Modelling hot water storage tanks within the Home Energy Model

A technical explanation of the methodology

Document reference: HEM-TP-11

Document version: v3.0

Issue date: January 2026

Home Energy Model version: HEM 1.0

Contents

Background to the Home Energy Model

What is the Home Energy Model?

The Home Energy Model (HEM) is a calculation methodology designed to assess the energy performance of homes, which will replace the government's Standard Assessment Procedure (SAP).

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 technical documentation (e.g. this document)

What: This document is one of a suite of technical documents, which explain the calculation methodology in detail. New documents will be added, and the content amended, when necessary to ensure documentation is sufficiently comprehensive. This will usually, but not always, occur alongside the release of a new version of HEM.

Audience: The technical documentation will be of interest to those who want to understand the detail of how the Home Energy Model works and how different technologies are treated.

The Home Energy Model consultation and government response

What: The Home Energy Model consultation introduces the overhaul to the SAP methodology and sought views on the approach taken by the new Home Energy Model. The Home Energy Model consultation summarises the feedback to the consultation and the actions taken subsequently in development, ahead of the initial release of HEM.

Audience: The Home Energy Model consultation will be of interest to those seeking a general introduction to HEM and its role in government policy on domestic energy performance.

The Home Energy Model reference code

What: The full Python source code for the Home Energy Model core engine has been published as a Git repository. Note the reference code for official HEM wrappers is published separately.

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 or those wishing to use it within their own projects.

Related Content

Hot water storage tanks (also known as hot water cylinders) store hot water for later use after being heated by a heat source such as an immersion heater, boiler or heat pump. The performance of a storage tank depends on its volume, heat losses, the pattern of hot water draw-offs and the control arrangements of heat sources (temperature setpoints and timing).

This paper sets out the methodology for modelling storage tanks and smart hot water tanks within the Home Energy Model core engine. For information on relevant assumptions made in the FHS assessment wrapper, please see HEMFHS-TP-03 FHS domestic hot water assumptions.

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

src/hem_core/heating_systems/storage_tank.py

Methodology – Standard Storage Tank

1. Overview

The Home Energy Model (HEM) storage tank model is based on Method A from BS EN 15316-5:2017 and splits the tank into 24 layers. The standard provides a calculation methodology for a multi-layered tank model, it was chosen as the method explicitly models the temperatures inside the tank.

Hot water is drawn off from the top of the tank and replaced by fresh cold water at the bottom which is then heated in the tank by one or more heat sources. It is assumed that the water is stratified by temperature.

An example of the storage tank in relation to the heat source, and primary/secondary pipework can be seen in Figure 1 below.
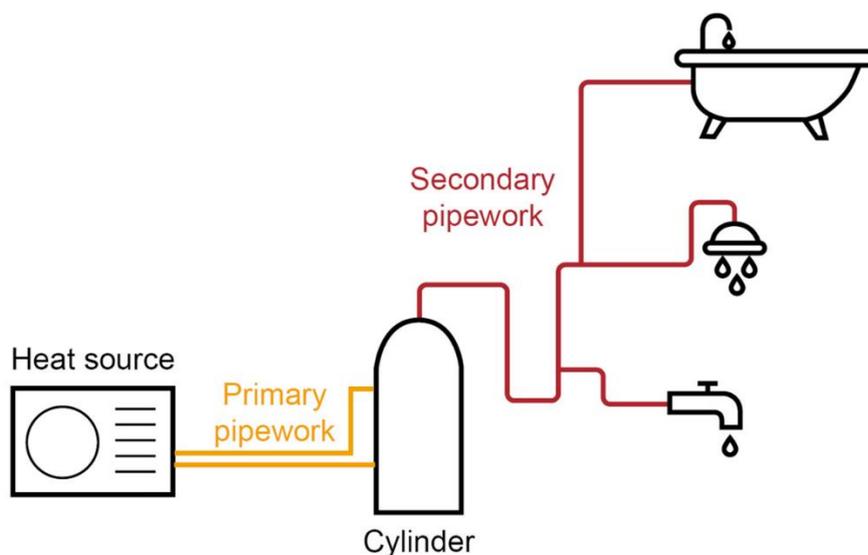
Figure 1 – Storage tank (Cylinder) in relation to the heat source, and primary/secondary pipework

The minimum and maximum setpoint temperatures are specified in the inputs or by a wrapper. The setpoint temperature is set per heat source and per timestep. Control schedules must be provided, for the maximum temperature and for the minimum temperature. Control schedules may include null entries. A null minimum setpoint indicates the heat source must not switch on in that timestep. A null maximum setpoint forces the heat source to switch off during that timestep regardless of the achieved temperature.

