attempting to be efficient?
How much does shower duration vary? Is it reasonable to calculate average duration or does people’s behaviour fall into distinct groups with different averages?	Ability to target water/carbon efficiency messages at particular groups of people, such as those who are using the most, or those who might be most amenable to change.
The data shows that the volume of water used in showering is increasing, but is this due to increased frequency, flow rate or duration?	Need to understand the way in which shower use is changing in order to determine the best way of addressing the CO_2 impacts of this. This might lead to a behavioural campaign (on duration), or water efficient appliances legislation (on flow rate).
Are there properties where a boiler was changed, with no change in occupancy? What effect did this have on hot water using events?	To what extent will improvements in boilers lead to CO_2 savings? Will people’s behaviour change and negate some of these savings?
Are there properties where the billing method has changed from rateable value to measured, and what effect has this had on hot water use?	The effect of water metering on hot water use and the potential for CO_2 saving by installation of water meters.
Is there a difference in hot water use between social groups? Can this be explained by a behavioural difference or is it due to differences in appliance ownership or specification?	Which groups do we need to target, and with what type of message? Are there particular types of appliance that need regulating to minimise their CO_2 impact?
Is there a fixed relationship between shower and bath use?	CSH water calculator assumes a shower:bath ratio, but there is no evidence that this is a valid approach.

In all these instances, it would be important to establish the likely magnitude of an effect compared to the natural variability in the dataset (i.e. the statistical power). This would give some idea of how realistic it is to expect a robust answer to the question posed. The most obvious way of prioritising what questions to answer is to consider the potential CO_2 savings of acting on the answer.

Re-analysis of other studies

Re-analysis of the data contained in Energy Saving Trust (2008) may be worthwhile. For example the higher volume of hot water used at the kitchen sink in properties with combi boilers is hypothesised to be due to the need for hotter water (and therefore higher run off volumes). However, since the frequency distribution of hot water events seems to be different between the groups, it is possible that the higher kitchen sink use is due to a higher event frequency rather than a higher event volume (which is entirely possible if the demographics of the groups are different). Another element of interest in this study is the fact that hot water micro-component data is available. Whilst this has been expressed as a volume of water, presumably it would be possible to determine the event frequencies, durations and flow rates for the hot water micro-components. There is a need to clarify how good the data is from this study on volume of water used at the appliance (since volumes weren’t measured at the appliance, but at the boiler, so if more than one event occurred simultaneously, volume of event data may not be accurate). A combination of hot water data from this study and the Anglian100 data is likely to provide more robust data on hot water use than would be generated by new trials. This data would allow some clear priorities to be set both in terms of the future trials needed and the ways in which water and energy efficiency messages can complement each other.

Scope for using metering data from water companies

As the number of metered water supplies increases, the body of evidence on domestic demand patterns is increased, since water companies must collect this data for billing purposes. Whilst this data is commercially sensitive and not in the public domain, it would be worth considering what type of questions could be answered with access to this data and whether or not it is a useful line of further research. It may also be the type of data that could be incorporated into a meta-analysis (see below), possibly in combination with energy use data. Similarly, data records at DMA level could well be a useful data source for certain types of question (as an example the influence of supply pressure on domestic water use was hinted at in Creasey (2006b).

Scope for meta-analysis

This is a powerful tool which allows data from a range of studies to be incorporated into a single analysis in a statistically valid way. This gets round some issues of statistical power and the impracticality of large sample sizes (discussed above). It also allows the methodological weaknesses in studies to be corrected in a statistical sense (by incorporation of statistical uncertainty). However, a meta-analysis is only as good as the set of studies on which it is based. Combining existing studies in a statistically robust way would allow the maximum value to be extracted from existing knowledge.
Meta-analysis of the Identiflow® dataset. Individual Identiflow® studies are of limited use since the sample size is generally limited by the number of loggers available and budgetary constraints. Whilst there is some concern about the limitations of Identiflow® as a technique for investigating hot water use, uncertainty regarding data quality can be incorporated into a meta-analysis in a statistical way that

limits the risk of over-interpretation. In this instance, since Identiflow® is a proprietary tool, the limitations are likely to be very similar between all Identiflow® studies, so incorporating this uncertainty is not particularly difficult (by differentiating the systematic error introduced by the tool from the random variation in the signal). If there is a sufficiently large part of the dataset where (for example) the plumbing systems is direct as opposed to indirect, occupancy is known, and there are some appliance details available, an analysis of that subset of the data might yield useful results. However, since the main limitations of the Identiflow® technique are related to hot water micro-components, an independent review of the usefulness and limitations of the tool itself would be necessary prior to any numerical analysis.

Meta-analysis of behavioural survey data. As discussed above, behavioural differences in water use are high, and so large sample sizes are required to ensure a sufficiently large sample size to get reasonable statistical power. There is an enormous body of household survey data on water using behaviours, largely collected by the water companies for the purposes of calculating future demand[14]. Whilst the ways in which these appliance use surveys are done will inevitably vary between water companies, this variability can be modelled as an uncertainty. It may be that there is sufficient existing data in this area to merit an independent review with a view to undertaking meta-analysis. Additional data from such as demographics and other factors which may be responsible for the variability is also necessary, but should be available as responders are generally asked for their postcode. Since most water companies repeat these surveys on a regular basis, combining the results of these surveys would allow some important questions regarding water use behaviour and how it is changing to be answered. This in turn would allow more focussed water efficiency and marketing campaigns. In the future, a combination of a standard approach for these surveys (perhaps facilitated by a project to develop a standard survey) in conjunction with public availability of the data resulting from them would avoid the current duplication of effort and would improve the robustness of answers obtained.

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[14] An example (from their Draft Water Resources Management Plan, 2008) is a 2007 postal survey by Thames Water, in which 59,000 surveys were sent out and almost 10,000 returned.

6 Appendix 6 – background data and further information on micro-components of water use

The majority of micro-component data sources available for this study fell into four types:

Water Resource Management Plans from water companies. These are usually based on a model (e.g. from UKWIR, Experian Business Strategies or Per Capita Solutions), in combination with company specific data, most often in the form of household surveys (postal) of ownership and use frequency. It is often not clear where company specific data has come from and in some cases it is used very selectively. In many instances the micro-component data in WRMP's appears to have been back projected from a conventional top-down demand management forecasting tool and then subdivided into micro-components according to company specific data, or standard pie charts on the micro-components of water use. Since the aim of the data in WRMP's is to demonstrate adequacy of supply:demand balance in extreme situations, data is given for scenarios defined as 'dry year annual average' and 'dry year critical period (peak week)'. For all of these reasons, data as presented in WRMP's is of limited use. The most useful element of this data is likely to be the results of behavioural surveys that underpin parts of the data.

Anglian100. This is a project set up in 1992 in which 100 domestic properties have water use monitored and recorded at all water using points at 15 minute intervals. ~60 of these properties are still being monitored. In addition to the basic monitoring data, there is some (incomplete) data on demographics, boiler type, and appliance ownership. Unfortunately this dataset was not directly available for the current study, but secondary sources referring to it have been used (primarily MTP, 2008i). This has meant a necessarily limited analysis (as it has not been possible to extract some of the variables of interest from the secondary sources).

Identiflow®. This is a system used by WRc to calculate micro-component water use from flow measurements made at the meter supplying the house. Each water-use event has a typical 'signature' (which might be its flow rate, duration, total volume, 'tail' etc) and these are identified by the Identiflow® software and allocated to the relevant micro-component. The loggers are typically installed for a 2 week period at each property monitored, and a database of over 500 properties now exists. Whilst this technique is not true measurement of micro-components, it is considerably easier to deploy than monitoring devices at the appliance level and has the advantage of the household not being aware of the monitoring occurring.

Manufacturers data. This tends to be limited to the basic performance of an appliance, such as maximum flow rate, volume etc.

6.1 Influence of boiler type on hot water use

It is widely predicted that properties with combi boilers use more hot water than properties with storage based water heating systems, owing to the potential for a combi boiler to produce an unlimited volume of hot water. So far, there is little evidence to support this prediction. Data is limited to the Anglian100 dataset and the recent Energy Saving Trust project on hot water use (Energy Saving Trust, 2008). Anglian100 data was only available from secondary sources, and it has not been possible to determine whether or not there is a difference in volumes of hot water used between properties with different boiler types (Figure 28). Other differences between properties could also correlate with any difference in hot water use, thus complicating interpretation of positive results. It is likely that some properties within the dataset have had conventional boilers replaced by combi boilers, but no data is available on the impact this has had within individual households.

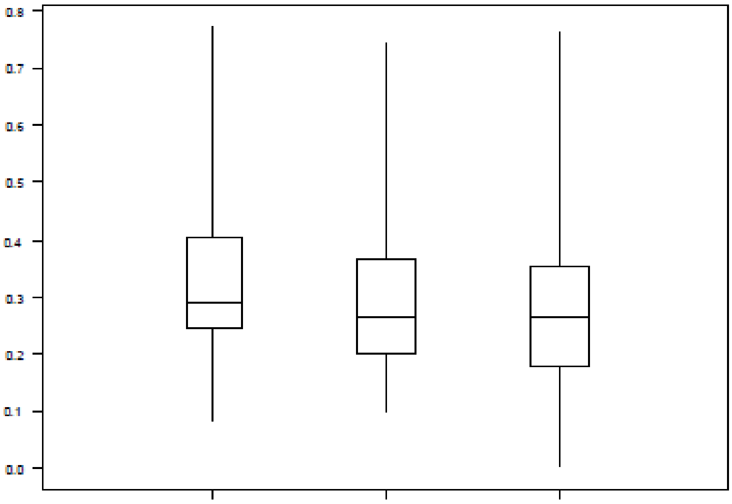

Figure 28 From MTP (2008i). Proportion of household water consumption that is hot water, according to boiler type. Left: combi boiler. Middle: gravity system. Right: gravity hot, mains fed cold. Box and whisker plot conventions: limits of box are 25th and 75th percentiles, line across the middle of the box is the median. The end of each whisker usually represent the smallest and largest values.

Energy Saving Trust (2008) did not find any correlation between total hot water volume used per household and boiler type; the only measured variable that correlated with hot water volume was occupancy. The same study however did indicate some difference in hot water use at the kitchen sink in households with combi boilers than in houses with regular boilers (Figure 29). It was suggested that this was due to requirements for hotter water at the sink, leading to greater run off volumes. However, this is not necessarily the case; no differentiation has been made between number of events and volume/event and as such it could equally well be a higher frequency of kitchen sink events in households with combi boilers (perhaps due to some difference in the demographics of the occupants). It could also be the case that whilst washing up, people rinse under a running tap. This can be done at a very low flow rate with a system boiler, but a higher flow rate is required to keep a combi boiler alight and perform the same function.

