Development of Conversion Factors and Overall Approach for International Comparisons of Water Heaters

Version 7.0: Storage, Heat Pump and Instantaneous Water Heaters
(Issue March 2016)

Foreword

The analysis of the energy performance of water heaters is the first time the IEA 4E Mapping and Benchmarking activities have attempted to compare products of similar functionality, irrespective of their energy source.

Given the complexity of the issues of comparing water heaters and the associated cross-energy comparisons, the 4E Executive Committee have requested the analysis be undertaken in a series of incremental phases with associated breakpoints. The first phase of analysis consisted of three work tasks which have now been successfully completed and published:

- **Water Heater Market Characterisation**: Providing a summary review of the various products available in participant markets, the regulatory frameworks in place and the data available which will define immediate and potential future analysis options.

- **[Storage] Water Heater Conversion Factors**: Developing the conversion factors to be used for comparing electric and gas water heater units. Based on these conversion factors, present initial outputs of comparative product performance and an assessment of whether it is likely a full benchmarking exercise can be undertaken. However, to minimise variables, the initial phase focused on electric and gas storage water heaters, with heat pump and instantaneous products to be added in a later phases where possible.

- **Water Heater Energy/Fuel Conversion Factors**: An investigation of the options for comparing products of differing energy sources on a primary and secondary fuel basis, and the benefits and drawbacks for interpretation and use of the various results by policy makers.

This document is the first of the second phase of analysis which extends the Water Heater Conversion Factors to include air source heat pump and instantaneous water heaters. When the conversion factors are approved, they will be followed by the publication of Mappings, comparing the performance of water heaters at the national level, and finally by the comparative international benchmarking of water heater performance.
Contents

Foreword

1. Introduction

2. Summary description of water heater types, functionality, operational characteristics and terminology
   2.1 Water Heater Types and Conceptual Energy Use
   2.2 Functional Definition of Water Heaters and Associated Performance Parameters

3. General Approach to Defining the Total Unit Energy Consumption of Water Heaters and Associated Test Methodologies
   3.1 All Water Heater Types
   3.2 Gas and Electric Storage Water Heaters
   3.3 Gas and Electric Instantaneous Water Heaters
   3.4 Heat Pump Water Heaters

4. General Approach Normalising the Performance of Water Heaters for Benchmarking Comparisons
   4.1 Normalisation of Gas and Electric Storage Water Heaters
   4.2 Normalisation of Gas and Electric Instantaneous Water Heaters
   4.3 Normalisation of Heat Pumps Water Heaters

5. Presentation of Data
   5.1 Mapping Document
   5.2 Benchmarking

Annex 1: Approaches to calculating energy consumption for heat pump systems
1. Introduction

The aim of this document is to develop conversion factors that may be used for comparing gas and electrical resistance storage, heat pump and instantaneous water heaters where original performance has been established based on national test methodologies.

The document is set out with the following structure:

- Section 1: Introduction.
- Section 2: A summary description of water heater types, functionality operational characteristics and terminology used in this report.
- Section 3 and 4: The approach developed for the normalisation of data to facilitate comparison of products tested under differing international conditions, and the associated assumptions used for the analysis.
- Section 5: Proposed data to be presented in the Mapping and Benchmarking reports

Data analysed in the preparation of the conversion factors and initial normalised result are shown in Table 1, although additional datasets are available and will be used in the full mapping and benchmarking analysis (please refer to Summary Characterisation of 4E Participant Water Heater Markets for a full listing of available datasets).

Primary analysis of raw data, test methodologies and development of conversion factors has been undertaken by Energy Efficient Strategies¹ (EES) to whom principle credit should be given.

Table 1 Summary of Data Sets Analysed in the Preparation of Energy Conversion Factors and Development of Performance Comparisons

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Country</th>
<th>Source</th>
<th>Product Level Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric storage</td>
<td>Australia</td>
<td>EnergyRating National Register</td>
<td>489</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>Federal Register</td>
<td>584</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>Department of Energy (DoE)/California Energy Commission (CEC)</td>
<td>1373/1370</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>Confidential</td>
<td>16</td>
</tr>
<tr>
<td>Gas storage</td>
<td>Australia</td>
<td>EnergyRating National Register</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>Federal Register/ENERGY STAR</td>
<td>1712/190</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>DoE/CEC/ENERGY STAR</td>
<td>3428/4223/734</td>
</tr>
<tr>
<td>Gas Instantaneous</td>
<td>Australia</td>
<td>EnergyRating National Register</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>CEC/ENERGY STAR</td>
<td>1705/374</td>
</tr>
<tr>
<td>Electric Instantaneous</td>
<td>USA</td>
<td>CEC</td>
<td>194</td>
</tr>
<tr>
<td>Electric air source heat pump</td>
<td>Australia</td>
<td>EnergyRating National Register</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>ENERGY STAR</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>USA</td>
<td>DoE/CEC/ENERGY STAR</td>
<td>171/107/119</td>
</tr>
</tbody>
</table>

2. Summary description of water heater types, functionality, operational characteristics and terminology

2.1 Water Heater Types and Conceptual Energy Use

The European Preparatory Study on Water Heaters\(^2\) provides a general definition of a water heater:

*A water heater is defined as an appliance designed to provide hot sanitary water. It may (but need not) be designed to provide space heating or other functions as well.*

This definition is broadly drafted as the range of designs, sizes/capacities and energy sources used to provide sanitary hot water in any particular country/region is extensive. The recent CLASP Water Heater Scoping Study\(^3\) provides a summary of these potential variations:

*Water heaters may be gas, electric or solar powered. They can be instantaneous, typically positioned close to the point of demand, or they may use storage tanks connected to the points of demand by a distribution system. Electric water heaters*

---


may use heat pump technology ([water, ground or] usually air-source) to increase the overall efficiency or they may be more conventional designs that simply use electric resistance heaters. In some economies, most notably Europe, water heating can also be provided by the same device used to provide the space heater through a “combi-boiler” design that has one heating loop for sanitary hot water and another to supply water into a hydronic heating system.

Figure 1 shows a simplified breakdown of the types of water heaters only devices (i.e. excluding those systems that also provide space heating) and their energy sources.

**Figure 1: Water Heater Types and Energy Sources (excluding combination systems)**

![Water Heater Types and Energy Sources Diagram]

Figure 2 provides a conceptual graphic of an unvented\(^4\) water heater. In the case of gas\(^5\) and electric storage water heaters, cold water enters a storage unit where it is heated (through combustion of the gas or through electrical resistance) to a given temperature for storage. The resulting stored hot water is then drawn from the unit for use and replaced with water from the cold supply. This incoming water is then heated immediately or during a following heat recovery cycle. Heat pump water heaters typically follow a similar conceptual design but with the heat being supplied to the water via a heat exchanger which draws energy from an external air, ground or water source (this analysis is restricted to air source units) via a vapour compression cycle. Instantaneous water heaters

---

4 While vented (or atmospheric) systems are used in some participating countries, the vast majority of storage water systems used are unvented (pressurised) systems and consequently the mapping and benchmarking analysis will be limited to unvented units.

5 Gas products typically include options for natural gas (Methane) and liquid petroleum gas (LPG or propane). In general terms, the performance of the same model running on the different gas types is similar so no differentiation is made during the analysis.
typically operate differently by heating water electrically or through gas combustion at the time the water is demanded, with little or no heated water storage capacity.

This conceptual approach can be extended to broadly illustrate the energy flows within a water heating system with the various energy inputs and losses varying by water heater type, design and capacity. As Figure 3 illustrates:

- Energy is used to raise the temperature of the cold water supplied to the required temperature for hot water delivery. The quality of hot water delivered, and the difference between the cold water inlet and hot water outlet temperatures, defines the embodied energy of the delivered hot water.

**Figure 3: Conceptual graphic of the operation of an unvented storage water heater**

However, in the course of the heating, storage (where applicable) and delivery of the hot water additional energy is consumed:

- During the water heating process, e.g. through energy losses to the flue gases vented to atmosphere after gas combustion, though embodied energy in supplied hot water that is yet to reach the required delivery temperature during the initial system heat up, etc.
- To replace the energy lost via heat transfer from the internal hot water to the lower temperature ambient environment through the any storage tank walls.

---

6 It should be noted that, for unvented water heaters with storage capacity, some water (and consequentially) energy can be lost as the water expands slightly when heated and a small amount of water is normally discharged. The water lost is dependent on the difference between the inlet and outlet water temperatures, but is around 1.6% for a temperature rise of 45K. Therefore, if the demand is 200 litres and the temperature rise is 45 K, approximately 3.2 litres maybe lost over a period of several hours. This water loss will be of hot water if there is only a single temperature/pressure relief valve installed, or it could be cold if a relief valve is on the hot side and a second, lower pressure, relief valve is on the cold inlet.
• In the distribution pipework when hot water is drawn from the tank to the point of use.
• By control and operation systems managing the water heating and storage process, e.g. electronic controllers, thermostats, pilot lights, etc.

Thus, in simple terms, the energy consumption by a water heating system can be described as:

\[
Total \ System \ Energy \ Consumption = \ Energy \ embedded \ in \ delivered \ hot \ water + \ Energy \ lost \ in \ the \ water \ heating \ process + \ Energy \ lost \ to \ ambient \ from \ the \ water \ during \ storage + \ Energy \ consumed \ by \ the \ operating/control \ systems + \ Energy \ lost \ in \ the \ distribution \ process
\]

How these various energy consumptions/losses are affected by the differing water heater types, designs and sizes is investigated in more depth in Section 3.