For each heat source, the location of the heater within the tank and the location of the thermostat controlling it are also inputs, but where there are several heat sources, the order of the heaters and the order of the corresponding thermostats must be the same (i.e., the lowest heater in the tank must be controlled by the lowest thermostat, etc.).

Thermal losses from the tank are based on a user-entered value for the losses under standard test conditions (according to BS 1566 or BS EN 12897) in kWh/day. Note that this means that changing just the volume of the tank in the inputs does not change the calculated thermal losses.

Storage tanks can also be chained together, e.g. where the cold water is pre-heated in a dedicated solar thermal tank before passing into the main tank, by specifying the pre-heat tank as the main tank's cold water source.

2. Calculation steps

The initial tank temperature is an input to the tank model, and the entire tank is initialised to this temperature before the start of the main calculation loop. The main calculation steps can be summarised as follows[1]:

1. The draw off events are inputs to the storage tank module at each timestep (see HEM-TP-09 Energy for domestic hot water). The draw off events specify the required temperature and volume for each draw off event.

2. The calculation loops through the layers of the storage tank for each draw-off event, starting from the top layer. If the water in the layer is at or above the minimum hot water temperature for the event, the volume withdrawn from the layer for the draw off is calculated. If the volume that would be withdrawn is greater than the volume of the layer, then the remaining energy demand is passed on to the next layer down, unless the current layer is the last one in which case the remaining demand is reported as unmet demand. Draw-off events may be fully met (if sufficient hot water is available across all layers), partially met (if the tank is exhausted before the full demand is satisfied), or entirely unmet (if no hot water at suitable temperature is available).

3. The temperature of each layer of the storage tank after draw off events have occurred is calculated (see Figure 2 for example). The volume withdrawn from the top layer of the tank is replaced with the same volume of water from the next layer down (and so on for other layers). If the volume withdrawn was greater than the volume of a single layer, then the water is replaced from lower layers or ultimately by cold water added to the bottom of the tank or by water from a pre-heat tank. The temperature of the water in each layer is then recalculated based on a volume-weighted average of the temperatures of the layers from which the water was drawn (or the cold feed temperature, if relevant) and by running the mixing algorithm (see Section 3) if necessary.

The following calculation steps are then executed for each heat source supplying heat to the tank, starting from the heat source closest to the bottom of the tank:

4. The maximum energy input from the heat source is calculated:

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[1] Steps 4 and 5 from the standard relate to the withdrawal of energy for space heating and are not currently implemented.

a. If the temperature of the tank at the relevant thermostat position is above the minimum setpoint temperature, then there is no demand, and the potential energy input is set to zero.

b. If the temperature of the tank at the relevant thermostat position is below the minimum setpoint temperature, the maximum energy contribution from the heat source, accounting for primary losses, if any (see section on primary circuit losses), is calculated and used to calculate the temperatures at each layer that would result, assuming at this stage that all of the energy stays in the layer that it is provided to (note that at this stage the layer temperatures may be calculated to be higher than the setpoint temperature). If the heat source controls specify that the heat source is off during the relevant timestep, then the maximum energy contribution from the heat source will be set to zero.