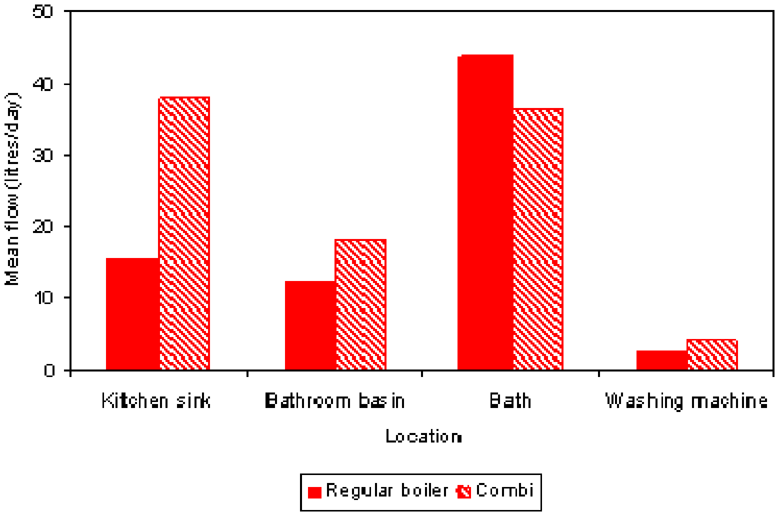

Figure 29 Graph showing the distribution of hot water volumes for different appliances. From Energy Saving Trust (2008).

Whilst this data is not shown for the kitchen sink specifically, the frequency distribution of total draw off events is different between the plumbing systems (Figure 30).

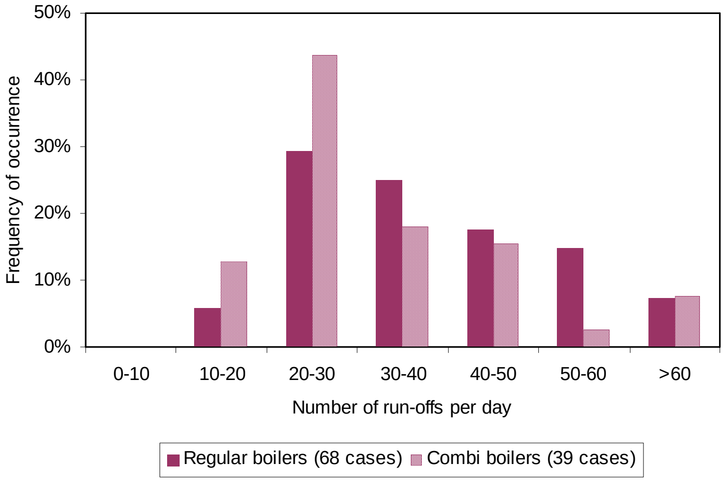

Figure 30 Hot water run-offs per day. From Energy Saving Trust (2008).

6.2 Trends in water use over time

There is a general perception that domestic hot water use is increasing over time. This is difficult to ascertain without direct reference to the Anglian100 data. However, the limited data available is given in Figure 31. Note that the hot water component of this data apparently does not include electric shower use, or cold fill washing machine use[15]. For 2008, these were approximately 19 litres/household/day (electric shower) and 37 litres/household/day (washing machine). A combination of data from Figure 31 and Figure 32 therefore gives 1992 hot water use (including all shower use and washing machines, but excluding kitchen sink [data not available]) as 137 litres/household/day, with the 2008 figure as 130 litres/household/day (Table 18).

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[15] This is not made clear in the report, but appears to be the only way that the various micro-components can add up to give the total.

Definitive occupancy details were not available but were stated to be 'stable' (Berkshire, 2009).

Appliance	1992	2008
Shower hot	2	14
Shower cold	7	19
Bath hot	32	32
Basin hot	18	22
Washing machine hot	9	5
Washing machine cold	69	38
Kitchen hot	Not available	30
Total (not including kitchen hot)	137	130

Table 18. Data from Anglian100 (MTP, 2008i), showing change in hot water use since 1992. All values in litres/household/day. Note that this data has been derived from graphs rather than numerical summaries of the data. Year-to-year variability is very high for baths and basins, but less so for other appliances (data not shown).

This data would suggest that at least in existing homes, hot water use is not increasing as a total, but that the commonly perceived increases in showering are at the moment being masked by improvements in washing machine efficiency. Since there are limitations in further efficiency gains to be had in washing machines (discussed in section 2.1.4), it is widely predicted that total household hot water use will soon start to increase dramatically. However, at least in Anglian100 data it would seem that annual variations in water use are bigger than any trend over time.

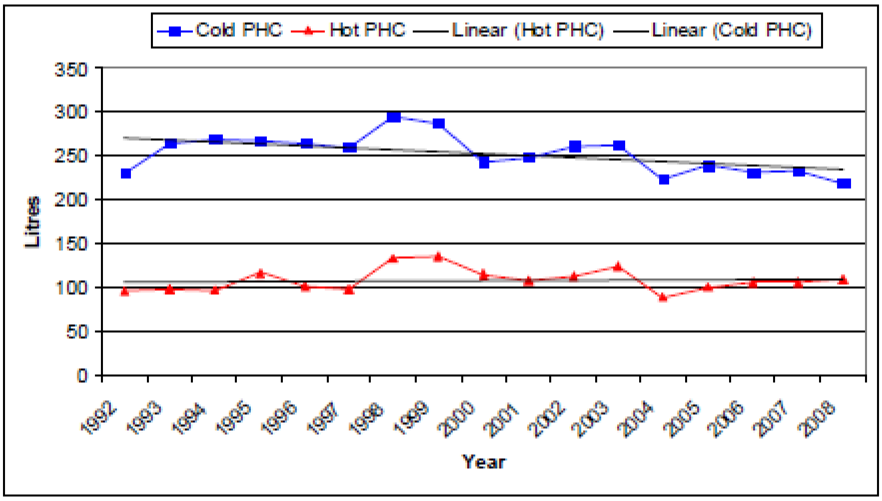

Figure 31. From MTP (2008i). Note that electric showers and cold fill washing machines are included in the cold component. PHC= per household consumption

6.3 Baths

Volume[16]	Frequency[17]	Tariff[18]	Reference	Comments
Manufacturers data				
65(165)			1	Undersized bath (1,600mm primarily)
65(140)			1	Corner bath
100(250)			1	Shower bath
88(225)			1	Standard bath
80(205)			1	Roll top bath
88(225)			1	Whirlpool/spa bath
variable			1	Outdoor spa bath
Household survey data				
70		M	2	
70		M	3	
88		U	2	
88		U	3	
80			4	
80			5	
80	1.1		6	
40%			10	Of capacity to overflow. From (8)
	0.289	M		
	0.316	U		
	0.32			
	0.08	M	5	
	0.1	U	5	
	0.258	M	7	
	0.303	U	7	
	0.726		8	Based on water company estimate of 265/year.
Measured data (Identiflow®, Anglian100)				
	0.403		9	
73.3	0.95(h)		9	skewed distribution
	~ 0.7(h)		9	Estimated median from above
	1.17(h)	M	11	New homes
68.55		M	11	New homes
52.7	0.7(h)	M	12	n=4, high st dev
76	0.9(h)	M	12	n=4, high st dev, water efficient
42.5	1.6(h)	M	12	n=4, high st dev, seasonal tariff
Other data				
	0.4		10	If shower
	1		10	If no shower. Claimed to originate from (9), but not evident.

Table 19. Available data on bath use.

References:

1: MTP (2008h).
2: Essex & Suffolk Water DWRMP (2008).
3: Northumbria Water DWRMP (2008).
4. Folkstone & Dover Water DWRMP (2008).
5. South West Water. DWRMP (2008).
6. Tendring Hundred. DWRMP (2008)
7. Waterwise (2008a).

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[16] Litres per use. Capacity (to overflow) in brackets where known.
[17] Per person per day unless followed by (h), denoting per household per day.
[18] Unmetered (u), metered (m). Blank if unknown.

8. MTP (2008l)
9. Chambers *et al.* (2005).
10. CSH Water Calculator.
11. MTP (2008d)
12. WRc. UC7853 (2008)

Bath data analysis

The most reliable data source on bath use (Anglian100) indicates that bath use is around 38 litres/household/day, although during the monitoring period (1992-2008) this has fluctuated between 28 and 58 litres (Figure 32). Without direct access to the data it is not possible to form a view on whether these fluctuations relate to frequency or volume.

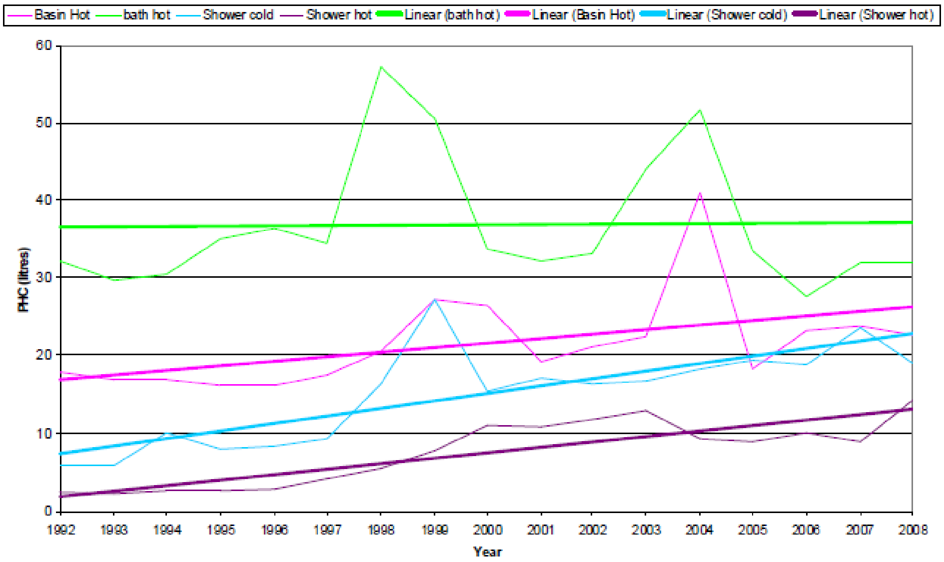

Figure 32. Anglian100 data on volumes of hot water used (litres/household/day) for basins, baths and showers.

