Hot water assumptions in the Home Energy Model: FHS assessment wrapper

A technical explanation

December 2023

Acknowledgements

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Any enquiries regarding this publication should be sent to us at: homeenergymodel@energysecurity.gov.uk

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Background to the Home Energy Model: Future Homes Standard assessment

What is the Home Energy Model: Future Homes Standard assessment?

The Home Energy Model: Future Homes Standard assessment is a calculation methodology designed to assess compliance with the 2025 Future Homes Standard (FHS).It builds on the government's Home Energy Model, which will replace the government's Standard Assessment Procedure (SAP).

The Home Energy Model: FHS assessment is still under development and its first version will be implemented alongside the FHS in 2025. We are publishing information about the model while it is still at a formative stage to enable industry to participate in the ongoing development process.

Where can I find more information?

This document is part of a wider package of material relating to the Home Energy Model:

Home Energy Model: FHS assessment technical documentation (e.g. this document)

What: This document is one of a suite of technical documents, which go into further detail on the assumptions and the validation exercises that have been carried out. We intend to update and produce further technical documentation throughout the model development process.

Audience: The technical documentation will be of interest to those who want to understand the justifications and evidence base behind the assumptions used in the model.

The Home Energy Model: Future Homes Standard assessment consultation

What: The Home Energy Model: Future Homes Standard (FHS) assessment consultation seeks views on the proposed methodology for demonstrating compliance with the FHS.

Audience: The Home Energy Model: FHS assessment consultation will be of interest to those who want to understand the proposed standardised assumptions around occupancy, energy demand etc. to be used when assessing compliance with the FHS, as well as the methodology for the calculation of the proposed FHS compliance metrics.

The Home Energy Model reference code

What: The full Python source code for the Home Energy Model and the Home Energy Model: FHS assessment has been published as a Git repository. This code is identical to that sitting behind the consultation tool. We are currently considering whether the open-source code could serve as the legal approved methodology for demonstrating whether new homes comply with energy performance standards in the Building Regulations.

Audience: The reference code will be of interest to those who want to understand how the model has been implemented in code, and those wishing to fully clarify their understanding of the new methodology. It will also be of interest to any potential contributors to the Home Energy Model.

Related Content

For information on how hot water events are simulated in the Home Energy Model core engine, please see technical paper *HEM-TP-09 Energy for domestic hot water*. The losses from hot water pipework after an event are described in paper *HEM-TP-10 Ductwork and pipework losses*.

To understand how this methodology has been implemented in computer code, please see:

src/wrappers/future_homes_standard/future_homes_standard.py
src/wrappers/future_homes_standard/FHS_HW_events.py
src/wrappers/future_homes_standard/decile_banding.csv
src/wrappers/future_homes_standard/day_of_week_events_by_decile.csv
src/wrappers/future_homes_standard/day_of_week_events_by_decile_event_times.csv

Methodology for hot water events

The Future Homes Standard assessment wrapper specifies inputs and outputs for the Home Energy Model, for the use of the model in assessing whether a new home complies with the requirements of Part L of the Building Regulations. Among the inputs are standardised inputs relating to domestic hot water use.

This paper sets out the assumptions in the wrapper for estimating how much hot water a household will use, and the methodology for attributing that use to a schedule of baths, showers, and other uses. The annexes explain how these assumptions have been derived from survey data.

The assumed use is dependent on the standardised occupancy of the dwelling, as set out in paper *HEMFHS-TP-01 FHS occupancy assumptions*.

Domestic hot water consumption is represented in the Home Energy Model using a sequence of tapping events, divided between baths, showers and other events, as described in *HEM-TP-09 Energy for domestic hot water*.

In the FHS assessment wrapper the events are generated as a pseudo-random sequence, in order to capture the variation that can be expected from day to day and in particular the possible peak loads on the storage capacity of the system from events clustering in time.

The schedule is derived in six stages:

1. The total daily demand for unmixed hot water is determined. This is a volume calculated as a function of the standardised occupancy of the dwelling. It is assumed in the wrapper to be delivered to the tap at 52°C.
2. This demand volume places the dwelling in one of the deciles of hot water demand found in a large sample of UK homes. For this decile, a table provides a frequency profile of the expected number of baths, showers and other hot water use “events” on each weekday, and their volumes. For baths and showers, the profile also varies by time of day.
3. The decile frequency for each type of tapping event is scaled so the total volume matches the original estimate from step 1.
4. For each day in a simulated year a schedule of tapping events is generated using a pseudo-random generator.
5. The volumes for each event are adjusted so the total volume, across the year, matches the original estimate from step 1.
6. A further adjustment to the duration of the events is made, to capture a seasonal variation in the amount of hot water used over the course of the year.

This document presents the above algorithm in detail. The evidence and analysis supporting this method are reported in Annexes 1 and 2. The complete event tables used in the algorithm are published in the FHS code repository.

1. Total volume

For a household with occ occupants, the average daily demand volume of hot water in litres (at 52°C) is estimated as

$$\boldsymbol{V_{HT} = 51.255\ occ^{0.72}}.$$

This is the demand volume at the tap for hot water, assumed to reach the tap at 52°C. It represents 85% of the typical daily volume V_B measured at the outlet of a combi boiler, as modelled from study data in Annex 1 below.

The factor of 85% represents the typical proportion of hot water drawn from the source that reaches the tap. The remaining 15% is assumed to be left in the pipework at the end of the event, attributed as described in Annex 1.

The total volume is calculated under the assumption that the shower flow rate in the dwelling is typical of the population. Dwellings with slower-flowing showers may meet their demand with a smaller volume of water: the Home Energy Model handles this elsewhere. The Home Energy Model also encodes thermostatic control of delivered water: if a storage cylinder holds water hotter than the delivery temperature of 52°C it will deliver a smaller volume, so that the mixed water drawn at the tap will be at the intended temperature (HEM-TP-09 Energy for domestic hot water).

For a typically-sized three-bedroom home the FHS assessment wrapper standardised occupancy of 2.98 gives an estimated volume at 52°C at the tap of 113 litres per day.

2. Hot water use profile

The total volume V_{HT} places the dwelling in one of the ten deciles of total consumption observed in the boiler study data described at Annex 2 below. The FHS assessment wrapper has a table with a weekly profile of water use for each decile. For each day of the week this gives the mean number of showers, baths and other events, and their volumes and duration, for that decile in the study sample. A part of the table is shown at Table 2 in Annex 2.

3. Calibration

The tabulated profile of events is an average of hot water use for real homes with a consumption close to the modelled daily demand V_{HT}. To calibrate the profile and match V_{HT} exactly, in expectation, the frequencies read from the table are adjusted by a ratio V_{HT}/V_{ref}.

Here V_{ref} is the average total volume from 1000 randomly generated annual event schedules created (as in step 4 below) directly from the unadjusted table. (The volume V_{ref} is for most deciles *more* than the daily consumption of any of the sample dwellings in the decile. In real homes there is a negative correlation between number and size of events: occupants taking more showers take shorter ones, for example. In the generated schedule all events of a particular type have the same volume, the mean for the decile).

4. Pseudorandom schedule

The frequencies found at step 3 are interpreted as probabilities. For example, if the calibrated table shows a typical frequency of 0.11 baths on Mondays, there is an 11% chance that the household will take a bath on any given Monday.

