Preparatory Study on

Eco-design of Water Heaters

Task 4 Report (FINAL)
Technical Analysis

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1 INTRODUCTION

1.1 Scope

The scope of Task 4 is Product System Analysis, describing technical features of Water Heaters and the system they form part of. Much of the information presented here will be used in the subsequent Task 5 (Definition of Base-case) and Task 6 (Design options - including modelling of water heater system).

1.2 Approach
Annex VII.4 of the Ecodesign Directive concerns the interaction of the EuP with the installation/system in which it operates and implies that the possible effects of the EuP being part of a larger system and/or installation are identified and evaluated.

This task includes therefore a functional analysis of the system to which the water heater belongs. Given that the technical modelling of the water heater itself will be subject of Task 6, the main system considerations in a strict sense will relate to the inputs (cold water temperature, piping lay-out, ambient conditions of the water heater), the system and its infrastructural aspects (chimneys, pipe lengths) and the outputs (as influenced by mixing valves, water saving shower heads, sewage systems with waste heat recovery, etc.).

The hot water comfort is an important performance characteristic and manufacturers are making design concessions in energy efficiency to reach certain comfort levels. E.g. the capacity (expressed as litres of water of ‘x’ degree Celsius per minute) determines the applicability (kitchen only, bath, bath + kitchen, etc.) and the comfort level. The convention is that policy measures rate energy efficiency, which means not only energy consumption but energy consumption per performance. The inclusion of performance characteristic should therefore be mandatory.

In principle, the consumer habits (tapping patterns) will determine the load (see Task 3). Task 4 will have to deliver the inputs for the technical model of the water heating system. These may cover energy losses in the appliance itself as well as heat losses in the piping (waiting time, water and/or heat wasted) and aspects related to the chimney (options for replacement / renovation). So the system also defines the overall net heat load (energy input).

As regards the position of the water heater in the house, e.g. close to the most frequently used outlet in the kitchen, this can have a significant influence on energy use and emissions. It is often the reason for consumers (waiting time) to purchase or not to purchase a second water heater just for the kitchen outlet (or other outlets further away from the primary water heater). Also in that context the EPBD standards will have something to say on these issues, that may well be of influence on Ecodesign measures for the water heater.

A negative effect (from the energy point of view) of long waiting times may be the use of so-called ‘comfort-switch’ found on many types of water heaters. This switch, that the consumer may or may not use, maintains the temperature of the appliance (heat exchanger, etc.) in order to reduce waiting times. And it may lead to an extra energy use of 50-100 m³/year.
Finally, it should not be forgotten that—in a wider sense—a large hot water tank represents an energy buffer to fill the gap between periods of energy supply (e.g. solar) and demand. And this demand may not only be for water heating, but also products are known where the thermal storage capacity of the tank contributes to the space heating system in the house. A study of the state-of-the-art in that area may also contribute in making a legislation that doesn’t discourage this type of innovation (if the solutions are valid from cost and environmental point of view).

The figure below indicates the elements considered.

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**1.3 Structure of report**

The report is divided into four sections.

**Section One - Chapter 2-5**

Describes the basic principles of heat generation in gas- and oil-fired water heaters and the major components involved in this. It includes a description of a basic mass and energy balance, emissions, types of burners and heat exchangers.

Emissions of electric water heaters are considered in subsequent tasks and modelling (see also the EcoReport results in Task 5).

**Section Two - Chapter 6-13**

Describes the main water heating products (following Task 2 market categories) and certain system aspects related to inputs (energy, water), outputs (hot water, energy losses) and the system environment (technosphere = infrastructure, constraints).

**Section Three - Chapter 14-15**

Describes two 'alternative' water heater(s) (systems) using renewable energy in the form of solar heat and ambient heat.

**Section Four - Chapter 16-19**

Describes aspects of the water heater system that are not really water heaters but can be relevant for the modelling of a Water Heater system, Task 5 (Definition of Base-case) and Task 6 (Design options). Described are systems to prevent Legionellosis, to prevent scalding and to recover heat from warm waste shower water.

**Annex A**

The Annex includes a section on vacuum insulation panels (VIPs) which is relevant for Task 6 (Design Options).
SECTION ONE - HEAT GENERATION
2 BASIC ENERGY AND MASS BALANCE

(This Chapter primarily applies to the heating operation of gas-/oil-fired boilers but the physics also apply to gas- and oil-fired water heaters. Note that wherever 'boilers' are mentioned in the text, this could be read as 'gas-/oil-fired water heaters' as well).

2.1 Introduction

In most energy policy studies on water heating appliances, the combustion process and the detailed energy- and mass balance of gas- and oil-fired water heaters are not explained. The scientific background is not very easy and in general it is not needed for readers in the policy field to go beyond the level of the gas- and oil-fired water heaters being a 'black-box' with a certain efficiency level according to a product test standard.

Yet, this approach has also led to a number of notions, myths and half-truths regarding efficiency and emissions in practice which can only be understood (and partially denied) when looking inside the black-box. For this reason we have made an attempt, as part of the system analysis, to provide some guidance for policy makers regarding the basics of the energy and mass balance with a boiler. We have taken methane, the main component of natural gas but also a fuel with a relatively simple structure, as an illustration of a fuel, although references to other fuels also occur. The mass- and energy values should be seen as illustrations, although also here we add results from research that is based on tests with actual water heaters.

Starting off with the global chemical reaction which mainly produces carbon dioxide and water vapour (paragraph 2.2), this chapter looks at the:

- Mass balance (paragraph 2.3), including:
  - Stoichiometric volume balance (the 'ideal' theoretical volume balance);
  - Air factor/lambda (excess air);
  - Humidity of combustion air;
  - Influence of CO, NOx, CxHy, SO2 and dust (PM) emissions (fraction of incomplete combustion);
  - Conversion of volume to mass balance.

Subsequently, we are discussing the energy balance of the heat generator, looking at the energy parameters of the combustion process, such as the flame temperature, combustion heat, latent heat of condensation, heat loss through excess combustion air and finally the energy loss concerned with incomplete combustion (paragraph 2.4). The approach is basic (secondary school) and pragmatic (focused on heat generators found in combi-boilers etc.), largely by-passing the many tools that exist at academic research level to numerically model and predict the combustion process.

Paragraphs 2.5 to 2.8 deal with the energy losses in the main heat generator components: the burner (paragraph 2.5), the primary heat exchanger (paragraph 2.6), secondary and tertiary 'condensing' heat exchangers (paragraph 2.7) and finally the energy penalties involved in storage components (paragraph 2.8). The most extensive report is on the efficiency of the primary heat exchanger in paragraph 2.6, where we will be looking at flue gas losses, generator losses and start-stop ('cycling') losses both in on-mode and off-mode.
Paragraph 2.9 gives a brief estimate of losses in auxiliary components such as pump, fan and controls (to be expanded in other parts of the study). Paragraph 2.10 presents an overview of energy flows through a heat generator during the heating process.

### 2.2 Global chemical reaction

In gas- and oil fired water heaters (and combi-boilers) the combustion is the stationary, rapid, medium to high-temperature oxidisation of a hydrocarbon with the oxygen in air. With gas- and oil-fired (combi-)boilers the combustion products of an ideal combustion process are always carbon dioxide (CO₂) and water vapour (H₂O). For instance, in the case of methane (CH₄), which is the main component of natural gas in Europe, the global chemical reaction can be summarized as:

\[ CH₄ + 2O₂ \rightarrow CO₂ + 2H₂O \]

The equation for e.g. heating oil is different but follows the same principle, with the hydrocarbon being more complex also the equations become more complex. Still, the outcome is again (mainly) CO₂ and H₂O.

### 2.3 Mass balance

#### 2.3.1 Stoichiometric volume balance

Using Avogadro’s Law and assuming that air is made of ca. 1 part of oxygen (O₂) and 4 parts of nitrogen (N₂) we can derive the theoretical volume of air that is needed for the reaction and the volumes of carbon dioxide and water vapour produced.

\[ 1 \text{ vol.} CH₄ + 2 \text{ vol.} O₂ + 8 \text{ vol.} N₂ \rightarrow 1 \text{ vol.} CO₂ + 2 \text{ vol.} H₂O + 8 \text{ vol.} N₂ \]

9.1% CH₄ + 90.9% air \( \rightarrow \) 9.1% CO₂ + 18.2% H₂O + 72.7% N₂

The above is known as stoichiometric combustion, i.e. assuming a perfect mixing of fuel and air at perfectly controlled pressure and temperature.

#### 2.3.2 Air factor/ lambda

In reality, the stoichiometric volume balance is theoretical. Manufacturers build in a safety factor, called air factor or lambda (\( \lambda \)), to make sure that there is always enough air/oxygen to guarantee a complete combustion. The air factor is actually intended to compensate for:

- inhomogeneous mixing of air/fuel (oil-fired ‘blue burner’ 5%, good ‘yellow burner’ 10%, less good burners 15%). In general the particle size of the fuel (with atomising

---

1 ‘Stationary’ as opposed to non-stationary combustion in motors, ‘Rapid’ as opposed to slow, low-temperature oxidation processes in biochemistry (rotting, etc.) and medicine (glucose in muscle power, etc.). ‘High-temperature’ is also referred to as ‘flame-combustion’ (>1500 K). ‘Medium-temperature’ is referred to as ‘flameless’ combustion (700-1500 K). Medium-low temperature combustion (400-1000 K reaction temperature) is e.g. ‘catalytic combustion’. The chemical oxidation in a fuel cell is classified as ‘catalytic combustion of hydrogen’.

2 Note that the quantity of water vapour depends on the fuel with its specific combustion reaction. For instance solid fuel combustion does not produce water.

3 “Equal quantities of gases and vapours at the same pressure and temperature have the same number of molecules, i.e. \( N_a = 6.022137 \cdot 10^{23} \) per mol.”
oil burners this is the size of the droplets) is a very important factor for the air factor 4.

- fluctuations in atmospheric pressure of the incoming air (around 6%);
- fluctuations in relative humidity of air (from 0,1 to 3,5%);
- fluctuations in fuel supply (between 5 and 10%, depending on maintenance, varying gas grid pressure, etc.);
- fluctuations in fuel quality/combustion value (e.g. in the Netherlands the Wobbe-index 5 can vary between 40,4 and 44,6 MJ/m³, requiring 8% extra air. In the EU these fluctuations are expected to increase with Russian gas imports);
- wind influence on chimney (up to 20% for atmospheric burners, 5% for premix burners with deflectors/draught limiters).

For instance, an air factor of 1,2 means that 20% extra air is added with respect of the stoichiometrically needed volume. Another way of describing the air factor is the oxygen content (O₂) of the flue gases. For instance an air factor \( \lambda=1,2 \) for natural gas equals around 3% O₂ in the flue gases.

So, with an air factor of \( \lambda=1,2 \) there is some 16,6% (0,2/1,2) extra air that goes into the process and the mass balance of the combustion of methane changes as follows:

\[
83,4\% \cdot (9,1\% \text{CH}_4 + 90,9\% \text{air}) + 16,6\% \text{air} \rightarrow \\
83,4\% \cdot (9,1\% \text{CO}_2 + 18,2\% \text{H}_2\text{O} + 72,7\% \text{N}_2) + 16,6\% \text{air}
\]

or, substituting 'air' with 20% oxygen and 80% nitrogen in the result:

\[
7,59\% \text{CH}_4 + 92,41\% \text{air} \rightarrow 7,59\% \text{CO}_2 + 15,18\% \text{H}_2\text{O} + 73,93\% \text{N}_2 + 3,3\% \text{O}_2
\]

So the 16,6% air in the flue gases equals an oxygen content of ca. 3,3% (20% oxygen in air). Normalizing this volume balance to the fuel input, we can say that for the combustion of 1 m³ of methane 12,17 m³ of air is used, resulting in 13,17 m³ of flue gases with the composition as mentioned above: 1 m³ carbon dioxide, 2 m³ water, 9,73 m³ nitrogen and 0,43 m³ oxygen.

To convert these results from methane to natural gas, we must consider that natural gas contains only some 95% of methane and therefore the oxygen content of the flue gases drops to close to 3% O₂.

### 2.3.3 Humidity of combustion air

Not only the combustion reaction produces water vapour as one of the outputs, but also a —relatively small— fraction of the water vapour in the flue gases comes from the humidity of the combustion air input. The EN standard prescribes a relative humidity (RH) of 70% and ambient temperature (20°C) for the air input. The look-up table 2-1 shows that the maximum water content (100% RH) of air at 20°C is 2,4 volume%. At 70% RH this is 1,68 vol.%. At 12,17 m³ of air that goes into the combustion, this results in 0,2 m³ of water vapour or around 0,16 litres of water that needs to be added.

<table>
<thead>
<tr>
<th>Temp.</th>
<th>-20</th>
<th>-10</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>%water</td>
<td>0,16</td>
<td>0,31</td>
<td>0,61</td>
<td>1,2</td>
<td>2,4</td>
<td>4,2</td>
<td>7,4</td>
<td>12,3</td>
<td>19,1</td>
<td>31,2</td>
<td>47,4</td>
<td>70,1</td>
<td>100</td>
</tr>
<tr>
<td>psat</td>
<td>155</td>
<td>308</td>
<td>611</td>
<td>1227</td>
<td>2367</td>
<td>4242</td>
<td>7375</td>
<td>12334</td>
<td>19919</td>
<td>31161</td>
<td>47359</td>
<td>70108</td>
<td>101325</td>
</tr>
</tbody>
</table>

4 In fact, the preparation of the fuel, especially the heating oil, is a discipline in itself whereby the viscosity and other physical properties of the oil are a limiting factor in themselves in decreasing droplet size when atomising the oil before combustion. Also the preheating of the oil up to 60°C is a factor. For more details see www.iwo.de

5 Natural gas is a mixture of gases. In the EU it is mostly it is methane, but there are also smaller fractions of propane, butane, etc.. The Wobbe-index is a measure of the combustion value of the mixture.
2.3.4 Influence of emissions

The balance is also incomplete because it does not contain the emissions of unburned fuel (CH₄) and pollutants: carbon monoxide (CO₂), nitrogen oxides (NOₓ) and total organic compounds (TOC).

Pfeiffer 2001 of the University of Stuttgart has done extensive tests of emissions of oil- and gas-fired (combi-)boilers, looking not only at the stationary (combi-)boiler operation—as is done in EN standard tests— but especially during cycling (D. Taktbetrieb). For the latter he used the (combi-)boiler loads as described in DIN 4702-8 and calculated the emissions for around 14000 start/stop cycles per year. This description of 'Taktbetrieb' applies to space heating operation, but also applies to water heaters when producing hot water at lower flow rates (e.g. below the minimum flow rate) of course with a different number of cycles.

As the tables below show, the emissions during cycling were much higher—on an annual basis—than during stationary operation, despite the fact that mainly above-standard pre-mix burners were tested. In terms of environmental impact—which will be elaborated at a later stage—these are significant numbers.

In terms of actual mass, the numbers are small. In our calculation of the methane combustion we will use a value of 100-120 mg/MJ: CO 24, CH₄ 26, NOₓ 25-30 mg/MJ + TOC 23 mg C/MJ (say 30 mg hydrocarbons). At 39.8 MJ/m³ for methane this comes down to a total 4-5 gram. This mass does not come on top of the emissions, but replaces a minute part of the other combustion products.