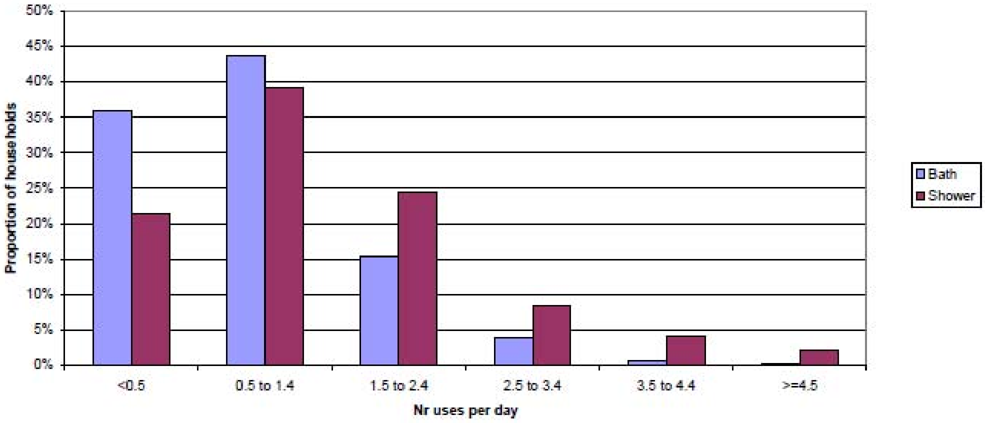

Figure 33. Bath and shower event frequencies from WRc (2005).

The prevailing view from behavioural survey data is that bath frequency is decreasing, but as shown in Table 19, the range of frequencies between these surveys is high (0.08-1.1/person/day). Identiflow® data suggests a frequency of 0.4 (but note from the data that this summary statistic is from a skewed distribution, and would only represent the behaviour of about a third of households, Figure 33).

Identiflow® bath volumes are 68.55 litres (new homes) and 73.3 litres (whole database). This is below the industry assumed volume of 80 litres (but this could be due to limitations within the Identiflow® technique). The existence of so many low volume bathing events in the data set (<50 litres) may relate to a top up of an existing bath, or use of the bath for bathing children (so increasing frequency and decreasing volume within the data). Differentiating between small bath events and kitchen sink events is also difficult with Identiflow®.

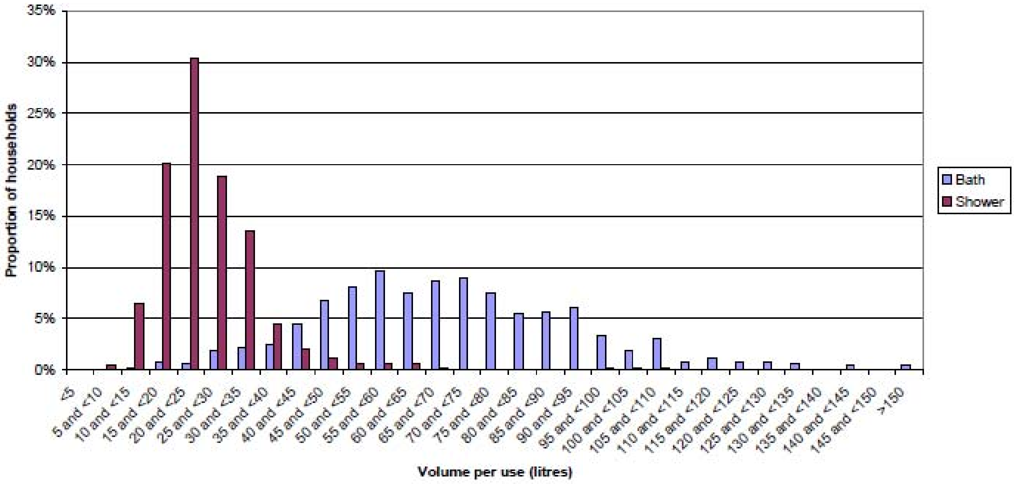

Figure 34. Bath and shower event volumes from WRc (2005).

MTP predict a slight increase in sales of shower baths (from 4% to 6%), but that by 2020 standard (225 litre) baths will still make up 73.5% of the market, with the primary influence on bath choice being bathroom size.

6.4 Showers

Flow rate or volume[19]	Duration	Frequency [20]	Tariff [21]	Ref	Comments
Manufacturers data					
7.88				1	Mixer, gravity
9.85				1	Mixer, integrated pump
11.82				1	Mixer, separate pump
6				1	Mixer, bath/shower
3.46				1	Electric, 7-7.9kW
3.96				1	Electric, 8-8.9kW
4.52				1	Electric, 9-9,9kW
4.99				1	Electric, 10kW +
8				14	All, including electric and gravity
Household survey data					
	6.6	0.62		2	
		0.875	m	4	Power shower
		0.869	m	4	Regular shower
		1	u	4	Power shower
		1	u	4	Regular shower
		0.7		3	
	6		m	3	
	6.6		u	3	
		0.6		13	
		0.53		7	
	6.88		m	7	10 minute interval
	7.15		u	7	10 minute interval
	6.53	0.69		14	Mains pressure
		0.6		14	Mains and pumped
		0.48		14	Electric and gravity
Measured data (Identiflow®, Anglian100)					
25.7 (v)				9	
31.97(h)				9	
		1.46(h)		9	Skewed distribution
		~1.3(h)		9	Median inferred from (9)
		1.86(h)		11	
41.17 (v, h)				11	No occupancy data (but low?)[22]
	~5			12	Median inferred from graph in (7)
		2.3 (h)		15	Bathing events (inc baths)
Other data					
	5			10	But origin is BRE 200456
		0.6		10	If no bath. Claims from (9)
		1		10	If bath present. Claims from (9)
12				16	Pumped and mixer. Measured with flow bag.
	5.2			8	
		0.5(h)		8	electric
		0.52(h)		8	mixer

Table 20. Available data for showers.

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[19] Litres/min, or (v) volume per event.

[20] Per person per day unless followed by (h), denoting per household per day.

[21] Unmetered (u), metered (m). Blank if unknown.

[22] Occupancy data not available from CP337, but if WC use is taken as a proxy of occupancy, occupancy was lower in new homes than the database.

References:
1: MTP (2008f)
2: Essex & Suffolk Water DWRMP (2008).
3: Northumbria Water DWRMP (2008).
4. Folkestone & Dover Water DWRMP (2008).
5. South West Water. DWRMP (2008).
6. Tendring Hundred. DWRMP (2008)
7. Waterwise (2008a).
8. MTP (2008l)
9. Chambers *et al.* (2005).
10. CSH Water Calculator.
11. MTP (2008d).
12. Waterwise (2008a)
13. Three Valleys. DWRMP (2008)
14. BRE Shower report (EAGA).
15. Creasey & Bujnowicz (2006)
16. Critchley & Philpps (2007).

6.4.1 Shower duration

Unfortunately, almost all data in Table 20 on shower duration is based on surveys, and these are unlikely to be accurate as most people are not good at estimating time durations unless they are less than around 30 seconds (Eagleman, 2008). The size of the time intervals used in surveys is wide (e.g. the respondent is offered a choice of time intervals of 5, or in some case 10 minutes), so even if an individual is good at estimating time, data resolution on actual shower durations is still poor.

Data on actual shower durations is limited to Identiflow® data on direct feed systems and suggests a median of 5 minutes (inferred from Figure 35), but Identiflow® will not give accurate durations on gravity fed systems (owing to the refilling of the header tank). The spread of shower durations is large even within an individual household (Figure 36, from Waylen *et al.*, 2007).

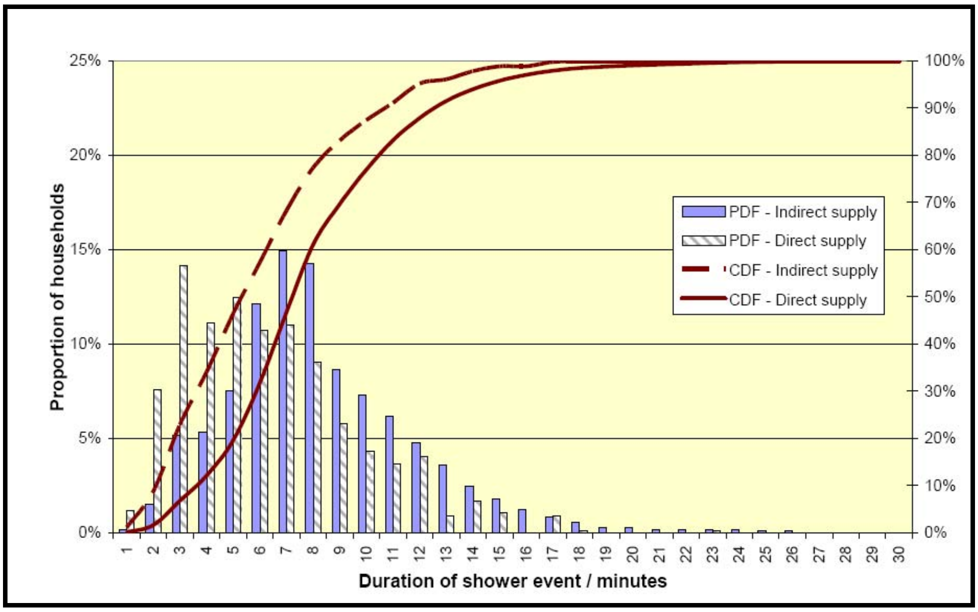

Figure 35. From WRc (2007), referred to in Waterwise (2008), showing median shower duration of 5 minutes in households with direct hot water supplies. NB. The cumulative frequency curves are mis-labelled, and the positive skew on the data for indirect systems is an artefact caused by the header tank refilling. CDF, PDF = cumulative distribution function, probability density function (allows the median to be calculated from continuously distributed data).

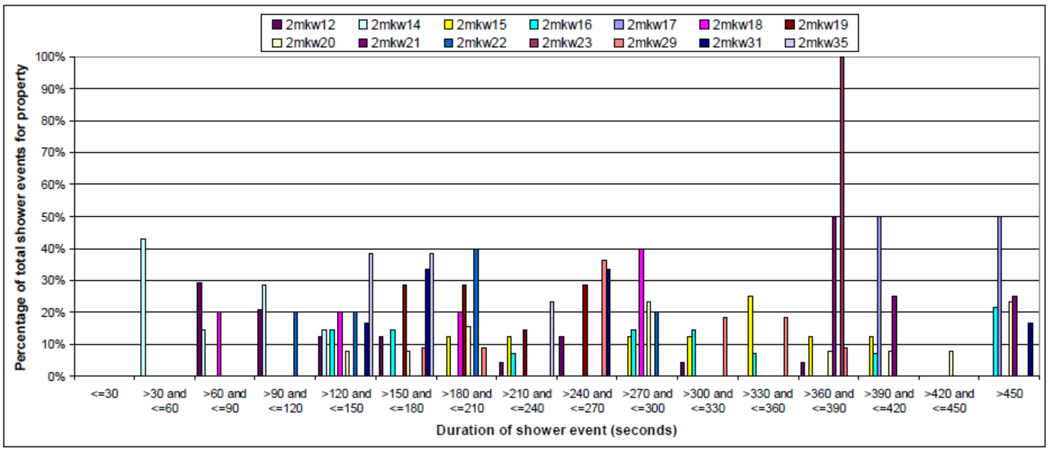

Figure 36. From Waylen (2007). The spread of the data indicates how difficult it is to calculate valid summary statistics on shower duration.