2.2 Functional Definition of Water Heaters and Performance Parameters

Obviously, the primary function of a water heater is to deliver “sanitary hot water”. However, in itself this is not a particularly useful definition as it does not give any indication of the speed, quantity or frequency of hot water delivery. Therefore, it is useful to look once again to the European Preparatory Study for a functional definition that may be of more value (edited):

\[
The \ ability \ to \ deliver \ a \ desired \ quantity \ of \ hot \ water, \ at \ a \ desired \ temperature, \ at \ a \ desired \ flow \ rate, \ at \ a \ desired \ frequency \ and \ at \ a \ desired \ quality.
\]

Although still somewhat generalised, such a functional definition allows articulation of a number of useful performance parameters (although noting that the precise terminology and detailed application varies:

• **Quantity of hot water delivered**: An amount of sanitary hot water (in litres) delivered at the point of use. In national test methodologies, typically this quantity of water is the amount that can be delivered within a fixed period of time, in many cases the first hour of operation and often referred to as the **first hour draw capability**; and/or a **series of fixed quantities of water delivered at specified intervals over a fixed period of time**, typically 24 hours.

Somewhat related is the **maximum deliverable hot water capacity**. In the case of storage and heat pump water heaters, this is the maximum quantity of hot water at the required minimum delivery temperature that may be supplied from a storage tank. This capacity is slightly less than\(^7\) the capacity of the storage vessel (**storage capacity**) when the stored water has been heated to within the allowable temperature fluctuation range, or maybe greater than the storage capacity, where the

---

\(^7\) Hot water capacity is typically defined as the volume of hot water that can be delivered within a defined temperature drop or above a fixed minimum temperature. The hot water delivered using this type of measure must be less than the storage capacity if there is no energy input and no external mixing. The ratio of hot water delivery to storage capacity is a useful assessment of the stratification and mixing inside the water heater during hot water delivery.
stored water is held at a higher temperature and mixed with cold water using a thermostatic valve prior to delivery for end use. In the case of instantaneous water heaters, this is sometimes defined as the maximum quantity of hot water that can be delivered over a specific period of time, but more typically as the continuous flow of hot water that can be delivered at the target temperature (see flow rate below).

- Where the water delivered is in a continuous flow at a specific flow rate, and is equal to or less than the maximum deliverable hot water capacity, this is typically referred to as a **draw (or tap)**. In actual usage, the volume and flow rate of a draw are defined by the users, as is the frequency at which individual draws occur. However, many national performance requirements define (or at least require the measurement of) the performance of the storage water heater under various draw conditions which together are often referred to as the **draw (or tapping) cycle**.

- The **flow rate** is the speed at which the hot water is delivered at the point of use (litres/minute);

- **Allowable temperature fluctuations** are the **minimum (and typically maximum) temperature** (in °C) at which hot water is delivered during a draw. In the case of storage and heat pump water heaters, the **target water storage temperature** (i.e. the temperature at which the water is stored within the storage vessel) may be within the allowable temperature fluctuation range, or may be at a higher temperature if mixed with cold water via a thermostatic valve prior to delivery.

- The **wait time** is typically considered to be the time (in seconds) before the minimum allowable temperature is attained by the hot water at the point of delivery. In the case of storage and heat pump water heaters, this is typically related to the period of time for the water to flow from the tank outlet to the point of delivery, plus the time for the distribution system to be heated by the distributed hot water to the point where the delivered water is at the desired delivery temperature. For instantaneous water heaters, again there is the time period required for the water to flow from the tank outlet to the point of delivery, plus the time for the distribution system itself to heat to the point where the delivered water is at the desired delivery temperature, but in addition there is a period of time for the water heater’s internal elements to heat to the point where water being delivered has attained the minimum temperature. However, as this analysis is considering comparisons of differing water

---

8 Storage water heaters typically hold stored water at a temperature that is ready to use, often around 55°C to 65°C (although some electric systems can operate at 75°C). Lower storage temperatures are better for reducing heat loss, but:
- There are potential issues with Legionella bacteria where storage temperatures always remain below 55°C.
- Storage of water at lower temperatures mean significantly less energy is stored and available for the end user.
- For safety reasons, many countries now require hot water at the outlet to be less than 50°C to reduce the risk of scalding. This is normally achieved by the installation of thermostatic mixing valves between the water heater and the relevant outlets.

9 Temperature is also used in reference to the ambient temperature in which the storage vessel is located, the “cold” water inlet temperature, etc. Given the various uses of “temperature” as a term, care must be taken to ensure clarity in which particular “temperature” is being referenced.

10 Or occasionally the quantity of water delivered in litres. In normal use this is often more a function of the hot water distribution system (length and diameter of pipe) rather than a function of the storage water heater.
heater types under similar conditions, the distribution systems can be considered identical and hence, where used, the wait period will be considered to be the time before the minimum allowable temperature is attained at the point of exit from the water heater.

- For storage and heat pump water heaters, following a draw of sufficient size\(^{11}\), a **recovery cycle** is initiated to heat the incoming cold water to the storage temperature. The time taken for the unit to complete the recover cycle (or its capacity to do so) is usually referred to as the **recovery time** (or **recovery capacity**).

3. General Approach to Defining the Total Unit Energy Consumption of Water Heaters and Associated Test Methodologies

As noted in Section 2.1, the energy consumption of a water heater can conceptually be described by:

\[
\text{Total Unit Energy Consumption} = \begin{align*}
&\text{Energy embedded in the delivered hot water} \\
&+ \text{Energy lost in the water heating process} \\
&+ \text{Energy lost to ambient from the water during storage} \\
&+ \text{Energy consumed by the operating/control systems} \\
&+ \text{Energy lost in the distribution process}
\end{align*}
\]

However, in this form the *measurement* of the individual energy consuming elements is challenging. Thus, it is somewhat easier to consider the same descriptive equation written in a slightly different format.

\[
\text{Total Unit Energy Consumption} = \begin{align*}
&\text{Total energy required to heat the water including non-useful energy consumption and losses occurring during this process} \\
&+ \text{Energy lost to ambient from the water during storage} \\
&+ \text{Energy consumed by the operating/control systems} \\
&+ \text{Energy lost in the distribution process}
\end{align*}
\]

Further, while most water heaters have an element of energy consumption associated with control, with the exception of Korea where the standby electrical consumption of gas instantaneous water heaters is measured and declared, few tests explicitly measure these values and/or require their declaration. Thus, for practical reasons it is necessary to ignore consumption by control systems where they are not inherently included as an element of other parts of the water heater energy consumption tests. Fortunately, compared to the overall energy consumption of most water heaters, this energy consumption is relatively small (a 2W control would equate to approximately 45 kWh/year when usage periods are

\(^{11}\) Note, dependent on the size of the draw, the size of the tank and the location of the temperature sensor, very small draw-offs may not trigger the system to enter a recovery cycle. Further, a recovery cycle may be initiated to replenish loss of sufficient heat in the stored water to trigger the thermostat. Where this occurs, the energy consumed in the recovery cycle is typically treated as part of the “standing losses” as described in Section 3.2.2.
taken into account, typically 1-2% of overall energy consumption over a year) so the error arising from its omission is relatively small\textsuperscript{12}.

Similarly, there are potentially substantial losses associated with the hot water distribution system. However, for the comparative analysis to be undertaken as part of this benchmarking, the losses associated with the distribution process may be ignored as they can be assumed the same for all water heater types.

Hence, the Total Unit Energy Consumption descriptive equation becomes:

\begin{equation*}
\text{Total Unit Energy Consumption} = \frac{E_{\text{hotwater}}}{\text{Overall Heating Efficiency}} + \frac{\text{timeperiod} \times \text{standby}}{1000}
\end{equation*}

This equation may be converted to a generalised formula for the delivery of specific hot water demand (assumed to be over a 24 hours period):

\begin{equation*}
TUEC = \frac{E_{\text{hotwater}}}{\text{Overall Heating Efficiency}} + \frac{\text{timeperiod} \times \text{standby}}{1000}
\end{equation*}

Where:

- \( TUEC \) = the daily total unit energy consumed to deliver hot water energy in a specific draw/tap cycle (kWh/day);
- \( E_{\text{hotwater}} \) = the increase in embodied energy in the hot water relative to the cold water input (kWh);
- \( \text{Overall Heating Efficiency} \) = the overall efficiency of the process generating \( E_{\text{hotwater}} \) (percentage);
- \( \text{Sta. ndby} \) = the rate of heat loss from any stored water under stable state conditions (watts);
- \( \text{timeperiod} \) = the time over which the standby heat loss occur (hours);

The following subsections examine each of these energy consuming elements of total (daily) unit energy consumption for each type of hot water heater.