5. The temperatures at each layer are recalculated using the mixing algorithm as defined in Section 3.

6. Thermal losses and the final temperature of each layer are calculated (see Figure 3 for example):

a. Thermal losses are calculated based on the daily loss under standard test conditions and the temperatures calculated in the previous calculation step. If this temperature exceeds the setpoint temperature and there is heating input, then the setpoint temperature is used instead.

b. Equation (13) in the standard implicitly assumes an hourly timestep, but HEM explicitly adds a multiplication by the timestep in hours to facilitate variation in the calculation timestep.

c. Thermal losses that have already been accounted for in the calculation for previous heat sources are subtracted to avoid double-counting.

d. There is an assumed error in the standard in equation (14) for calculating the change in the temperature of a layer due to thermal losses, where the formula adds values in the denominator instead of multiplying. The following equation is used instead:

$$\Delta\vartheta_{sto;vol,i} = \frac{Q_{sto;ls;vol,i}}{\rho_w \times C_{p;w} \times V_{sto;vol,i}} \tag{1}$$

e. The final value of the temperature is reduced by the thermal losses and is capped to the setpoint temperature if there is heating input.

7. The energy required from the heat source to reach the final temperature, accounting for thermal losses and primary losses (see section on primary circuit losses), is calculated and becomes an input to the relevant heating system module.

3. Mixing algorithm

Tank layers are assumed to mix (and their temperatures are averaged) due to convection when the temperature of the water in a layer is higher than the temperature of the water in the layer above. The calculation loops over all the layers, potentially multiple times, until the temperature in each layer is lower than or equal to the temperature of the layer above.

There is an assumed error in the standard in equation (12) which recalculates layer temperatures after mixing, where a volume and temperature are added instead of multiplied. The following equation is used instead:

$$\vartheta_{sto;vol,i} = \vartheta_{sto;vol,i+1} = \frac{\vartheta_{sto;vol,i} \times V_{sto;vol,i} + \vartheta_{sto;vol,i+1} \times V_{sto;vol,i+1}}{V_{sto;vol,i} + V_{sto;vol,i+1}} \tag{2}$$

4. Example

The following graphs show the temperatures over a 24-hour calculation period for an example tank. The plots below have been produced using 4 layers in the model so that the tank behaviour can be seen clearly. Additional layers may be used to give greater accuracy[2]. In this example:

- The heater is in layer 1 (the bottom layer) and is controlled by a thermostat in layer 2.
- The setpoint temperature is 60°C and the minimum hot water temperature is 52°C.
- The tank has been initialised to 60°C