For each day of the week and each event type, the calibrated frequencies are divided between the 24 hours in the proportions found in the Connected Devices study, as illustrated in Table 3 in Annex 2.

Now, for each hour of the year and each event type, we create a provisional schedule by sampling from a Poisson distribution with parameter λ equal to the hourly expected event count. Each event is allocated a random start time uniformly within its hour.

Successive bath and shower events are allocated in rotation between the baths and showers in the dwelling. If there are no baths present then bath events are reassigned to showers (but keeping their assigned duration; this is consistent with the interpretation of the survey data described in Annex 2, as shower events may be more than one person's shower, taken too close together in time for the monitoring sensor to distinguish them). If no showers are present in the dwelling, then showers are reassigned to baths (again, keeping their duration).

It is assumed that the heating system or water cylinder cannot supply two showers or baths simultaneously. If in the provisional schedule two such events overlap then the schedule is adjusted, moving one event by a random delay of up to half an hour. This adjustment is applied successively until no more overlaps occur. Instant electric showers are excluded from this adjustment: the cold water supply is assumed to be adequate to supply all appliances at once.

The generated schedule will be the same each time the wrapper is run, provided that the building occupancy is unchanged. The pseudorandom sampler produces an irregular pattern of events, statistically behaving like a randomly drawn Poisson sample. It is initiated with the same seed value each time it is called in the FHS assessment wrapper preprocessing function, so the schedule will be replicated exactly if a dwelling with the same daily demand V_{HT} is submitted.[1] This ensures replicability of results and comparability of dwellings expecting the same standard occupancy.

5. Recalibration

The total volume V_Y of hot water consumed over the year in the resulting schedule of events is calculated. The duration of all events in the schedule is adjusted by the factor

$$FHW = (365 \times V_{HT})/V_Y$$

so that the mean realised consumption over the year matches the required demand V_{HT}.

6. Monthly behavioural factors

A further adjustment to the duration of each event is made to account for behavioural differences over the course of the year. Separate factors are applied to bathing and to other events. Note that this final adjustment may de-calibrate the overall demand slightly.

An example schedule of modelled hot water demand after application of this algorithm is shown in Figure 1.

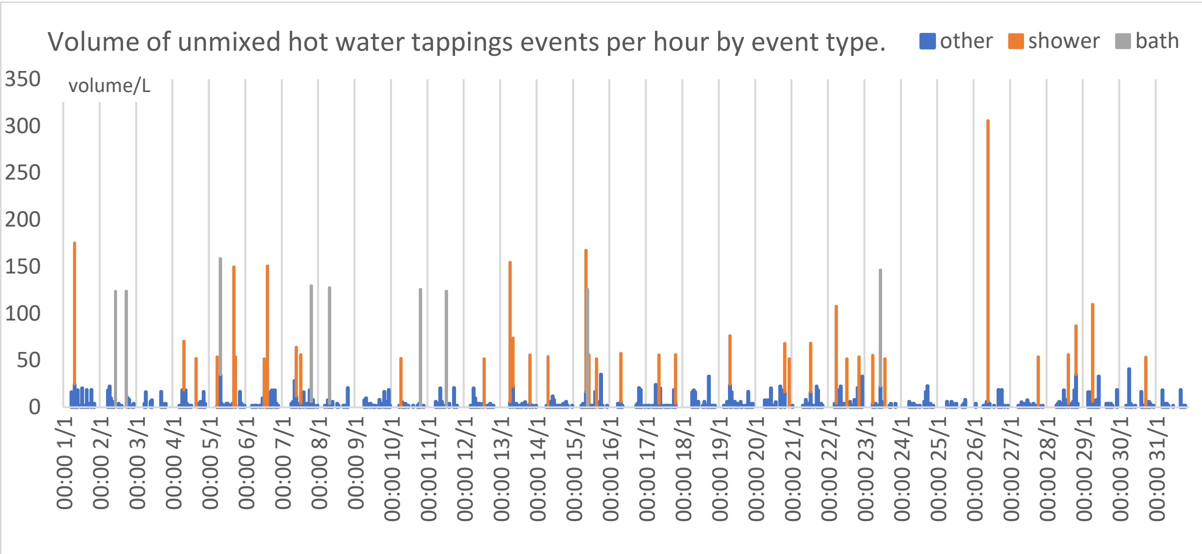


Figure 1 – Example generated profile for 3.9 occupants, showing total volume of HW tapping events per hour for each event type for the first month of the year (744 hours), stacked.

[1] Provided that the random number generator code itself does not change between runs. The consultation version of the Future Homes Standard assessment wrapper uses *random* from Python 3.8 and *np.random* from numpy version 1.19.5.

Temperatures, heating times and other default values

Table 1 records the assumed values of other variables used in calculating the energy used for domestic hot water and fixed by the FHS assessment wrapper.

Table 1 – Standard temperatures and volumes

Variable	Value	Interpretation
Hot water temperature	52.0	The temperature of unmixed hot water at the tap. Assumed to be equal and constant for all events.
Hot water storage temperature	60.0	The temperature set point for any hot water storage cylinder. When the cylinder draw-off temperature falls below 52.0°C water heating starts, until the temperature reaches 60.0°C.
Mixed temperature for showers	41.0	Temperature in °C of mixed hot/cold water run in showers
Mixed temperature for baths	42.0	Temperature in °C of mixed hot/cold water run in baths
Cold water feed temperatures		Seasonal value as shown in table 2
Water heating hours		For cylinder, heat to the hot water storage temperature (see above) and maintain this from 00:00 to 07:00 and then for the rest of the day, switch on when the temperature falls below the hot water temperature (see above) and switch off when the temperature rises to the hot water storage temperature. For instantaneous systems (e.g. combi boiler), always available.
Default bath-sized event – volume	100.0	Volume in litres (of mixed water) of an event of type “bath” when there is neither a bath nor a shower in the dwelling

Default flow rate	8.0	Flow rate in litres/second for an event of type “bath” when there is neither a bath nor a shower in the dwelling.

The assumed hot water delivery temperature of 52.0°C is unchanged from the assumption previously used in SAP 10.2. It is derived from an Energy Saving Trust study, which found that average delivery temperatures were consistent across the year, although they were lower for combi boilers (50.0°C) than regular boilers with a hot water cylinder (52.9°C). The 2022 DESNZ Connected Devices study, analysed along with the EST study in Annex 1 below, provided new evidence which is broadly consistent with this assumption (see Annex 2).

The assumed hot water storage temperature of 60.0°C is set in line with Health and Safety Executive (HSE) recommendations for legionella control https://www.hse.gov.uk/healthservices/legionella.htm.

The temperatures assumed for mixed water baths and showers are unchanged from those in SAP, on evidence outlined in SAP 2016 consultation paper CONSP:08[2]. No new evidence was identified.

The temperature of the cold-water feed to the DHW system depends on the time of year, and on whether water is drawn directly from the mains or from a header tank. The average monthly temperatures are averages across the UK of the measurements found in the Energy Saving Trust 2008 study. If regional weather data is introduced to the FHS assessment wrapper in future then these could also be revised to use the regional values from that study.