\textsuperscript{12} While energy consumption by the control system is being ignored for all water heating types, it should be noted that these loads can be significant relative to some other regulated energy consuming products. For instantaneous water heaters, the standby and control may total approximately 100 kWh a year which is a relatively small proportion of the total water heater energy consumption, but is still significant in comparison with other regulated energy consuming domestic appliances within many countries. Korea provided the only data set that separately reports electrical standby power for instantaneous gas water heaters. The average of these Korean values is approximately 5W, with the best of 1.1W and the worst 13.7W (a small number had 0W suggesting a gas pilot light or flow activated ignition). Australian field data from the period 2002 to 2008 suggested that many instantaneous systems had an electrical standby power in the range 8W to 14W. However, this has improved considerably, in part due to standby targets set in Japan from where many Australian products are sourced. Most new products are now in the range 2W to 5W.

In addition to this standby power, there may be a relatively high power demand for electronic controls, fans, solenoids etc (typically 40W) when units are operating.
3.1 All Water Heater Types

3.1.1 Increase in Embodied Energy ($E_{\text{hotwater}}$)

For all water heater types this is simply the energy increase in the stored or delivered hot water relative to the cold water supplied, i.e. the increased embodied energy in the delivered hot water. This is equal to the rise in temperature of the quantity of water heated multiplied by the specific heat capacity of water.

3.2 Gas and Electric Storage Water Heaters

3.2.1 Energy Required to Heat the Water (Overall Heating Efficiency)

As both gas and electric systems have fully immersed heating systems or heat exchangers the overall heating efficiency (normally referred to as the recovery efficiency) is not significantly affected by variations in water temperature, ambient conditions or the actual draw cycle.\(^{13}\)

Given the nature of the direct heating provided by electric immersion heaters, in the vast majority of cases a test is not undertaken to establish the overall heating/recovery efficiency of the electrical storage water heaters. A value of 98% is normally applied for the heating/recovery efficiency (accounting for small radiant heat losses at the element flange which occur when the element is operating). Where not otherwise stated, throughout the analysis this 98% overall heating/recovery efficiency value will be assumed for all electrical storage water heaters where a measured value is not provided.

For gas storage water heaters, the overall heating/recovery efficiency in all test methods is a measured value based of the total input energy required to heat an amount of water to the specified storage temperature, relative to the increase embodied energy in the water. Typically this test (often known as a draw-off test) uses a tank of cold water at the start, or a large draw volume from the tank, giving the water heater a large energy task to perform.\(^{14}\) The heating/recovery efficiency being the increase in embodied energy of the water during the test divided by the total energy consumed. However, during the heating phase, some heat losses occur due to temperature difference between the hot water and the ambient air and therefore some standing heat losses are included in the measured recovery efficiency.\(^{15}\)

\(^{13}\) For gas storage water heaters, it is possible to cause “stacking” where repeated small draw-offs over a long period result in an accumulation of high temperature water in the top of the tank from repeated small recovery cycles. This rarely occurs during normal use as convective mixing will usually even out storage temperatures after a short period of no use (where recovery cycles are spread out) and larger recoveries events result in more complete tank mixing during the recovery process.

\(^{14}\) While some normal use will include smaller recovery events, the operating efficiency of storage systems does not change substantially with the size of the recovery event and the temperature of the water. However, performing a large energy task gives a more accurate overall measurement compared a small draw-off where small differences in cut-out temperature and mixing in the tank can appear as significant variations in the measured efficiency.

\(^{15}\) Given that normal draw off events are somewhat less than the whole tank volume, this measurement slightly underestimates heat losses during normal use as noted in the following section. However, measurement of a large recovery event provides the most accurate assessment of recovery efficiency.
3.2.2 Standing heat loss (or standby loss)

Simplistically, standby heat loss occurs for both gas and electric storage water heaters whenever the tank is filled with hot water ready for use but there is no hot water demand. The element or burner is still required to activate on a regular basis to replenish the energy lost from the stored water to the ambient air, but these activations are for short periods with the energy use counted in the steady state heat loss value. Thus, the rate of (standby) heat loss may be defined as the constant energy input required to maintain the temperature of the stored water for immediate use (i.e., at the target storage temperature). Typically this standby loss is measured by a dedicated heat loss test over a long period (48 to 72 hours), and includes a whole number of heating cycles with no hot water draw-off. Corrections are normally made for any difference in the temperature control cut-out value at the start and the end of the test.

However, the tested standby heat loss rate only applies when there is no hot water demand (when the tank is operating in a steady state condition). In this steady state, the recovery cycles for both gas and electric water heaters are very short period to maintain the stored water at the target temperature. In practice, when a large draw occurs, the water temperature of the tank falls resulting in a reduction in the rate of standby losses for the period of recovery (as the differential in temperature between the stored water and the ambient air is lower than when the tank is at target storage temperature). Hence, this has the practical implication that the standby heat loss rate is not constant over the 24 hour period used in the total unit energy consumption calculation. The impact of this variation manifests itself differently for electric and gas storage systems as follows:

- **For gas storage water heaters:** As noted in section 3.2.1, the standby energy losses occurring during the recovery time(s) are included in the energy consumed during the draw-off tests. Therefore, simplistically, the standby period could be assumed as 24 hours less the recovery time.

- **For electric storage water heaters:** In contrast to the gas units, the recovery efficiency for all electric systems is assumed to be 98% (where not measured), and hence does not include “standby” heat losses occurring during the recovery time. Further, for electric water heaters, the recovery time is often significantly longer than for gas units as the input power is normally limited, typically one third of that found in gas water heaters. Therefore, at least some of the time taken for the water heater to recover from the draws should also be included in the calculation of the standby losses.

To take these variations in standby heat loss into account, it is necessary to introduce a factor that accounts for the reduced heat loss that occurs when the burner/element is operating during the recovery cycle. Thus, the Total Unit Energy Consumption calculation can be modified to:

\[
\text{TUEC} = \frac{E_{\text{hotwater}}}{\text{Efficiency}} + \left(24 - t_{\text{rec-loss}}\right) \times \frac{\text{standby}}{1000}
\]
Where:

\[ E_{\text{hotwater}} = \text{Country value for total hot water delivered (i.e. the increase in embodied energy in the hot water relative to the cold water input) per day (where given)} \text{ in kWh/day} \]

Where

- **Country** = Value of variable when tested using national methodology or drawn from national regulation
- **Efficiency** = Declared recovery efficiency of burner or element (in %)
- **sta.ndby** = Declared or calculated heat loss rate (W)
- **tnloss** = An estimate of the effective hours per day when no net heat loss occurs due to reduced tank temperatures following draw-offs

\[ = \left( \frac{E_{\text{hotwater}}}{\text{Efficiency} \times \text{Input}_{\text{rated}}} \right) \times (HL_{\text{factor}}) \]

Where

- **Input\text{\textsubscript{rated}}** = Declared rated power of the element (kWh)

For electric storage water heaters\(^\text{16}\):

\[ HL_{\text{factor}} = \left[ \frac{V_{\text{hotwater}}}{V_{\text{tank}}} \times 0.5 \right] \]

\[ V_{\text{hotwater}} = \text{equivalent volume of hot water for the specified energy demand (l)} \]

\[ = \frac{E_{\text{hotwater}}}{\text{specific heat capacity of water}} \times (T_{\text{HWD}} - T_{\text{CWS}}) \]

Where

- **\( T_{\text{HWD}} \)** = Hot water delivery temperature (°C)
- **\( T_{\text{CWS}} \)** = Cold water supply temperature (°C)
- Specific heat capacity of water = 0.0013367 (kWh/l \(°K\))

\[ V_{\text{tank}} = \text{the volume of the electric storage tank (l)} \]

For gas storage water heaters:

\[ HL_{\text{factor}} = \text{is assumed to be 100\% for all hot water demands as heat loss is included in the measurement of recovery efficiency.} \]

\(^{16}\) In this form the standby losses are assumed to average half the normal heat losses over the period in which recovery is occurring.
3.3 Gas and Electric Instantaneous Water Heaters

3.3.1 Energy Required to Heat the Water

Rather than heating water for storage to supply future demand, instantaneous water heaters heat the water at the time of the demand. Because of the need to rapid heat the inflowing cold supply water to the required delivery temperature as the water passes through the heat exchanger, the gas combustion unit or electrical heating elements must be significantly larger than their storage water counterparts. Further, unlike storage systems, the water flow rate becomes more significant as the higher the flow rate required at the point of delivery, the larger the heat capacity required to heat the water as it passes through the heat exchanger.

In operation, when a draw occurs, the instantaneous water heater senses the flow of water and ignites the burner (the element is switched on in the case of electric systems). If there has been an extended period since the preceding draw, the heat exchanger will have a temperature close to the ambient air temperature, and as such, some energy is required to heat the components of the water heater to the steady state hot water temperature. Depending on the design of the unit, this warming process typically takes 5 to 15 seconds. During this period, cold water will be flowing through the heat exchanger and hence the initial flow (typically 1.5 to 4 litres) of delivered water will not be heated to the desired delivery temperature. This may be considered as wasted energy. The initial heating of the water heater components and the "wasted" water flow can be considered together as the Start-up Energy of the instantaneous water heater.

Once this “start-up” phase is complete and the water heater has reached operational temperature, the water flowing through the heater will be fully heated to the desired temperature.

Hence, when considering the Total Energy required to Heat the Water of instantaneous water heaters, it is useful to separately consider the Start-up Energy and the energy required to heat the continuously flowing delivered hot water once the target delivery temperature is reached.