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[2] The number of layers is an optional input to the model, but it defaults to 4 layers if no input is provided.
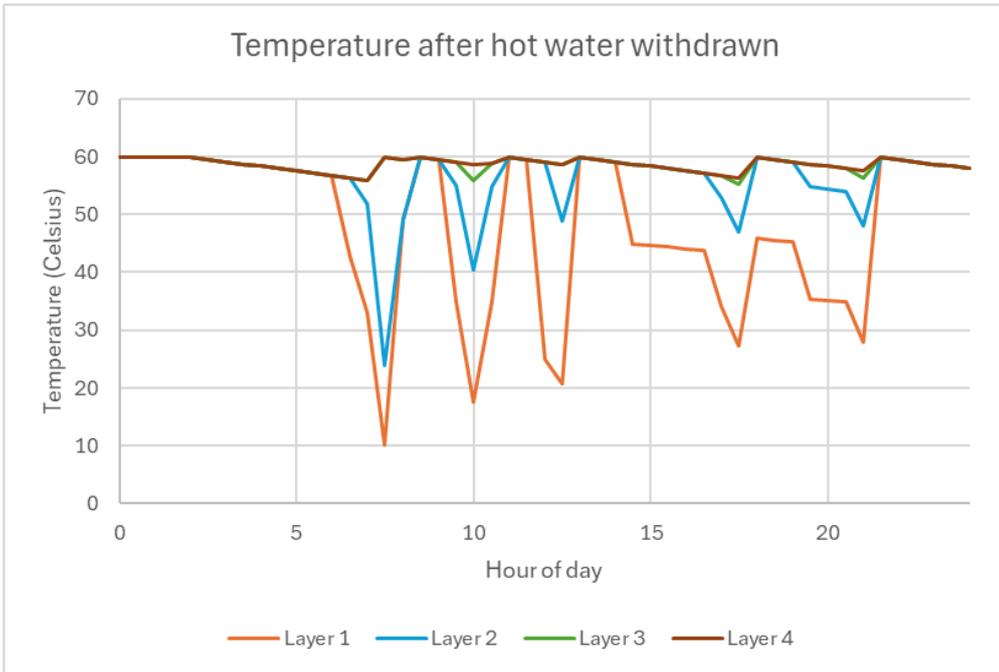
Figure 2 Temperature of tank layers after hot water is drawn off in each timestep over 24 hours.
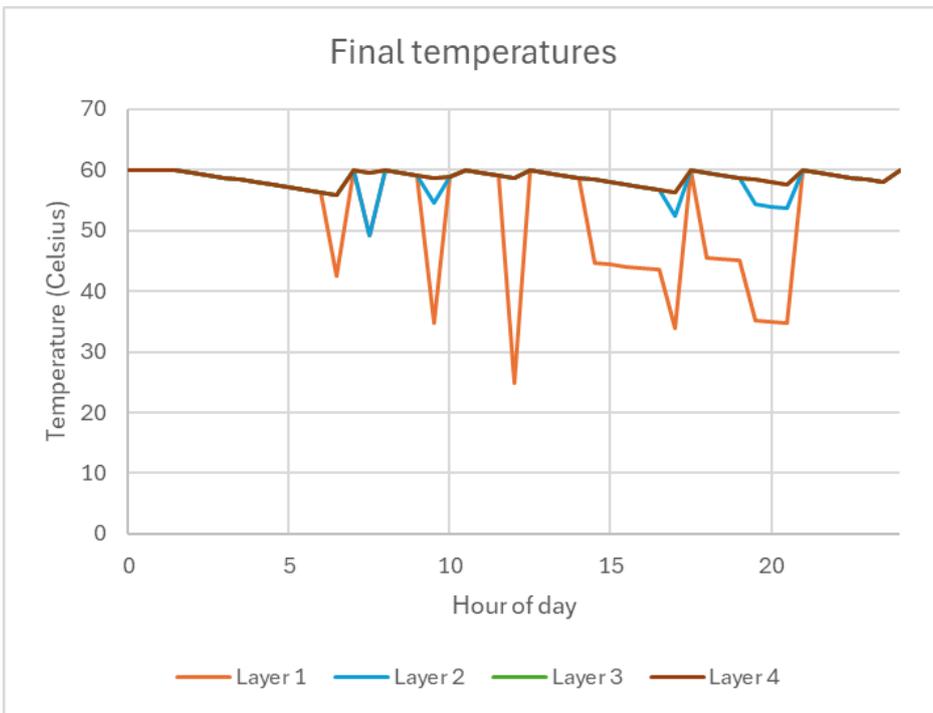
Figure 3 Final temperature of tank layers in each timestep over 24 hours, accounting for both hot water draw-off and heating.

5. Primary pipework losses

At the start of a heating event (a timestep where there is energy input to the tank where there was no energy input in the previous timestep), the energy of water in the primary pipework is subtracted from the maximum output of the relevant heat source in step 4 and is included in the demand on the heat source in step 7. This represents the energy used to heat up the primary pipework at the start of the heating event.

During a heating event (any timestep where there is energy input to the tank), the energy lost due to primary pipework losses is calculated for each user defined section (flow and return) using the section's characteristics and location. Losses from the sections inside the thermal envelope are added to the internal gains; losses from external sections are treated as losses to the outside. The pipework temperature used for loss calculations is based on the heat source's maximum setpoint temperature (falling back to the previous timestep's value if no setpoint is defined)

At the end of a heating event (a timestep where there is no energy input to the tank but there was energy input in the previous timestep), the cool down energy loss from primary pipework located inside the thermal envelope is added to the internal gains. This represents the loss of the energy that was used to heat up the primary pipework at the start of the heating event. Cool down losses from external pipework sections are lost to the outside and therefore not included as gains.

For details of how the pipework losses are calculated based on the pipework characteristics, see HEM-TP-10 Ductwork and pipework losses.