Table 2 – Monthly assumed cold feed temperatures

Cold water temp. /°C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
From header tank	11.1	11.3	12.3	14.5	16.2	18.8	21.3	19.3	18.7	16.2	13.2	11.2
From mains	8.0	8.2	9.3	12.7	14.6	16.7	18.4	17.6	16.6	14.3	11.1	8.5

Table 3 reports the monthly behavioural factors applied at stage 6 in the schedule algorithm. These factors replicate those in tables J5 and J2 of SAP 10.2, as derived from tables 8 and 9 in paper CONSP:08[3] and based on the EST study.

[2] “Consultation Paper: CONSP:08 Amendments to SAP’s hot water methodology”, https://bregroup.com/sap/standard-assessment-procedure-sap-2016/sap-2016-technical-papers/
[3] “Consultation Paper: CONSP:08 Amendments to SAP’s hot water methodology”, https://bregroup.com/sap/standard-assessment-procedure-sap-2016/sap-2016-technical-papers/

Table 3 – Monthly behavioural usage factors applied to hot water event frequency

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baths and showers	1.034	1.021	1.007	0.993	0.979	0.965	0.965	0.979	0.993	1.007	1.021	1.035
Other events	1.100	1.060	1.020	0.980	0.940	0.900	0.900	0.940	0.980	1.020	1.060	1.100

Water heating hours (for systems with storage) are by default to heat to the hot water storage temperature (see Table 1 above) and maintain this from 00:00 to 07:00 and then for the rest of the day, switch on when the temperature falls below the hot water temperature (see Table 1 above) and switch off when the temperature rises to the hot water storage temperature.

For instantaneous systems (e.g. combi boiler), the system is assumed to be always available.

Future development

We may revisit the assumption that the observed pattern of events for a combi boiler is representative of the household's true demands (see Annex 1). As it stands the generated schedules may include unreasonably large events which could not be met by any ordinary size of storage cylinder.

The assumed water heating hours do not align with usual household water heating patterns when using gas boilers with storage cylinders. We may wish to revise this assumption either to match the observed typical behaviour or to permit a pattern which works better with heat pumps. In the EST study the most typical pattern was to heat during the hours 08:00—10:00 and 18:00—23:00 daily, but most households heated water only as and when it is required, and for a much shorter time than this: the mean heating time was 2.6 hours/day. No more recent study was available (the Connected Devices study being of combi boilers only).

Annex 1: Estimating the relationship between hot water consumption and occupancy

This analysis is informed by two data sets:

- "EST", Energy Saving Trust data from 2008[4]: mean daily consumption for 112 households, of which 39 have combi boilers. This data includes household occupancy, for which the sample is biased: it has a mean occupancy of 3.04, against a population mean of 2.37 (per the EHS 2018).
- "Connected Devices" ("CD")[5] – high-frequency metered data for 45,000 contemporary combi boilers gathered between May 2021 and May 2022; it is also the source of the event schedule described in Annex 2. The CD sample is large and current but is not matched to household type or occupancy, and may not be wholly representative of the underlying stock (no statistical sampling has been used to compensate for any biases).

In both cases the data is of water drawn from the boiler, V_B. A separate deduction is made to estimate the volume of hot water reaching the hot tap, V_{HT}: see section 6 in Annex 1.

In the broadest terms the approach taken is to impute the contemporary distribution of hot water consumption onto the 112-home sample. We assume that although the distribution of demand has changed, the households' relative position within the distribution has not, so that a home with median (or 25th centile) consumption in 2008 would have median (or 25th centile) consumption in 2022. We will then find a best-fit dependency of this imputed consumption measure on dwelling occupancy.

The picture is complicated by the differences in the EST sample between consumption by combi and by conventional boilers, and the EST sample being biased towards larger households. The methodology described below takes these aspects of the data into account.

The Connected Devices sample, despite being much larger, is not representative of all households: the devices studied are all newer boilers with data connections, so some tenures and income deciles are unlikely to be captured and this may also distort the distribution of occupancies in the sample. We have not attempted to compensate for biases in the CD sample.

[4] Measurement of Domestic Hot Water Consumption in Dwellings, EST 2008. https://www.gov.uk/government/publications/measurement-of-domestic-hot-water-consumption-in-dwellings

[5] As detailed in DESNZ Research Paper: *Domestic Hot Water Use: Observations on hot water use from connected devices*.

Table 1 – Summary characteristics of survey samples, including average delivery temperatures for each sample

Data	Sample size	Mean litres/day (std dev)	Median litres/day
Boiler data, combi	26246	109.4 (82.5)	89.5
EST, combi (50.0°C)	39	141.8 (90.0)	115.7
EST, conventional (52.9°C)	73	110.8 (99.1)	76.6
EST, all (52.0°C)	112	121.6 (96.8)	87.5

From this data, we note that: consumption by combi boilers is significantly lower in the more recent data; conventional boilers in the 2008 study consumed much less than combi boilers; the data in both samples is significantly skewed.

Although there is a strong dependency of consumption on boiler type, for the FHS assessment wrapper we require an estimated consumption independent of the technology delivering it. As combi boilers deliver hot water on demand, unconstrained by cylinder capacity, the consumption by households fitted with them is taken as the true demand. Accordingly we do not use boiler type in fitting the transformed data back onto the EST data set, nor in the final dependency.

Both EST and Connected Devices studies reported temperature data as well as volumes but not in a way to let us improve the analysis by looking at the delivered energy of an event. Accordingly we do not consider variation in temperature of the water when estimating the distribution of the volumes demanded.

It is conjectured that the difference between combi and conventional boilers is explained partly by shower and tap flow rates, as combi boilers deliver water at higher pressure than conventional boilers with vented cylinders, which may be represented in the data set. The EST study report also suggests that at the kitchen tap (but not elsewhere) consumers may run off more water from combi boilers as they take longer to heat to the demand temperature.

Method

1. Identifying the median dwelling in a small sample of highly non-normal data is contentious. The middle three points in the ranked EST combi boiler data have consumptions 102, 116, 119 litres/day; the midmost point could have been chosen anywhere in a range of 17l/d. The scale of the possible sample error here is as large as the secular change in median consumption which we are modelling. Instead of looking at the sample median we look at the whole distributions.

2. To compensate for the bias in the EST data, we treat it as a stratified sample by occupancy and weight each stratum to match the proportion of dwellings of that size found in the English Housing Survey 2017-2020 (used also in the analysis for the FHS assessment wrapper standardised occupancy).
3. Identify the distribution of daily consumption across the CD population. Assuming that the distribution of demand has remained constant over time although the level has changed, we fit distributions of the same family to the weighted EST data.
4. Find a linear transformation which, applied to the EST sample, matches the median of the fitted distribution to the CD median.
5. Apply this transformation to the EST data and test possible regression relations for the final dependency.

1. Weighting the EST data.

We trim outliers from the EST data, discarding one dwelling recording hot water use above 500 litres/day.

We group the largest English Housing Survey dwellings together. The EST sample is overweight in all households with four or more people. The derived weights are applied in both the subsequent steps of analysis: transforming the EST data to match a modern consumption pattern, and in fitting the best-fit consumption estimate as a function of occupancy.