6.4.2 Interactions between flow rate and duration

In many instances volumes and flow rates are estimated from the rated maximum flow of the appliance but there is little data on what shower settings people use in practice. It is highly likely that a 4 l/minute showerhead will be used at maximum flow whereas a 20 l/minute showerhead is more likely to be used at less than full flow, but there is no evidence for this. The consequence of this is that water savings from shower retrofits may not be as large as that predicted (as illustrated in Table 21).

There is also a weak correlation between flow rate and duration, with people spending less time in higher flow showers in one study (Figure 37) although a similar correlation was not observed in another (Figure 38). An Australian water calculator (BASIX, NSW Government, 2006) assumes a correlation between flow rate and duration, but it is unclear whether this is based on evidence or anecdote.

Rated flow (l/min)	% of flow in use	Actual l/min	Mins/day	l/use	CSH l/use
20	70%	14	5	70	100
9	90%	8.1	5.5	45	45
6	100%	6	6	36	30

Table 21. Estimated water use for showers (Wilkenfield 2003) .

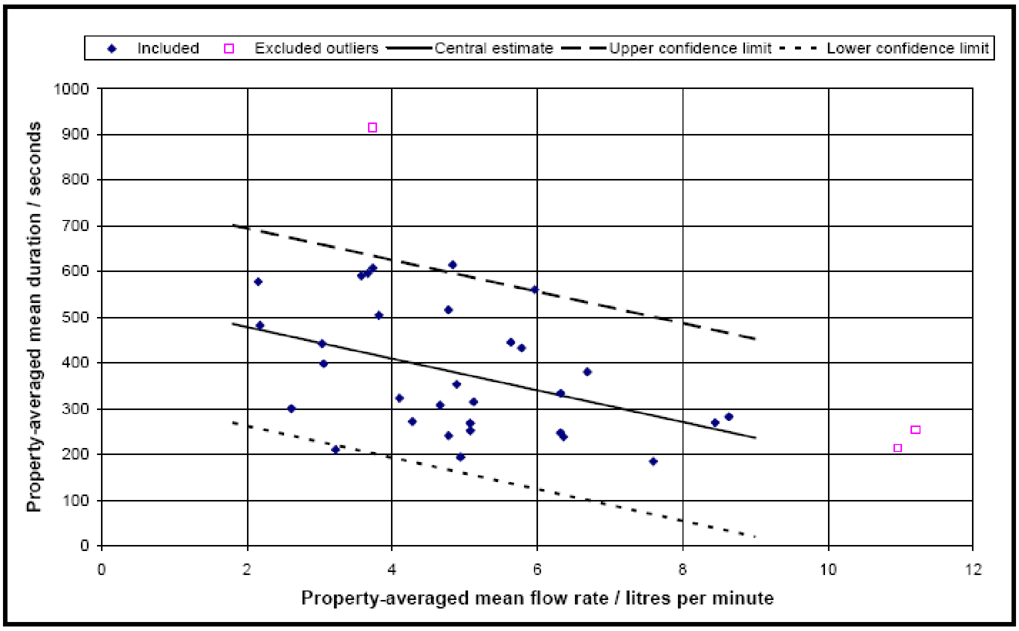

Figure 37. A weak correlation between flow rate and shower duration. From WRc (2007), referred to in Waterwise (2008).

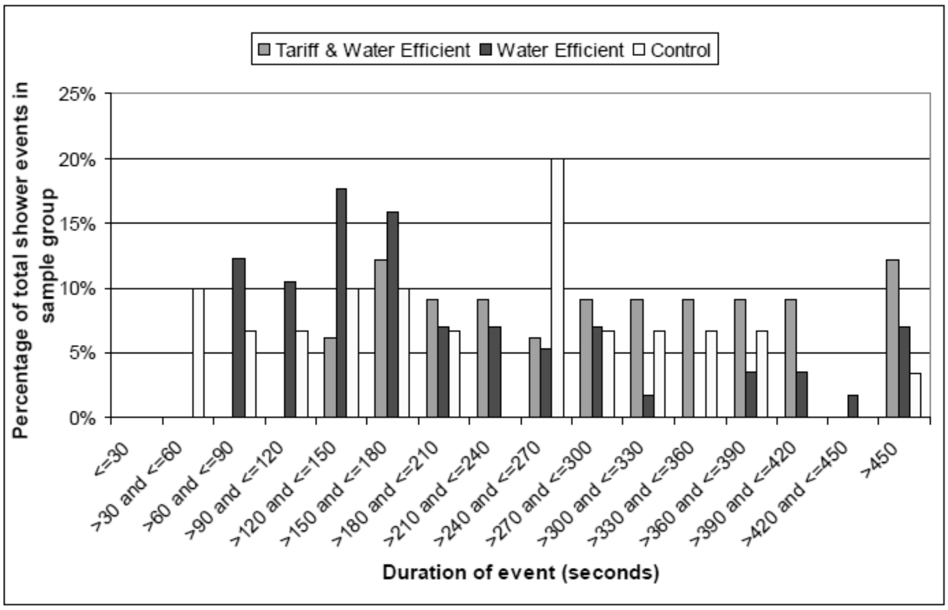

Figure 38. From Waylen *et al.*, (2007), showing no clear effect of flow rate (maximum 10l/min in the water efficient and tariff houses) on shower duration.

6.4.3 Acceptable flow rates

Showers are a good example of an appliance whose water use is difficult to predict and where variables due to individual behavioural differences and preferences dominate. Focus groups on shower use preferences (MTP 2008e) have identified issues such as flow rate, force of spray, temperature stability, soap removal, spray pattern and area of body covered by water. Test methods for flow rate and spray pattern are defined in BS 6340-4, AS/NZS 3662, BS EN 13904 and BS EN 1112, but there is no common way of testing other parameters and therefore it remains difficult to have any universal definition of what constitutes a ‘good’ shower. From the perspective of CO_2 emissions, water use in showers is of prime importance, and these issues therefore require further work.

Minimum acceptable flow rates
The risk with specifying too low a flow rate is that the fitting will be replaced by users, possibly with a much higher flow rate fitting. Where the user does not have choice about the shower fitting (gravity hot water, hotel guests, teenagers etc) baths might be taken in preference to a poor shower thus increasing water use compared with a slightly higher flow shower that might be used in preference to a bath.

Research into “Showers Types Use and Habits” (Essex & Suffolk Water, 2006) found that 92% of people (sample size 104) were satisfied with their electric shower, despite the fact that electric shower flow rate is limited by the fixed heat input which typically limits the flow rate to 3-6 litres/minute[23]. In 2007 the average flow rate of installed showers was 6.8 litres/minute (MTP, 2008d) (consisting of 9.26 litres/minute for mixer showers and 4.31 litres/minute for electric showers).

Critchley and Phipps (2007) trialled aerated showerheads and found that 8 out of the 9 householders chose to keep the (7- 8.4 l/min) water saving head despite flow rate reductions (at full flow) averaging 27.5% (range 3-45% reduction). Interestingly the individual who chose not to keep the water saver shower had the highest flow shower (23.6 litres / minute) but gave it a satisfaction score of only 23 compared to the average score for the water saver showers of 33 (range 31-35).

In the USA the Federal Energy Policy Act of 1992 ANSI/ASME A112.18.1M-1996 requires shower heads to use no more than 2.5 US gpm at 80 psig (9.5 l/min at 5.5 bar). The Water Services Association of Australia (WSAA) National Water Conservation Labelling Scheme awards an AAA rating (High) for 9 litres/minute.

6.4.4 Showering frequency

Data on showering frequency acquired from surveys may be reasonably accurate, although there are two major caveats:

- It is not clear from most of these data sources whether the question refers to the individual completing the survey (and is multiplied by an occupancy either assumed or calculated), or to the household average
- Perceived social norms may well skew reported data, with people anxious to give the ‘correct’ answer. However, this is more likely to be problematic in face to face interviews than in telephone or postal surveys. (Bryman, 2004).

There is considerable spread in shower and bathing frequency, as shown in Figure 40. The fact that frequency data collected using different techniques (e.g. Identiflow® and household surveys) produce similar results suggests that these limitations are not severe. Both techniques suggest a mean frequency of around 0.6/person/day (Figure 39), although as with shower duration, a mean is not a good summary statistic.

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[23] Flow (l/min) = 14.3 x P (kW) /Temperature rise (C).e.g. 14.3 x 8.9kW/32°C = 4 l/min (5 l/min for a 25°C temperature rise, e.g. in summer).

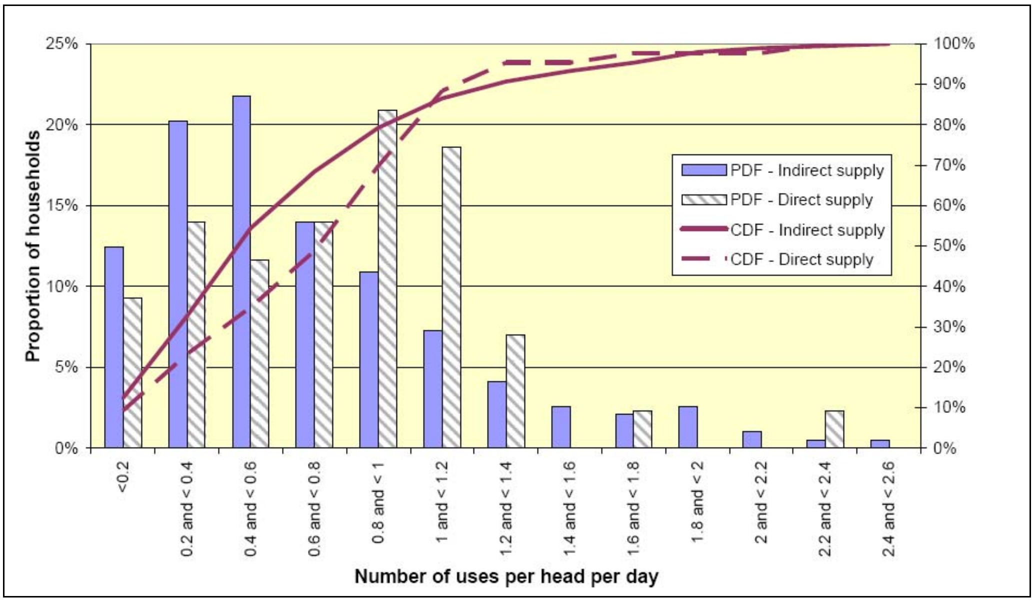

Figure 39. Showering frequency per day, from WRc (2007), reported in Waterwise (2008). Note the non-normal distribution which leads to a difference between the reported mean (0.6/day) and the median.