### Table 2-2. Emissions gas fired boilers (source Pfeiffer, 1)

<table>
<thead>
<tr>
<th>Gas fired appliance</th>
<th>CO [mg/MJ]</th>
<th>CH₄ [mg/MJ]</th>
<th>TOC [mgC/MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steady state</td>
<td>Cycling*</td>
<td>Steady state</td>
</tr>
<tr>
<td>Boiler with premix burner</td>
<td>H1-G1</td>
<td>2.2 32</td>
<td>0.42 19</td>
</tr>
<tr>
<td>Premix condensing, flat burner</td>
<td>G2</td>
<td>0.43 21</td>
<td>0.49 36</td>
</tr>
<tr>
<td>Premix condensing, flat burner</td>
<td>G3</td>
<td>3.9 10</td>
<td>2.6 33</td>
</tr>
<tr>
<td>Instantaneous boiler, flat burner</td>
<td>G7</td>
<td>14 16</td>
<td>0.89 16</td>
</tr>
<tr>
<td>Instantaneous boiler, flat burner</td>
<td>G8</td>
<td>6.5 15</td>
<td>0.45 23</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>5 19</strong></td>
<td><strong>0.97 25.4</strong></td>
<td><strong>1.05 21.6</strong></td>
</tr>
</tbody>
</table>

*Cycling operation based on relative boiler load acc. DIN 4702 / Part 8

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6 Dipl.-Ing. Frank Pfeiffer; Bestimmung des Emissionen klimarelevanter und flüchtiger organischer Spurengase aus Öl- und Gasfeuerungen kleiner Leistung; Fakultät Energietechnik der Universität Stuttgart; 2001

7 For a regular boiler this is fairly close to the German average (other sources like Farago mention 16000 cycles). For instantaneous combi-boilers, with on average 50-60 draw-offs per day, the amount of cycles can triple (e.g. 40000 per year).
Table 2-3. Emissions oil fired boilers (source: Pfeiffer, 1)

<table>
<thead>
<tr>
<th>Oil fired boiler</th>
<th>Ref.</th>
<th>CO [mg/MJ]</th>
<th>CH₄ [mg/MJ]</th>
<th>TOC [mgC/MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steady state</td>
<td>Cycling*</td>
<td>Steady state</td>
</tr>
<tr>
<td>Boiler 1 with jet burner 1</td>
<td>H1-B1</td>
<td>&lt; 0,33</td>
<td>2,3</td>
<td>&lt; 0,40</td>
</tr>
<tr>
<td>Boiler 1 with jet burner 2</td>
<td>H1-B2</td>
<td>&lt; 0,35</td>
<td>1,9</td>
<td>&lt; 0,43</td>
</tr>
<tr>
<td>Boiler 1 with jet burner 3</td>
<td>H1-B3</td>
<td>&lt; 0,34</td>
<td>3,7</td>
<td>&lt; 0,41</td>
</tr>
<tr>
<td>Boiler 1 with jet burner 4</td>
<td>H1-B4</td>
<td>0,34</td>
<td>2,4</td>
<td>&lt; 0,41</td>
</tr>
<tr>
<td>Boiler 1 with jet burner 4</td>
<td>H1-B5</td>
<td>1,2</td>
<td>43</td>
<td>&lt; 0,42</td>
</tr>
<tr>
<td>Boiler 2 with jet burner 5</td>
<td>H2-B5</td>
<td>4,0</td>
<td>7,3</td>
<td>&lt; 0,40</td>
</tr>
<tr>
<td>Boiler 3 with jet burner 6</td>
<td>H3-B6</td>
<td>5,4</td>
<td>7,8</td>
<td>&lt; 0,41</td>
</tr>
<tr>
<td>Boiler 3 with jet burner 7</td>
<td>H3-B7</td>
<td>4,3</td>
<td>3,3</td>
<td>&lt; 0,38</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2</td>
<td>9</td>
<td>0,4</td>
</tr>
</tbody>
</table>

* Cycling operation based on relative boiler load acc. DIN 4702 / Part 8

Please note, that the values measured by Pfeiffer on commercially available boilers in 2001 were already much lower than the ones mentioned in the EN standards.

Having said that, the above tables also do not take into account a number of emissions in practice. In the paragraph 1.4.5 on energy contained in lost fuel this will be discussed in more detail. In short:

- The measurements were done in a laboratory and did not take into account real-life fluctuations in combustion air (pressure, temperature, enthalpy), fuel supply and quality, flue gas duct pressure (wind), etc. In analogy with the air factor we add an extra 25% for all emissions
- The measurements were done with DIN 4702-8 conditions (39% load \( \Rightarrow 14000 \) cycles/year) for regular boilers. Correcting for the lower load factor in practice (9%) and the fact that most boilers deliver hot sanitary water (40 000 cycles) this gives a factor 2,8.
- Gas leakage at (combi)boiler level was not taken into account. Following prEN 13836:2005 this adds another 0,1% of methane emissions.

All in all, we estimate that around 10-11 g of fuel is lost per m³ of methane input, or around 1,5 weight %.

### 2.3.5 Converting volume into mass balance

To convert the volume balance into a mass balance, we can use the atomic mass of the elements involved (O=16, N=14, C=12, H=2), also knowing that the mol-volume at ambient conditions is ca. 22 litres\(^8\). For instance, 22 litres of CH₄ would then weigh 20 (=atomic weight) grams or 0,909 g/l. = 0,909 kg/m³. Table 2-3 gives the conversion from volume to mass balance of the methane combustion.

---

\(^8\) From Avogadro: In the reference situation of 0 °C and 1013 mbar the mol-volume is 22,41 litres and the kilomol volume around 22,41 m³. At ambient conditions the mol-volume is ca. 22 litres. Furthermore, it is assumed that the ultimate flue gas temperature and pressure equals the temperature and pressure conditions of the fuel and air inputs.
Table 2-4. Conversion from volume to mass balance of 1 m³ methane combustion

<table>
<thead>
<tr>
<th>Input</th>
<th>volume</th>
<th>ato.mass</th>
<th>calc. density</th>
<th>mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>1,00</td>
<td>16</td>
<td>0,73</td>
<td>0,73</td>
</tr>
<tr>
<td>air 12,17 m³</td>
<td></td>
<td></td>
<td>(1,31)</td>
<td></td>
</tr>
<tr>
<td>- O₂, 21%</td>
<td>2,56</td>
<td>32</td>
<td>1,45</td>
<td>3,72</td>
</tr>
<tr>
<td>- N₂, 79%</td>
<td>9,61</td>
<td>28</td>
<td>1,27</td>
<td>12,24</td>
</tr>
<tr>
<td>H₂O in air*</td>
<td>0,20</td>
<td>18</td>
<td>0,82</td>
<td>0,16</td>
</tr>
<tr>
<td>Total</td>
<td>13,37</td>
<td></td>
<td></td>
<td>16,84</td>
</tr>
</tbody>
</table>

| Output                        |        |          |               |       |
| CO₂                           | 1,00   | 44       | 2,00          | 2,00  |
| H₂O combustion*               | 2,00   | 18       | 0,82          | 1,64  |
| H₂O in air*                   | 0,20   | 18       | 0,82          | 0,16  |
| N₂                            | 9,74   | 28       | 1,27          | 12,39 |
| O₂                            | 0,44   | 32       | 1,45          | 0,63  |
| CO/CH₄/TOx/NOₓ                |        |          | 0,01          |       |
| Total                         | 13,37  |          | 16,84         |       |

*= water vapour, not liquid —> density < 1

As mentioned, this mass balance is for 100% methane and not exact for natural gas.

2.4 Energy balance combustion

2.4.1 Introduction

During the combustion the chemical energy of the fuel reacting with the oxygen is transformed into three types of heating energy:

- Radiation energy of the flame/burner
- Convection energy of the combustion products (temperature of the flue gases) and
- Latent heat of the water vapour (the heat released when the vapour condenses into liquid)

Furthermore, the combustion process has to carry the ballast of the excess air, due to the air factor, and at the most parts of the emissions—the ones containing carbon⁹—count as lost fuel.

All in all, the general mass balance for the inputs in the methane combustion in our previous example looks like this:

⁹ For oil this also includes sulphur.
The total heat released by the combustion process is the combustion heat, also known as combustion energy or enthalpy, symbol ΔH. The unit is MJ (megajoules, 10^6) or kWh of heating energy, often expressed as the Gross Calorific Value GCV or the upper heating value uhv (D. Brennwert) of the fuel. The equation for methane (at 273 K, 1013 mbar) is:

\[ \Delta H_{\text{methane}} = Q_{\text{flame}} + Q_{\text{latent}} + Q_{\text{excess air}} + Q_{\text{fuel-loss}} = 39,8 \text{ MJ/m}^3 \]

If we leave out the latent heat contained in the water vapour, i.e. the heat released when the water condenses, we find a value known as the Net Calorific Value, the ‘dry gas’ combustion value or the lower heating value ulv (D. Heizwert). In the global combustion reaction the ΔH has a negative connotation in the right-hand side of the equation, indicating that the reaction is exothermic (produces heat, as opposed to an endothermic reaction which consumes heat).

The table below gives the enthalpies for some fuels:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gross calorific value Hs [MJ/m³]</th>
<th>Net calorific value Hi [MJ/m³]</th>
<th>Hs/Hi</th>
<th>ΔHs – Hi [MJ/m³]</th>
<th>Volume of condensate (theoretical) [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Town gas</td>
<td>19,73</td>
<td>17,53</td>
<td>1,13</td>
<td>2,20</td>
<td>0,89</td>
</tr>
<tr>
<td>Natural gas LL</td>
<td>35,21</td>
<td>31,79</td>
<td>1,11</td>
<td>3,42</td>
<td>1,53</td>
</tr>
<tr>
<td>Natural gas E</td>
<td>41,25</td>
<td>37,26</td>
<td>1,11</td>
<td>3,99</td>
<td>1,63</td>
</tr>
<tr>
<td>Propane</td>
<td>100,87</td>
<td>92,88</td>
<td>1,09</td>
<td>7,99</td>
<td>3,37</td>
</tr>
<tr>
<td>Fuel oil (fig.relate to 1 ltr)</td>
<td>38,45</td>
<td>36,29</td>
<td>1,06</td>
<td>2,16</td>
<td>0,88</td>
</tr>
</tbody>
</table>

\[^{10}\] Note that for gases the temperature is an important parameter, e.g. at 25°C the GCV of methane is 36,3 MJ/m³.
In the rest of the paragraph we will explore to see what is the share of $Q_{\text{flame}}$, $Q_{\text{latent}}$, $Q_{\text{air}}$, $Q_{\text{fuel-loss}}$ and what temperature levels are associated with these heat energy outputs.

Note that the energy balance of the combustion process is only the first step of the total energy balance, but we will deal with the heat transfer in the burner, heat exchanger(s), etc. in the following paragraphs.

### 2.4.2 Combustion heat $Q_{\text{rad}} + Q_{\text{conv}}$

**Flames**

Starting point of a high-temperature combustion is the flame. In a ‘normal’ flame, e.g. of a candle, there are three zones:

- **A fuel-preparation zone** where the gaseous fuel is heated up to a temperature—the ‘ignition temperature’—starting the dissociation process (breaking up the hydrocarbon molecules in smaller fractions) leading up the combustion chain reactions. When the gas reaches the ignition temperature (around 300-500°C) it attracts the minimum amount of air necessary from its surroundings (e.g. air factor of 0,5) and starts combustion. In the case of a liquid fuel (oil) this process is preceded by a step where the oil is atomised into droplets, which are then vaporized.

- **A ‘rich combustion’ zone** where the flame is above the ignition temperature and minimal air factor but has too little oxygen/air with respect of the stoichiometric combustion ($0,5 < \text{air factor} < 1$). In this zone very small soot particles are formed and burnt, emitting a yellow light. Rich combustion is also usually accompanied by higher emissions of CO.

- **A ‘lean combustion’ zone** (air factor $> 1$) with a blue flame colour. At a certain temperature the flame temperature attracts so much air/oxygen that the air factor becomes too high (e.g. higher than 2) and the flame has reached its visible boundaries. Lean combustion is also usually accompanied by higher emissions of NOx.

Such a flame is known as a ‘diffusion flame’, where the air input to the combustion process is dependent on the flame-temperature and the mixing of air/fuel takes place concurrently with the combustion. This flame is typical of candles, matches, etc. but also to a large extend of partial pre-mix burners (a.k.a. ‘atmospheric burners’, type B), in simple combi-boilers and many gas-fired instantaneous water heaters, where the primary air flow is regulated (pre-mixed) through a venturi with the fuel flow and secondary air completes the job during combustion. In contrast, in pre-mix burners the air input to the combustion process is independent of the flame-temperature and a combustion fan gives an exact dosage of air to the mixture. The fuel/air is fully pre-mixed before entering the burner and produces a flame with a very different temperature distribution profile (see picture) but also a more favourable emission profile.

**Figure 2.2.**
Temperature distribution in a diffusion-flame (left) and a pre-mix flame (right) of a Bunsen-burner [Farago, 2004]

**Flame temperature**

Calculating the temperature of the flame is not an easy task. A first theoretical value called the *calorific flame temperature* can be calculated from the enthalpy of the
fuel under the simple assumption that all energy is converted into hot combustion products. The temperature increase (above ambient) of the combustion products $\Delta T$ comes from the enthalpy of the fuel $\Delta H$, the mass of the combustion products $m$ and their specific heat $c_p$:

$$\Delta H_{\text{methane}} = m \cdot c_p \cdot \Delta T$$

The reaction temperature $T_{\text{reaction}}$ is then defined as $T_{\text{reaction}} = T_a + \Delta T$, where $T_a$ is the start temperature of the combustion products (usually ambient, i.e. 20°C).

The enthalpy of the fuel is known (see paragraph 2.4.1: 39, 8 MJ/m³), the mass of the combustion products is taken from the mass balance in the previous paragraph 2.3 and the specific heat is a look-up materials property (see table below).

### Table 2-6. Density and specific heat of some substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>formula</th>
<th>density $\rho$ (kg/m³)</th>
<th>specific heat $c_p$ (kJ/(kgK))</th>
</tr>
</thead>
<tbody>
<tr>
<td>water (H₂O)</td>
<td>1</td>
<td>4,18</td>
<td></td>
</tr>
<tr>
<td>air (79% N₂, 21% O₂)</td>
<td>1,29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>oxygen (O₂)</td>
<td>1,43</td>
<td>1,4</td>
<td></td>
</tr>
<tr>
<td>nitrogen (N₂)</td>
<td>1,25</td>
<td>1,25</td>
<td></td>
</tr>
<tr>
<td>methane (CH₄)</td>
<td>0,72</td>
<td>2,21</td>
<td></td>
</tr>
<tr>
<td>propane (C₃H₆)</td>
<td>2,02</td>
<td>1,53</td>
<td></td>
</tr>
<tr>
<td>(iso-) butane (C₄H₈)</td>
<td>2,67</td>
<td>1,61</td>
<td></td>
</tr>
<tr>
<td>carbon monoxide (CO)</td>
<td>1,25</td>
<td>1,05</td>
<td></td>
</tr>
<tr>
<td>carbon dioxide (CO₂)</td>
<td>1,98</td>
<td>0,82</td>
<td></td>
</tr>
<tr>
<td>sulphur dioxide (SO₂)</td>
<td>2,93</td>
<td>0,64</td>
<td></td>
</tr>
<tr>
<td>acetylene (C₂H₂)</td>
<td>1,18</td>
<td>1,67</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2-7. Calculating calorific flame temperature for 1 m³ methane at air factor = 1.2

<table>
<thead>
<tr>
<th>Output</th>
<th>mass $m$ kg</th>
<th>spec. heat $c_p$ (kJ/(kgK))</th>
<th>mass*spec. Heat $H_s$ (kJ)</th>
<th>Temperature increase at fuel enthalpy in K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>2,00</td>
<td>0,82</td>
<td>1,64</td>
<td></td>
</tr>
<tr>
<td>H₂O combustion*</td>
<td>1,64</td>
<td>4,18</td>
<td>6,84</td>
<td></td>
</tr>
<tr>
<td>H₂O in air*</td>
<td>0,16</td>
<td>4,18</td>
<td>0,68</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>12,39</td>
<td>1,04</td>
<td>12,89</td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>0,63</td>
<td>1,40</td>
<td>0,89</td>
<td></td>
</tr>
<tr>
<td>CO/CH4/TOx/Nox pm</td>
<td>pm</td>
<td>pm</td>
<td>pm</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>16,84</td>
<td>22,94</td>
<td>1735</td>
<td></td>
</tr>
</tbody>
</table>

This calorific flame temperature is in practice never reached, because of dissociation effects (incomplete combustion), especially at air factor=1 (stoichiometric combustion). Another value that takes into account the dissociation process is the adiabatic flame temperature. Especially for gases the adiabatic flame temperature is fairly close to the calorific flame temperature at practical air factor values. The adiabatic flame temperature is independent of the size of the flame and the dimensions of the combustion chamber and the power output of the burner.
2.4.3 Latent condensation heat $Q_{\text{latent}}$

As mentioned in the introduction, the latent condensation heat is the heat contained in the water vapour from combustion when condensing. Numerically it is the difference between Gross and Net Calorific Values (GCV and NCV) of the fuel.