Table 2 – EST survey sample and English Housing Survey total weights, by household size

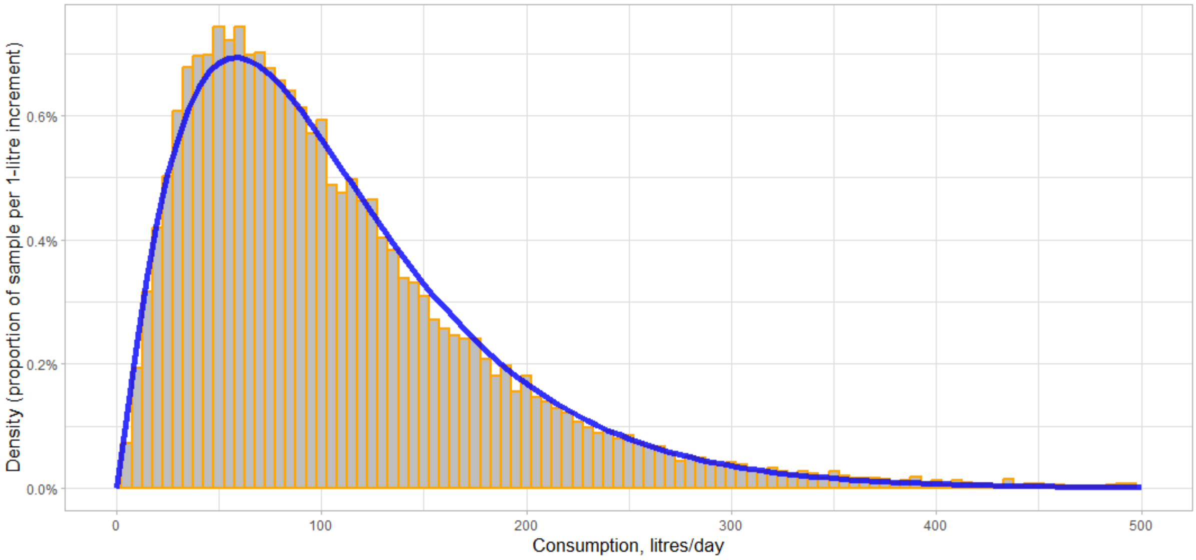
Occupancy	**1**	**2**	**3**	**4**	**5**	**6**	**7+**
EST count	11	38	18	29	13	2	1
EHS count	6,721,432	8,533,532	3,623,831	3,215,192	1,088,983	300,972	177,809
Weight	611,039	230,636	201,324	110,869	83,768	150,486	177,809

2. Distribution of consumption in the two samples.

We trim outliers from the CD data to discard dwellings recording a median daily consumption of zero (which were unoccupied for most of the sample dates) or above 500 litres/day (which are likely to be non-domestic premises).

The remaining sample of 26,139 dwellings has mean consumption following a Gamma distribution with parameters alpha (shape) = 2.17, beta (rate) = 0.0202; write this $\Gamma(\alpha = 2.17, \beta = 0.0202)$. See the histogram in Figure 2, below.

Figure 2: CD data - distribution of daily hot water demand
Histogram of Connected Devices sample, mean daily consumption. Blue: fitted Gamma distribution



This is a surprisingly good fit, and it suggests that an explanatory model is possible. Gamma distributions arise as the waiting time for multiple arrivals in a Poisson process, which has at least some relation to meeting an expected demand.[6]

Fitting the same Gamma family to the EST data gets distributions as shown in the following table and charts.

Table 3 – Gamma distributions fitted to each data set

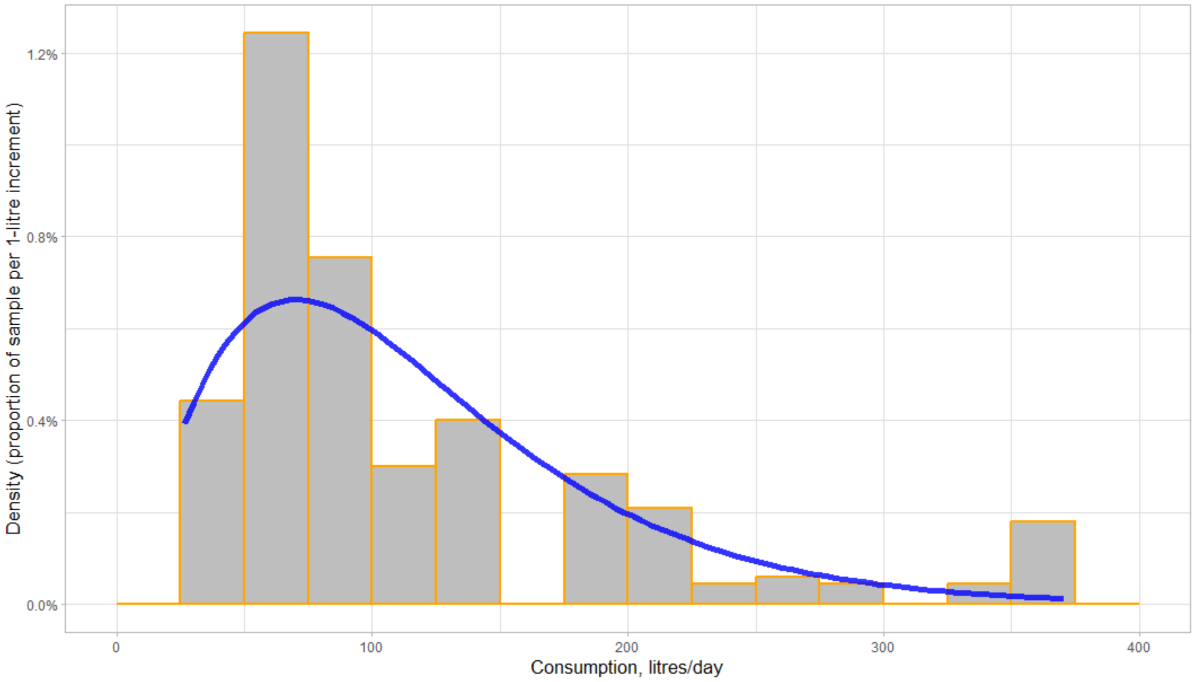
Data	**Fitted distribution**	**Median of distribution (litres/day)**
CD, combi	$\Gamma(\alpha = 2.17, \beta = 0.0202)$	91.5
EST, all	$\Gamma(\alpha = 1.77, \beta = 0.0191)$	76.4
EST, combi	*$\Gamma(\alpha = 2.51, \beta = 0.0215)$*	*101.5*
EST, conventional	*$\Gamma(\alpha = 1.41, \beta = 0.0149)$*	*73.2*

Note that as expected the medians of the distributions differ markedly from the EST sample medians.

[6] If a steady stream of water is diverted into a new bucket at random but on average every 50 litres, then the observed distribution would occur if each household was allocated a consumption of 2.17 buckets (in an appropriate sense). More realistically, households have a number of activities needing unequal amounts of water, but differ in how much they consume for each use. This data gives support to a conjecture that their preferred depth of a bath or duration of a shower follows more a Poisson than a normal distribution.