The influence of showering on bathing and vice versa can not be determined from the current data available, and there is no evidence (e.g. Figure 33) that it is appropriate to express this relationship as a ratio (which is the approach used in the CSH water calculator).

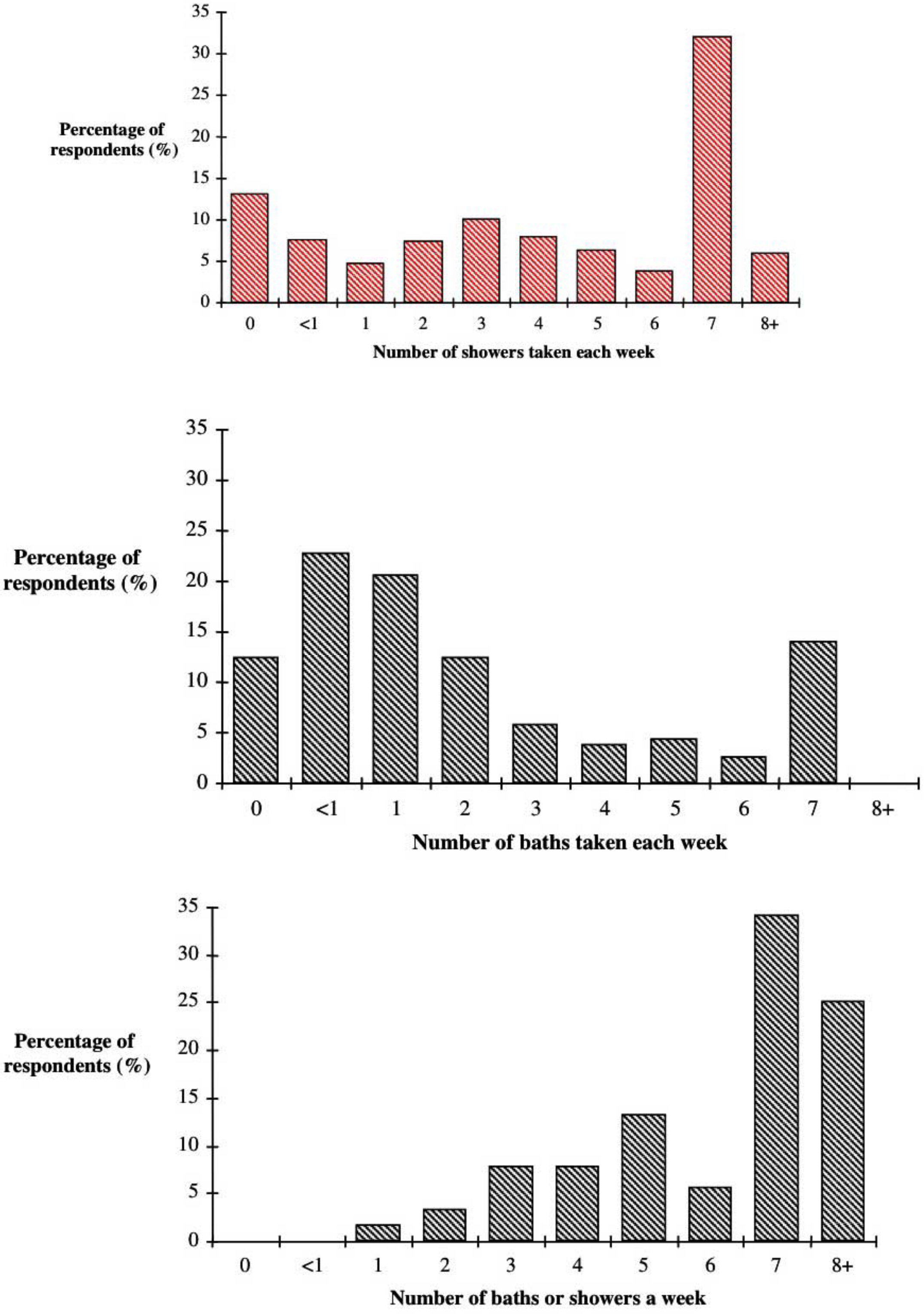

Figure 40. Demonstrates considerable data spread in shower and bathing frequencies; summary statistics will not reflect a high percentage of respondents. Data from BRE.

6.4.5 Influence of shower type and age of house

Electric showers will always have low flow rates (maximum flow rate around 5 l/min). Showers from gravity plumbing systems also have limited flow rates, depending on pressure, and limit to the total volume of hot water available.

Unfortunately, data on the type of plumbing systems is rarely available in studies, making analysis of the effect of shower type difficult. An Identiflow® study of properties with direct and indirect plumbing systems (Creasey & Bujnowicz, 2006b) was inconclusive, owing to differing water pressures between the two groups.

The Identiflow® study comparing water use in new houses compared to old was not available for this study, but data from it is referred to in MTP (2008d). There is an apparent increase in the amount of water used by showers in new homes (from 31.97 litres/household/day to 73.6 litres/household/day), attributed partly to an increase in showering frequency, with a larger increase in volume per showering event. It is not known how many of these new homes have gravity fed plumbing systems although it is likely to be lower than older homes. Occupancy was not measured, so it is difficult to draw conclusions regarding changes in shower frequency per person. However, the increase in volume per event may well indicate a shift of shower type reflecting the generally perceived trend towards higher volume showers.

Effect of shower type on temperature required

Energy use by a shower is closely related to the temperature rise required in the water. The temperature rise required is complicated by several variables; firstly the temperature drop between the shower head and ankle height for a range of different showerheads as shown in Figure 41.What is not certain from this data is how much a bather would increase the temperature of the mixed water to compensate for the cooling effect. Increasing the temperature by the same amount as the measured temperature drop would lead to scalding at head height.

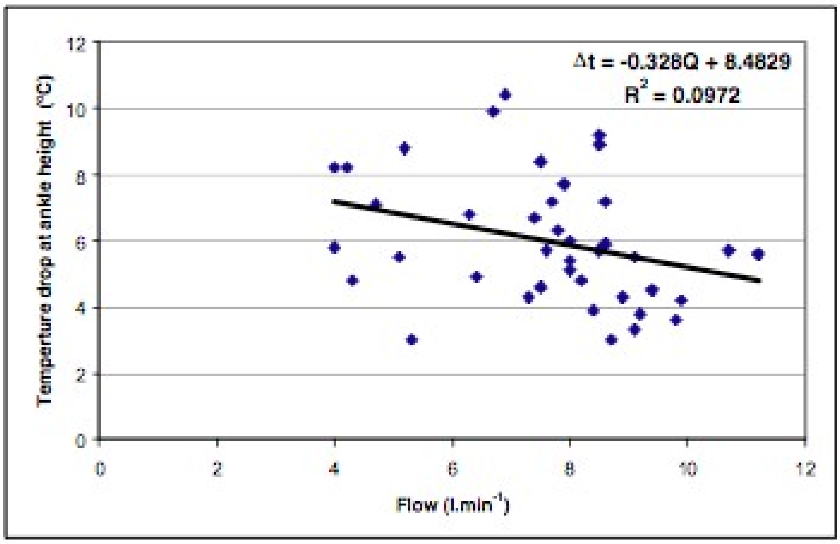

Figure 41. Temperature drop measured in a shower cubicle from Critchley and Phipps (2007). An r^2 value this low is generally not regarded as demonstrating correlation.

Additional complications come from the effect of shower flow rate and spray pattern on required temperature rise. We carried out some preliminary experiments to put actual figures on the variation in delivered hot water temperature for differing shower flow rates. The base case shower at 10 l/min was set at 39°C for comfortable showering. Switching to a regulated 6 l/min conventional spray led to the temperature being increased to 41°C for equal comfort. This is assumed to be to compensate for the lower total heat transfer from the water to the body at the lower flow rate. Then using an aerating showerhead, also around 6 l/min, the temperature required for equal comfort was 43°C. The effect of body cooling over time was not responsible for the increase in temperature required; when the non-aerating shower head was re-attached, this temperature was too hot for comfort.

Many variables may be affecting thermal comfort in showers (e.g. air temperature, relative humidity, radiant heat loss, air currents and water droplet size), and these require further investigation in order to determine what affects acceptability as anecdotal reports vary. However, even in the above case, the energy reduction between 10 l/min and 6 l/min aerating was 31%, despite the delivery temperature being increased to 43°C.

6.5 Taps

Tap type[24]	Flow rate/ volume[25]	Duration[26]	Use Frequency[27]	Tariff [28]	Ref	Comments
Manufacturers data						
all	3.54 (l/min)				19	
Household survey/water company data						
b(h+c)			3.94	M	6	
b(h+c)			4.03	U	6	
b(h+c)	7.9				6	
k(h+c)	10.1				6	
k, b	2 (e)				6	Assuming 30s event duration
Washing up	10 (e)		20 (h/week)		2	No dishwasher
Wash up	10 (e)		9 (h/week)		2	Dishwasher
b			2.5	m	4	
b			4.2	u	4	
k			2.874	m	4	Excluding washing up
k			4	u	4	Excluding washing up
k	4.25			m	5	Excluding washing up
k	5.25			u	5	Excluding washing up
k	12.39			m	5	Just washing up and cleaning
k	12.02			u	5	Just washing up and cleaning
b	9.5			m	5	
b	12.13			u	5	
Measured data (Identiflow®, Anglian100)						
All	2.3 (e)		37.9(h)		9	Difficulty distinguishing k and b, inc' cold.
All	87.17(h)				9	
All	50.23 (h)				11	Difficulty distinguishing k and b, inc' cold.
All	1.52 (e)				11	Difficulty distinguishing k and b, inc cold.
b	~19-25 (h)				11	Inferred from graph, high range
k	~22-40 (h)				11	Inferred from graph, high range
All			26.33 (h)		15	All indoor taps (including cold)
all	2.32(v)				15	All indoor taps (including cold)
all			26.33 (h)		15	All internal tap events
all	2.32(v)				15	All internal tap events
Other data.						
All		40	7.9		10	
All hot			28(h)		17	All hot water draw offs
b	12.5 (h)				17	Regular boiler
b	18.3 (h)				17	Combi boiler
All		<10 s			17	50% of all internal tap events
all		<20 s			17	70% of all internal tap events
All	<0.5				17	40% of all internal tap events
All	< 1				17	60% of all internal tap events

Table 22. Data summary for taps.

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[24] Hot (h) or cold (c), kitchen (k) or basin (b)

[25] Volume (litres)/person/day unless otherwise stated. (e) = volume per event. (h) = volume litres)/household/day

[26] Per event (seconds)

[27] Per person per day unless followed by (h), denoting per household per day.

[28] Unmetered (u), metered (m). Blank if unknown.