In the case of our example of methane combustion around 1.8 kg of water vapour is produced per m³ of methane (see mass balance: 1.64 kg from combustion, 0.16 kg from humidity in the incoming air at air factor 1.2). The specific latent condensation heat of water is 2.27 MJ/kg, so per m³ of methane 4.09 MJ of condensation heat is available. Compared to the GCV of methane of 39.8 MJ/m³, this is 10.2%. Compared to the NCV it adds an extra 11%. As natural gas consists mostly of methane, the same numbers apply roughly to natural gas.

For other fuels, the stoichiometric combustion equations are different and therefore the water vapour and the maximum amount of latent heat is different. For oil-fired (combi)boilers this is around 6% and for propane it is 8-9%.

In theory, the latent condensation heat can be fully recovered, if somewhere in the water heater before the flue gases go up the chimney or flue duct the flue gases are cooled to ambient temperature (<20°C).

In a non-condensing heater the flue gases —after flowing through the heat exchanger— leave the water heater at a temperature of somewhere between 200 and 300°C still in the form of water vapour. Somewhere in the atmosphere the water vapour will condense against the cooler outside air, but in principle all the latent heat of the condensation process is lost for the water heater.

To establish where this point of total-loss is, we can use the EN standards that define that if the flue gas temperature stays above 160°C there is no risk of condensing. This is a technical level, taking into account extreme circumstances.

The EN standards speak of a dedicated condensing boiler (same applies to water heaters) at flue gas temperatures of lower than 80°C. ‘Condensing’ relates to the fact that the water vapour in the flue gas comes into contact with a cold surface of the heat exchanger and than turns into liquid, releasing the latent heat of condensation. This condensation of air with a 100% relative humidity (RH) takes place at a temperature level that is known as the ‘dew point’. This dew point also depends on other parameters, but in general one can say that condensing starts at a surface temperature of the heat exchanger (=boiler temperature) of just below 57°C for gas and
46°C for oil. At a boiler return temperature of 30°C some 70-80% of all latent heat is recovered. At 35°C boiler return temperature around 50% is recovered.

The graph below gives the water vapour dew point at (near) stoichiometric combustion. At higher lambda’s, the dew point will even be lower. Natural gas starts condensing at 57°C and oil at 47°C. At lambda’s of 1,25 the CO₂ content decreases and with it also the dew point to approximately 53°C for gas and 44°C for oil.

**Figure 2-4.** Dew point water vapor for gas- and oil flue gasses

**Figure 2-5.** Steady state efficiency and amount of condensate related to return temperature of gas fired boiler.

**2.4.4 Heat loss in excess combustion air \( Q_{\text{exair}} \)**

To complete the picture of the energy balance of the combustion process we include the excess air that is the consequence of the air factor.

Obviously, the extra air into the combustion process comes at a penalty. For instance, in a 10 kW gas-fired heat generator with an air factor \( \lambda = 1.3 \) this means that an extra 3 m³ is heated from ambient temperature to e.g. 1000°C combustion temperature. With
respect of the stoichiometric process this initially costs some 9% extra\textsuperscript{11}, of which of course in the heat exchanger a large part is recuperated. But still, 'losses' in the order of magnitude of 2% remain. A rule-of-thumb is that every 1% \text{O}_2 extra results in 0.5\% efficiency loss. This is of course only true when measuring flue gas exit temperatures, but it gives an order of magnitude for the partitioning.

All in all, as described in the EN standards, an air factor of 1.2-1.25 is standard practice for higher power outputs of gas- or oil fired premix burners. For lower outputs (<10 kW) or not-premix burners it can be 1.3 or higher (up to 1.5-1.6).

\textbf{2.4.5 Fuel loss }Q_{fuel-loss}\textbf{ }

The research by Pfeiffer, as mentioned in the mass balance, allows us to quantify the energy lost because of incomplete combustion. In principle, we can say that all carbon (C) that ends up in the emissions comes from the methane and quantifies the fuel lost. This leaves out the NO\textsubscript{x} emissions, but we are still left with 24 mg/MJ CO (ato. mass 28), 16 mg/MJ CH\textsubscript{4} (ato. mass 16) and 12 mg carbon/MJ TOC (carbon ato. mass is 12). Calculating these numbers on a mass basis this means that the equivalent of ca. 3 g of methane is lost per m\textsuperscript{3} methane of carbon-containing emissions. At a density of 0.73 kg/ m\textsuperscript{3} this means that some 0.4\% of fuel energy is lost.

Obviously, this was measured in a laboratory, which means that the fluctuations in combustion air (atmospheric pressure, temperature, etc.), fuel (pressure, wobbe-index), etc. were not taken into account. Following an analogy with the air factor, we can assume that in real-life the emissions are some 25\% higher, i.e. 0.5\%.

Furthermore, it has to be considered that Pfeiffer did his measurements at DIN 4702-8 conditions, which means on average a heat load of 39\% (space heating). In reality, as a

\textsuperscript{11} Air at 1 kJ/K.m\textsuperscript{3} for a 3 m\textsuperscript{3} with a temperature increase of 1000 K \(\rightarrow\) 3000 kJ = 3 MJ= 0.9 kWh/h = 0.9 kW \(\rightarrow\) 9\% of 10 kW.
study of Wolfenbüttel pointed out, the heat load in the heating season is more in the area of 9%. At a modulation ratio of 30% this still means that the average number of on-off cycles in reality is higher than the 14000 cycles assumed by Pfeiffer. No statistics on average cycling behaviour are available, but anecdotal evidence suggests numbers in the range of 16000 - 20000 cycles. This then leads to an annual loss of 0.65% for a regular heating boiler at say 18000 cycles/year.

Pfeiffer tested regular boilers, i.e. without the sanitary hot water function. In case of an instantaneous combi-boiler that switches at every draw-off, the number of cycles is much higher, e.g. in the range of 40-50 000 cycles. The corresponding fuel-loss in that situation is almost triple, say 1.5%. According to the BED Market study 2006 by BRG Consult around 90% of the gas-fired boilers are operated with a sanitary hot water function, either as a combi or with an external cylinder, and the vast majority of these are instantaneous.

Pfeiffer did not take into account gas leakage. No statistics on the subject are known, but the prEN 13836 specifies that a boiler satisfies the requirements if the leakage is of the gas valve is less than 0.06 dm³/h (upstream gas pressure 150 mbar) and 0.14 dm³/h for the whole boiler. One might argue that these are maximum values; on the other hand these are laboratory measurements where no inaccuracies in installation practice should occur. Per annum (8760 hours) this equals some 0.5 to 1 m³ per annum. At an average consumption of 1000 m³/year (example for space heating) this adds another 0.1% energy loss.

All in all, we estimate for average EU combi-boilers, a figure of 1.5% of energy in fuel losses (combi boiler, largely instantaneous, 40000 cycles/a).

In summary, the heat balance for the combustion process of a gas-fired boiler methane with air factor 1.2 looks like this. Please note that the latent heat includes not only the water vapour from combustion, but also the potential condensation heat of the water from the incoming air.

**Figure 2-7.**
Energy balance of combustion process methane

![Diagram of energy balance of combustion process methane](image-url)
2.5 Energy balance burner

Many authors do not distinguish between the energy balance of combustion and the burner, because in terms of actual measurements it is very difficult to measure the flame temperature without some sort of burner. Yet, in explaining the heat balance of the whole process it is functional, because in the interaction between the flame and the burner construction there is much more going on than meets the eye.

For starters, when you measure the temperature of the combustion products at the burner, the so-called combustion temperature (D. Verbrennungstemperatur), there always seem to be 100-200°C missing compared to the adiabatic flame temperature. The graph below gives an illustration of the above in an actual combustion chamber and burner operated at 10, 20 and 35 kW.

If we assume the power output of the burner as a measure of the flame size, the picture shows that at a smaller flame size (10 kW on a 35 kW burner), the combustion temperature, i.e. the temperature of the combustion products, is significantly lower than at nominal power/ flame size. Between 35 and 10 kW power the temperature difference is some 350 K. Assuming this is proportional to the temperature difference with the ambient (ca. 1700°C) this means that at 10 kW (30% load) the share of radiation energy has increased by 20% with respect of 35 kW (100% load). On average, every 10% decrease in load has yielded around 2.5-3% more radiation share. It may seem contra-intuitive that a smaller flame gives off relatively more radiation heat, but the keyword here is ‘relative’, because in fact the size of the burner bed and the combustion chamber do not change. In other words, one could also say that with a larger burner plate (compared to its nominal capacity in W/cm²) the radiation share increases (and the convection share, i.e. the temperature of the combustion gases, decreases) 12.

Of course there is a limit to decreasing the burner load, which has to do with air and flame velocity, flame stability, laminar and turbulent flame fronts, etc.. We will not go into that complex matter 13, but stick to the more profane thermodynamics.

---

12 Electro-magnetic waves in the visible light spectrum, but also in the UV (ultra-violet) and IR (infra-red) spectrum. In fact, the radiation in the UV-spectrum of the flame is the basis for optical flame-ignition control sensors.

13 Dietzinger 2006 gives a good overview of the latest insights in flame modelling techniques and numerical tools available.
On the next page there are several illustrations of research concerning temperature levels inside a burner, showing that there is more to be considered.

The university of Eindhoven has done experiments of a ‘flame in a box’, which amongst others give a detailed insight into the temperature fields of a pre-mix burner. The picture shows temperatures near a nozzle of a conventional nozzle, showing that the flame temperature at the burner nozzle is around 600-800 K (300-500°C). From this we assume that the temperature of a conventional burner plate, made of perforated thin refractory steel plate (surface around 240 cm² for 24 kW burner → weight ca. 80-100 g.) is on average around 400°C. The flame temperature itself rises to around the adiabatic flame temperature of 2000 K (1730°C).

Dietzinger [2006] at the university of Stuttgart has done several experiments on the propagation of the temperatures of a methane/air mixture in a porous ceramic burner, showing the propagation of the temperature at the Z-axis of the burner. In the area between the hole plate (‘flame barrier’) and burner bed the temperature rises to the ignition temperature (550-600°C) and then —at the bottom of the 20 mm thick burner bed— jumps to a temperature of around 1600°C. Inside the burner bed of this ‘flameless burner’ the temperature then decreases to around 1100-1200°C before leaving the burner. Already at a height of 5 mm above the burner bed the temperatures have dropped to below 1000°C and laboratory measurements of the flue gases may lead to believe that this is a low temperature burner, whereas in reality the high temperatures are there, but inside the burner. In fact, in this case the average temperature of the burner bed is 1300°C.

The results from Eindhoven and Stuttgart represent two extremes in pre-mix burners. Somewhere in between we find ceramic surface burners, where in fact the flames ‘sit’ halfway inside the burner nozzles. There, the burner plate reaches temperatures up to 1000°C and the temperature of the combustion products is around 1100°C.

The table below gives an estimate of temperature levels between burner bed, flame and combustion products.

**Table 2-8. Estimated temperatures and loads for pre-mix burners (at air factor 1.2, no preheat air)**

<table>
<thead>
<tr>
<th>Pre-mix burner type</th>
<th>Burner plate temperature [°C]</th>
<th>Combustion products temperature at 10 mm [°C]</th>
<th>Radiation share [%]</th>
<th>Max. load [W/cm²]</th>
<th>Surface for 20 kW [cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel plate</td>
<td>400</td>
<td>1300</td>
<td>5%</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Radiation burner (ceramic/steel)</td>
<td>900</td>
<td>1100</td>
<td>20-25%</td>
<td>300-400</td>
<td>70</td>
</tr>
<tr>
<td>Porous ceramic burner</td>
<td>1200</td>
<td>900-1000</td>
<td>25-30%</td>
<td>300 (&gt;1000, experimental)</td>
<td>70</td>
</tr>
</tbody>
</table>

The table also gives typical burner loads in terms of watts burner output per surface area, showing that the radiation burners can be much more compact for the same output power.
Figure 2-9.
Numerical result of a 2D temperature field of a flame in a box
[source: TU Eindhoven, faculty Mechanical Engineering, 2006]

Figure 2-10.
Ceramic porous burner:
Propagation of temperature with a methane/air mix. The graphs show an experiment whereby the temperature is measured in the flame barrier and throughout the thickness of a 20 mm porous ceramic burner. Note that the initial temperature after ignition is close to the calculated adiabatic flame temperature and that the combustion products —while giving off their heat to the burner— cool down to a level <1000°C already 10 mm after the burner surface. [Dietzinger, 2006]

Figure 2-11.
Thermographic pictures of boilers. Left: Steel boiler with jet burner (www.trm.at) Middle: Cast iron boiler (www.trm.at). Right Detail of boiler, burner in red, flue duct in orange.
The wall thickness of a refractory steel plate burner plate is ca. 0.5-0.7 mm, weighing 80-100 g for 20 kW power (+burner frame of 200-250 g). Ceramic radiation burners are 3.5 mm thick and the commercially available porous ceramic burners are now 15 mm thick. For non-stationary (cycling) operation this is relevant, because burner plates cool down in a matter of 3-10 seconds, which means that at every start-up this mass has to be heated.

### Calculation example

Assume 350 grams of steel burner+frame with a specific heat of 0.46 kJ/(kgK), to be heated to an average temperature difference \(dT=300\) K. This is 48.3 kJ per cycle. At 40 000 cycles per year, this represents 1932 MJ or 536 kWh. On a total energy consumption of e.g. a combi boiler of 14 000 kWh/year this is around 4%. This energy is not lost. Most of the cooling down will take place during the after-purge at the end of each cycle, where the combustion air will then give off its heat to the heat exchanger and boiler water. If this is then ‘useful energy’ and not lead to a room temperature overshoot will depend on whether the boiler controls anticipate this extra energy input.

During stationary operation, i.e. during the combustion process, there is also heat transfer.

Steel plate burners are usually fixed to the heat exchanger boiler, which means that a large part of the heat is transferred usefully to the combustion chamber and heat exchanger on the side of the burner. Another part of the heat will be transferred to the space between heat exchanger body and the surrounding casing, where in modern boilers it is picked up to a large extend by the combustion air fan, i.e. it preheats the incoming combustion air. For another part, it will be a major contributor to the heating of the casing, i.e. radiation losses of the boiler to the ambient. The picture at the bottom of the previous page shows thermo-graphic pictures of the boiler casing, showing clearly the ‘hot spot’ of the burner location.

The following equations summarize the above:

\[
Q_b = Q_{b\_conv} + Q_{b\_rad} + Q_{b\_cond}
\]

with

\[
Q_{b\_conv} = Q_{b\_conv\_combust} + Q_{b\_conv\_case}
\]

\[
Q_{b\_rad} = Q_{b\_rad\_combust} + Q_{b\_rad\_case}
\]

\[
Q_{b\_cond} = Q_{b\_cond\_exch} + Q_{b\_cond\_case\_air}
\]

where

\(Q_b\) = heat out burner

\(Q_{b\_conv}\) = convection heat burner (combustion temperature* mass combustion products)

\(Q_{b\_rad}\) = radiation heat burner/ flame

\(Q_{b\_cond}\) = conduction heat of burner to surroundings

and

\(Q_{b\_conv\_combust}, Q_{b\_conv\_case}\) is convection heat transfer to combustion and casing;

\(Q_{b\_rad\_combust}, Q_{b\_rad\_case}\) is radiation heat transfer to combustion and casing;

\(Q_{b\_cond\_exch}, Q_{b\_cond\_case\_air}\) is conduction heat to heat exchanger and to the air between casing and heat exchanger.

The picture below gives a Shankey-diagram of the flows. Percentages relate to \(Q_b = 100\%\).
2.6 Heat balance primary heat exchanger

2.6.1 Introduction

In the primary heat exchanger—and in case of non-condensing heat generators (as in many instantaneous combi-boilers) the only heat exchanger—the radiation heat and convection heat coming from the burner is transmitted to the primary water\textsuperscript{14}. This primary water returning from the CH-circuit (‘boiler return temperature’) has a temperature somewhere between 25 and 70°C to avoid too large heat stress. It is heated by somewhere in the range of 5 to 20°C before it leaves the primary heat exchanger.

In the heat exchanger/combustion chamber there are the parts that can be ‘seen’ by the burner and that are subject to the radiation heat. All parts of the heat exchanger are subject to the convection, i.e. the hot flue gases.