“Continuous Flow” Water Heating Energy: As noted above, once the “start-up” phase is complete and the water heater is at operational temperature, a constant flow of water will then be fully heated to the delivery temperature unit the draw is terminated.

---

17 For example, a shower flow rate of 7 litres per minute and requiring a temperature rise of 32K (from 10°C to 42°C) requires an input power of 15.2kW before any conversion losses are considered, i.e. approximately 20kW input power for a burner with an efficiency of 75%, and it is not unusual for larger instantaneous gas systems to have a rated input of twice this size). From a supply side perspective, these high input gas systems can create significant pressure drop on the supply system where the supply mains are old or constrained. Similarly, larger electric instantaneous systems can create large, short duration peak loads on the electricity system. Therefore the flow rate and temperature rise for electric systems can be limited (many smaller systems are designed only for a sink or hand basin).

18 Some electronic systems can restrict the initial water flow rate during start-up to minimise the volume of water delivered below the required hot water temperature. This type of flow restriction also reduces the "waste energy".

19 For an application such as a shower, the hot water that is below the required temperature will mostly likely be wasted. However, for a bath or a washing machine, where hot water is accumulated for the end use, it can be argued that the initial hot water that is below temperature is actually not wasted.
Different test procedures approach measurement of this steady state energy consumption in slightly different ways. However, most use a variant where water is supplied at the rated (or regulated) flow rate for a given time or until specified volume of water is delivered. The heating efficiency is then calculated from the embodied energy of the delivered hot water (based on the temperature rise and volume of the hot water delivered) divided by the energy supplied to the water heater. This value is declared for all available datasets.

Hence, under these stable conditions,

\[ \text{“Continuous Flow” Water Heating Energy} = \frac{E_{\text{hot\,water}}}{\text{Efficiency}} \]

Where:

\[ \text{Efficiency} = \text{Heating efficiency}^{20} \text{ (in %)} \]
\[ E_{\text{hot\,water}} = \text{Country value for total hot water delivered per day (where given)} \text{ (kWh/day)} \]

Where

\[ \text{Country} = \text{Value of variable when tested using national methodology or drawn from national regulation} \]

**Start-up Energy:** Where hot water draws are widely spaced, the water heater components will cool between the draws and hence the full start-up energy will apply. However, more closely spaced starts will require lower start-up energy, as the components will have some residual heat energy from the previous draw. Similarly, in some applications not all of the warming water that has failed to reach delivery temperature may be considered as waste\(^{21}\). Hence, the impact is highly influenced by the specific draw-off profiles and individual water heater design\(^{19}\). Therefore, it is necessary to introduce a “start-up” factor to the instantaneous water heater energy consumption calculation, whereby\(^{22}\):

\[ \text{Total Start-up Energy} = [n \times (E_{\text{cold\,start}} \times F_{\text{deltatemp}} \times F_{\text{nonuseful}})] \]

Where:

\[ n = \text{Country value for number of draws per day} \]
\[ E_{\text{cold\,start}} = \text{Declared value for energy required to heat water heater components and water to point where hot water delivered is at least 90\% of required country hot water delivery temperature from a cold start (kWh/draw)} \]

---

\(^{20}\) Instantaneous water heaters have to impart as much of the energy as possible to the water flowing through a relatively small heat exchanger. Because of the very high power input to instantaneous water heaters and the practical limitations on the size of the heat exchanger, the operating efficiency for instantaneous systems is generally somewhat lower than a storage water heater, where a relatively large heat exchanger is fully immersed inside the tank of water to be heated. However, many of the best performing instantaneous gas systems operate well into the condensing range, with operating efficiency values as high as 95\% or more.

\(^{21}\) For example in hot-fill washing machines and dishwashers in the USA, although the warm water may not have reached full delivery temperature, the embodied energy in the “warm water” is still useful for the application.

\(^{22}\) Technically this should be an integrating function which accounts for the component start energy and useful water from each draw in the draw cycle. However, given the limitation of data available for even the total Start-up Energy value for a single draw (or draw cycle), an average value is used in the analysis.
\( F_{\text{deltatemp}} \) = the hot water delivery temperature relative to the ambient temperature and the residual starting temperature of the water heater (i.e. the water heater may not have lost all energy to ambient since the previous start) (%) 

\[ F_{\text{deltatemp}} = \frac{\text{Country } T_{\text{HWD}} - \text{Residual } T_{\text{WH}}}{\text{Country } T_{\text{HWD}} - \text{Country } T_{\text{A}}} \times 100\% \]

Where:

\[ E_{\text{hotwater}} = \text{Country value for total hot water delivered per day (where given)} \]

\( T_{\text{HWD}} \) = Hot Water Delivery Temperature (\( ^{\circ} \text{C} \))

\( T_{\text{WH}} \) = Water Heater Temperature (\( ^{\circ} \text{C} \))

\( T_{\text{A}} \) = Ambient temperature of environment surrounding water heater (\( ^{\circ} \text{C} \))

\( F_{\text{nonuseful}} \) = 100% minus the percentage of the embedded energy in the delivered warm water that is considered useful prior to the point where target \( T_{\text{HWD}} \) is achieved (in %).

Country = Value of variable when tested using national methodology or drawn from national regulation

However, while some test methods identify and separately measure \( E_{\text{coldstart}} \), from the data available it appears that this is not generally the case\(^{23}\). The notable exception is Australian requirements for gas instantaneous water heaters. These Australian water heaters typically require 0.2 - 0.5 MJ (0.056 - 0.139 kWh) per start dependent upon the design, with an average value of approximately 0.1 kWh for gas units and 0.056kWh for electrical units (from a cold start to the point where delivered hot water is close to the required hot water temperature). Therefore, for countries with both gas and electric instantaneous water heaters, (with the exception of Australia where test values are used), the following will be assumed:

\[ E_{\text{coldstart}} = \text{Average } E_{\text{coldstart,Ref}} \times \frac{\text{[(Country } T_{\text{HWD}} - \text{Country } T_{\text{A}})/(\text{Reference } T_{\text{HWD}} - \text{Reference } T_{\text{A}})]}{(\text{kWh})} \]

Where

\[ \text{Average } E_{\text{coldstart,Ref}} = 0.1 \text{kWh for gas instantaneous units or 0.056kWh for electric instantaneous units} \]

\[ \text{Reference } T_{\text{HWD}} - \text{Reference } T_{\text{A}} = 45^{\circ} \text{C} \]

\[ T_{\text{HWD}} = \text{Hot water delivery temperature (}^{\circ} \text{C}) \]

\(^{23}\) The Australian test method (AS4552) has an explicit test procedure for the start-up energy of gas instantaneous water heaters (the energy consumed in order to reach 90% of the selected temperature rise is measured). Other test procedures do not appear to separately quantify this energy parameter, with the effect of indirectly included in test procedures that have a specific draw-off profile. The Korean test method KS B 8116 has a parameter which is called the heating speed, which is the time it takes to reach 90% of the selected temperature rise. However, the energy consumed to this point does not appear to be specified in this standard.
\[ T_A = \text{Ambient temperature of environment surrounding the water heater (°C).} \]

\[ \text{Country} = \text{Value of variable when tested using national methodology or drawn from national regulation} \]

Where specified in national regulations, the typical numbers of draws are generally relatively low, spaced over significant periods of time (1 hour or more), and therefore the heater can be considered to have cooled between draws. However, in some cases, the number of draws per day may be high. Unfortunately little public data has been found on the residual energy retained by the water heaters, nor the period over which this energy dissipates. Therefore, it has been assumed that residual heat energy will be lost to ambient in an exponential fashion, as follows:

\[
\text{Residual } T_{WH} = \left[ e^{\left(\frac{-60}{s\cdot t_c}\right)} \right] \times (\text{Country } T_{HWD} - \text{Country } T_A) + \text{Country } T_A 
\]

Where:

\[ s = \text{The number of draws per hour (draws assumed to occur over a period of 18 hours per day}^{24})\]

\[ t_c = \text{The time constant for the water heater in minutes. Nominally the time for the water heater temperature to cool by 63.2% of the temperature difference between the hot water temperature and the ambient temperature. This value is set to be 15 minutes in the absence of better data.} \]

\[ T_{HWD} = \text{Hot water delivery temperature (°C)} \]

\[ T_A = \text{Ambient temperature of environment surrounding the water heater (°C)} \]

\[ \text{Country} = \text{Value of variable when tested using national methodology or drawn from national regulation} \]

As noted above, during the warming phase, hot water is delivered below the target water temperature. For the majority of applications, this water is simply discharged to waste. However, in a small number of fill applications (e.g., hot fill washing machines and dishwashers), the water is not discharged and the embedded energy may be considered useful as it requires less additional energy to be added at the point of application.

There is no known test method or regulation that considers the water produced during the warming phase to be useful, so there is an argument that such energy should be discounted (i.e., \( F_{\text{nonuseful}} = 100\% \)). However, provisionally \( F_{\text{nonuseful}} \) values have been set as follows:

\[ ^{24} \text{Note 18 hours is used rather than 24 hours as, in most instances, there are likely to be at least some period over a 24 hour period where no draws are made.} \]
\[ F_{\text{nonuseful}} = 100\% \text{ minus the percentage of the embedded energy in the delivered warming water that is considered useful prior to the point where target hot water temperature is achieved.} \]

\[ = 80\% \text{ for the US, 95\% for all other countries} \]

### 3.3.2 Total Unit Energy Consumption of Instantaneous Water Heaters

As noted in section 3.3.1, most instantaneous water heaters have little or no hot water stored ready for use. This means that during periods of no hot water demand, the system does not require any energy to maintain water in a heated state and therefore, for instantaneous water heaters, the “heat loss” element of the Total Unit Energy Consumption equation may be ignored.