References:

1: MTP (2008f)
2: Essex & Suffolk Water DWRMP (2008).
3: Northumbria Water DWRMP (2008).
4. Folkestone & Dover Water DWRMP (2008).
5. South West Water. DWRMP (2008).
6. Tendring Hundred. DWRMP (2008)
7. Waterwise (2008a).
8. MTP (2008l)
9. Chambers *et al.,* (2005).
10. CSH Water Calculator.
11. MTP (2008d)
12. Waterwise (2008a) quoting WRc (2007).
13. Three Valleys. DWRMP (2008)
15. Creasey & Bujnowicz (2006)
16. Critchley & Phipps (2007).
17. Energy Saving Trust (2008)
18. Waylen *et al*. (2007)
19. MTP (2008k).

Taps data analysis summary

The characteristics of tap events are known with even less certainty than showering and bathing events. There is no obviously useful data available from surveys of water using behaviour (people are unlikely to know how much water they use in sinks and basins, or even how many times per day they use them). The extent to which Identiflow® can identify tap events with a high degree of certainty is unclear and there is no differentiation between hot and cold tap events, or between kitchen sink and basin events. It is certainly unlikely to produce accurate data for properties with indirect plumbing systems (owing to the lag introduced by the header tank refilling). Unfortunately, the type of plumbing system is not known in many studies.

The main parameters of interest when considering taps are flow rate, duration, event frequency and event volume. Whilst the total amount used per event or per person per day is the most important data for the purposes of calculating a CO_2 impact, assumptions regarding the relationship between volume, flow rate and duration are built into the CSH water calculator, which is a concern given the lack of data. It is likely for example, that at both kitchen and basin, some uses require a fixed volume (e.g. filling a kettle, saucepan, or basin for shaving), whereas others require a duration of flow (e.g. hand washing or rinsing). Taps are required to perform many different functions and each tap should be regarded as a separate appliance in order to better understand use characteristics.

Flow rate

Manufacturers data on the flow rate of taps is largely concerned with maximum flows, but given the influence of water pressure and the fact that there is no evidence that these flow rates occur in practice, manufacturers data is of little practical use. As discussed above, evidence from Identiflow® on tap flow rates will only be robust for properties with direct plumbing systems. Whilst Chambers *et al.* (2005) does not give data on tap flow rates, it is referred to in MTP (2008k), Figure 42, Figure 43. Note that the frequency distributions are bi-modal, so an ‘average’ tap flow rate is not a useful summary statistic (although it is stated in the report to be 3.54 l/min for both kitchen and basin taps). There is no data available from the Anglian100 dataset on tap flow rates.

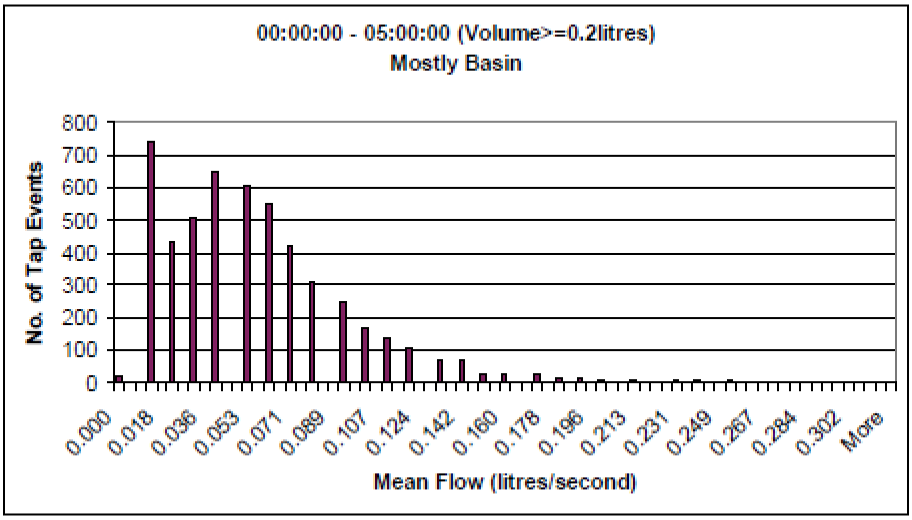

Figure 42. Identiflow® tap flow rates, assumed to be basin (from MTP, 2008k).

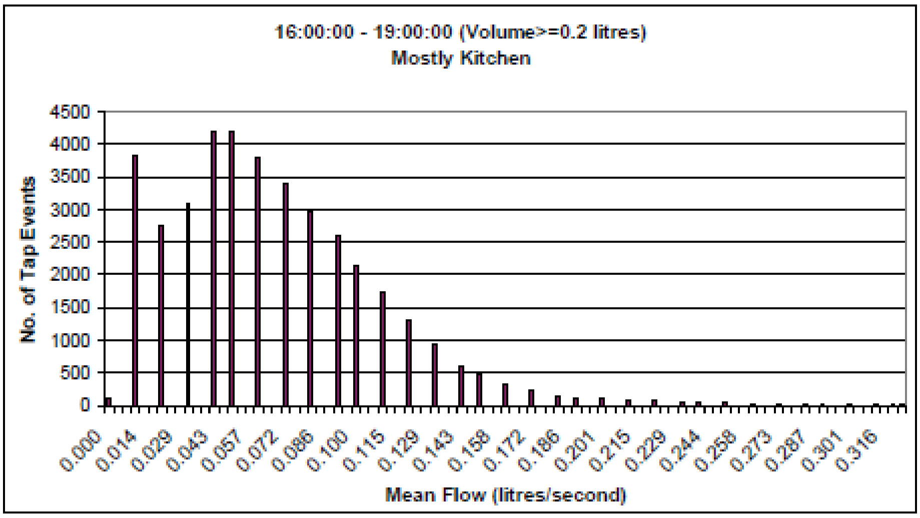

Figure 43. Identiflow® tap flow rates, assumed to be kitchen sink (from MTP, 2008k).

Duration

Whilst we can consider tap events as a total volume of water, the duration of tap events is of interest since it is used by the CSH water calculator to calculate water use. Identiflow® data on tap use is shown in Figure 44, from Waylen *et al.*, (2007); most tap durations are very short (since these are new properties, plumbing systems are likely to be direct rather than indirect, so duration data from Identiflow® may be fairly robust). Whilst it is unclear how these durations relate to hot/cold, kitchen/basin events, further work is needed to establish this in order to establish the importance (or otherwise) of dead legs in plumbing systems. For example if the majority of hot tap events are so short that even in a well designed plumbing system the dead leg volume means that hot water doesn't actually reach the tap, then use of the hot tap for short events represents energy wastage, and energy/water efficiency messaging could be directed to encouraging people to use the cold tap for short duration events.

Whilst tap durations are not given in Chambers *et al.*, (2005), they are quoted in MTP (2008k) to be 39.27 seconds for both kitchen and basin taps. The current CSH water calculator has a fixed assumption of a 40 second tap duration. It will be important to establish whether the discrepancy between old WRc data (~40s duration) and new WRc data (70% of events <20 seconds) is due to problems with incorporating data from indirect plumbing systems. Anglian100 data does not have sufficient time resolution to determine the duration of tap events.

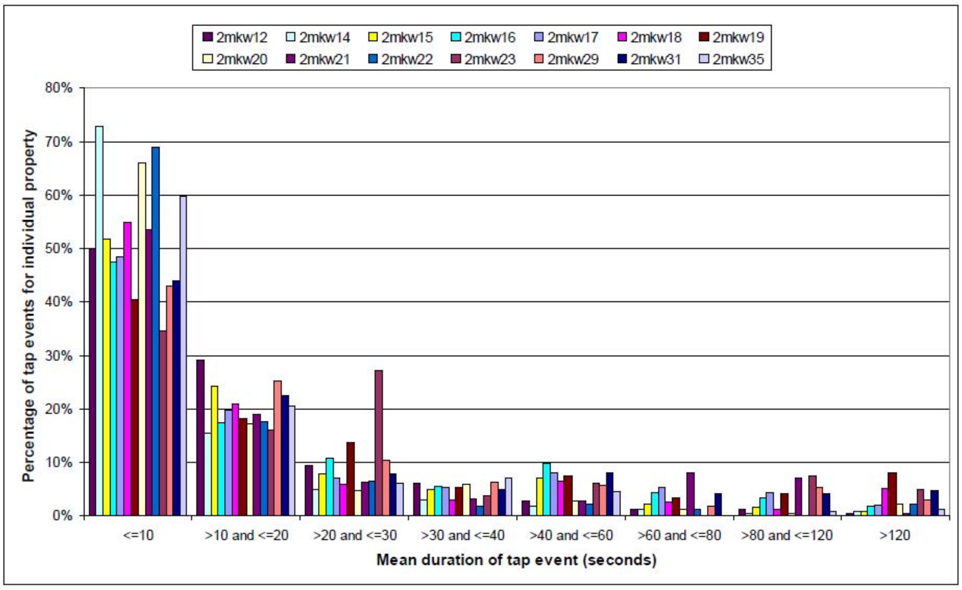

Figure 44. Tap duration across the households studied in Waylen *et al.*, (2007).

Uses per day

Whilst data on volume and duration of events is unlikely to be accurate, event frequency may be more robust, and Identiflow® data demonstrates a high variability in the frequency of draw off events (with some similarities to that found in Energy Saving Trust (2008), Figure 30 above).

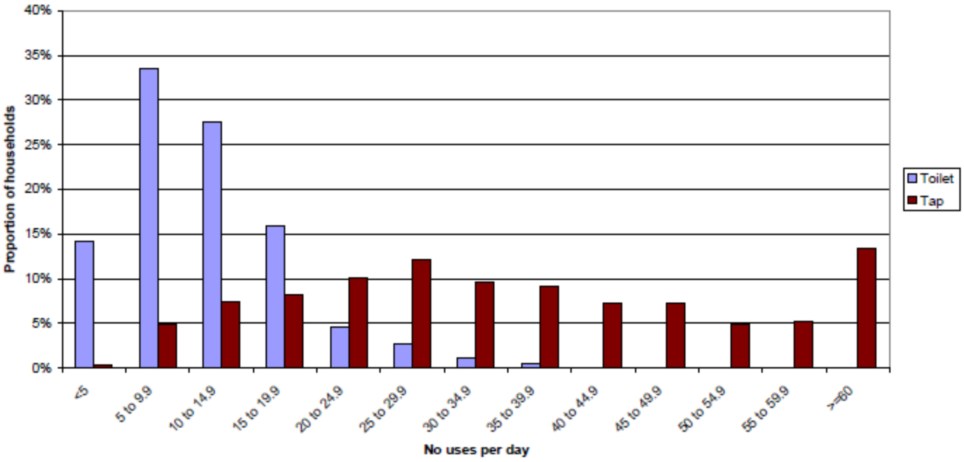

Figure 45. The frequency of tap events per household is very variable, so is difficult to express with a meaningful summary statistic. From WRc (2005).