Radiation and convection heat transfer are very much linked, but in a publication of the Verbundnetz Gas AG\textsuperscript{15} an attempt was made at some simplified radiation modelling in an industrial burner, starting from the general Stefan-Bolzmann formula:

$$Q_{\text{rad}} = A \cdot \varepsilon_{\text{res}} \cdot \sigma_s \cdot (T_g^4 - T_w^4)$$

where

- $Q_{\text{rad}}$ : the radiation heat energy
- $A$ : the surface of radiation heat transfer in m\textsuperscript{2},
- $\varepsilon_{\text{res}}$ : the resulting emission-factor
- $\sigma_s$ : the constant of Stefan-Bolzmann: $5.67 \cdot 10^{-8}$ W/m\textsuperscript{2}K\textsuperscript{4},
- $T_g, T_w$ : temperatures of the gas and the wall in K

\textsuperscript{14} Some instantaneous gas-fired combi’s have a dedicated circuit for heating tap water directly (no need for primary water and a heat exchanger) - in this the primary water is the hot water itself.

\textsuperscript{15} Erdgas-Report 1/03, *Industrielle Gasbrenner*, Verbundnet Gas AG
The graph below gives an example of the resulting emission factor for an industrial burner/combustion chamber. It shows that for this burner the maximum radiation is achieved at a height of the combustion chamber of 1 m. At a height of 0.5 m the $\varepsilon_{\text{res}}$ is almost 50% lower and at 2 m the $\varepsilon_{\text{res}}$ is around 25% lower. This shows that the dimensions of the combustion chamber are important in maximizing the radiation fraction.

Furthermore, the graph shows that the radiation emission factor increases at a lower temperature from 0.31 at 1000°C to 0.18 at 2000°C.

The *Erdgas Report 1/03* mentions a value of $\varepsilon = 0.2$ to 0.3 for normal burners and $\varepsilon = 0.6$ for radiation burners.

The convection heat transfer is depending linearly on the temperature difference. A simplified equation for the convection heat transfer is given by the same source:

$$Q_{\text{conv}} = A \cdot \alpha \cdot (T_g - T_w)$$

where

- $A$ = heat transmission surface
- $\alpha$ = heat transmission coefficient in W/m/K
- $T_g, T_w$ = temperatures of the flue gas and the wall.

The convective heat transmission coefficient depends on the velocity of the flue gas, as shown in the graph below.
Combining the two graphs it is clear that at lower heat output of a modulating boiler (at constant air factor) the convection heat transfer decreases, whereas—given the lower burner load—at the same time the radiation heat transfer increases.

We will not use the formulas for radiation and convection losses directly in describing the heat balance, but they may be useful in describing some of the phenomena in Task 6 (design options).

For the heat balance we will follow the elements of the Boiler Cycle method, distinguishing between energy transfer during ‘burner-on’ and ‘burner off’ mode, as well as some additional findings regarding start-stop losses. The important issues are:

‘Burner on’ operation:
- Flue gas losses;
- Radiation, convection and conduction losses through the generator envelope;

‘Burner off’ operation:
- Standing losses (radiation, convection (incl. flue gas) and conduction);

‘Start-stop’ losses:
- Pre-purge losses;
- After purge losses/gains;
- Efficiency losses caused by cycling (German: Takten).

2.6.2 Flue gas losses in on-mode
The primary heat exchanger is designed to capture the radiation heat from the burner and —after that— to best transfer the heat from the flue gases to the primary boiler water, but without condensation of the flue gases.

The important parameters are the heat exchanger surface (A), the temperature difference between the flue gas and the primary water (dT) and convection coefficients that are typical of a configuration (k’ and k”). Most heat exchangers are counter flow, i.e. with the hottest flue gases hitting the hottest boiler water (just before exiting) and the coldest flue gases hitting the coldest part of the heat exchanger, i.e. just where the colder return primary water enters the heat exchanger.

A tap water heat exchanger (as employed in most instantaneous combis) allows the primary water flowrate and temperature regime to be different from the tap water
flowrate and temperature regime. At maximum power many combis can produce some 8 l/min of 60°C tap water. This tap water entered the tap water heat exchanger at approximately 10 to 15°C. This is however not the same at the primary side of the heat exchanger. Here the temperature difference is limited to what the heat exchanger can withstand (with an average product life in mind): some 5 to 20°C. The flowrate is governed by an internal circulation pump (often the same as used for central heating) that sends enough water over the primary heat exchanger to absorb the heat and transfer this to the tap water.

In short, the primary boiler water can be some 80°C with the return water being e.g. 60°C before it goes back into the primary heat exchanger, i.e. above the dew point. Effectively the heat exchanger is working at a 60/80°C (or even 90/70) regime, whereas from the point of view of the tapping point the combi appears to be working at e.g. a 60°C regime. Lower temperatures can be achieved through modulation of burner power, up to the point where cycling (Takten) occurs.

The combustion efficiency $\eta$ (D. feuerungstechnischer Wirkungsgrad) can be explained as measuring the temperature of the flue gases and then calculating the sensible heat loss, i.e. without taking into account the latent heat (steady state operation):

$$\eta_f = 100\% - \frac{Q_f}{H_i} \text{ (in %)}$$

where:

$Q_f$ = sensible heat of flue gases [kW] (product of mass flow, specific heat $c_p$ and $\Delta T$ of the combustion products);

$H_i$ = Heat flow of combustion related to the lower combustion value NCV = (methane 35,89 MJ/m³). As a rule of thumb: 10°C decrease in flue gas temperature represents approximately 0,5% decrease in flue gas losses.

In countries like Germany there is specific legislation regarding the flue gas losses, saying that they should be not higher than 11%, when compared to the net calorific value (NCV).

The Boiler Cycling method gives the following default values for the flue gas losses (applies to heating operation, but indicative for water heating):

<table>
<thead>
<tr>
<th>Description</th>
<th>$\theta_{gn,\text{test}}$ [°C]</th>
<th>$P'_{\text{ch, on}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric boiler</td>
<td>70</td>
<td>12</td>
</tr>
<tr>
<td>Force draught gas boiler</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>Oil boiler</td>
<td>70</td>
<td>11</td>
</tr>
<tr>
<td>Condensing boiler (acc. BED)</td>
<td>50</td>
<td>6</td>
</tr>
</tbody>
</table>

Please note that the losses of condensation heat are not included here. Those will be discussed in the paragraph on the secondary heat exchanger.

As the average EU-boiler is moving towards an efficiency on NVC of 90% (82% on GCV), we can take this as a reference for boilers with only primary heat exchangers, meaning flue gas losses of around 6 - 7% (at an average boiler temperature of 50°C and flue gas temperatures of around 150°C).

(To calculate the losses in specific real life situations, corrections on test figures will be necessary to compensate for the differences between the test- and the actual boiler water temperature and cycling behaviour.)
2.6.3 Losses through the generator envelope in on-mode

During operation the heat exchanger will transmit heat directly to the casing and the air between heat exchanger and casing. In case of a type C heater (closed system) and an open combustion air fan (D. ‘Luftumspült’), the heated air from the heat exchanger that ends up in the envelope will be picked up by the fan and the heat is recovered.

The heat that is transmitted to the envelope itself (mounting frame and casing) is not recovered for the heat transfer. This heat is mainly lost through radiation and to a smaller extend through convection round the envelope and through conduction (e.g. through wall).

Heat losses through the heater envelope in on-mode can be determined as the difference between the combustion efficiency and the net efficiency of the boiler and can be indicated as a percentage of the input power.

These heat losses through the heater envelope in burner 'on mode' depend on:

- combustion temperatures (type of burner);
- heat-exchanger/burner configuration;
- primary water temperature;
- insulation, material and finishing of heater envelope.

The Boiler Cycling method gives default values for these 'envelope-losses' at test conditions with the formula:

$$ P'_{gn,env} = A + B \cdot \log P_n $$

A and B are appliance specific parameters, but the following default values are given:

<table>
<thead>
<tr>
<th>Generator insulation type</th>
<th>A [-]</th>
<th>B [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well insulated, high efficiency new generator</td>
<td>1,72</td>
<td>0,44</td>
</tr>
<tr>
<td>Well insulated and maintained</td>
<td>3,45</td>
<td>0,88</td>
</tr>
<tr>
<td>Old generator with average insulation</td>
<td>6,9</td>
<td>1,76</td>
</tr>
<tr>
<td>Old generator, poor insulation</td>
<td>8,36</td>
<td>2,2</td>
</tr>
<tr>
<td>No insulation</td>
<td>10,35</td>
<td>2,64</td>
</tr>
</tbody>
</table>

Whether the envelope losses are considered as 'recoverable' will depend on the position of the heater. For instance, the Boiler Cycling method considers 90% of the radiation losses as useful if a type C (closed system) heater (generator) is in the heated space. See table below.

<table>
<thead>
<tr>
<th>Generator type and location</th>
<th>k_{gn,env} [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator installed within the heated space</td>
<td>0,1</td>
</tr>
<tr>
<td>Atmospheric generator installed within the heated space</td>
<td>0,2</td>
</tr>
<tr>
<td>Generator installed within a boiler room</td>
<td>0,7</td>
</tr>
<tr>
<td>Generator installed outdoors</td>
<td>1</td>
</tr>
</tbody>
</table>

Based on this Boiler Cycling method approach and also on the values mentioned in DIN 4702-1, default values for the envelope losses (under test conditions) in the on-mode can be varying from around 2% for the well insulated new appliances to over 14% for old not insulated generators. To calculate the losses in specific real life situations,

16 $P_n$ is the nominal boiler power in kW. Note that for $P_n=20$ kW, $\log P_n= 1,3$. At 30 kW, $\log P_n=1,5$
corrections will be necessary to compensate for the differences between the test- and the actual boiler room and primary water temperature. Please note that the room temperature for type B boilers will generally be lower because of the mandatory ventilation provisions.

The average figure for a new well insulated condensing boiler (at average water temperature of 70°C) is estimated at 2% and for the average new boiler at 4% (if no envelope losses are recovered). Half of this was already attributed to the burner, which is much smaller than the heat exchanger, but also much warmer. The other half we will attribute to the heat exchanger.

For an atmospheric standard boiler (or combined water heater) with poor insulation these envelope losses are around 10%.

2.6.4 Standing losses in off-mode

When the burner is switched off, the heat generator still loses heat through radiation, convection and conduction. The convection through the *chimney* attributes largely to these standing losses (most boilers have no flue-valve installed). The other part consist of the radiation, convection and conduction losses of the *boiler envelope*. These standing losses through the boiler envelope and chimney in burner off-mode depend on:

- average primary water temperature;
- average water flow;
- use of a flue valve;
- insulation, material and finishing of boiler envelope;
- use of pilot flame (not very common any more);
- For boilers, the operating time of the pump (continuously running or switched off after each burning cycle) is also important.

For water heaters, after the tap is closed, no more heat is transferred to the system. In most combis the pump stops running after closing the tap. Additional parameters that influence the standing losses are:

- heat capacity of the generator;
- operating time of the pump after burner switch off;
- tappings periods over the day;

**Pump continuously running**

*This section primarily applies to the heating operation of combined boilers - it is included here to show the methodology and calculations for determining the standing losses in case the heat is transferred to a system*

The standing losses with a primary pump continuously running are measured in the EN 303 standards by using an electric heater in the CH-boiler loop to keep the temperature at a pre-set level (30°C ± 5°C above ambient) and are expressed in [kW]. For installations with the pump continuously running, this test figure can be used to calculate the total standing losses in real life, by correcting for the actual average boiler water temperature and actual boiler room temperature.

The ‘Case specific boiler efficiency method’ of the prEN 15316-4-1:2005 proposes the following formula for correction (formula nr. 8):

\[
\Phi_{gn,l,P0,corr} = \Phi_{ge,l,P0} \left[ \frac{T_{gn,w} - T_{igl}}{30} \right]^{1.25} [W]
\]

In which:

- \(\Phi_{ge,l,P0}\) = standby losses according EN 303
- \(T_{gn,w}\) = actual average boiler water temperature
The method also gives the following default values for $\Phi_{ge,l,P0}$ in annex B, Table B.1.2 in case the certified test figures for standing losses are not available:

Default stand-by heat losses can be calculated with:

$$\Phi_{gn,l,P0} = \Phi_{Pn} \cdot (E + F \cdot \log \Phi_{Pn}) \quad [W] \quad \text{(formula B3)}$$

With values of E and F given in the following table.

<table>
<thead>
<tr>
<th>Generator type</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard boiler</td>
<td>25</td>
<td>-8</td>
</tr>
<tr>
<td>LT boiler</td>
<td>17.5</td>
<td>-5.5</td>
</tr>
<tr>
<td>Condensing boiler</td>
<td>17.5</td>
<td>-5.5</td>
</tr>
</tbody>
</table>

A 24 kW condensing or LT-boiler would have default standing losses of 238 watts; a standard boiler would have 335 watts. To calculate the total real life standing losses per year we would need to correct for the actual average boiler temperature and actual boiler room temperature and then multiply this figure with the operating time of the pump (while burner is off). If average boiler- and room- temperature are identical to test conditions (no corrections necessary) and the additional operating time of the pump is 2/3 of the heating period of 5200 hours, the yearly default standing losses for a condensing 24 kW boiler are:

$$238 \, [W] \times \frac{2}{3} \times 5200 \, [h] \times 3600 \, [s] = 2970 \, [MJ] \text{ or } 825 \, [kWh] \text{ (partly recoverable when the boiler is installed in a heated space).}$$

The 'Boiler cycling method' calculates the chimney losses separately from the envelope losses in the burner-off mode. If they are not declared by the manufacturer, default values can be used according to annex C table C.6. The default values mentioned in this table are expressed as % of the nominal boiler load. For a 24 kW boiler with premix burner the default value is 0.2% of 24 = 48 watts. A Wall mounted gas fired boiler (24 kW) with fan and wall flue gas exhaust would have 0.4% of 24 = 96 watts.

Atmospheric boilers with long chimneys (>10 m) could go as high as 1.6% x 24 = 384 watts.

According to the 'Boiler cycling method', the standing losses through the boiler envelope in burner off-mode are the same as in boiler on-mode. As explained in the previous paragraph, the average figure for envelope losses for a new well insulated condensing boiler according to this method is estimated at 2% (480 watts for a 24 kW boiler at 70°C). At an average boiler water temperature of 50°C and a boiler room temperature of 20°C, this 2% can be corrected with the factor $[(50-20)/(70-20)] = 30/50 = 0.6$. Envelope losses will in this case be 1.2% of 24 kW or 288 watts. If we assume the boiler-off period 2/3 of the total heating period of 5200 hours, the yearly default envelope losses for a 24 kW condensing boiler would be: $2/3 \times 5200 \, [h] \times 3600 \, [s] \times 288 \, [W] = 3594 \, [MJ] \text{ or } 998 \, [kWh] \text{ (partly recoverable, depending on location of boiler)}$

A more hands-on approach for the assessment of the standing losses through boiler envelope would be to calculate the radiation and convection losses on the bases of rule of thumb formula's or to compare it with known data from comparable appliances.

Standing losses of electric storage heaters (kept at 60°C) with a volume that is comparable to that of a 24 kW wall hung or standing condensing boiler range from 65 [W] for the best appliance to 123 [W] for the worst appliance (source: Save water heaters, Task 2. Technical Analysis). Of course boilers are not continuously kept at 60°C and the insulation quality differs a lot (water heaters are generally a lot better insulated than boilers), but the figures give some indication on the order of magnitude.
A rule of thumb formula for the calculation of radiation losses is:

\[ q_{\text{rad}} = A_{\text{env}} \cdot \varepsilon_{\text{env}} \cdot \sigma \left( T_{\text{env}}^4 - T_{\text{blr.}}^4 \right) \]

in which

- \( A_{\text{env.}} \) = Surface of the envelope (appr. 2 m² for a wall-hung condensing boiler)
- \( \varepsilon_{\text{env}} \) = Emissivity factor envelope (between 0.1 and 0.9 depending on material and finishing)
- \( \sigma \) = Radiation constant of Stefan-Boltzmann (5.67 \cdot 10^{-8} \text{ W/m²K}^4)
- \( T_{\text{env}} \) = Average temperature of boiler envelope (in degrees Kelvin)
- \( T_{\text{blr.}} \) = Average temperature boiler room (in degrees Kelvin)

With a boiler room temperature of around 15°C, a surface temperature of the envelope of 30°C, and an emissivity factor of 0.9 (white painted steel plate) the radiation according to this formula would be: 158 watts. A 40°C surface temperature of the envelope would give radiation losses of 277 watts.