Figure 3: EST combi boilers - distribution of daily hot water demand

Histogram of combi boiler sample in weighted EST data. Blue: fitted Gamma distribution



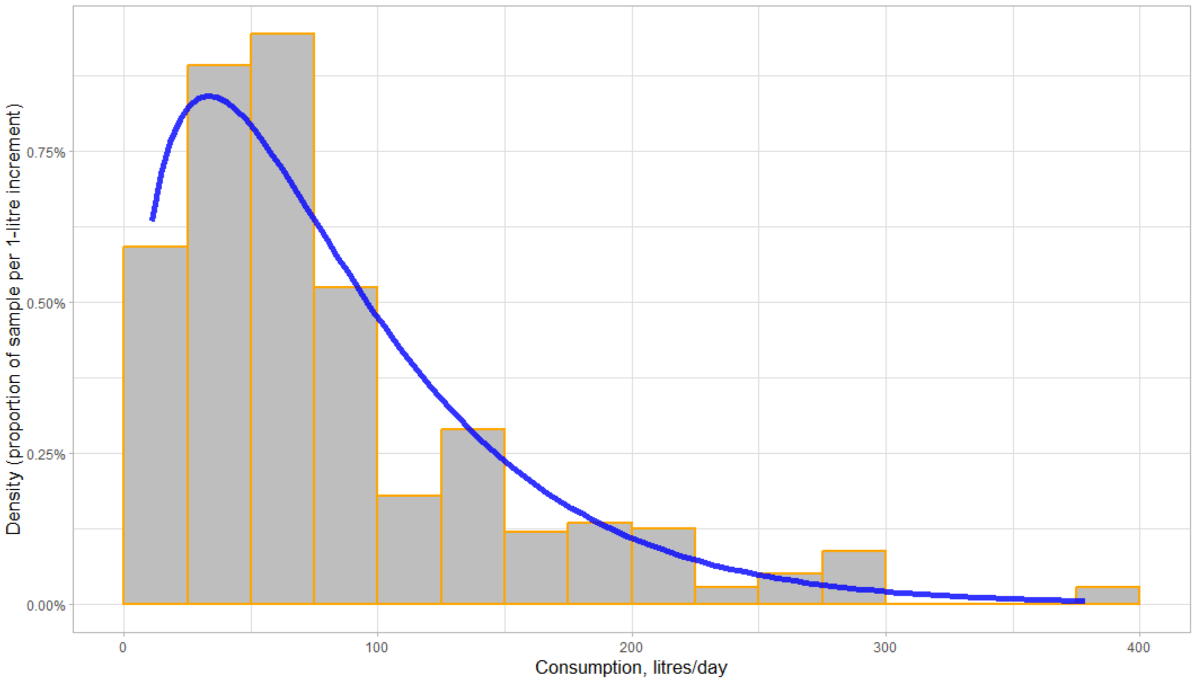
Looking only at the EST combi boilers, we can now calculate a reduction factor,

$$R = \frac{\text{median(CD combi distribution)}}{\text{median(EST combi distribution)}} = \frac{91.5}{101.5} = 0.902.$$

This value represents a reduction of nearly 10% in the typical hot water draw from a combi boiler since 2008. This is a smaller reduction than comparing sample mean or median values would have implied.

Figure 4: EST conventional boilers - distribution of daily hot water demand

Histogram of conventional boiler sample in weighted EST data. Blue: fitted Gamma distribution



3. Transformation of EST consumption to simulate Connected Devices distribution

The linear transformation applied to the EST data is, where $V_{observed}$ is the measured daily consumption of a home in the sample:

$$V_{adjusted} = 1.01\, V_{observed} + 11.68.$$

The decline in typical consumption over time, from 2008 to 2021, is more than matched, across the whole sample, by typical consumption from combi boiler systems being greater than from conventional boilers. The combined effect is best captured by a nearly constant increase in consumption across all dwellings. This subsection explains how the above transformation is derived.

The Gamma distribution of the combi-only subsample has a similar shape parameter, α, to that of the CD sample, and a simple scaling by R = 0.902 would be a satisfactory update. However for the full sample including conventional boilers a shape transformation is needed.

We apply this in three stages:

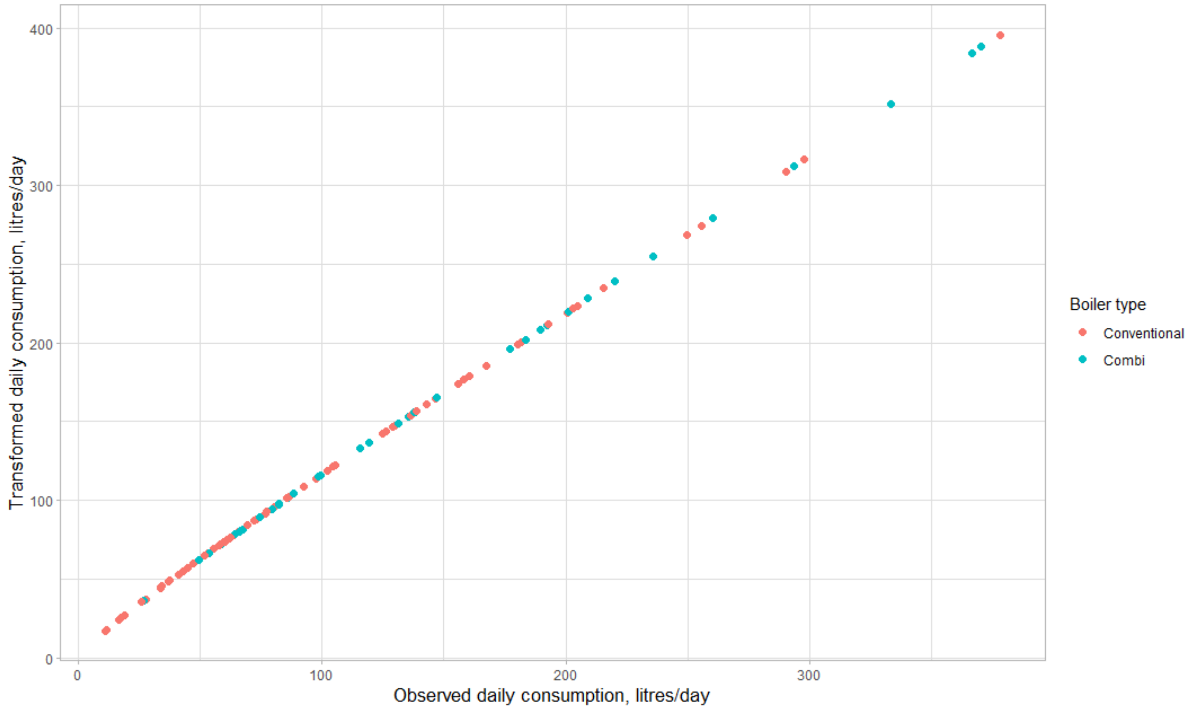
3.1. construct the exact, non-linear transformation between the EST and BD distributions;
3.2. approximate the exact transformation with a linear map, for transparency;
3.3. apply a further reduction factor to match the median of the resulting distribution (in order to compensate for the loss of fidelity with the linear map).