Volume per event and per day

The limited analysis of Anglian100 data in MTP (2008i) indicates basin hot water use is around 22 litres/household/day and is shown in Figure 46. Hot water use at the kitchen sink was higher (Figure 47).

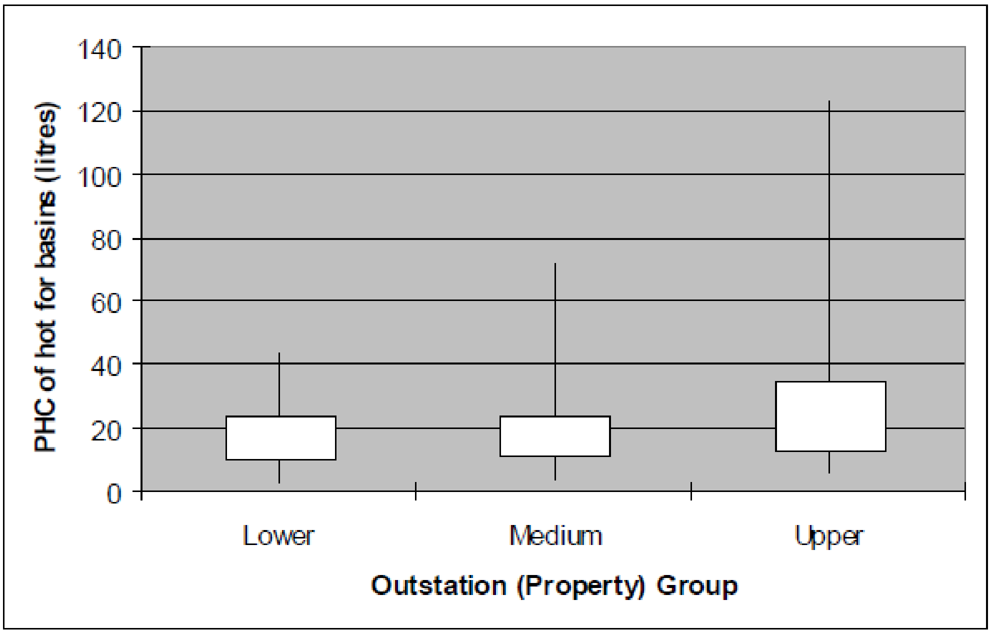

Figure 46. Hot water use in basins (household/day) in Anglian100 properties.

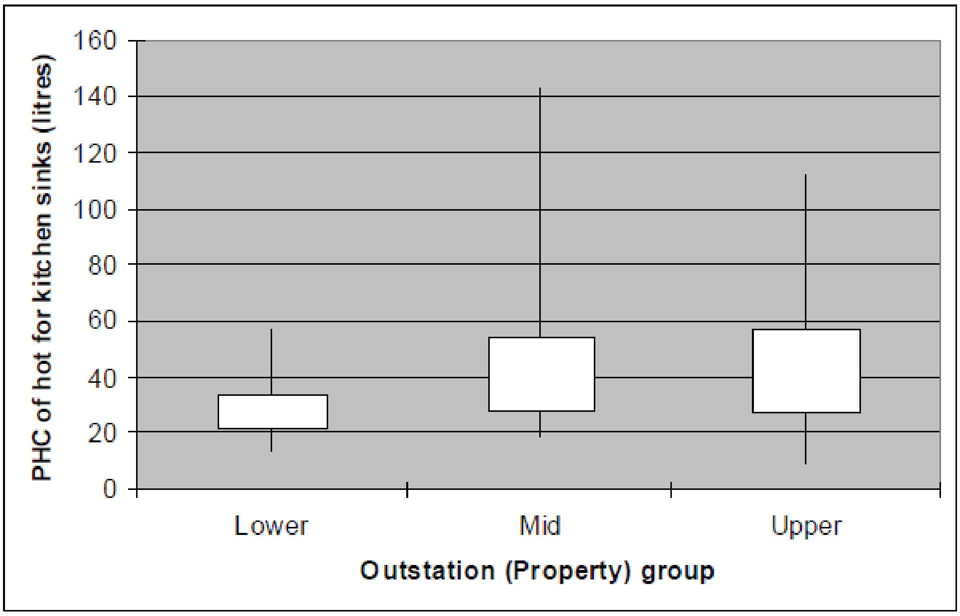

Figure 47. Hot water use at the kitchen sink in Anglian100 properties (MTP, 2008i).

There is no evidence that water efficient taps have a significant effect on the volume of water used (Figure 48, Waylen *et al.*, 2007). This is a concern given that the CSH water calculator assumes this to be the case.

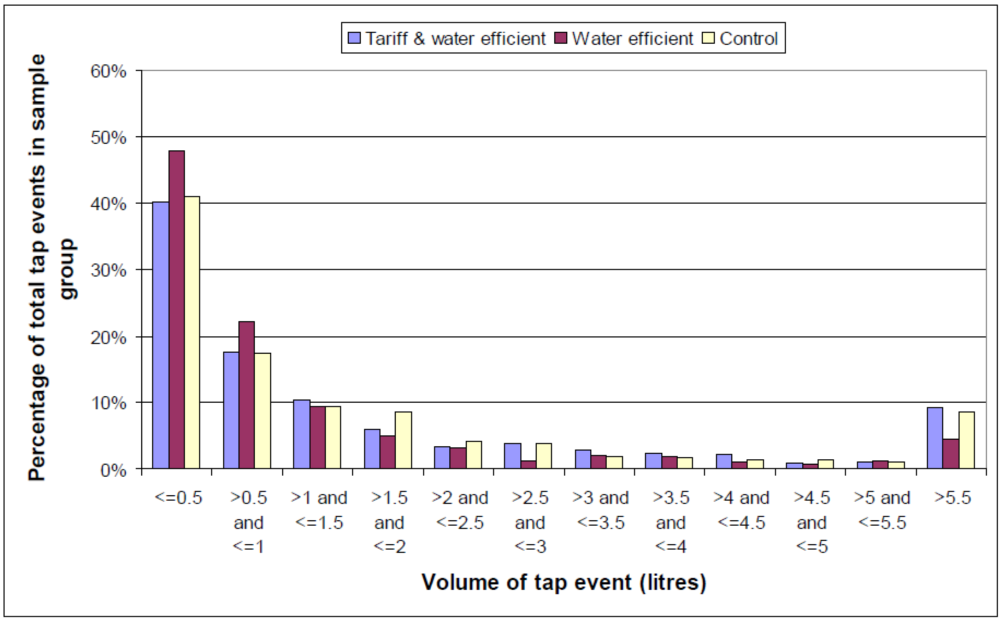

Figure 48. Tap volumes from Waylen et al., 2007, which do not demonstrate a clear benefit of water efficient taps.

Change in tap water use over time

Figure 32 shows the limited data available from the Anglian100 dataset, indicating the increase in hot water use by taps over time, although the increase appears to be minimal compared to the annual fluctuation.

6.6 Dishwashers

Whilst typically more water efficient than washing up by hand, dishwashers are less energy efficient (MTP, 2008g). The conflict between water and energy efficiency is illustrated in Figure 49, which plots energy against water use for dishwashers on the Waterwise database. As we would expect, there is a trend for water and energy efficiency to go hand in hand. However if a short list were narrowed down to the two machines circled on the graph we would be faced with a choice between best water and best energy efficiency. Assuming one load per day of a 12 place setting machine we get the following results:

The more energy efficient model uses:
1.25 litres x 12 places x 365 days = 5.5 m^3/y
0.053 kWh x 12 x 365 = 232 kWh/y

The more water efficient model uses:
0.72 litres x 12 places x 365 days = 3.2 m^3/y
0.077 kWh x 12 x 365 = 337 kWh/y

Selecting the more water efficient model should save 2.3m^3/y[29] at an energy cost of 105 kWh. This equals 46 kWh/m^3, about 100 times the energy needed to supply mains drinking water. Similar results can be found for washing machines.

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[29] About 2 litres per person per day.

There may be many other reasons to choose the slightly less water efficient model, for example build quality, brand loyalty and washing performance. The potential water savings (if they even exist in reality) are too small for this to be a rational consideration.

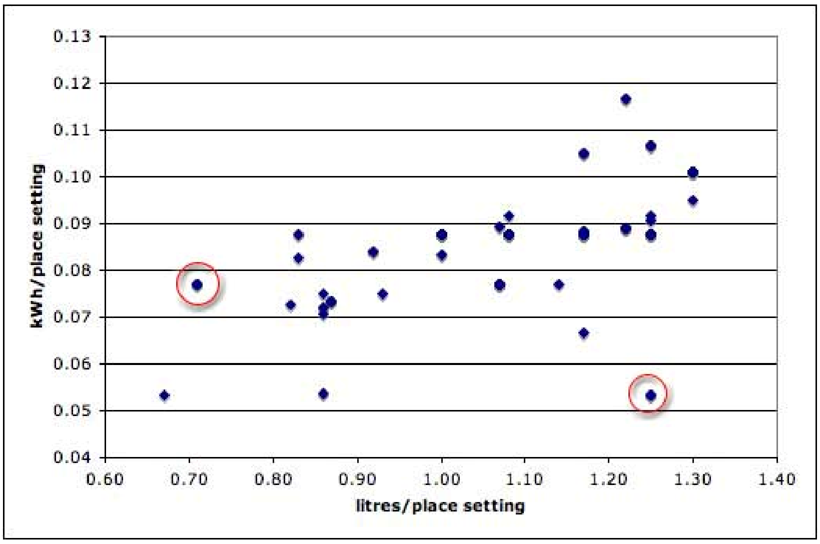

Figure 49. Energy against water use (per place setting) for dishwashers. Data from Waterwise. The two circled machines are the ones compared in the example calculation on the previous page.

Interaction between dishwasher use and kitchen sink use

There is no published data on the effect of dishwasher ownership on kitchen sink water use, although it might be available from a subset of the Anglian100 data, and an inverse correlation is stated in MTP (2008i), although the magnitude is not stated. A laboratory study of washing up habits (University of Bonn) indicated extremely high kitchen sink water use that does not appear to be consistent with total measured kitchen sink hot water use and is presumed to be an artefact of laboratory conditions. Behavioural survey data yields the values in Table 23 and Table 24.