Hence, bringing the start-up and normal water heating element together:

\[
\text{TUEC} = \left[ \frac{E_{\text{hotwater}}}{\text{Efficiency}} \right] + \left[ n \times (E_{\text{coldstart}} \times F_{\text{deltatemp}} \times F_{\text{nonuseful}}) \right]
\]

Where:

- \( E_{\text{hotwater}} = \) Country value for total hot water delivered (where given) in kWh/day
- \( \text{Efficiency} = \) Declared heating efficiency of burner or element (%)
- \( n = \) Country value for number of draws per day where given
- \( E_{\text{coldstart}} = \) Average \( E_{\text{coldstart}_{\text{Ref}}} \times \left[ \frac{(\text{Country } T_{\text{HWD}} - \text{Country } T_{\text{A}})}{(\text{Reference } T_{\text{HWD}} - \text{Reference } T_{\text{A}})} \right] \) (kWh)

Where

- Average \( E_{\text{coldstart}_{\text{Ref}}} = 0.1\text{kWh} \) for gas instantaneous units or 0.056kWh for electric instantaneous units
- Reference \( T_{\text{HWD}} - \text{Reference } T_{\text{A}} = 45^\circ\text{C} \)
- \( T_{\text{HWD}} = \) Hot water delivery temperature (\(^\circ\text{C}\))
- \( T_{\text{A}} = \) Ambient temperature of environment surrounding the water heater (\(^\circ\text{C}\))
- \( F_{\text{deltatemp}} = \left[ \frac{(\text{Country } T_{\text{HWD}} - \text{Residual } T_{\text{WH}})}{(\text{Country } T_{\text{HWD}} - \text{Country } T_{\text{A}})} \right] \times 100\% \)

---

25 The useful energy in the USA are assumed to be higher given the greater number of hot fill applications in use, therefore the \( F_{\text{nonuseful}} \) energy is assumed to be a lower value

26 There appears to be a current market trend to introduce “hybrid” instantaneous water heaters where the instantaneous water heater also have significant (20+ litre) storage capacity, although the actual temperature of stored water is unclear from the data available. Further, from this available data, it appears such hybrid systems are mostly available in the USA although this appearance maybe due to the self-selecting nature of the data available.

27 Frost protection is a feature of some instantaneous water heaters that may consume significant energy in some climates and installations. This is commonly fitted in instantaneous water heaters where they are installed in colder climates and where the unit is installed in a location that is not space conditioned (this may be indoors or outdoors). The frost protection stops water freezing inside the water heater, which may damage pipes and the heat exchanger. However, due to the highly variable climate and installation configurations, and having no information on this energy consumption in any of the datasets available, this energy component has not been included for this analysis.
Where:

\[ \text{Residual } T_{\text{WH}} = \left[ e^{-\frac{s}{5tc}} \right] \times (T_{\text{HWD}} - T_A) + T_A \]

Where:

\[
\begin{align*}
    s & = \text{The number of draws per hour (noting draws assumed to occur over 18 hours per day)} \\
    tc & = 15 \text{ minutes} \\
    T_{\text{HWD}} & = \text{Hot water delivery temperature (°C)} \\
    T_A & = \text{Ambient temperature of environment surrounding the water heater (°C)} \\
    F_{\text{nonuseful}} & = 80\% \text{ for the US, 95\% for all other countries} \\
    \text{Country} & = \text{Value of variable when tested using national methodology or drawn from national regulation Heat Pump Water Heaters}
\end{align*}
\]

On a basic level, heat pump water heaters are similar to the gas and electric storage water heater units in that energy is supplied to heat water stored in a tank for consumption at a later time. However, the method of delivery of energy to the water differs.

Conceptually, most heat pump water heaters are a split system air conditioner but where the condenser is immersed inside the hot water storage tank. The heat pump evaporator gathers ambient energy from the surrounding air and concentrates this energy in this storage tank using the vapour compression cycle to pump energy into the storage tank (condenser). However, as heat pumps are able to utilise the benefits of the vapour compression cycle with typical operating efficiencies (i.e., coefficient of performance or COP) in the range 2 W/W to 3 W/W; the heat pump water heaters could typically have an electricity consumption that is 30 to 50% of a standard electric storage water heater, depending on use and location.

The same energy related factors influencing gas and electric units also apply to heat pump water heaters, i.e., ambient air temperature relative to the stored water temperature driving a standing heat loss, and the cold water supply temperature relative to the stored water temperature defining the water heating load \( E_{\text{hotwater}} \). But there is an additional effect from changes in the outdoor ambient air temperature because the efficiency of the vapour compression cycle is partly affected by the temperature difference between the air (energy source) and the stored hot water (energy sink). As this temperature difference increases, the overall operating efficiency of the system decreases. This adds a significant extra

\[ 28 \] Heat pump systems are also available which source ambient energy from ground or water sources, but these systems are currently excluded from this analysis.

\[ 29 \] Operating in very cold ambient temperatures can also reduce the system efficiency, although the impact depends to some extent on the system design, the refrigerant used, and whether resistive boost elements are used. Boost elements are common in North American products. This allows the product to provide adequate hot water in very cold outdoor conditions or during high use periods, but their use substantially decreases the overall system efficiency. Detailed information on the testing, rating and principles used in heat pump water heaters is contained in the 2013 report “Heat Pump Water Heaters: Potential for Harmonization of International Standards” from CLASP (http://clasp.ngo/Resources/Resources/PublicationLibrary/2013/SEAD-Analyzes-Potentials-for-HPWH-International-Test-Standard-Alignment).
complication to the analysis of heat pump performance as, in all tests used in national data available (USA, Australia and Japan), a range of external temperatures are used to formulate a measure of overall unit performance. These temperature ranges vary by country, and in some cases within region in a country. However, in all cases, the specific performance characteristics of the units at the various temperature conditions are not declared. As a result, adjustments to other ambient conditions to enable comparisons between products and/or countries is not directly possible. Hence, it has been necessary to develop an indirect approach to establishing comparable levels of product performance, based on the relative product performance in comparison to an Australian dataset. This approach is detailed in Annex 1 of this document with the resultant approach summarised mathematically below:

\[
TUEC = \frac{E_{\text{hotwater}}}{COP_{\text{marginal}}} + \frac{(24 - t_{\text{no-loss}}) \times (s \tan dby / 1000)}{COP_{\text{marginal}}}
\]

and

\[
COP_{\text{overall}} = \frac{E_{\text{hotwater}}}{TUEC}
\]

(therefore)

\[
COP_{\text{marginal}} = \left[ \frac{E_{\text{hotwater}} + [(24-t_{\text{no-loss}}) \times (\text{standby} / 1000)]}{E_{\text{hotwater}}} \right] \times COP_{\text{overall}}
\]

Where:

\[
E_{\text{hotwater}} = \text{Country value for total hot water delivered per day in kWh/day}
\]

\[
COP_{\text{overall}} = \text{Overall operating efficiency for a given set of environmental and operating conditions (total energy out / total energy in) (W/W)}
\]

\[
COP_{\text{marginal}} = \text{Marginal operating efficiency for change in load at a given set of environmental and operating conditions (marginal energy out / marginal energy in) (W/W)}
\]

\[
\text{standby} = \text{Declared or derived value heat loss rate (W)}
\]

\[
(\text{or when unknown}) 25.6W + 0.1446 W/litre (\text{at } T_{\text{HW,ref}} - T_{\text{A,ref}} = 40K)
\]

\[
T_{\text{HW}} = \text{Hot water storage temperature (°C)}
\]

30 Use of the Overall COP for comparative purposes is rather challenging as the curve/ slope of the COP (or Marginal COP) changes significantly with varying hot water demand. As the hot water demand tends to zero, the fixed element of the heater energy consumption becomes increasing significant and, conversely, as demand increases, this fixed element becomes less important. Hence, a plot of the Overall COP against increasing water demand tends towards an elbow shape (as illustrated in Annex 1, Figure 8 and Figure 9). Thus, providing the system is supplying a reasonable large load, i.e., at a point past the elbow, the Marginal COP is almost constant for given operating conditions and can be adjusted simply by accounting for the variations in load either directly or through variations in water temperature differentials (from the data available this is actually a very slight negative slope, i.e., Marginal COP declines very slightly with increases in load).
\[ T_A = \text{Ambient temperature of environment surrounding storage tank (°C)} \]

\[
t_{\text{loss}} = \left[ \frac{E_{\text{hotwater}}}{\text{HeatingCapacity}} \right] \times (HL_{\text{factor}})
\]

Where

\[ \text{HeatingCapacity} = \text{Compressor Rating} \times COP_{\text{overall}}^{31} \text{ (kW)} \]

\[ HL_{\text{factor}} = \left[ \frac{V_{\text{hotwater}}}{V_{\text{tank}}} \times 0.5 \right] \]

\[ V_{\text{hotwater}} = \text{is the equivalent volume of hot water for the specified energy demand (l)} \]

\[ = E_{\text{hotwater}} / \text{specific heat capacity of water} \times (T_{\text{HWD}} - T_{\text{CWS}}) \]