The exact transformation takes the form, for x the daily consumption of a dwelling in the EST sample:

$$T_0(x) = q_{\Gamma(2.17,0.0202)}\left(\mathrm{p}_{\Gamma(1.17,0.0191)}(\mathrm{x})\right).$$

Here p_Γ is the cumulative distribution function, and q_Γ is its inverse, the quantile function. The composition map is very close to linear, as shown in Figure 5:

Figure 5: Quantile transformation from EST distribution to simulate Connected Devices data



The linear approximation to this curve is $T_1(x) = 1.03x + 11.89$. After transformation with T_1 the sample has the fitted distribution Γ(α = 2.38, β = 0.0220). We can accept this value of α but to match the median of the desired CD distribution we need a further scaling factor,

$$T_2 = \frac{\text{median(CD combi distribution)}}{\text{median}(t_0\text{(EST) distribution)}} = \frac{91.5}{93.1} = 0.983.$$

The final transformation is then $T(x) = T_2T_1(x) = 1.01x + 11.68.$

We adjust the EST data, both combi and conventional boilers, by applying this linear transformation to give a modelled daily consumption from the same sample if measured today, with combi boilers installed.

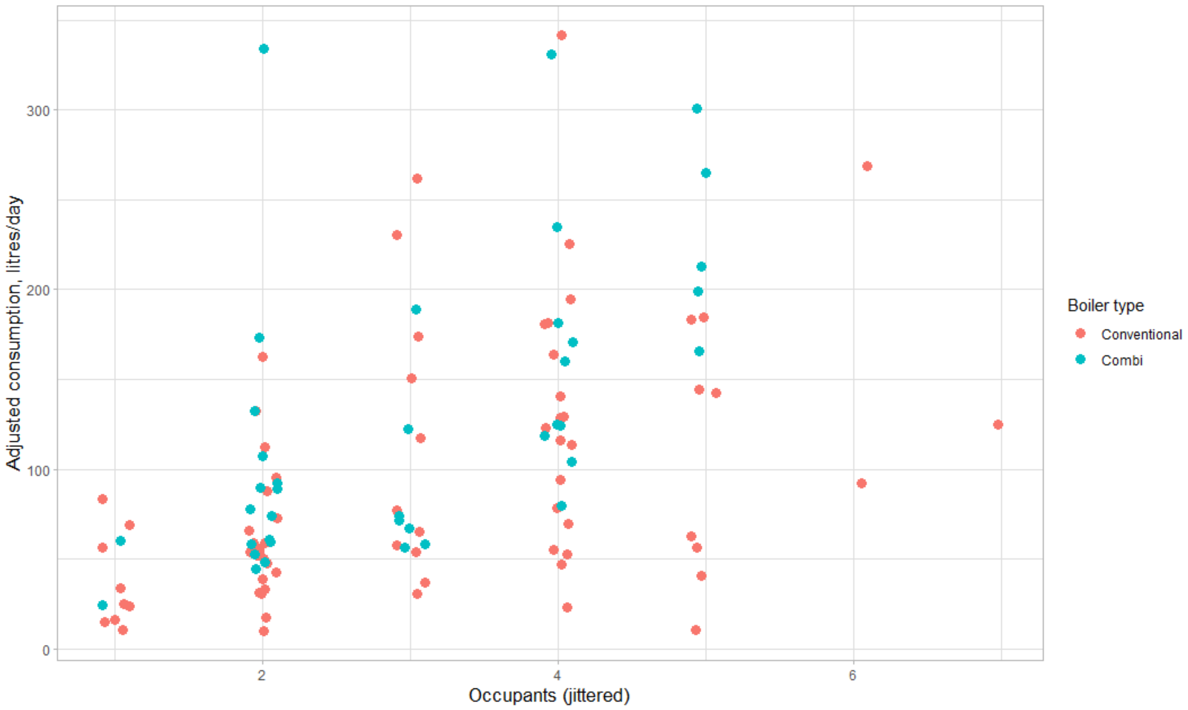
As a check of the method we fit a Gamma distribution to the transformed data. The fitted parameters are Γ(α = 2.38, β = 0.0224) and this has the desired distribution median of 91.5.

4. Dependency of modelled consumption on household size and boiler type.

The sampled relationship between adjusted consumption and occupancy is shown in the jittered[7] scatter plot at Figure 6. (Recall that although boiler type for the dwelling is shown, the transformed consumption is modelling an all-combi-boiler stock.) There is a visible upward trend in consumption with occupancy, but a wide variance about the trend.

[7] Jittering separates points that would otherwise overlap by plotting them to left or right of their true position, which in this chart is always a whole number of occupants.

Figure 6: Adjusted daily consumption by occupancy and boiler type



To select a model, we consider linear, log-linear and power-law relationships, fitting to the weighted sample data. We additionally fit a power law using linear regression after a log-log transformation, for reasons discussed below.

Table 4 – Alternative models fitted to the data in Figure 6

Model	Formula	Adjusted R²
Linear, occupancy	$V \sim 32.89\, occ\ +\ 29.96$	28.96%
Log-linear, occupancy	$V \sim 79.52 \log(occ) + 50.71$	29.97%
Power law, occupancy	$V \sim 60.32\, occ^{0.7119}$	29.79%
Log-log, occupancy	$V \sim 49.80\, occ^{0.7629}$	37.32%* (26.10%)

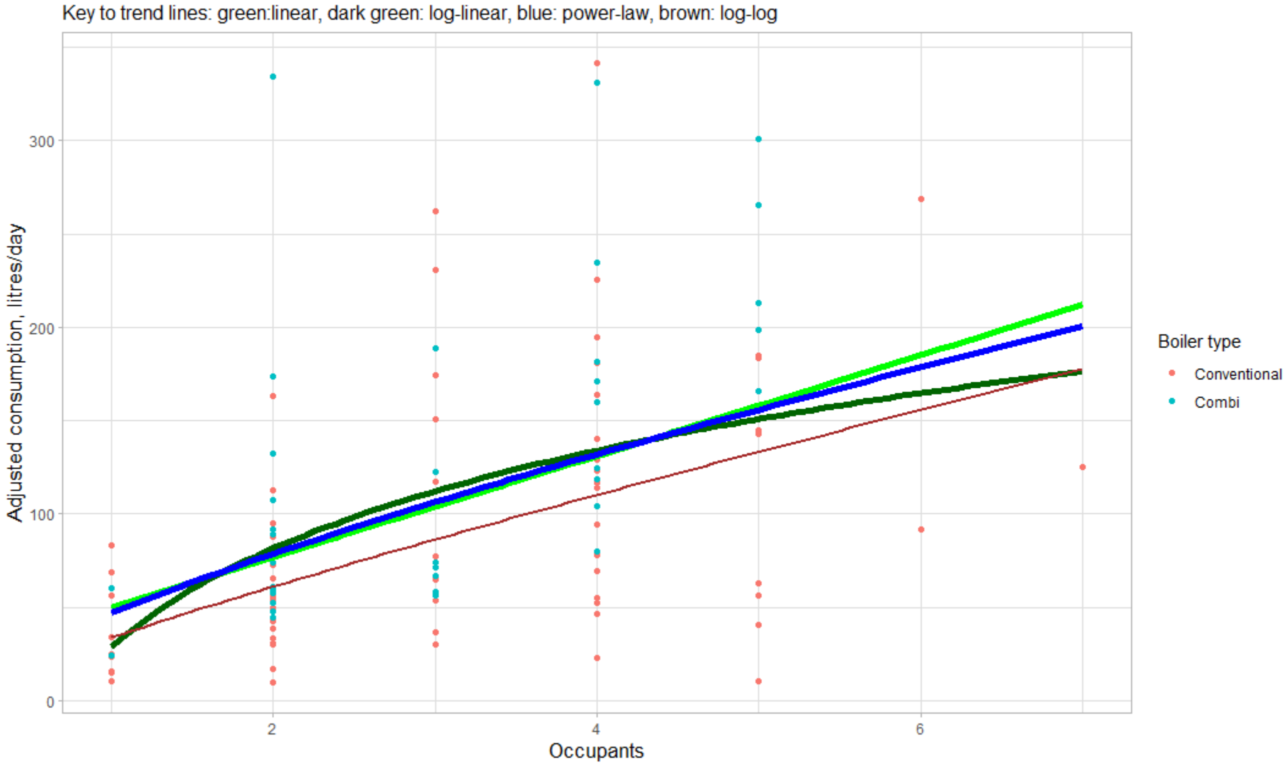
Here L denotes consumption in litres/day; a = dwelling occupancy.