For heat dissipation through natural convection of the boiler envelope the following rule of thumb formula can be used (formula of Nusselt):

\[ q_{\text{conv}} = 2.6 \cdot A_{\text{env}} \cdot (T_{\text{env}} - T_{\text{blr.}})^{1.25} \]

Using the same temperature values and a convecting surface of 1.5 m², the calculated convection losses of a boiler envelope are approximately 115 watts. A 40°C surface temperature would result in 218 watts of convection losses.

If the conduction losses (e.g. through the wall) are neglected, the calculated total envelope losses (boiler room temperature = 15°C and surface temperature = 30°C) would add up to 273 watts.

**Pump switches off 10 minutes after each burning cycle**

[This section is applicable to water heating operation of combined boilers with a pump feeding a tap water heat exchanger]

In principle standing losses are lower in case the pump switches off after each burning cycle, since no heat from the system is transported to the boiler and the appliance is allowed to cool down.

In this case the heat capacity of the generator determines how much energy (heat) can be stored, and with that also how much heat can be lost. Depending on the mass of the appliance (mainly heat exchanger and water content) a (combi-)boiler can easily contain 2 to over 4 MJ of heat (40 resp. 80 kg).

The operating time of the pump after burner switch-off in water heating mode is assumed to be zero, meaning that no stored heat is transferred to the tap water.

The number of operating periods per day and the time between operating periods indirectly determine the number of complete cool-downs of the appliance.

During an operating period the radiation and convection losses depend on the average appliance temperature.

The use of a flue valve (valve that switches off the flue duct after each cycle) and the use of insulation for the generators envelope will reduce the radiation and convection losses.
Example

If we assume that a 40 kg generator experiences 10 cool down cycles during a day the annual energy loss can roughly be calculated with the following formula:

$$Q_{\text{rad\&conv, p,sw}} = a \cdot d_h \cdot c_{av} \cdot m \cdot \Delta T_{\text{appl,avg}}$$

In which:
- $Q_{\text{rad\&conv, p,sw}}$: Energy losses through radiation & convection of boiler during pump off –period in [J]
- $a$: Average number of complete cool downs per day (10)
- $d_h$: Number of heating days per year (365 dagen)
- $c_{av}$: Average specific heat of generator (800 [J/(kgK)])
- $m$: mass of appliance (40 [kg])
- $\Delta T_{\text{appl,avg}}$: average temperature difference between start and end of cooldown period (40 [ºC])

Filling in average values gives:

$$Q_{\text{rad\&conv, p,sw}} = 10 \cdot 365 \cdot 800 \cdot 40 \cdot 40 = 4672 \text{ [MJ]}$$

The Boiler cycling method gives a correction on the envelope losses and the chimney losses in burner off mode, for situations in which the pump is switched off.

This correction factor can be calculated, depending on the load factor FC (which is the quotient of the generator-on time and total generator stand-by time) and an exponent ‘m’, that depends on the type of boiler.

For a wall mounted boiler exponent $m = 0,5$; for a steel boiler $m = 0,4$ and for a cast-iron boiler $m= 0,3$ (see Annex C table C.5 of prEN 15316-4-1).

The correction factor for a wall hung boiler that operates (= burner on) 1/3 of the total time is $0,33 ^{0,5} = 0,57$. If the envelope losses are 1% of nominal power when the pump is continuously running, in a situation were the pump is switched off, the losses are $1 \times 0,57 = 0,57\%$ of nominal power. For a 24 kW boiler this is 137 [W].

If we assume the boiler-off period 2/3 of the total heating period of 5200 hours, the yearly default envelope losses would be: $2/3 \times 5200 \text{ [h]} \times 3600 \text{ [s]} \times 137 \text{ [W]} = 1707 \text{ [MJ]}$ or 474 \text{ [kWh]} (partly recoverable, depending on location of boiler). For water heating the tapping pattern determines the number of on-hours.

Standing losses increase as the overall standby period is longer. Losses also increase with higher boiler water temperatures. If the pump switches off after each burning cycle, the losses can be reduced with 50% or more, mainly depending on heat capacity of the boiler.

Data from real life measurements for space heating function can be taken from the Wolfenbüttel study. In their final report\(^{17}\) the Fachhochschule Braunschweig Wolfenbüttel mentions that the average standing-losses of the 60 condensing boilers that were monitored correspond with a fraction of 0,468% of the input power of the boiler. In other words, a boiler of 24 kW would have 112 W standing losses as an average.

2.6.5 Start-stop losses

The graph below describes the energy profile during start-up and cool-down. It shows that –depending on the burner load and the heat capacity of the boiler— it takes some time before the heater system has reached a steady state situation. During this start-up time, as mentioned earlier, there are the most emissions of fuel and other emissions.

---

\(^{17}\) Fachhochschule Braunschweig Wolfenbüttel, Felduntersuchung: Betriebsverhalten von Heizungsanlagen mit Gas-Brennwertkesseln, April 2004
causing a fuel loss\textsuperscript{18} that –with 40,000 cycles/year—result in some 1.5\% of fuel loss. During this time the appliance is heated-up until thermal equilibrium is reached, and from that moment on the steady state efficiency (acc. EN 303) applies.

The graph also shows the so-called purge losses, which come from fan action during 'burner-off', which we will discuss hereafter.

Another issue that needs to be addressed here is the fact that energy is lost when the heat generator starts cycling. This cycling occurs when the supplied heat is higher than the primary water can dissipate and the heat generator is switched off by the boiler thermostat shortly after burner start. Steady-state efficiencies (acc. to NEN 303) are not achieved in those situations. Losses that are related to this phenomena will be further explained.

\textbf{Pre-purge}

For safety reasons the combustion chambers of type C boilers need to be purged before each burning cycle. This pre-purging implicates that cold (ambient) air is blown through the combustion chamber and heat exchanger and because of that heat is lost.

According to prEN 13836 a pre-purge period of 30 seconds with an airflow that corresponds to nominal heat generator load would comply.

With the following formula a rough calculation can be made off the energy losses related to these purge cycles:

\[
Q_{\text{loss; purge}} = t_{\text{purge;bf}} \cdot \Phi \cdot \rho_{\text{air}} \cdot c_{\text{air}} \cdot \Delta T_{\text{air;avg}}
\]

\textsuperscript{18} Please note that “fuel loss” does not equal methane (CH\textsubscript{4}) emissions and also note that 40,000 cycles per year is a maximum and not an average. To calculate “fuel loss” we took into account the mass balance of all emissions of carbon-compounds (CO, CH\textsubscript{4}, TOC) as found by Pfeiffer in par. 2.3.4. Marcogaz protests strongly against this value and claims that CH\textsubscript{4} emissions from a Ruhrgas/CGB study shows values that are a factor 10 lower. We see no contradiction here, especially if the CGB tests were performed at steady state efficiency or with (Danish) boilers with a high primary store.
In which:

\[ Q_{\text{loss; purge}} \]: Energy losses per burning cycle caused by pre- and after purge of appliance

\[ t_{\text{purge;bf}} \]: pre-purge time in [s]

\[ \phi_{\text{fan}} \]: air flow in [m³/s]

\[ \rho_{\text{air}} \]: density of air [kg/m³]

\[ c_{\text{air}} \]: specific heat of air [J/(kgK)]

\[ \Delta T_{\text{air;avg}} \]: average temperature difference of the purge air [s] before and after passing the appliance

If we assume a pre-purge time of 30 seconds, an after purge time of 10 seconds, an air flow of 24 m³/h (6.7 liters per second, e.g. for a 20 kW boiler) and an average temperature difference of the purge air of 30 ºC we can make an indicative calculation:

\[ Q_{\text{loss; purge}} = 30 \times 0.0067 \times 1.2 \times 1000 \times 30 = 7.2 \text{ [kJ]} \]

A generator with 40000 starts (heating and hot water) would loose 288 MJ-year (80 kWh).

**After purge**

At the end of a cycle the EN standards also prescribe an after-purge of around 10 seconds. The reason for this after-purge is safety, e.g. removing fuel from the combustion chamber. However, up to a certain degree where the flue gases are warmer than the boiler water, the after purge is also beneficial to transfer the residual heat of the burner and heat exchanger body to the boiler water. With the burner it was already calculated that this contributed up to 4%. Also with the heat exchanger, typically containing 3-5 litres of hot flue gases and with a heat exchanger surface considerably warmer than the boiler water at the time of shutting down the burner, there may be an extra gain from the after-purge. For heating operation of (combi)boilers we will not consider the heat transfer of 10 s. after-purge as losses, provided of course—as with the residual burner heat—that the extra contribution of the after purge is taken into account in the boiler control. For water heating operation the after purge are losses, assuming the water heaters is left to cool down completely, before the next tapping occurs.

**Cycling losses**

A boiler starts cycling when the energy input is too high for the heat output realized by primary water flow. These situations especially occur when the water content of the heat generator is small, the minimal load of the heat generator is too high and the heat demand from system side is low. An increase isn start-stop losses can be expected for water heaters.

**2.6.6 Primary heat exchanger: Flow diagram**

The picture represents an energy flow diagram of the primary heat exchanger. The diagram does not make a distinction between ‘burner off’ or ‘burner on’ energy transfer, but sums the flows on an average annual basis.
2.7 Heat balance secondary and tertiary heat exchanger

2.7.1 Secondary heat exchanger

[This section applies to water heaters with condensing heat generators, e.g. condensing gas-fired storage water heaters or combined-boilers with a storage facility that allows feeding the storage tank with lower temperatures]

In the case of condensing heat generators there is also a secondary heat exchanger. In reality, this can be as simple as an extension of the surface of the primary heat exchanger. In the case of a cylindrical burner and a spiral-tube heat exchanger (round or oval) this may really be a secondary spiral. Or in the case of a jet burner with a plate heat exchanger it may be a second plate heat exchanger. In most cases this secondary heat exchanger is a flue-gas / boiler-water heat exchanger; in some cases (some oil boilers) this can also be a flue-gas / combustions-air heat exchanger in which case it is always a separate (plate) heat exchanger.

In any case, the function of the secondary heat exchanger is to further cool the flue gases to a temperature level where most of the latent heat can be recuperated, alongside of course the remaining sensible heat in the flue gases. The EN standard and the BED foresee that this happens at a primary water return temperature of 30°C, resulting also in flue gases of the same temperature level. If that happens, some 90% of the remaining flue gas losses and of the latent heat can be recovered.

The energy flow diagram of the secondary heat exchanger, neglecting losses to the casing, will look like the picture below.
With lower average primary water temperatures (around 40°C) and longer operating periods (e.g. for storage water heating), the standing losses in off-mode will also decrease. An additional 2% can be gained compared to the values mentioned in the energy flow diagram of the primary heat exchanger.

In case the secondary heat exchanger is a gas / water HE the amount of latent- and flue gas heat that can be regained strongly depends on the return water temperature. If the installation and the control systems do not facilitate low return water temperatures this energy can not fully be regained.

Please note that if the heat exchanging process stops here, the boiler efficiency on GCV is $75.5 + 8 + 2 = 85.5\%$, which is in line with the results from the Wolfenbüttel study for condensing boilers.

### 2.7.2 Tertiary heat exchanger

The tertiary heat exchanger is a flue gas to combustion air heat exchanger. This heat exchange can take place in the concentric flue/air duct or in a separate plate heat exchanger. For oil boilers this pre-heating is also functional at higher flue gas temperatures to preheat the incoming air in order to consequently promote the oil vaporisation process. In gas-fired boilers the heat exchange already takes place (to a small extent) through the concentric flue/air tubes, but until now a dedicated counter flow (or cross flow) flue-to-air heat exchanger was not used.

In any case, an effective counter flow tertiary heat exchanger ($\eta=80-90\%$) allows recouperation of the last bit of latent heat and sensible flue gas losses. We will discuss this further in Task 6 with the design options. For now, we will just present the flow-diagram.
Calculation of the effect of the tertiary heat exchanger in case of space heating (including an additional reduction of the standing losses with 1%) gives a total real life efficiency of around 93% on GCV for an average house with a heat load of 7250 kWh. For water heating the effect depends on the applicable tapping pattern. Indicative losses would be:

- fuel losses: 1.5%
- flue gas losses: 0.5%
- latent heat: 1%
- start/stop losses: 1%
- envelope and standing losses: 3%

Whether these envelope & standing losses should be counted as irrecoverable or not, depends on whether the heater is in the heated space. If the heater has a closed flue/air system (Type C), has the right dimensions and answers noise requirements, this type of credit could be appropriate. Furthermore, standing losses in off-mode can be further reduced by prolonging the operation periods. At the same time the fuel losses are reduced to <0.5% and start/stop will be lower (< 0.5%) losses because of the fewer burning cycles.

In any case, even without giving the credit for casing losses to the heated space, the total heater efficiency on GCV could be as high as 96-97% (105-106% on NCV). This is of course without taking into account the auxiliary electrical energy for pump, fan, controls, etc..

### 2.8 Heat balance with storage facilities

In the previous sections we have often assumed that the heat generator follows the heat demand, when it is needed and at the capacity that is needed (instantaneous mode). These combi boilers are designed for direct hot water delivery.

But the drawback is relatively long waiting times (thermal mass, purge times etc.) and possible cycling (plus subsequent wear of components, noise and cycling losses - see paragraph 2.6.5).

To solve these problems a storage vessel for sanitary hot water (or central heating water - with heat exchanger for tap water). In fact, the primary and/or secondary heat exchanger may already be such a storage vessel. In the Task 1 report most of the currently known configurations with a storage facility are listed and we will not repeat this here.
With proper appliance insulation, cycling losses can be reduced without increasing the
evelope and standing losses too much.

However, some practical standing losses are given, to show the penalty of using storage
vessels:

- 4 litre combi store: 15-20 W (insulation 30mm, 80-240 kWh/year, 1-2.5% efficiency
  loss).
- 80 litre at 65°C (>100 mm insulation): 55-60 W (500 kWh/year = 5% efficiency
  loss/ year).
- 150 litre (120mm insulation): 65-70W (600 kWh/year, 6% efficiency loss).
- 350 litre solar (110mm insulation): 100 W, 870 kWh/year (8-9% efficiency loss).

Please note that these values are already much lower (ca. factor 3) than the maximum
values suggested by e.g. EN 303-6.

2.9 Auxiliary energy

Many gas- or oil-fired water heaters, especially the combined ones (combi-boilers), use
electrical components for their operation. Practically all premix modulating combi-
boilers use an electronic control unit, a pump (to circulate primary water through the
heat exchanger), a fan and electrically powered gas valves.

Oil boilers use in addition to the above, electricity for preheating the oil and an oil
pump for pressurizing or atomizing the fuel.

Gas and oil igniters also use electricity but only for a short period (10 – 35 seconds). The
electricity consumption related to this will be neglected.

Table 2-13 gives an overview of the typical power consumption for the various
components from the Boiler Savelec study. Please note that these values may be subject
to change later in the underlying, e.g. following the preparatory study on the CH
circulators.

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical instantaneous power [W]</th>
<th>Consumption during system off mode</th>
<th>Consumption during system on burner off mode</th>
<th>Consumption during system on burner on mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>55 – 80</td>
<td>Depends on type of T control system</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fan</td>
<td>30 – 50</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Control unit</td>
<td>2 - 6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gas valve</td>
<td>6 - 10</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Stand-by consumption</td>
<td>5 - 15</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Oil preheat</td>
<td>40 - 150</td>
<td>No</td>
<td>No</td>
<td>Yes, during 50s, for cold start only</td>
</tr>
<tr>
<td>Oil pump / atomization</td>
<td>75 - 200</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
2.10 Total energy balance

Based on the previous paragraphs, the figures below give an illustration of the total energy balance for some characteristic heat generators in (gas-fired) water heaters (e.g. a combi-boiler).

**Figure 2-19.** Energy flow diagrams of the heat generator in gas-fired water heater (e.g. combi-boiler)
3 EMISSIONS

3.1 Introduction

Emissions of air pollutants from the combustion process in gas- and oil-fired CH boilers and water heaters are carbon dioxide (CO₂), nitrogen oxides (NOₓ), carbon monoxide (CO) and methane (CH₄). In oil-fired boilers or water heaters you have these emissions plus sulphur oxides (SOₓ), Volatile Organic Compounds (CₘHₘ) and “soot” (Particulate Matter, PM).