In order to incorporate the effect of dishwasher ownership on kitchen sink water use, the following assumptions were made for the amount of water used for hand washing:

- Households without dishwasher: 80 litres hot water/person/week (8 washing up events, 1 bowl of 10 litres each event)
- Households with dishwasher: 23 litres hot water/person/week (2.3 hand washing events, 1 bowl of 10 litre each event)

This led to the assumption that hot water use at the kitchen sink was 8 litres/person/day lower if a dishwasher was owned. The confidence level in this assumption is low, and is highly dependent upon occupancy assumptions (because washing up is a ‘household’ activity, and the amount of water used by a person at the kitchen tap will be different depending according to household size). Because of the uncertainties surrounding this assumption it is not incorporated into the scenarios investigated in section 4.4, but is considered separately in section 5.4.2.

	Events/person/week
Household without dishwasher	
Hand washing events	8
Household with dishwasher	
Dishwasher events	1.6
Hand washing events	2.3

Table 23. Washing up frequency from behavioural survey data (from ISIS, 2007).

Washing up method	% people
Household without dishwasher	
Sink or bowl	72
Running tap	8
Combination	20
Household with dishwasher	
Sink or bowl	61
Running tap	20
Combination	19

Table 24. Method of washing up reported in a behavioural survey (from ISIS, 2007).

A feature of note in both the work from Bonn and ISIS (2007) is the extreme differences in behaviour of people between different EU countries in terms of washing up method; the proportion of people in behavioural surveys who stated that they washed up under a running tap was lower in the UK than in every other country studied (9 other countries, highest use of running tap was 64% in Polish households with dishwasher). There are also considerable discrepancies between standard assumed UK data and the findings of ISIS (2007) in a number of areas (e.g. UK dishwasher ownership stated to be 74% in ISIS, number of washing up events seems high at 18/household/week).

6.7 WC

WC flush volumes and use frequencies are well documented and will not be discussed in detail here. The values chosen are 9.4 litres/flush, and 11.52 uses/household/day (based on Chambers *et al.*, 2005). As flush volumes reduce, data becomes less certain, owing to the existence of half and full flushes, and issues related to valve leakage. The range of flush volumes reported in MTP (2008i) from new homes is striking and requires further investigation.

The CO_2 cost due to WCs is mostly due to the cooling effect of the cold water being warmed by the building’s heating system. Indeed even when considering a conservative scenario, heat loss accounts for over 80% of the entire life cycle impact of a WC (Gandy *et al.*, 2008). Whilst the absolute effect will be greater in older buildings with un-insulated pipes and larger WCs, the cooling is only proportionally significant in buildings to the Passivhaus Standard where this loss is calculated[30] (PHPP 2007).

Gandy *et al.* considered a number of scenarios and a heat loss figure of around 16kJ/litre of flushed water was obtained for toilet flushing during the heating season. Dividing by the specific heat capacity of water (4.19kJ/K) suggests a temperature rise of about 4°C. This is very close to the value obtained empirically by the authors (Grant 2008). However our calculations suggest that the CO_2 emissions due to heat loss are of a similar order to those due to water supply and sewage treatment which is in disagreement with the DEFRA study. Whilst interesting for low energy building the energy savings are too modest to inform Energy Saving Trust/Environment Agency policy for retrofitting although the benefit of water savings remain and have been covered in some detail elsewhere (e.g. Keating, Lawson. 2000).

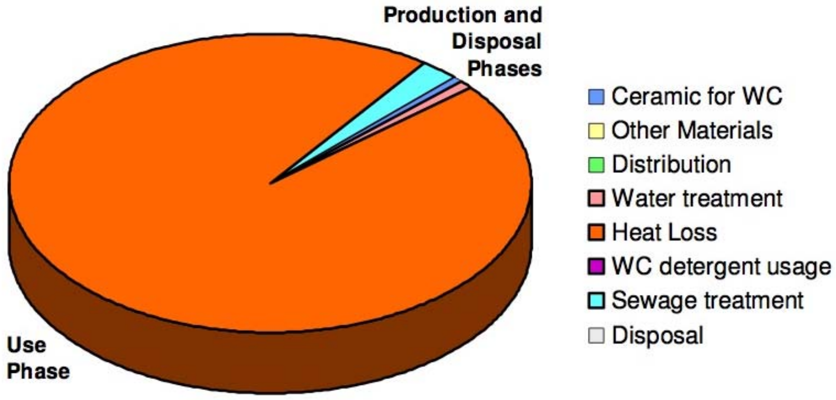

Figure 50. Graph from Gandy et al 2008 showing heat loss to be the main life cycle impact of WCs. The results presented in this report support the heat loss estimate but find the CO_2 emissions for water supply and sewage treatment to be of a similar order to to this.

6.8 Washing machines

Manufactuers data on washing machines indicates around 50 litres/cycle for a machine purchased in 2007. The number of uses per day has a strong occupancy influence, but is given by Anglian100 data as 38 litres/household/day. According to MTP water heating accounts for about 80% of the energy use of a washing machine (MTP 2008b), so energy consumption is very dependent upon wash temperature (Table 25). This suggests that about 15 litres per cycle is actually heated to the specified wash temperature, which is close to the figure of about 17 litres given by MTP (MTP 2007). Ownership was 94% in 2008 (MTP 2008b).

Washing machines account for about 13% of domestic water consumption (MTP 2006a) and consume about 216 kWh_e/household.annum.

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[30] For domestic buildings the heat loss to cold water is subtracted from the estimated heat gain to hot to give an overall figure of -5W/person. For non domestic buildings WC heat loss is calculated depending on use.

The decrease in total water used by washing machines shown in Figure 51 from Anglian100 data can be explained by a decrease in the volume per wash, whilst masking a predicted increase in use frequency. Volume/use and use frequency data from the Anglian100 dataset was not available, but the use frequency data from Chambers *et al.* (2005) shows a large spread of frequencies, and demonstrates that it is inappropriate to consider an average use frequency (Figure 52).

kWh/cycle	A+	A	B
90°C wash	1.66	1.77	1.77
60°C wash	1.00	1.06	1.06
40°C wash	0.60	0.64	0.64
30°C wash	0.32		

Table 25. Energy use by Energy label rating and temperature. MTP 2008b, except for 30°C wash, which is from University of Bonn.

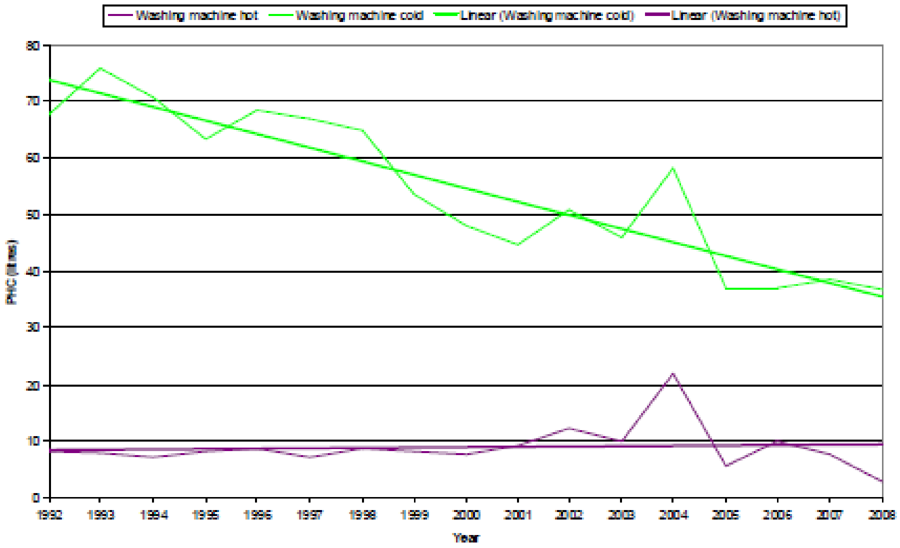

Figure 51. Anglian100 data for the change in washing machine use over time.

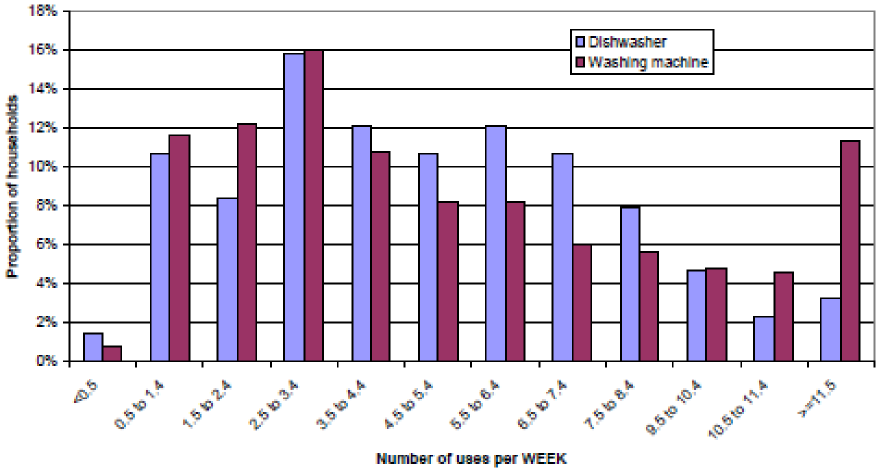

Figure 52. From Chambers *et al.* (2005), showing how variable dishwasher and washing machine frequency are.

Load size

The manufacturers stated capacity of a washing machine (in kg) is much higher than is possible unless clothes are carefully folded into the machine, and this may in part explain why monitored washing machine loads are low (UK Whitegoods website, Table 26).

Drum size quoted (kg)	Drum size usable (kg)
5	2-2.5
6-7	2.5-3
8	3-3.5

Table 26. Quoted and usable drum capacity UK Whitegoods website.

Hot fill

The issues surrounding the pros and cons of hot fill are involved but covered in full in the MTP washing machines FAQ document (MTP 2007) and on the UK Whitegoods website (UK Whitegoods 2009). There is also an ongoing discussion on the AECB technical forum[31]. In summary, a hot fill connection offers theoretical cost and CO_2 savings for hot washes where a low carbon source of hot water is available (e.g. gas boiler or solar). However in practice the small volume of hot water used per fill operation means that unless the machine is very close to the hot water supply then only the cold dead leg is likely to be drawn off leaving hot water in the pipe to cool. Additionally some machines only draw hot water for washes hotter than 60°C since the hot water supply might be too hot for cooler washes with sensitive fabrics or biological detergents. Even hot wash programs usually only use hot water for the main wash cycle which might be 15-17 litres. Since almost all new machines are now cold fill only, we have not considered hot fill in any detail but have included hot and cold fill in our spreadsheet model.

In Holland, prototype washer driers have been tested that make use of an integral heat exchanger and connection to a district heat main to utilise CHP. Whilst interesting, such options are currently experimental and have not been considered as part of this project. Similarly designers of very low energy houses may develop custom solutions such as using preheated water with cold fill machines.

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[31] http://www.aecb.net/forum/index.php?topic=1056.30

Environment Agency

energy saving trust®

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Aztec West, Almondsbury, Bristol BS32 4UD
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