R^2 for the log-log models is calculated with respect to residuals in the log-transformed variables. The value in brackets is the R^2 with respect to residuals in the untransformed variables.

Figure 7 plots the models under consideration. Note that the log-log fit lies below the other lines, which are otherwise very close for dwellings with two to four occupants. Under the log transformation, the regression minimises the total *proportional* error, and this weights points below the regression line more, those above the line less.

Figure 7: Comparison of fitted models

Key to trend lines: green:linear, dark green: log-linear, blue: power-law, brown: log-log



Examining further diagnostic plots (residuals vs fitted, residual scale/location, not shown in this report) shows that the untransformed data does not have uniform variance of residuals as occupancy varies (i.e. it is not homoscedastic). Larger households have, unsurprisingly, a wider variance in their consumption; while unusual usage patterns can include very large daily volumes on one hand but cannot become negative on the other. The log-log-transformation brings the data more closely in line with the assumptions for a linear regression and this is reflected in the much higher R^2 achieved. This relationship could appropriately be used to represent the typical hot water use of a household with no unusual demands.

The remaining three models are close together, especially among 2 - 4 person households in their predicted values, and very close in the R^2 measure of their predictive success. The highest R^2 is achieved by the log-linear model but this implies unrealistically low consumption for one-person households: 50.7 L/day, against 105.8L/day for a two-person household. The second person in the home should not consume more hot water than the first, and this rules the log-linear model out of contention. The power-law model is accordingly preferred.

The R^2 values are sensitive to outliers and excluding the single dwelling with improbably high consumption from the EST sample roughly doubles R^2 for all models.

5. Conclusions and selected model

Previous analysis of the EST data, both in the original report and in technical papers for SAP[8], has grappled with the difference between conventional and combi boiler consumption volumes, which is noticeable but not statistically significant.

The stock of boilers has changed since 2008 and it is not reasonable to make implicit use of the ratio of combi and conventional boilers in the EST sample to predict consumption for a generic contemporary building. In this analysis we explicitly model the consumption of all buildings as if they had combi boilers in the Connected Devices stock, while preserving the scatter of households of different sizes across the quantiles of the consumption distribution.

Rejecting the log-linear model for its unrealistic predictions for small households, the best fitting of the models considered is the power law:

$$V_B \sim 60.32 occ^{0.7119}$$

where consumption is proportionate to the 0.7119 power of the number of residents. As the exponent is <1, additional household members contribute less to the total than the initial ones, as expected.

Parsimonious rounding reduces the model used for the FHS assessment wrapper to

[8] STP 11/B09 Changes to the treatment of heating and hot water systems with boilers in SAP 2012, https://www.bre.co.uk/filelibrary/SAP/2012/STP11-B09_BoilerChanges.pdf

$$\boldsymbol{V_B \sim 60.3 occ^{0.72}}$$

For a home with the average 2.37 residents this predicts consumption of 112L/day at 52°C.

Table 5 – values of V_B at different occupancy levels

Household size	**1**	**2**	***2.37***	**3**	**4**	**5**	**6**
Consumption at the boiler, litres/day of unmixed hot water	60.3	99.3	*112.2*	133.0	163.6	192.1	219.1

For households with two or more occupants the predicted consumption (at the hot tap) is within 3 litres/day of the SAP 2012 assumption, which was based on the EST data alone. For 1-member households it is 16% lower. The similar outturn is arrived at by a different route, as the SAP assumption takes the best linear fit from EST data (trimmed more robustly than we have done) and makes an adjustment to account for systematic errors in the logging data.

6. Adjustment of total hot water volume to account for pipework losses

The Home Energy Model defines a tapping event as the period for which hot water is flowing at the tap or shower head. Before this can begin the existing ambient-temperature water in the pipe must be drained and replaced with water from the hot supply; an equivalent volume of hot water remains in the pipe after the event.

The total volume of hot water that remains in pipes was estimated by modelling a home with the average 2.37 occupants. The daily number of showers, baths and other tapping events were taken from the medium load profile provided in BS EN 13203-2:2018. The shower head flow rate was assumed to be the same value used in the standard, 6 litres/minute. Pipe runs to each tapping point were assumed to be 8m in length with 13mm inner pipe diameter. The volume of water remaining in the pipe after each tapping event was calculated and found to be 18% of the total drawn from the taps. Equivalently, this is 15% of the water drawn from the boiler or cylinder. With V_B the volume of water drawn from the boiler or cylinder, and V_{HT} the water reaching the hot tap or other final outlet, we have:

$$V_{HT} = 0.85\, V_B$$

This approach is expected to provide a reasonable allowance for pipe losses in new buildings but may be optimistic for many of the existing buildings in the boiler data used to calculate the FHS total daily hot water volume. Further research is recommended to more accurately understand typical pipe losses, to minimise double or undercounting these losses in the FHS total daily hot water volume.

Distributing a 15% reduction over all events in the sample implies 9 – 10 seconds of flow to charge the pipe (varying slightly by decile, as flow rates vary between them) and the duration and volume of each event has been reduced by this amount in the tables in Annex 2[9].

To reiterate, the assumed 15% volume remaining in the pipe has been used to derive the standard estimate for demand at the tap V_{HT} from the sample data which measured draw-off at the boiler V_B. When the Home Energy Model calculates the energy used for hot water in a given dwelling (and the associated space heat gains due to pipework losses), this assumption is not used and the specifics of that dwelling are taken into account.

[9] Some larger events recorded in the sample may represent adjacent or overlapping uses of water in the monitored home; for example, successive showers. There is no time between these events for the (shared length of) pipework to revert to ambient temperature, so no extra allowance is needed here.

Annex 2: Schedule of events

The Home Energy Model distinguishes three use cases for hot water: baths, showers, and other tap draws (which include handwashing and washing up, for example). These differ in their treatment of thermal gains (to the space or to waste-water heat recovery) and in the building parameters that affect them (bath volume and shower flow rate). The model simulation requires a schedule of events of each type. We use monitoring data of the water drawn from the boiler in a sample of UK homes and impute uses onto these draws. From this we construct tables of when events of each type occur. This Annex describes how this is done.

The Connected Devices study[10] analysed a cohort of 45,000 internet-connected boilers monitored during a full annual heating year, from May 2021 to May 2022. This is the first full year since the legally mandated Covid-19 lockdowns. Within this cohort a sample of 2,700 homes provided measured observations of hot water drawn from the boiler output tap: these consisted of about 24,000,000 events (i.e. continuous periods of flow through the output tap).