In the MEEUP methodology study (VHK 2005) ‘default values’ for the emissions per GJ of heat output were presented for a number of heat generators. An extract (excluding water and waste) is given in the table below.

Table 3-1. Use phase: Energy and emissions per GJ heat out CH boiler, (excl. Electricity for fossil fuel based heating) [VHK 2006, based on Öko-institut GEWIS database]

<table>
<thead>
<tr>
<th>HEATING nr.</th>
<th>Energy primary GWP MJ</th>
<th>CO₂ g</th>
<th>VOC mg</th>
<th>POP mg</th>
<th>PAH &amp; HM i-Teq mg</th>
<th>PM g</th>
<th>EUP mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 Electric, η 96%, per GJ</td>
<td>3045</td>
<td>132,9</td>
<td>784</td>
<td>1147</td>
<td>20</td>
<td>180</td>
<td>17</td>
</tr>
<tr>
<td>68 Gas, η 86%, atmospheric</td>
<td>1163</td>
<td>64,3</td>
<td>19</td>
<td>846</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>69 Gas, η 90%, atmospheric</td>
<td>1111</td>
<td>61,4</td>
<td>18</td>
<td>809</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70 Gas, η 101%, condens.</td>
<td>990</td>
<td>54,7</td>
<td>16</td>
<td>721</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>71 Gas, η 103%, condens.</td>
<td>971</td>
<td>53,7</td>
<td>16</td>
<td>706</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>72 Oil, η 85%, atmospheric</td>
<td>1176</td>
<td>87,8</td>
<td>110</td>
<td>1519</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>73 Oil, η 95%, condens.</td>
<td>1053</td>
<td>78,5</td>
<td>98</td>
<td>1360</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

78 Extra for fossil fuel extraction & transport: Gas +7% (row 68-73), Oil +10% (row 72-73), for Wood pellets and logs add 5% of row 72

Please note that all efficiency values are given in NCV

Data for fossil-fuel fired boilers were taken from GEMIS 4.2 for fossil fuel powered 10 kW Central heating (CH) boilers in GJ heat produced at the heat generator exit. These data are assumed to apply to water heaters as well (GJ heat produced at tap water outlet). They do not include the auxiliary electricity consumption for pump, fan and controls. The table below gives some details for the specific operating conditions.

Table 3-2. Boiler operating conditions (GEWIS 4.2)

<table>
<thead>
<tr>
<th>Row nr.</th>
<th>Gas CH</th>
<th>Oil CH</th>
</tr>
</thead>
<tbody>
<tr>
<td>% O₂</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>% CO₂ in flue</td>
<td>9,96%</td>
<td>13,11%</td>
</tr>
<tr>
<td>Nm³/h flue</td>
<td>11,7</td>
<td>11,2</td>
</tr>
</tbody>
</table>

The tables are from GEMIS 4.2. More recent information on emissions from oil- and gas-fired appliances are found in the updated GEMIS 4.3 software package in which emission values for GWP and AP are considerably more favourable than in GEMIS version 4.2 (information supplied to VHK by Eurofuel).

VHK has taken this into account in its final recommendation (Task 7), but for the underlying study we used the MEEuP values, as of contract.
In this chapter we will not discuss the emissions from electricity production because their composition cannot be influenced by an (electric) boiler designer. The ‘only’ problem he or she has to face is to use the electric kWh as efficiently as possible.

First we will look at the environmental impacts of oil- and gas-fired boilers and water heaters following the MEEUP methodology and expanding on that. Subsequently, we will look at the emissions from the angle of their origin and some basic design measures. Next the focus is on two most interesting groups from the design point of view: The non-\(\text{CO}_2\) hydrocarbon emissions (\(\text{CO}, \text{CH}_4, \text{C}_x\text{H}_y\), soot) and especially the nitrogen oxides (\(\text{NO}_x\)). Finally, it is examined where the contrast and the similarities between energy-efficient and environmentally-friendly design of boilers lies.

### 3.2 Environmental impact

When looking at the combustion emissions from the angle of their relative environmental impact, there are a number of categories.

**Global Warming Potential (GWP).** These include \(\text{CO}_2\), \(\text{CO}\) and \(\text{CH}_4\) emissions. Legal basis is the Kyoto protocol\(^20\) and the weighting factors for the GWP-100 are prescribed by the Intergovernmental Panel on Climate Change (IPCC). The unit of GWP-100 is \(\text{CO}_2\)-equivalent (\(\text{CO}_2=1\)). Carbon monoxide has –per weight unit— a \(\text{CO}_2\)-equivalent of 1.57. Methane (\(\text{CH}_4\)) has a significantly higher GWP at \(\text{CH}_4=21\).

**Acidification Potential (AP).** These include \(\text{SO}_x\) and \(\text{NO}_x\) emissions. The policy framework for regulating acidification consists of several European Community directives and the so-called Gothenburg Protocol\(^21\). This protocol considers \(\text{SO}_2\) to be 50% more harmful in terms of acidification than \(\text{NO}_x\) (weighting factor 1 versus 0.7 respectively. This relationship is also reflected in the emission limit values of the 1999/30/EC daughter directive of the Ambient Air Quality Directive (AAQD)\(^22\). The AAQD is an interesting framework directive, because the collection of –so far— 4 daughter directives show the relative importance that the legislator gives to very different types of emissions, which are all assessed in a similar (grid-based) method.

From this comparison (see table 3) it is clear that the legislator thinks \textbf{NO}_x \textit{some 50 times more harmful than CO-emissions} from the viewpoint of ambient air quality. This is very significant, because up till now the boiler and (gas/oil-fired) water heater sector has mostly treated the emission limits for \text{CO} as equivalent to \text{NO}_x (see Task 1 report). This is not in line with EU environmental policy. If the sector—and the governments in Member States—have treated \text{CO} equally stringent this must be due to other reasons, e.g. historical safety reasons when boilers and water heaters were not room sealed and \text{CO}-poisoning was a real danger with open (not room-sealed) units.

### Table 3-3. Target/Limit values in EC Ambient Air Quality directives (VHK, MEEUP, 2006)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Target/ limit values* in ng/m³</th>
<th>EC Air Quality directive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzo(a)pyrene (as a measure for polycyclic aromatics PAHs)</td>
<td>1</td>
<td>2004/107/EC</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>5</td>
<td>2004/107/EC</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>6</td>
<td>2004/107/EC</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>20</td>
<td>2004/107/EC</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>500</td>
<td>1999/30/EC</td>
</tr>
<tr>
<td>Particulate Matter (PM10)**</td>
<td>50,000</td>
<td>1999/30/EC</td>
</tr>
</tbody>
</table>

\(^{20}\) Council Decision 2002/358/CE of 25 April 2002 concerning the approval on behalf of the European Community of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCC) and agreed upon by the Conference of the Parties at its third session.  


\(^{22}\) Another piece of EU legislation that is relevant is the National Emissions Ceiling Directive (NECD, 2001).
### Volatile Organic Compounds (VOC)

These include the C₅Hₓ emissions from oil-fired boilers/water heaters. Strictly also methane (CH₄) is part of VOCs, but because the effect on the environment is different it is excluded. For this reason VOCs are often called NMVOCs (non-methane VOCs).

VOCs appear in Directive 2002/3/EC of 12 Feb. 2002 due to their role in (ground level) ozone and in Directive 1999/13/EC dealing with organic solvents. Furthermore, the European IMPEL network is monitoring fugitive NMVOCs, amongst others from combustion processes. There are no weighting factors mentioned and the MEEUP study proposes to simply make an inventory on a weight basis.

Formation of VOCs in commercial and industrial boilers (e.g. feeding separate hot water storage cylinders) primarily result from poor or incomplete combustion due to improper burner set-up and adjustment. To control VOC emissions from commercial and industrial boilers, no auxiliary equipment is needed; properly maintaining the burner/boiler package will keep VOC emissions at a minimum. Proper maintenance includes keeping the air/fuel ratio at the manufacturer’s specified setting, having the proper air and fuel pressures at the burner, and maintaining the atomizing air pressure on oil burners at the correct levels. An improperly maintained boiler/burner package can result in VOC levels over 100 times the normal levels. Furthermore, as VOC emissions mainly occur at start-up and the end of a burning cycle, a very important measure is a reduction of the number of cycles.

### Heavy Metals (Toxicity)

Although not a Heavy Metal, the MEEUP classifies CO as a toxic agent, albeit as an outdoor emission—with a very low weighting factor. Carbon monoxide is a pollutant that is readily absorbed in the body and can impair the oxygen-carrying capacity of the hemoglobin. Impairment of the body’s hemoglobin results in less oxygen to the brain, heart, and tissues. Even short-term over exposure to carbon monoxide can be critical, or fatal, to people with heart and lung diseases. It may also cause headaches and dizziness in healthy people.

### Particulate Matter (PM)

This refers to ‘soot’ from oil-fired boilers/water heaters. Emission limit values are mentioned in Directive 1999/30/EC, which indicate that the European legislator takes PM 10-emissions very serious indeed (see table 4). In fact, the emission limits on a weight basis are 4 times more stringent than the ones for NOₓ.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Limit Value</th>
<th>Directive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur dioxide (SO₂)***</td>
<td>125 000</td>
<td>1999/30/EC</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂)***</td>
<td>200 000</td>
<td>1999/30/EC</td>
</tr>
<tr>
<td>Ground-level ozone****</td>
<td>120 000</td>
<td>2002/3/EC</td>
</tr>
<tr>
<td>Benzene (aromatic HC, C₆H₆)</td>
<td>5 000</td>
<td>2000/69/EC</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>10 000 000</td>
<td>2000/69/EC</td>
</tr>
</tbody>
</table>

**Sulphur dioxide (SO₂) and NO₂ are included in the separate category of acidifying agents with more or less the same relative weighting factor (1 vs. 0.7 for eco-toxicity, 1 vs. 0.62 here)**

***Particulate Matter is a separate impact category/indicator in our methodology.***

****Ground-level ozone is not a direct anthropogenic emission but the result of a photochemical reaction (see text).
PM emissions are primarily dependent on the grade of fuel fired in the boiler/water heater. Generally, PM levels from natural gas are significantly lower than those of oils. Distillate oils result in much lower particulate emissions than residual oils.

When burning heavy oils, particulate levels mainly depend on four fuel constituents: sulfur, ash, carbon residue, and asphalenes. These constituents exist in fuel oils, particularly residual oils, and have a major effect on particulate emissions. By knowing the fuel constituent levels, the particulate emissions for the oil can be estimated.

Methods of particulate control vary for different types and sizes of boilers/water heaters. For utility boilers, electrostatic precipitators, scrubbers, and baghouses are commonly utilized. For industrial and commercial boilers, the most effective method is to utilize clean fuels. The emission levels of particulate matter can be lowered by switching from a residual to a distillate oil or by switching from a distillate oil to a natural gas. Additionally, through proper burner set-up, adjustment and maintenance, particulate emissions can be minimized, but not to the extent accomplished by switching fuels.

The above refers to emissions to air. To complete the picture it must be mentioned that in some regions of the EU there are strict regulations regarding the emissions to water, which—when using heating oil with a higher sulphur content—can apply to affluent of condensate to the sewer.

3.3 Emissions grouped by origin

Taking the angle of their origin, the emissions from gas-and oil-fired boilers can be split into four groups:

Unavoidable products from the combustion reaction. As already explained in the previous chapter water vapour and carbon dioxide (CO₂) are the main combustion products from the reaction between a hydrocarbon and oxygen. The CO₂ production is completely linked with a) the specific fuel and b) the energy efficiency of combustion. Regarding the fuel the CO₂ emissions per MJ gas are 20-30% lower than with oil. Regarding the efficiency, it depends very much on the design. At best the oil-fired heat generators in the top-end of the market can keep up (but not surpass) the best gas-fired heat generators.

Pollutants that are unavoidable because they are already contained in the fuel. This is the case with SO₂ production from sulphur. In principle, without end-of-pipe measures, the sulphur emissions are independent of the design of the combustion process. If we use heavy fuel oil with 3% sulphur, this amount will also result from the combustion process. If we use low-sulphur (<50 ppm) gas heating oil the corresponding lower amount will result. The only design-measure that a boiler designer can take is to make sure that the boiler/water heater (also) works with low-sulphur oil, but it is the user—or the regulations on the sulphur content of heating oil in a particular country—that will determine the outcome.

Emissions that are a consequence of incomplete combustion. Basically, these are all other carbon-containing compounds, besides CO₂: Carbon monoxide (CO), Methane (CH₄), hydrocarbons (CₓHᵧ) and soot (PM). The carbon in these compounds comes from the fuel and is an indicator of how much fuel was subject to incomplete combustion. The most well known cause of this is the lack of sufficient air/oxygen. But there may be other causes, such as the temperature of the fuel is too low to permit oxidation (combustion) to occur. It can occur as a result of flame impingement (flame in contact with metal) because parts of the flame are cooled—quenched—below the burn temperature of the fuel. For instance, on a gas range burner, flame impingement always occurs when a pot is on a burner. As the pot becomes hotter, the carbon monoxide production decreases because the flame is not cooled as much by the impingement. This

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23 Eurogas mentions a figure of 24%, citing the International Gas Union. The MEEUP table shows even higher differences (>30%) for comparable boilers.
makes measurement of carbon monoxide difficult; as impingement surfaces change temperature, the carbon monoxide emissions change. Quenching of a flame can also occur if air blows across a flame rapidly enough to cool it to below its burn temperature. A rule of thumb is that—in order to keep the CO-emissions low—the combustion temperature should be well above 900°C. Finally, the most obvious cause of non-CO₂ carbon emissions is during start- and stop of combustion, i.e. when unburned fuel remains in the combustion chamber. This causes of course a considerable amount of unburned fuel emissions (CH₄ or CₓHₙ), but also gives peaks in CO-emissions as the circumstances at start-up (cold heat exchanger) are so favourable for CO-formation. As mentioned in chapter 2, 80-90% of the non-CO₂ carbon emissions occur not during steady-state but during start-up and stop.

**Emissions that do not involve the fuel, but are chemical reactions between air molecules triggered by the specific combustion conditions.** This relates to emissions of nitrogen oxides (NOₓ), NO and NO₂, from the reaction between the oxygen and nitrogen molecules in the air. This occurs only when there is enough air around (excess air, e.g. air factor > 1.4), when the temperature is high enough (above 1200°C) and when there is enough time for the reaction to take place at this high temperature (the so-called ‘residence time’ should be long enough).

Basically the above is about all there is to tell about the amount of CO₂ and SOₓ emissions (point 1 and 2). Once the fuel is chosen, the amount of SOₓ and CO₂ emissions follow directly from the fuel input per functional unit.

We will now expand on the points 3 and 4 mentioned above.

### 3.4 Low non-CO₂ Carbon Emission

#### 3.4.1 Formation

The global chemical reaction just shows the results of what in reality is a complex series of simultaneous and consecutive chemical reactions. The picture below gives an impression of that complexity during methane combustion, whereby the molecules are first dissociated into smaller fractions before entering the chain reactions and finally the end-stage.

![Possible reactions during methane combustion](image)

And a minute amount is subtracted for unburned fuel (<1.5%, see Chapter 2)
The picture shows the steps in the methane combustion. From left to right it presents the oxidisation steps whereby hydrogen (H) is split off. From top to bottom it represents the oxidisation through taking up oxygen and splitting larger hydrocarbon molecules into smaller parts. In a ‘rich combustion’ (air factor < 1) the reactions predominantly follow the steps in the upper lines. In a ‘lean combustion’ (air factor >1) the reactions predominantly follow the steps in the lower lines of the picture. In the lower line the intermediate products are formaldehyde (H₃CO) and aldehyde (HCO) before arriving at carbon monoxide (CO) and finally carbon dioxide (CO₂). In the upper line acetylene (C₂H₂) is the most important intermediate product.

From this it will also be clear that in case of imperfect combustion CO is a combustion by-product. In case of rich combustion there will be a high C₂H₂ – concentration, which increases the tendency for soot-formation. In case of lean combustion there is a concentration of H₂CO, which reduces the formation of soot, but favours the formation of aldehyde.