Where

\[ T_{\text{HWD}} = \text{Hot Water Delivery Temperature (°C)} \]
\[ T_{\text{CWS}} = \text{Cold Water Supply Temperature (°C)} \]
\[ \text{Specific heat capacity of water} = 0.0013367 \text{ (kWh/l °K)} \]
\[ V_{\text{tank}} = \text{the volume of the electric storage tank (l)} \]

Reference = Default reference values assumed for Benchmarking (excluding Standby value which is defined above)

Country = Value of variable when tested using national methodology or drawn from national regulation Heat Pump Water Heaters

4. General Approach Normalising the Performance of Water Heaters for Benchmarking Comparisons

Having established a consistent approach to the calculation of Total Unit Energy Consumption for all water heater types under analysis, normalisation of performance of the various product types for comparison becomes a relatively simple task. This involves the adjustment of energy consumption to account for differences in the relative local test conditions to those set for the reference Benchmarking conditions. These provisional

\(^{31}\text{HeatingCapacity}\): While it is more technically correct to use a \(COP_{\text{marginal}}\) value to calculate the \(\text{HeatingCapacity}\), this is not directly available for any data set in this analysis. Further, the use of \(COP_{\text{marginal}}\) in this part of the calculation leads to an iterative calculation of TUEC during the later normalisation process. While this equation can be solved through iteration, the use of \(COP_{\text{overall}}\) in this equation leads to very small variations in outcomes given other uncertainties inherent in the approach. Further, in the majority of datasets available, the compressor rating is not declared. However, expert opinion suggests that heat pumps have average compressor ratings of approximately 1000W. Hence, these values are used where no compressor rating is declared.
reference conditions are provided in Table 2, and are based on the US test methodology\(^{32}\). However, two variables have been modified from the US standard conditions as follows:

- In addition to the “standard” 12,113 kWh/day water heating load \((E_{\text{hotwater}})\) used in the US, analysis will also be conducted on two other loads, 0 kWh/day representing standby only energy consumption, and 20 kWh/day representing a relatively large domestic demand.

- The number of draws has been changed from 6 per day to a function whereby 3.2 draws of equal size/kWh of hot water delivered is assumed.\(^{33}\)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Benchmarking Reference Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total hot water delivered per day ((E_{\text{hotwater}}))</td>
<td>0 kWh/day (zero load, standby only) 12,113 kWh/day (typical demand based on US) 20 kWh/day (relatively large domestic demand)</td>
</tr>
<tr>
<td>Number of draws/start per day ((n))</td>
<td>3.2 draws/kWh hot water delivered assumed to be of equal size 20°C</td>
</tr>
<tr>
<td>Cold water temperature (T_{\text{CW}})</td>
<td>20°C</td>
</tr>
<tr>
<td>Hot water delivery temperature (T_{\text{HWD}})</td>
<td>60°C</td>
</tr>
<tr>
<td>Ambient temperature - internal (T_A)</td>
<td>20°C</td>
</tr>
<tr>
<td>Average ambient external temperature (T_{AE})</td>
<td>15°C</td>
</tr>
</tbody>
</table>

In addition to the standard values used in the USA test methodologies, a number of further assumptions are made in the normalisation process as shown in Table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Benchmarking Reference Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy required for cold start in instantaneous ((F_{\text{nonuseful}}))</td>
<td>0.1kWh for gas systems, 0.056 kWh for electric systems (where not measured)</td>
</tr>
<tr>
<td>Non-useful energy in instantaneous start-up ((F_{\text{nonuseful}}))</td>
<td>95% (for all datasets including the USA)</td>
</tr>
<tr>
<td>Heat loss rate for heat pump units at (T_{\text{HWD}}-T_A = 40K)</td>
<td>25.6W + 0.1446 W/litre</td>
</tr>
<tr>
<td>Average compressor rating of Heat Pumps</td>
<td>1kWh (where not known)</td>
</tr>
</tbody>
</table>

### 4.1 Normalisation of Gas and Electric Storage Water Heaters

As the efficiency of the heating element or burner is relatively unaffected by variations in the temperature of cold water supply, or the target hot water temperature, the only variable directly affected by changes to operating conditions is the standby heat loss rate due to the changes relative hot water storage temperature and ambient external temperature. As heat loss is assumed to be linear in proportion to hot water and ambient temperature differential,

\(^{32}\) This is in line with the Mapping and Benchmarking Convention where normalisation is undertaken to the conditions in the geographic areas with the highest number of available datasets, hence resulting in the minimum risk of errors during the normalisation process.

\(^{33}\) Note this value is significantly higher than used in many test methodologies. However, it is towards the lower end of available data using intrusive household surveys.
the normalisation of this variable is achieved by simply using the ratio of country and benchmarking reference values for these variables, as follows:

\[
\text{Normalised Standby Power} = \text{Country Mapping heat loss rate} \times \left(\frac{\text{Benchmarking } T_{\text{HWD}} - \text{Benchmarking } T_A}{(\text{Country } T_{\text{HWD}} - \text{Country } T_A)}\right)
\]

Other variables are also affected, for example the volume of hot water delivered (and consequently \(t_{\text{tanoloss}}\) period) is changed by the differing levels of demand and relative cold water input and hot water storage temperatures. However, these affects are automatically revised as part of the calculation process. Hence, to enable direct Benchmarking comparisons with products from other countries, the gas and electric storage water heater Total Daily Unit Energy Consumption maybe defined as:

\[
TUEC = \frac{E_{\text{hotwater}}}{\text{Efficiency}} + \frac{(24 - t_{\text{tanoloss}}) \times \text{standby}}{1000}
\]

Where:

\[
E_{\text{hotwater}} = \text{Benchmarking reference value for total hot water delivered in kWh/day}
\]

\[
\text{Efficiency} = \text{Country Mapping recovery efficiency} (\%)
\]

\[
\text{Standby} = \text{Country Mapping heat loss rate} \times \left(\frac{\text{Benchmarking } T_{\text{HWD}} - \text{Benchmarking } T_A}{(\text{Country } T_{\text{HWD}} - \text{Country } T_A)}\right) \text{ (kWh)}
\]

\[
T_{\text{HWD}} = \text{Hot water storage temperature (°C)}
\]

\[
T_A = \text{Ambient temperature of environment surrounding storage tank (°C)}
\]

\[
\text{Country Mapping} = \text{Declared, regulated or derived Mapping value}
\]

\[
t_{\text{tanoloss}} = \left(\frac{E_{\text{hotwater}}}{\text{Efficiency} \times \text{Input}_{\text{rated}}}\right) \times (HL_{\text{factor}})
\]

Where

For electric storage water heaters:

\[
HL_{\text{factor}} = \left[\frac{V_{\text{hotwater}}}{V_{\text{tank}}} \times 0.5\right]
\]

\[
\text{Input}_{\text{rated}} = \text{Country Mapping rated power of burner or element (\%)}
\]

\[
V_{\text{hotwater}} = \text{is the equivalent volume of hot water for the specified energy demand (at the reference Benchmarking water temperatures) (l)}
\]

\[
V_{\text{tank}} = \text{the volume of the electric storage tank (l)}
\]
For gas storage water heaters:

\[ H_L \text{factor} = 100\% \]

heat loss is included in the measurement of recovery efficiency

### 4.2 Normalisation of Gas and Electric Instantaneous Water Heaters

For instantaneous water heaters, a number of variables are affected by the movement to the comparative reference Benchmarking values. However, in all cases these affects are automatically revised as part of the calculation process. Hence, to enable direct Benchmarking comparisons with products from other countries, the gas and electric instantaneous water heater Total Daily Unit Energy Consumption maybe defined as:

\[
TUEC = \left[ \frac{E_{\text{hotwater}}}{\text{Efficiency}} \right] + [n \times (E_{\text{coldstart}} \times F_{\text{deltatem}} \times F_{\text{nonuseful}})]
\]

Where:

- \( E_{\text{hotwater}} \): Benchmarking reference value for total hot water delivered (where given) in kWh/day
- \( \text{Efficiency} \): Country Mapping heating efficiency of burner or element (%)
- \( n \): Benchmarking reference value for number of draws per day where given
- \( E_{\text{coldstart}} \): Average \( E_{\text{coldstart\_Ref}} \times \left[ \frac{(\text{Benchmarking reference } T_{\text{HWD}} - \text{Benchmarking reference } T_{\text{A}})}{\text{Reference } T_{\text{HWD}} - \text{Reference } T_{\text{A}}} \right] \) (kWh)

Where:

- Average \( E_{\text{coldstart\_Ref}} \): 0.1 kWh for gas instantaneous units
- Average \( E_{\text{coldstart\_Ref}} \): 0.056 kWh for electric instantaneous units

Reference \( T_{\text{HWD}} \) – Reference \( T_{\text{A}} = 45^\circ C \)

- \( T_{\text{HWD}} \): Hot water delivery temperature (°C)
- \( T_{\text{A}} \): Ambient temperature of environment surrounding the water heater (°C)

\[
F_{\text{deltatem}} = \left[ \frac{(\text{Benchmarking reference } T_{\text{HWD}} - \text{Residual } WHT)}{(\text{Benchmarking reference } T_{\text{HWD}} - \text{Benchmarking reference } T_{\text{A}})} \right] \times 100\%
\]