Methodology - Smart Hot Water Tank

1. Overview

The Home Energy Model (HEM) smart hot water tank model is based on Method A from [BS EN 15316-5:2017](#) as with the standard hot water tank. However, some parts of the calculation are replaced with alternative algorithms for the smart hot water tank, and the model uses 100 layers instead of 24.

2. Calculation steps

The calculation steps for the smart hot water tank can be summarised as follows:

1. The calculation begins by following steps 1-5 of the standard storage tank calculation. This gives the temperatures of the storage tank after draw off events have occurred.

2. The calculation then determines whether the heat source is switched on. For the smart hot water tank, whether the heat source switches on is based on the state of charge of the tank. Section 3 details how the state of charge is calculated. The heat source is then switched on if the current state of charge is less than or equal to the minimum state of charge at the current timestep for the heat source. The minimum state of charge is an input that must be specified.

3. If the heating is switched on the maximum energy input from the heat source is calculated. It is worth noting that the smart hot water tank model is currently limited to a single main heat source (either immersion or fed hydronically via primary pipework) plus optionally a diverter (immersion only).

4. The calculation must ensure that the heat source does not heat the tank beyond its maximum state of charge. To do so, the energy required to reach the maximum state of charge is calculated as described in Section 4. The maximum state of charge is an input that must be specified.

5. The temperatures at each layer are recalculated, accounting for mixing due to convection as defined in Section 3 of the Storage tank calculation.

6. The smart hot water tank uses a pump to move water from the bottom of the tank to the top of the tank to maintain the target temperature at the top of the tank when the tank is being heated. More details on the how the top pump volume is calculated can be found in Section 5 and the temperatures in the tank after the top pump has run can be found in Section 6.

7. The tank is again rearranged using the mixing algorithm defined in Section 3 of the Storage tank calculation.

8. The temperatures are then modified to capture the effect of thermal losses as in Step 6 of the storage tank calculation.

9. The heat source is switched off if the current state of charge is greater than or equal to the maximum state of charge.

10. The energy required from the heat source becomes an input to the relevant heating system module as in Step 7 of the storage tank calculation.

11. The energy required from the heat source is used to calculate the heat source output. This is then used to calculate the actual volume of water pumped from the bottom of the tank to the top by the top up pump, as described in Section 5.

12. The actual volume of water pumped from the bottom of the tank to the top by the top up pump is then used to determine the pump energy consumption, as described in Section 7.

3. State of charge

A key difference between standard tanks and the smart hot water tank is that the smart hot water tank has an array of temperature sensors which allow it to monitor the temperatures across the tank. The temperature readings are then used to calculate the state of charge, SOC, using the formula:

$$SOC = \frac{\int_{0,T \geq T_u}^{h} 1 + \left[\frac{-T_u}{T_u - T_c}\right] dh}{1 + \left[\frac{T_{sp} - T_u}{T_u - T_c}\right]} \tag{3}$$

Where:

h is the height of tank from the base

T is the temperature at any vertical location

$T(h)$ is the temperature at the height of the tank

T_u is the usable temperature beneath which temperature is seen as cold water

T_{sp} is the maximum setpoint temperature (can be entered as a schedule).

T_c is the cold water temperature.

Note that the state of charge can be above 100% if the maximum setpoint temperature decreases from one timestep to the next.

4. Heat input required to reach target state of charge

The heat input into the smart hot water tank should not exceed the energy required to meet the target maximum state of charge. In order to ensure this, the calculation carries out a series of steps as follows:

1. For each layer in the tank, starting from the bottom:

    a. First, the calculation checks whether raising the temperature of the current layer to the minimum usable temperature would result in meeting or exceeding the target maximum state of charge. If it would then the calculation loop terminates as the energy to reach the target state of charge has been found.

    b. Next, the calculation checks whether raising the temperature of the current layer to the maximum setpoint temperature would result in meeting or exceeding the target maximum state of charge. If it would then the energy required is calculated by interpolating between usable and maximum temperatures to reach the target maximum state of charge. The calculation loop then terminates as the energy to reach the target state of charge has been found.

    c. Otherwise, raising the temperature of the current layer to the maximum temperature is insufficient to meet the target state of charge. Therefore, the current layer is raised the maximum temperature, and the calculation continues.

    d. If there is insufficient remaining energy available from the heat source to heat the bottom layer to the setpoint, then a partial layer is pumped to the top. The volume to be pumped is determined by dividing the total available energy by the energy required for the bottom layer. Then the calculation loop returns to step a.

    e. If there is sufficient remaining energy available from the heat source to heat the bottom layer to the setpoint, then the entire bottom layer is pumped to the top of the tank. Then the calculation loop returns to step a.