3.5 Low NOₓ technology

[This is a non-appliance specific text: Where the text states ‘boilers’ one may read this as ‘water heaters’ as well]

3.5.1 Introduction

In the discussions of nitrogen oxide combustion products and their impact to environment, the major nitrogen oxide species of concern are nitric oxide (NO) and nitrogen dioxide (NO₂).

Under high temperature combustion conditions, the formation of NO is favoured and consequently, less than 10% of the NOₓ in typical exhaust is in the form of NO₂ (Pereira and Amiridis, 1995). However, a higher percentage of NOₓ in the form of NO₂ has been experienced in domestic applications. NO when it cools down in the atmosphere combines with oxygen in air to form NO₂ (Eqn. 1).

\[
2\text{NO} + \text{O}_2 \rightleftharpoons 2\text{NO}_2 \quad \text{[Eqn. 1]}
\]

In warm, sunny days the NO₂ breaks down into NO and a nascent oxygen atom (Eqn. 2) which can combine with a molecule of oxygen to form ozone (Eqn. 3). The ozone reacts with NO to yield back NO₂ almost as fast as it is formed.

\[
\text{NO}_2 \rightleftharpoons \text{NO} + \text{O} \quad \text{[Eqn. 2]}
\]

\[
\text{O} + \text{O}_2 \rightleftharpoons \text{O}_3 \quad \text{[Eqn. 3]}
\]

When volatile organic compounds (VOC) exist in the air, they combine with the NO in the present of sunlight to change it back to NO₂. Less NO is then available to remove the nascent oxygen, and hence ozone accumulates, resulting in photochemical smog.

The term low NOₓ technology used in the industry has a broad range in terms of the NOₓ emission level achieved. In some instances, an emission of 70 - 80 ppm at 0% O₂ on dry basis is regarded as "low". In other instances, it may be down to 10 - 15 ppm or less. In the EU the threshold level of <40 ppm (70 mg/kWh) seems the most appropriate, being used in the German Blue Angel labelling scheme and the Dutch ‘Low- NOₓ’ label and it is the lowest class limit (class 5) in the European Standard prEN 267.

Conversions:

Europe: 1 ppm (at 3% O₂) = 1.83 mg/kWh = 0.508 mg/MJ = 0.508 ng/J.
US: 100 ppm (at 3% O₂) = 0.118 lb/MMBtu (1 lb= 0.4535 kg; 1 Btu= 1,0546 kJ) = 183 mg/kWh.
ppm (at 3% O₂) = (21-3)/(21 – O₂ actual) ppm actual.
1 ppm (at 3% O₂) = 18/21= 0.857 ppm (at 0% O₂).
This section is based on a study for the Australian government by environmental consultant Bob Joynt and combustion engineer Stephen Wu, which gives a good overview of the subject, also mentioning technology not strictly from a European angle.

### 3.5.2 Formation of NO\textsubscript{x}

NO\textsubscript{x} formed during combustion is the predominant source of NO\textsubscript{x} to atmosphere. The source may be mobile or stationary, cars or boilers. NO\textsubscript{x} consists of NO and NO\textsubscript{2}. For the convenience of discussion on a theoretical basis, only NO is discussed in this section.

NO can be categorised into the following:

- Thermal NO;
- Fuel NO;
- Prompt NO.

For gas combustion burners such as Bunsen burners and flat flame burners which have a high flame temperature (> 1550°C), the NO formed is predominantly thermal NO, with a small fraction as prompt NO.

**Thermal NO**

Thermal NO is found mainly in the high-temperature post-flame zone. It is formed by the oxidation of molecular nitrogen in combustion air and fuel gases by the extended Zeldovich mechanism:

\[
\begin{align*}
O + N_2 & \rightarrow NO + N & \quad \text{[Eqn. 4]} \\
N + O_2 & \rightarrow NO + O & \quad \text{[Eqn. 5]} \\
N + OH & \rightarrow NO + H & \quad \text{[Eqn. 6]}
\end{align*}
\]

where the nascent oxygen atom in Eqn. 4 is formed (with a large activation energy) from the H\textsubscript{2}-O\textsubscript{2} radical pool or possibly from the dissociation of O\textsubscript{2} (Glassman, 1996).

The hydroxyl (OH) radical in Eqn. 6 may come from the following reaction, which obtains the hydrogen atom from the dissociation of hydrocarbon fuel:

\[
H + O_2 \rightarrow OH + O
\]

Eqn. 4 is rate-determining. To reduce thermal NO formation, O (nascent oxygen atom) must be reduced. The formation of O, and hence thermal NO, is more dependent on the combustion temperature and less dependent on the oxygen concentration. It increases with temperature. For combustion systems like those obtained on Bunsen and flat flame burners, the temperature, and hence the mixture ratio, is the prime parameter in determining the quantities of thermal NO formed.

**Fuel NO**

Fuel NO is formed by the oxidation of nitrogen chemically bound in fuel. In the production of natural gas and liquid petroleum gas, combustible gaseous nitrogen compounds such as ammonia and amines have been removed to insignificant levels and little or no fuel NO would be formed.

**Prompt NO**

Prompt NO is most frequently observed in fuel-rich flames and at low temperatures, and its formation is found to be relatively independent of temperature. There are three possible sources of prompt NO (Glassman, 1996):

Non-equilibrium nascent oxygen (O) and hydroxyl (OH) radical concentrations in the reaction zone and burnt gas, which accelerate the rate of thermal NO (Zeldovich) mechanism.
A reaction sequence initiated by reactions of hydrocarbon radicals, present in and near
the reaction zone, with molecular nitrogen (Fenimore prompt NO mechanism):
\[ CH + N_2 \rightleftharpoons HCN + N \]  \[ Eqn. 8 \]
\[ C_2 + N_2 \rightleftharpoons 2 \text{CN} \]  \[ Eqn. 9 \]
The nascent N atom can yield NO by reactions such as Eqn. 5 and Eqn. 6, and CN can
form NO with a nascent oxygen atom or oxygen molecule.

Reaction of nascent oxygen (O) with molecular nitrogen to form nitrous oxide (N\textsubscript{2}O) via
the three-body recombination reaction (Eqn. 10) and the subsequent reaction (Eqn. 11)
to form NO:
\[ O + N_2 + M \rightarrow N_2O + M \]  \[ Eqn. 10 \]
\[ N_2O + O \rightarrow NO + O_2 \]  \[ Eqn. 11 \]
The non-equilibrium O and OH concentration mechanism is more important for non-
pre-mixed flames, stirred reactors for lean conditions, or low pressure premixed flames.
The Fenimore prompt NO mechanism is dominant in fuel-rich pre-mixed hydrocarbon
combustion.
The nitrous oxide mechanism becomes more important when the fuel-air ratio
decreases, when the burnt gas temperature decreases, or when the pressure increases.
At common combustion temperatures, increase in aeration can reduce prompt NO
formation.

**Formation of NO\textsubscript{2}**

Despite the favoured formation of NO dictated by thermodynamics and reaction
kinetics, high concentrations of NO\textsubscript{2} have been experienced in domestic applications,
e.g., Glassman (1996) cited that high concentrations of NO\textsubscript{2} were reported in the
exhaust of range-top burners.

It was observed that NO\textsubscript{2} was formed by HO\textsubscript{2} and NO in the low-temperature regime of
visible flames (Eqn. 12) and suggested that the conversion of NO\textsubscript{2} to NO and oxygen in
the near-post-flame zone (as given by Eqn. 11) was quenched.
\[ \text{NO} + \text{HO}_2 \rightarrow \text{O}_2 + \text{OH} \]  \[ Eqn. 12 \]

### 3.6 Principles of Primary Control of NO\textsubscript{x} Emissions

*This is a non-appliance specific text: Where the text states 'boilers' one may read this
as 'water heaters' as well*

NO\textsubscript{x} control may be:

- Primary - to reduce NO\textsubscript{x} formation.
- Secondary - to remove NO\textsubscript{x} formed.

There are three basic principles of primary NO\textsubscript{x} control to reduce NO\textsubscript{x} formation:

- Reduction of high combustion/flame temperature since more NO\textsubscript{x} will be formed at
  higher temperatures under thermodynamic equilibrium conditions.
- Reduction of residence time at high combustion temperature to resist the NO\textsubscript{x}
  formation approaches thermodynamic equilibrium concentration.
- Reduction of oxygen concentration and hence the nascent oxygen concentration in
  the high temperature zone.

It is possible to quench the NO\textsubscript{x} reactions, obtain the chemical heat release and prevent
NO\textsubscript{x} formation (non-equilibrium Zeldovich mechanism) but in practice efficiency often
suffers if quenching is done by adding a non-reacting mass such as water or steam to the system.

Any acceptable NOₓ control technology should reduce NOₓ emissions, at the same time maintain or decrease CO and formaldehyde emissions, and maintain or increase thermal efficiency.

The primary NOₓ control technologies involve either or both of the following:
- Modification of fuel/air delivery-burner system.
- Modification of gas burner.

### 3.6.1 Modification of Fuel/Air Delivery-Burner System

The strategies to modify fuel/air delivery-burner systems can be summarized as follows:

- Increasing the primary pre-mixed air from ~ 50% to more than 100%
- Low excess air (LEA) firing
- Flue gas recirculation (FGR). Recirculating combustion exhaust gases into primary combustion air.
- Staging combustion into more than one discrete step, with heat extracted between steps.
- Delaying, distributing, or dispersing fuel/air mixing within the combustion chamber.
- Humidifying fuel gas, combustion air, or the flame.

### Increasing the Primary Premixed Air

This measure applies to an atmospheric (partial pre-mix) burner, which uses both primary ('pre-mix') and secondary air. NOₓ emissions from blue flames could be reduced from ~ 100 ppm to < 70 ppm (oxygen (O₂) free) by increasing the primary air from ~ 50% to ~150% of the stoichiometric air required.

Effectively any excess air above 100% stoichiometric dilutes the combustion exhaust and brings down the combustion temperature from a maximum of ~ 1900°C to ~ 1200°C, causing less NOₓ to be formed.

Lower combustion temperature would result in longer combustion time at high temperature because of slower burning rate. This would encourage NOₓ formation, but this effect was observed to be secondary and a net decrease in NOₓ emission would result.

Means to increase the primary air flow to ~ 50% excess are a very large venturi, a fan and higher gas- or air-line pressure. In the EU boilers, the use of fans in a full pre-mix burner is the most common measure.

In Japan (Tokyo Gas, Rinnai) and US (Burnham, Gas Research Institute) one would find new designs of aspiration such as alternating burner ports fire with primary air < 100% in one port and up to ~ 85% excess air in the adjacent ports to achieve ~ 70 ppm. Also there are new burner design to accelerate the velocity of the burning pre-mixture and shorten the residence time besides reducing combustion temperature, with a hemispherical bluff body re-stabilises the flame.

Burners designed for excess primary aeration would have deeper ports and thicker walls than the usual stamped metal burners. Secondary aeration would not be required and could be eliminated by closed combustion chamber or baffles.

### Low Excess Air (LEA) Firing

As a safety factor to assure complete combustion, boilers are fired with excess air. One of the factors influencing NOₓ formation in a boiler is the excess air levels. High excess air levels (>45%) may result in increased NOₓ formation because the excess nitrogen and oxygen in the combustion air entering the flame will combine to form thermal NOₓ.
Low excess air firing involves limiting the amount of excess air that is entering the combustion process in order to limit the amount of extra nitrogen and oxygen that enters the flame. Limiting the amount of excess air entering a flame is accomplished through burner design and can be optimized through the use of oxygen trim controls. Low excess air firing can be used on most boilers and generally results in overall NOₓ reductions of 5-10% when firing natural gas.

**Recirculating Combustion Exhaust Gases**

Recirculation of flue gases could be achieved by:

- Buoyancy
- Aspiration
- Fan

The cooled combustion exhaust gases (mainly molecular nitrogen and oxygen, carbon dioxide and water vapour) are mixed with air entering the burner. The recirculated gases dilute the primary air and lowers the oxygen concentration of the air mixture from ~ 21% by volume to ~ 18%. Consequently the flame temperature is lowered. Research on larger scale applications has demonstrated that NOₓ could be reduced by ~ 75% when the primary air contains ~ 30% recirculated flue gas.

Ducting of the exhaust gases to the fuel/air delivery system would be required. The combustion chamber and heat exchanger of the appliance may become larger to accommodate the higher total gas flow rate and lower flame temperature to maintain baseline thermal efficiency. The burner may have to be upgraded to light and stabilise the fuel-air-exhaust mixture which is more difficult to ignite and slower in combustion, although the warm mixture (if the exhaust gases are mixed at a few hundred degrees C) would alleviate this to some extent. Another concern is that lower flame temperature and oxygen concentration would favour CO formation.

Raghavan and Reuther (1994) pointed out that recirculation of combustion exhaust gases had been used at industrial scale to reduce NOₓ emission but not in domestic application, which is still true. Because of the high NOₓ reduction potential, they felt that domestic application of this strategy should be explored further. Recirculation often requires a fan driven system that may have to work at elevated temperatures and this would increase the cost of the appliance and its operation.

US industrial boiler manufacturer Cleaver Brooks identifies flue gas recirculation (FGR) as the most effective and popular technology for industrial boilers. And, in many applications, it does not require any additional reduction equipment to comply with regulations.

Flue gas recirculation technology can be classified into two types; external or induced.

- **External flue gas recirculation** utilizes an external fan to recirculate the flue gases back into the flame. External piping routes the exhaust gases from the stack to the burner. A valve controls the recirculation rate, based on boiler input.

- **Induced flue gas recirculation** utilizes the combustion air fan to recirculate the flue gases back into the flame. A portion of the flue gases are routed by duct work or internally to the combustion air fan, where they are premixed with the combustion air and introduced into the flame through the burner. New designs of induced FGR that utilize an integral FGR design are becoming popular among boiler owners and operators because of their uncomplicated design and reliability.

Up to a recirculation ratio of 1, this can be done with conventional flames. Above this ratio of 1, the temperature of the burner/combustion chamber have to be involved in the process to keep the temperature level above ignition temperature. Between a ratio of 1 to 3.5 it is not possible to realize the combustion process, but at the recirculation ratio’s of 3.5 and higher there is a flameless combustion reaction in a large surface. This flameless combustion process is known as **FLOX** (Flameless Oxidation). The temperature and re-circulation rates are shown in the picture below (see also Chapter on Burners).
The FLOX technology has been used in industrial burners, but now —through a new collaboration between DLR and WS Wärmeiprozesstechnik— will be further developed for gas turbines.  

FLOX technology can be combined with the staged combustion (see below and Chapter on burners).

**Staging Combustion**

Staged combustion can be conducted in two stages, the first is the fuel-rich combustion with < 100% primary aeration and the second is fuel-lean, with inter-stage cooling such as radiant heat loss from a radiant burner, or heat exchange with air or water. In principle, more stages can be used but the design, manufacture and operation will be more complicated and more expensive.

Staging can be achieved by modifying the gas burner or the combustion chamber, or both. The flame temperature at the two stages is lower than the dual flame combustion using the same overall (primary plus secondary) aeration. In a combined approach for a fan-assisted space heater prototype with a radiant burner, a reduction of NO\textsubscript{x} emission by ~75% was reported (Raghavan and Reuther, 1994).

Design and manufacture of staged combustion gas appliances are more complicated and expensive. Many of the components such as channels, flame holder, ignition system, combustion chamber and heat exchanger may have to be increased in number or in physical size. This will increase the manufacturing cost of the appliance.

In principle, staged combustion can be performed with stable flame without fan assistance, but the problem of increased CO emission and decreased thermal efficiency must be addressed together with NO\textsubscript{x} reduction.

In the US staged combustion techniques are applied in residential low NO\textsubscript{x} burners. Reportedly the US Gas Research Institute (GRI) co-developed boilers and furnaces with staged combustion and internal flue gas recirculation with US manufacturers Burnham, Empire Comfort and Trane, reaching a low NO\textsubscript{x} level of 25-29 ppm at 3% O\textsubscript{2} and CO was found to be less than 50 ppm air-free.

In Europe the use of staged combustion is primarily limited to industrial and commercial boilers.

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**Delaying Combustion**

Different from staged combustion, delaying combustion allows the combustion process to occur continuously rather than at discrete stages, over lower temperatures, to retard NO\textsubscript{x} formation. This is achieved by dispersion, with slower heat release, over larger volumes and time.