Where:

Residual \( T_{\text{WH}} = \left[ e^{\left( \frac{-60}{60^\circ C} \right)} \right] \times (\text{Benchmarking reference } T_{\text{HWD}} - \text{Benchmarking reference } T_{\text{A}}) + \text{Benchmarking reference } T_A \)
Where:

\[ s = \text{The number of draws per hour (noting draws assumed to occur over 18 hours per day)} \]

\[ tc = 15 \text{ minutes} \]

\[ T_{HWD} = \text{Hot water delivery temperature (°C)} \]

\[ T_A = \text{Ambient temperature of environment surrounding the water heater (°C)} \]

\[ F_{\text{nonuseful}} = \text{Benchmarking reference value (％)} \]

\[ \text{Country Mapping} = \text{Declared, regulated value or derived Mapping value} \]

4.3 Normalisation of Heat Pumps Water Heaters

In line with the other water heater types, the majority of variables are automatically revised to comparative normalised values as part of the calculation process, and standby heat loss rate is adjusted in exactly the same way as for storage water heaters. However, for heat pump water heaters there is one major difference to other units with normalisation of the \( \text{COP}_{\text{marginal}} \) value being required to account for the changes in operating conditions. Analysis of the Australian data used detailed in Annex 1 suggests, for the higher heat loads associated with the post elbow stabilisation of \( \text{COP}_{\text{marginal}} \) values (refer to section 0 for details), the slope of the \( \text{COP}_{\text{marginal}} \) value is given by:

\[ \text{COP}_{\text{slope}} = 0.03 \text{ (per K increase in } T_{\text{HWD}} - T_{\text{EA}}) ^{34} \]

Where

\[ T_{\text{HWD}} = \text{Hot water storage temperature} \]

\[ T_{\text{EA}} = \text{External ambient air temperature} \]

Thus, the comparative heat pump water heater Total Daily Unit Energy Consumption maybe defined as:

\[ \text{TUEC} = \frac{E_{\text{hotwater}}}{\text{COP}_{\text{marginal ref}}} + \frac{(24 - t_{\text{no-loss}}) \times (St.andby/1000)}{\text{COP}_{\text{marginal ref}}} \]

Where

\[ E_{\text{hotwater}} = \text{Benchmarking reference value for hot water delivered per day (kWh/day)} \]

\[ \text{COP}_{\text{marginal ref}} = \text{COP}_{\text{marginal map}} + [(\text{Benchmarking reference } T_{\text{HWD}} - \text{Benchmarking reference } T_{\text{EA}}) - (\text{Country Mapping } T_{\text{HWD}} - \text{Country Mapping } T_{\text{EA}})] \times \text{COP}_{\text{slope}} \]

\[ ^{34} \text{ Note this is contrary to expectation as it would be expected this slope would be a positive value, with COP increasing with increasing load. However, the empirically derived value is used.} \]
Where

\[ \text{COP}_{\text{marginal}\_\text{map}} = \text{Country Mapping COP}_{\text{marginal}} \ (\text{W/W}) \]

\[ T_{\text{HWD}} = \text{Hot water storage temperature} \ (^\circ\text{C}) \]

\[ T_{\text{EA}} = \text{External (location of evaporator) ambient air temperature} \ (^\circ\text{C}) \]

**Standby** = Country Mapping heat loss rate \( x \ [\text{Benchmarking reference} \ T_{\text{HWD}} – \text{Benchmarking reference} \ T_{\text{A}}]/ \left( \text{Country Mapping} \ T_{\text{HWD}} – \text{Country} \ T_{\text{A}} \right) \) (kWh)

Where

\[ T_{\text{A}} = \text{Ambient temperature of environment surrounding storage tank} \ (^\circ\text{C}) \]

\[ T_{\text{HWD}} = \text{Hot water storage temperature} \]

\[ t_{\text{no\_loss}} = \left \{ \frac{E_{\text{hotwater}}}{\text{Heating Capacity}} \right \} \times (HL_{\text{factor}}) \]

Where

\[ \text{Heating Capacity} = \text{Compressor Rating} \times \text{COP}_{\text{overall}}^{35} \ (\text{kW}) \]

\[ HL_{\text{factor}} = \left \{ \frac{V_{\text{hotwater}}}{V_{\text{tank}}} \right \} \times 0.5 \]

where:

\[ V_{\text{hotwater}} = \text{is the equivalent volume of hot water for the specified energy demand at Benchmarking reference conditions} \ (\text{l}) \]

\[ = E_{\text{hotwater}} / \text{specific heat capacity of water} \times (\text{Benchmarking reference} \ T_{\text{HWD}} – \text{reference} \ T_{\text{CWS}}) \]

Where

\[ T_{\text{HWD}} = \text{Hot Water Delivery Temperature} \ (^\circ\text{C}) \]

\[ T_{\text{CWS}} = \text{Cold Water Supply Temperature} \ (^\circ\text{C}) \]

\[ \text{Specific heat capacity of water} = 0.0013367 \ (\text{kWh/l}°\text{K}) \]

\[ V_{\text{tank}} = \text{the volume of the electric storage tank} \ (\text{l}) \]

\[ T_{\text{A}} = \text{Ambient temperature of environment surrounding storage tank} \]

**Country Mapping** = Declared, regulated value or derived Mapping value

---

35 Heating Capacity: While it is more technically correct to use a \text{COP}_{\text{marginal}} value to calculate the Heating Capacity, this is not directly available for any data set. Further, the use of \text{COP}_{\text{marginal}} in this part of the calculation leads to an iterative calculation of TUEC during the later normalisation process. While this equation can be solved through iteration, the use of \text{COP}_{\text{overall}} in this equation leads to very small variations in outcomes given other uncertainties inherent in the approach. Further, in the majority of datasets, the compressor rating is not declared. However, expert opinion suggests heat pumps have average compressor ratings of approximately 1000W. Hence, these values are used where no compressor rating is declared.
5. Presentation of Data

5.1 Mapping Document

Mapping Documents present nationally declared performance data\textsuperscript{36} for all available dataset from an individual country and will include the following material:

- Graphic 1: Current and historic regulatory requirements.

- Graphic 2: Product performance data as declared in kWh/day (with load profile added where necessary) for the most recent year available overlaid with regulatory requirement.

- Graphic 3: Product performance data as declared in kWh/day (with load profile added where necessary) for the most recent year available based on standard local conditions.

- Graphic 4: Product performance data as declared in kWh/day (with load profile added where necessary) for the most recent year available based on standard local conditions.

- Graphic 5 (group): Historic data on average performance of storage and heat pump waters heaters, average volumes, and performance by volume category.

- Graphic 6 (group): Historic data on average performance of instantaneous water heaters, average flow rates, and performance by flow ranges.

- Policy and cultural information.

- Data on individual data set manipulation to meet Mapping requirements.

5.2 Benchmarking

Benchmarking provides the comparison of product performance \textit{between} countries. Provisionally, benchmarking analysis will include, at a \textit{minimum}, analysis of the following (including breakdown by volume/flow rates):

**Gas Storage Water Heaters**

- Recovery Efficiency

**Gas and Electric Storage and Heat Pump Water Heaters**

- Storage Volume

- Standby Heat Loss

- Total Daily Unit Energy Consumption

\textsuperscript{36} In some cases it is necessary to assume some values to enable graphics to be presented. Where this is the case, details are included in the individual country mapping.
Instantaneous Water Heaters

- Flow rates
- Burner Efficiency

All Water Heater Types

- Approach to, and stringency of, regulation
- Total Daily Unit Energy Consumption
Annex 1: Approaches to calculating energy consumption for heat pump systems

Essentially two different heat pump water heater data sets are available for developing comparative analyses\textsuperscript{37}. The first data set is from the US: these appear in the US DOE listing (172 models), the CEC also has a separate heat pump listing (107 modes) and ENERGY STAR includes heat pumps (127 models). There are many common models in these data sets, but there are some unique models as well. The US has a common test method for all water heater types, so heat pumps are tested under CFR430 Subpart B Appendix E under the same conditions that are used for electric and gas water heaters.

The second data set is from Australia. This includes 182 models that are included in the Small Scale Renewable Energy Scheme (SRES) operated by the Australian government. This is a voluntary scheme where products are tested and rated in 5 different climate zones. The energy savings relative to a specified water heater are calculated. Each MWh of energy savings over a 10 year period is awarded a Renewable Energy Certificate (or REC) at the time of installation. RECs are a tradable certificate under the national renewable energy target. See http://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target/How-the-scheme-works/Small-scale-Renewable-Energy-Scheme

Products in Australia are tested according to AS/NZS4234. This standard effectively specifies a range of measurements that need to be undertaken and then specifies a simulation approach using a TRNSYS\textsuperscript{38} model to estimate the energy consumed in a range of climates under a range of hot water usage conditions. AS/NZS4234 defines the following parameters:

- Hourly weather data for 5 climate zones, for a typical year (TMY data). The Zone 1 is tropical and Zone 5 is a relatively cold climate for Australia.
- Hot water draw-off profiles (time of day)
- Scaling of hot water demand by season (typically summer is around half of the demand in winter)
- Different levels of daily hot water demand (from very small to very large)
- Changes in cold water inlet temperature by month
- Number of hot water events by hot water demand (for instantaneous gas systems).