2. After the calculation loop is complete, the total energy input is summed across all layers to determine the energy required to meet the target maximum state of charge.

5. Volume of water moved by top up pump

The smart hot water tank has a pump that moves water from the bottom to the top of the tank when the temperature in the top layer reaches the setpoint temperature.

The calculation determines what fraction of each layer needs to be pumped from the bottom to the top of the tank to achieve the target temperature at the top of the tank. The volume fraction for each layer is multiplied by the volume of that layer to get that layer's contribution to the heated volume at the top of the tank. These are then summed (excluding the layers that were already above the heater position) to get the total volume to be pumped from the bottom of the tank to the top

The volume of water moved from the bottom to the top of the tank is limited by the maximum flow rate of the pump.

The temperature to be achieved in the top part of the tank can be defined in terms of volume fractions and temperatures. Where the volume fraction is each layer's contribution to the volume of water to be heated in the current timestep.

$$T_{target} = \frac{\sum_{L=0}^{N-1}[T_L * F_L]}{\sum F_L} \tag{4}$$

Where

T_{target} is the target temperature

T_L is the temperature in a layer

F_L is the volume fraction of a layer

N is the number of layers in the model

L is index of an individual layer

This equation can be rearranged to solve for F_X, which is the volume fraction in X, the current layer and T_X is the temperature of the current layer

$$F_X = \frac{\sum_{\substack{L=0 \\ L \neq X}}^{N-1}[T_L * F_L - T_{target} * F_L]}{T_{target} - T_X} \tag{5}$$

The equation loops over the layers (starting from the bottom of the tank), where F_L is initialised to 1 for layers above the heating element and 0 for layers below the heating element. If F_L is calculated to exceed 1, then it is set to 1 and the calculation moves on to the next layer.

6. Water temperatures after operation of top up pump

After the volume of water moved by the top up pump has been calculated, the water in the tank is redistributed from higher layers to replace water removed from the lower layers; for each layer (starting with the bottom layer and moving upwards) the calculation first looks at the layer above to find available water, then the one above that, and so on until enough water is found to replace the water that has been removed by the top up pump. If this algorithm reaches the top layer of the tank and an insufficient volume of replacement water has been found, then the algorithm will loop round to the bottom layer (i.e. water moved down the tank from higher layers to replace water removed from lower layers by the top up pump may be replaced by the water that was moved from lower layers to the top of the tank by the top up pump). As the

calculation finds available water and moves it, the new temperature of each layer is calculated based on a volume-weighted average of the layers that the water was moved from.

7. Top up pump electricity consumption

The top up pump electricity consumption is calculated using the following formula:

$$Pump\ electricity\ consumption = \frac{volume\ pumped}{flow\ rate\ per\ min} \times pump\ power \qquad (6)$$

Future development

Currently, there is no control setting that guarantees a certain temperature is reached for a certain amount of time (e.g. to model sterilisation cycles). This may be incorporated in future versions.

The number of layers in the tank model may also be increased in the future to provide more granularity regarding the tank temperature and positioning of thermostats and heaters. BS EN 15316-5:2017 supports a model with up to 24 layers. However, there has been no specific reason found why the model could not use more layers than this. The smart hot water tank simulation uses 100 layers, and the standard tank could also be modelled to 100 layers in the future if this leads to a significant improvement in accuracy.

The primary pipework calculation can be improved to account for the warm-up and cool-down time and to calculate the return temperature from the flow temperature, heat exchanger characteristics and flow rate.

For smart hot water tanks with a PV diverter, the calculation takes a relatively long time to run. There may be further research in the future into whether the execution time can be improved.