The sample of homes is ordered into deciles by total consumption, as in Table 1.

Table1 – Hot water demand deciles

Decile	Lower bound / L	Median daily hot water demand at the tap / L	Upper bound / L	Calibration volume / L[1]	Dwellings in decile under FHS assumptions[2]
1	19.7	**37.9**	47.9	*51.1*	
2	47.9	**56.0**	63.2	*71.3*	
3	63.2	**69.8**	76.8	*86.2*	1-bed
4	76.8	**82.8**	90.0	*99.2*	
5	90.0	**96.1**	101.8	*111.1*	2-bed
6	101.8	**109.8**	116.0	*120.7*	3-bed
7	116.0	**123.3**	131.4	*135.0*	4-bed
8	131.4	**141.1**	152.3	*148.4*	5-bed
9	152.3	**162.9**	179.6	*170.2*	
10	179.6	**197.8**	220.7	*196.9*	

1. This is the average daily draw from a pseudorandom schedule generated from the events in this band, used to calibrate the schedules generated for dwellings in the FHS assessment wrapper (as in the main section of this document).
2. Variation of the floor area of a dwelling does not affect FHS standardised occupancy enough to change its band.

Allocation of events to use types

The available data from the Connected Devices study classified all water-drawing events into five bands by duration. There is no comparable study of domestic hot water able to provide a fine-grained allocation of events to different uses. For this analysis we therefore attributed all events from a band to the same use.

There has been a secular change in personal bathing habits since 2002 with showers increasingly supplanting baths, but there is little recent systematic data. In the At Home With

[10] As detailed in DESNZ Research Paper (to be published) "*Domestic Hot Water Use: Observations on hot water use from connected devices*."

Water study, conducted in 2012, the averages reported imply a typical use of 264 litres/week of mixed water in showers and 104 litres in baths: that is, about 28% of bathing water was taken in baths. There was wide distribution in shower lengths: a mean shower was 7.5 minutes with a range of 0 to 30+ minutes.

In the tables for the FHS assessment wrapper the two shortest bands of event are allocated to ‘other’. Baths make up the fourth band, which are events with an average volume of 69 litres. Events in the third and fifth bands are allocated to showers. Under these assumptions baths make up 29% of bathing water use, reproducing the 2012 sample proportion within each individual dwelling.

Table 4: Mean volumes and durations of events, across all deciles

Initial label	Mean volume / L	Mean duration / s	Final label
0	1.4	14.4	0_small_tap
1	10.5	108.7	1_long_tap
2	37.0	349.3	2_shower
3	69.4	650.2	3_bath
3_big	104.7	991.0	2b_shower_big

Although the resulting standardised water use profile is in obvious ways unrealistic, it is consistent with the available data both in the pattern of drawings (determining the demands on the hot water supply) and the overall proportion of water uses (determining the attributable heat gains).

Since only events of the type “shower” are influenced by measures to control flow rates, the attribution of events between baths and showers is of significance to the

Temperatures of events

Boilers in the study had a wide range of set points, with a median of 55°C. For events in the three longer bands (interpreted as showers and baths) the median temperature achieved was between 52.4 and 53.2°C. The shorter tap events achieved median temperatures of 46.3 – 49.8°C. The evidence did not provide a clear reason to vary the assumed delivery temperature of water from 52°C. A future extension of this work might consider short events in more detail.

These events are categorised into five bands, by duration of the event. For each decile, and each day of the week, the mean daily frequency of events in each band is reported: this includes the mean volumes and durations within the band. An excerpt for decile 1 is shown here as table 2.

The Future Homes Standard assessment wrapper interprets the average daily event count found in this data as the *expected* number of such events for a building in its standardised use, given the decile into which its standardised total consumption of hot water falls.

A second table reports the overall frequency of events of each band for each hour in the week. This data is only available for the largest three bands (interpreted as baths and showers). A weighted average of the number of events in these bands is imputed to the two smaller ones, as illustrated in table 3 with outlined bars. The FHS assessment wrapper assigns the probability of hot water events to times within a day in proportion to this observed hourly data.

A worked example: a dwelling in band 1 has a 28% likelihood of a shower event on a Monday (Table 2). Of these, 7% occur in the hour 8am – 9am (table 3). Hence each Monday the pseudorandom schedule assigns a 1.98% chance of a shower to this hour. The Poisson sampler allows for the possibility that two showers will take place (with likelihood less than 1 in 2500). If a shower does occur it is equally likely to start in any minute between 08:00 and 08:59; if two do, their start times are adjusted so that they don't overlap.

Table 2: events by decile and day

Decile	Day	Event band	Mean events / day	Mean event volume / litres	Mean duration / seconds
1	Monday	0_small_tap	10.792	1.7	17.9
1	Monday	1_long_tap	1.295	9.7	104.8
1	Monday	2_shower	0.283	31.7	331.5
1	Monday	3_bath	0.094	59.6	647.2
1	Monday	2b_shower_big	0.056	89.7	1079.7
1	Tuesday	0_small_tap	10.513	1.7	17.9
1	Tuesday	1_long_tap	1.236	9.7	104.5
1	Tuesday	2_shower	0.279	30.5	325.4
1	Tuesday	3_bath	0.094	61.2	651.8
1	Tuesday	2b_shower_big	0.063	92.0	1086.4
1	Wednesday	0_small_tap	10.086	1.6	17.9
1	Wednesday	1_long_tap	1.192	9.7	104.9
1	Wednesday	2_shower	0.280	30.0	324.5
1	Wednesday	3_bath	0.091	59.7	644.7
1	Wednesday	2b_shower_big	0.060	93.0	1085.8
1	Thursday	0_small_tap	10.143	1.7	18.0
1	Thursday	1_long_tap	1.192	9.8	104.8
1	Thursday	2_shower	0.273	30.7	327.9
1	Thursday	3_bath	0.091	58.4	644.5
1	Thursday	2b_shower_big	0.063	92.2	1063.8

Table 3: events by hour

Count of events		Event type				
Day	hour	0_small_tap	1_long_tap	2_shower	3_bath	2b_shower_big
Monday	0			407	70	86
Monday	1			274	50	30
Monday	2			262	45	23
Monday	3			681	107	35
Monday	4			2285	453	215
Monday	5			7357	1558	659
Monday	6			13349	2851	1067
Monday	7			14491	2708	1066
Monday	8			11712	2224	825
Monday	9			8801	1843	747
Monday	10			6332	1439	738
Monday	11			4322	1094	589
Monday	12			3281	815	480
Monday	13			2954	658	447
Monday	14			3138	722	384
Monday	15			4386	1019	548
Monday	16			6436	1591	857
Monday	17			8978	2194	1127
Monday	18			9662	2328	1269
Monday	19			8060	2065	1110
Monday	20			6015	1402	904
Monday	21			3916	873	508
Monday	22			2017	462	257
Monday	23			868	178	149
Tuesday	0			379	53	62

Hourly data is not available for types 0_small_tap and 1_long_tap and for the FHS wrapper they are imputed with the average of the other bands.
The count of events in the hourly data is not directly comparable with the proportions of events in the full daily data, as it is based on a subset of the full sample.

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