The standard also allows simulation of different hot water loads and different climates, and facilitates the comparison of a wide range of solar thermal systems\textsuperscript{39}.

\textsuperscript{37} A third data set from Japan may become available as the analysis progresses.
\textsuperscript{38} Transient System Simulation Tool. Refer to http://www.trnsys.com/
\textsuperscript{39} Solar thermal systems also earn RECs based on their energy savings under the SRES. Solar thermal systems are not included in this analysis.
Public listings of heat pump models show only their brand, model, approval date and the RECS earned in each of the 5 specified climate zones under AS/NZS4234. From a range of data such as supplier websites, the tank size for each model has also been estimated. The difference in RECS earned from the best to the worst varies from as little as 4 RECS for Zone 1 to as much as 9 RECS in Zone 4 (colder, cloudy climate). Most heat pump systems are classified as “medium” sized under AS/NZS4234, so with data about the reference water heater energy consumption in each climate zone, it is possible to work out the COP\textsubscript{overall} of the system from the RECs allocated. This requires careful analysis of data contained in the relevant standard, and the detailed calculations are not included in this report. The relationship between RECs and overall systems COP is shown in Figure 5.

Figure 4: Australian heat pump water heaters – RECs earned by climate zone\textsuperscript{40}

![Diagram](image)

Figure 5: RECs earned under SRES and overall system COP for a medium system only, Australia

\textsuperscript{40} Note that the use of lines in this graphic suggests that climate zone is a continuous variable. This is not the case, but lines are used to link the change in performance of individual models over the different climate zones.
When RECs are converted to overall COP using this approach, all 170 models (that have a valid REC value for each of the 5 climate zones) can be plotted for comparative purposes, as shown in Figure 6.

**Figure 6: Australian heat pump water heaters – estimated annual COP by climate zone**

![Graph showing estimated annual COP by climate zone](image)

The spread of overall COP in Figure 6 is somewhat wider than the RECs earned (illustrated in Figure 4). This is because the relationship between RECs earned and COP is non-linear, as illustrated in Figure 5.

In order to allow some comparative data across climate zones to be assessed, the following parameters have been calculated for each of the 5 climate zones in AS/NZS4234. Firstly, analysis of climate data files shows that seasonal variation in air temperatures.

**Figure 7: Seasonal monthly average ambient temperatures for the AS/NZS4234 climate zones.**

![Graph showing seasonal monthly average ambient temperatures](image)
Table 4: Key parameters temperature for the AS/NZS4234 climate zones.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Hot water (°C)</th>
<th>Winter</th>
<th>Summer</th>
<th>Annual average ambient (°C)</th>
<th>ΔT for heat loss</th>
<th>Cold water (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1 Rockhampton</td>
<td>60</td>
<td>Mild (16°C)</td>
<td>Hot (27°C)</td>
<td>21.8</td>
<td>38.2</td>
<td>22.2</td>
</tr>
<tr>
<td>Z2 Alice Springs</td>
<td>60</td>
<td>Cool (10°C)</td>
<td>Hot (28°C)</td>
<td>20.3</td>
<td>39.7</td>
<td>17.6</td>
</tr>
<tr>
<td>Z3 Sydney</td>
<td>60</td>
<td>Cool (11°C)</td>
<td>Warm (23°C)</td>
<td>17.9</td>
<td>42.1</td>
<td>15.6</td>
</tr>
<tr>
<td>Z4 Melbourne</td>
<td>60</td>
<td>Cold (9°C)</td>
<td>Mild (20°C)</td>
<td>15.0</td>
<td>45.0</td>
<td>12.8</td>
</tr>
<tr>
<td>Z5 Canberra</td>
<td>60</td>
<td>Cold (5°C)</td>
<td>Mild (19°C)</td>
<td>12.1</td>
<td>47.9</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Notes: Cold water temperature is weighted by seasonal hot water demand. Ambient temperatures are monthly averages (24 hour per day). Temperature difference will influence both the tank heat loss and the overall system COP. Melbourne is typically cool and cloudy while Canberra is typically cold and sunny in winter.

The relative performance of a specific heat pump water heater in four climate zones (Zones 1 to 4) is illustrated in Figure 8. The most important point to note is that, for a specific water heater, the energy input is mostly dictated by the hot water demand, with climate having a relatively small overall impact. However, there are significant differences in performance between different water heaters as shown in Figure 6.

Figure 8: Relative energy input for a heat pump water heater in four AS/NZS4234 climate zones, Australia.

This data can be split into overall COP values (total energy out divided by total energy input) or margin COP (incremental energy out divided by incremental energy input).
Figure 9: Overall and marginal COP for a heat pump water heater in four AS/NZS4234 climate zones, Australia.

Importantly, the marginal COP tends to stay relatively constant with large changes in hot water demand (as expected), while the overall COP changes substantially with hot water load. This is because the fixed heat losses become an increasing large part of the overall system efficiency as hot water demand becomes small. Figure 8 shows that the change in energy input for a heat pump system is relatively linear with a change in hot water demand, but there is a fixed energy component at zero hot water demand. This is essentially the standing heat loss from the tank. The energy for standing heat losses for heat pump systems appears to be very small because the actual heat loss energy is divided by the marginal COP of the refrigeration system.

Heat pump systems are essentially a standard hot water storage tank with some different fittings and penetrations to accommodate the refrigeration system and heat exchanger (condenser) inside the tank. It would be a reasonable assumption that the overall heat loss from the tank for a heat pump system would be comparable to that for a similar sized electric storage system. Currently none of the data sets available have data on standing heat loss measurement for each model. However, heat loss data for Australian and Canadian electric storage water heaters is readily available as shown in Figure 10.
The regression for heat loss values for the Australian data has been used to estimate the heat loss for different sized heat pump water heaters (noting that this value is corrected to a hot water ambient temperature difference of 40 K). The function is 25.6 W + 0.1446 W/litre. This raw heat loss value can then be corrected to provide an estimated total heat loss under the various climate zones in AS/NZS4234 (see Table 4).

The next step is to assume that the overall COP of a heat pump system is given by the following equation:

\[
\text{Overall COP} = \frac{\text{Energy}_{\text{hotwater}}}{\text{Energy}_{\text{input}}}
\]

However, the energy input can be represented as two separate factors as follows:

\[
\text{Energy}_{\text{input}} = \frac{\text{Energy}_{\text{hotwater}}}{\text{COP}_{\text{marginal}}} + \frac{\text{Heatloss}}{\text{COP}_{\text{marginal}}}
\]

It is then possible to estimate the marginal COP for a given heat pump system if the overall COP is known for a specific hot water load and the heat loss for the tank can be estimated (from the regression in Figure 10). This approach assumes that the marginal COP is constant with load, which does not always appear to be exactly the case, but it is a fair approximation for this analysis. Using this approach it is then possible to calculate an overall system COP across a range of hot water demands by rearranging the previous equations:

\[
\text{COP}_{\text{marginal}} = \left[\frac{\text{Energy}_{\text{hotwater}} + \text{Heatloss}}{\text{Energy}_{\text{hotwater}}}ight] \times \text{COP}_{\text{overall}}
\]
This equation is only valid for a non-zero hot water energy demand. Care is required to ensure that consistent units are used. For all Australian models, it is possible to calculate an overall trend in the marginal COP by climate zone.

Figure 11: Changes in marginal COP of models according to climate zone under AS/NZS4234, Australia.

Figure 11 shows that there is a general trend of reducing marginal COP in colder climates, which is to be expected. There appears to be a non-linear climatic effect for Zone 2 (Alice Springs in Central Australia has hot dry summers and cold winters). The impact on COP is larger than expected for this climate zone, especially for higher efficiency models, but this may be due to the use of boost elements in some models. It is possible to plot the temperature difference between hot water and the ambient air (this is effectively the temperature difference that drives both the heat loss from the tank and the overall efficiency of the heat pump refrigeration system). While the slope is slightly different for each performance band shown in Figure 11, the overall average value is a reduction of 0.03 COP for each degree K increase in the temperature difference between the hot water and the air temperature. This assumes a constant annual hot water temperature (condenser) and a variation in the air temperature (evaporator). This level of COP change is fairly representative of different types of compressor performance maps, so this provides some level of confidence in the results. The overall trend is necessarily complicated by the seasonal nature of the hot water demand and the very different climate files used in AS/NZS4234 for each climate zone. But it is a useful overall relationship that can be used to compare data between the US and Australia at a high level and to adjust the overall performance to different reference conditions so that heat pump systems can be compared with conventional water heaters. This relationship may not be perfectly valid at an individual model level, so it needs to be treated as an indicative adjustment factor.

Climate Zone 1 under AS/NZS4234 has an average annual hot water to ambient air temperature difference of 38.2 K and the US test method has hot water to ambient air temperature difference of 37.5 K. Therefore, Zone 1 for Australia should provide a
reasonable direct comparison with US data for US DOE, CEC and ENERGY STAR data sets.

For the purposes of adjusting heat pump performance under different reference conditions for this report, the COP slope of -0.03 per degree K increase in hot water to air temperature difference has been applied when calculating overall energy consumption under reference conditions.