Raghavan and Reuther (1994) cited from the literature four examples of burner design to delay combustion, with one suitable for air heaters and the other for water heaters. They recognised that although this approach was effective to lower NO\textsubscript{x} emissions (by up to \sim 75\%) and amenable to a variety of atmospheric or powered burners, the development had been limited, which could be related to higher CO emissions and lower efficiency. The fuel/air delivery might need to be pressurised, the burner, combustion chamber and heat exchanger might need enlargement, and the ignition system might require improvement.

In the EU no examples of delayed-combustion technology were found, probably due to the drawbacks mentioned.

**Humidifying the Fuel Gas, Combustion Air or Flame**

Humidification can be conducted by:

- Spraying water to the combustion air.
- Spraying water to the combustion chamber.
- Spraying steam to the combustion air or fuel gas.
- Spraying steam to the combustion chamber.

Steam dilutes the combustion exhaust in the same way as recirculated combustion exhaust gases. The effect of water is two fold: water evaporates by absorbing a large quantity of heat (latent heat of evaporation) from the combustion system and the steam evolved dilutes the combustion exhaust gases. Both result in cooling the combustion system.

The spraying rate of water to combustion air is restricted by the ambient humidity conditions and the efficiency of water atomisation. The spraying rate of water to the combustion chamber and the spraying rate of steam would depend on flame stability.

The investigation of the humidification for domestic appliances was limited even though the NO\textsubscript{x} reduction could be up to \sim 50 - 60\% (Raghavan and Reuther, 1994). It has not been attractive probably because the efficiency of the system will decrease with humidification, unless steam in the exhaust gases is condensed and the heat extracted is recoverable. Condensation would complicate the combustion system, create corrosion problem and increase the equipment cost.

Humidification has been used in commercial scale continuous gas turbine operation but not in domestic situations. The loss of efficiency in gas turbine application is traded off with the increase in power output by the higher mass flow through the gas turbine.

Under normal operating conditions, water/steam injection can result in a 3-10\% boiler efficiency loss (Cleaver- Brooks).

### 3.6.2 Modification of Gas Burner

Raghavan and Reuther (1994) identified the major modifications of gas burners as follows:

- Flame Inserts.
- Blue-flame burner redesign.
- Blue-flame burner replacement.

**Flame Inserts**

A simple means to reduce flame temperature is to insert a foreign object, such as a solid rod or porous screen, into a blue flame and allow the object to radiate red hot. As part of
the heat liberated is transferred by radiation, the flame temperature is reduced and hence the NOx emissions are reduced. The inserts could be made of refractory metals or ceramics.

Raghavan and Reuther (1994) cited five different flame inserts patented for atmospheric burners:

- A ring shaped solid insert for range or water heater burners.
- A rod shaped solid insert for furnace burners.
- A porous screen insert.
- A solid channel insert for furnaces.
- Small solid fin inserts integral with the burner but not in the flame.
- A perforated radiant insert for fan-assisted power burner was also illustrated.

From the literature search, Raghavan and Reuther indicated that most flame inserts could achieve a ~60% reduction but the CO emissions would typically increase, since the combustion conditions remain the same except at a lower temperature which favours CO formation. Adjusting the position of insert or using secondary-air baffles may alleviate CO formation. Thermal efficiency could be an issue, but it may be overcome depending on the application and design.

Compared to other NOx control techniques, Raghavan and Reuther believed that flame inserts had the least impact on gas appliance component design. However, because of the change in heat transfer and flame shape, heat exchangers, particularly those used in space heaters, might require re-design.

Flame inserts are typical of reducing NOx in atmospheric burners. In the US, new designs are developed by DSL Technologies and Lennoxx.

**Blue-Flame Burner Redesign**

Blue-flame burners could be redesigned either by changing the burner’s thermal mass, port loading, or port design to achieve reduced NOx emissions.

*Thermal Mass*

Cast iron burners are more “thermal active” than the traditional stamped steel and aluminium burners, and are found to emit less (~30%) NOx and CO. This is achieved by dissipating more heat via their high thermal mass (and structure).

Cast iron atmospheric or power burners have been applied to ranges and water heaters to lower NOx (down to < 70 ppm at 0% O2 dry basis). Thermal efficiency was reported to increase slightly (Raghavan and Reuther, 1994).

*Port Loading*

NOx emissions depend on port loading — the heat released per port area per time. It was reported that NOx emissions from atmospheric blue flames could be reduced by half if the port loading was reduced by one third. Reducing port loading is achieved by increasing burner size if the same heat input rate is maintained. Thermal efficiency may increase or remain the same, but CO emissions could increase and flashback may occur.

*Port Design*

Port spacing determines the extent of flame aeration and interaction, which affect NOx formation. If the heat dissipated by the ports is increased and the secondary aeration of flames is improved, NOx emissions can be reduced.

Raghavan and Reuther (1994) described the Worgas hyperstoichiometric burner as an example. The Worgas burner uses a venturi-burner system with unique port spacing and 80 - 160% stoichiometric air requirement. The burner is larger than the traditional Bunsen type blue flame burner. It has improved secondary-air entrainment, yielding violet flames with low and uniform temperature distribution. The butterfly-wing flame shape has the aerodynamics designed to bring combustion products back to the flame.
Laboratory results indicated that the Worgas burners could achieve 40 ppm NO\textsubscript{x} at 3% O\textsubscript{2}, dry basis, which is equivalent to 45 ppm at 0% O\textsubscript{2}, dry basis. Thermal efficiency is claimed to be high, and the technology can be used in boilers, instantaneous water heaters, storage water heaters, and room/air heaters.

**Blue-Flame Burner Replacement**

Blue flame burners have been suggested to be replaced with “flameless” burners which adopt radiant combustion, catalytic combustion, or pulse combustion.

**Radiant Combustion**

Radiant combustion occurs near or within burners which are either porous or ported, and may be fan-assisted. The burners can have different shapes to suit different heat exchangers. In operation, the burners glow in a red-orange colour (> 680°C).

Similar to flame inserts, radiant burners restrict NO\textsubscript{x} formation by lowering the combustion temperature, but in a better and more complete manner. NO\textsubscript{x} emission < 25 ppm and CO emission < 50 ppm O\textsubscript{2}-free have been reported (Raghavan and Reuther, 1994). Facilitated with high excess aeration and reduced port loading, radiant burners could achieve < 10 ppm NO\textsubscript{x} O\textsubscript{2}-free. In combination with staged combustion, NO\textsubscript{x} emissions < 10 ppm O\textsubscript{2}-free was experienced. With proper location of heat exchangers, higher thermal efficiency can be obtained.

Radiant burners are normally larger than blue-flame burners. Modification of other components is often required. Pressurisation of the fuel/air delivery system and filtering may be required depending upon burner port size. Usually the combustion chamber is reduced but the ignition system would require upgrading. The heat exchanger would have to be relocated closer to the burner.

In the US Alzeta Corp\textsuperscript{26} and Global Environmental Solutions are manufacturers. In Australia Bowin\textsuperscript{27} has developed a patented technology in this respect.

Pre-mix radiation burners are the state-of-the-art in the EU. For instance burner-manufacturer Bekaert in Belgium produces metal fibre burners for premixed gas surface combustion, developed by Acotech\textsuperscript{28}. They can be operated in either radiant combustion mode or blue flame surface combustion mode. In the former mode NO\textsubscript{x} emission < 10 ppm at 0% O\textsubscript{2} dry basis is claimed to be achieved. In the latter mode, it is claimed that low NO\textsubscript{x} levels (30 ppm NO\textsubscript{x}) are achieved at 30% excess air. CO emission is claimed to be < 10 ppm. Other advantages such as homogeneous combustion with high modulation rate, high efficiency, low pressure drop, resistance to thermal shock and flashback safety are also claimed. Major boiler manufacturers such as Vaillant, Viessmann and Buderus in Germany, Remeha in Holland, and Ecoflam and Baltur in

\textsuperscript{26} Alzeta: Pre-mix radiant burner with a trade name as Pyrocore/Duratherm from alumina-silica fibres fibres which are formed into either cylinders or flat plates with high porosity. This technology has been used by Alzeta’s OEM partner, Nuovi Sistemi Termotecnic in Italy on domestic boilers and instantaneous water heaters

\textsuperscript{27} Bowin mfg. Pty. Ltd (Australia) Bowin has been manufacturing a number of ultra-low NO\textsubscript{x} flued and flueless natural aerated and powered domestic flue heaters using Bowin’s patented surface combustion technology. The technology is also applicable to domestic water heaters and cooking appliances (John Joyce, personal communication).

The Bowin low NO\textsubscript{x} technology is a hybrid of staged-premixed-radiant combustion technology with a major surface combustion preceded by a minor radiant combustion. In the Bowin burner, air and fuel gas are premixed at a ratio greater than or equal to the stoichiometric combustion requirement.

Combustion is maintained at or adjacent to a combustion surface formed from one or more layers of conductive heat resistant material such as nickel based steel mesh with uniform porosity of 20 - 60% (Australian Patent Document Number: AU-B-64743/90). The porosity provides a flow rate of air-fuel mixture that results in a combustion temperature of 600 - 900°C and radiant heat transfer that maintains the combustion temperature.

Low NO\textsubscript{x} (≤ 2 ng/J or ~ 4 ppm at 0% O\textsubscript{2} on dry basis) and CO emissions have been achieved (as measured by The Australian Gas and Light Company (AGL)). Further reduction in NO\textsubscript{x} emission could be achieved by using baffles, barriers walls or enclosed combustion chamber to restrict or prevent cold secondary air contacting the flame before combustion is completed (Australian Patent Document No.: AU-B-16047/92).

Currently Bowin is collaborating with an Australian water heater manufacturer to develop a prototype low NO\textsubscript{x} water heater using Bowin’s technology.

\textsuperscript{28} A joint Shall/Bekaert company www.acotech.com
Italy have reportedly been using this technology (see Chapter on burners, also for other radiation burner solutions).

**Catalytic Combustion**

Catalytic combustion may be fully catalytic (or simply catalytic), or partial which is also known as catalytically stabilised (Ro and Scholten, 1997).

In catalytic combustion, a catalyst such as palladium or platinum is used to reduce the activation energy of combustion and allow the fuel gas to be oxidised by air at a low temperature of 500 - 1000°C. The reaction temperature is maintained low by effective removal of heat liberated from oxidation to the heating medium. Because the reaction temperature is low, Ro and Scholten stated that NOx levels < 5 ppm could be achieved.

In catalytically stabilised combustion, part of the fuel gas is oxidised by catalytic combustion, and the remaining gas is oxidised by homogenous (blue flame) combustion after or during catalytic combustion. Providing heat is removed from the catalytic system, the product gases from catalytic combustion dilute the exhaust gases from the homogenous combustion and lower the overall combustion temperature, and hence NOx emission, in a way similar to flue gas recirculation.

Ro and Scholten compared the performance of boilers using catalytic combustion and catalytically stabilised combustion. They concluded that catalytically stabilised combustion had a higher reliability because it could be operated as a conventional radiant burner even if the catalyst was poisoned and totally de-activated, and the security and control system required for temperature/combustion control would be more easily developed. Catalytic combustion on the other hand, emitted less NOx and CO, and its method of catalyst coating was easier.

In the review performed by Raghavan and Reuther three years earlier than Ro and Scholten, a catalytic burner used in a gas-fired appliance was cited. The burner surface was a matrix of ceramic fibres interspersed with chrome (catalyst) fibres. NOx emission < 15 ppm and CO emission < 10 ppm O2-free were reported.

Catalytic converters similar to those used in automobiles were also cited by Raghavan and Reuther. The converter completed catalytically the combustion of the products from an earlier fuel-rich combustion with more cool air at a temperature < 540°C. NOx emission from this two-staged combustion was lower than that from a second stage combustion which was non-catalytic but conducted at a higher temperature.

Raghavan and Reuther suggested that the requirements of fan-assistance to overcome the problem of low temperatures and low heat fluxes, larger heat-exchange areas, and smaller combustion chamber volumes might be the main drawbacks of wide application of catalytic combustion to gas appliances.

**Pulse Combustion**

In this mode, combustion occurs intermittently and the combustion gases experience high temperatures for very short time only. Heat transfer from gases to heat exchange surfaces is fast due to high turbulence, which maintains a lower temperature and hence lower NOx emissions.

NOx levels of < 50 ppm were reported, and the technology had been commercialised in residential heating appliances (Raghavan and Reuther, 1994).

The noise level of pulse combustion systems would be high, and this could limit the application of pulse combustion in domestic situations.

Pulse combustion is used by US manufacturers such as Lennox and Empire Comfort Systems. In Europe it is developed by Auer Gianola in a CH boiler "Pulsatoire", the bulk of the applications however are industrial.
3.6.3 Primary NO\textsubscript{x} Control Technology Status

Ro and Scholten (1997) summarised the NO\textsubscript{x} emissions achieved by various types of burners. The results are reproduced in Figure 3-3:

On the basis of the above and the summary of Raghavan and Reuther (1994) the status of different primary NO\textsubscript{x} control technologies around the year 2000 is reproduced in Table 3-4.

Table 3-4. Comparison of primary NO\textsubscript{x} control strategies for residential gas appliances\textsuperscript{*}.
(source: Joynt, B, Wu, S., 2000)

<table>
<thead>
<tr>
<th>Primary NO\textsubscript{x} Control Technology</th>
<th>Likely Lowest NO\textsubscript{x} (ppm, O\textsubscript{2}-free)*</th>
<th>Likely Change in CO Emissions*</th>
<th>Likely Change in Thermal Efficiency*</th>
<th>Technology Status for Domestic Application*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premixed, High Excess Air</td>
<td>~ 20</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Current</td>
</tr>
<tr>
<td>Flue-Gas Recirculation</td>
<td>~ 25</td>
<td>Increase</td>
<td>Decrease</td>
<td>Not Commercialised</td>
</tr>
<tr>
<td>Staged Combustion</td>
<td>~ 25</td>
<td>Increase</td>
<td>Decrease</td>
<td>Current</td>
</tr>
<tr>
<td>Delayed Combustion</td>
<td>~ 25</td>
<td>Increase</td>
<td>Decrease</td>
<td>Not Commercialised</td>
</tr>
<tr>
<td>Humidified Combustion</td>
<td>~ 25</td>
<td>Increase</td>
<td>Decrease</td>
<td>Not Commercialised</td>
</tr>
<tr>
<td>Flame Inserts</td>
<td>~ 40</td>
<td>Increase</td>
<td>Decrease</td>
<td>Current</td>
</tr>
<tr>
<td>Thermally Active Burner</td>
<td>~ 65</td>
<td>Decrease</td>
<td>Increase</td>
<td>Current</td>
</tr>
<tr>
<td>Port-Loading Reduction</td>
<td>~ 50</td>
<td>Increase</td>
<td>Increase</td>
<td>Current</td>
</tr>
<tr>
<td>Port Redesign</td>
<td>~ 45</td>
<td>Decrease</td>
<td>Increase</td>
<td>Current</td>
</tr>
<tr>
<td>Radiant Combustion</td>
<td>~ 4 - 10</td>
<td>Decrease</td>
<td>Increase</td>
<td>Current</td>
</tr>
<tr>
<td>Catalytic Combustion</td>
<td>~ 5</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Not Commercialised</td>
</tr>
<tr>
<td>Pulse Combustion</td>
<td>~ 20</td>
<td>Increase</td>
<td>Increase</td>
<td>Current</td>
</tr>
</tbody>
</table>

3.6.4 Secondary Control of NO\textsubscript{x} Emission

NO\textsubscript{x} can be removed from combustion exhaust gasses in three approaches:

- Selective catalytic reduction (SCR).
- Selective non-catalytic reduction (SNCR).
- Hybrid SNCR/SCR.
These technologies are expensive because consumable reagents and additional NOx removal systems are introduced. Moreover, the additives such as ammonia if not consumed in the process will escape to the atmosphere which would lead to NOx. Until now, applications of secondary control are mostly to power generation and other industrial combustion processes.

In the context of the underlying study they are not considered viable and will not be further discussed.

### 3.7 Low emissions vs heat generator performance / efficiency?

[This text is primarily non-appliance specific: Where the text states 'boilers' one may read this as 'water heaters' as well]

What effect does NOx control technology ultimately have on a heat generators performance? Certain NOx controls can worsen heat generator performance while other controls can appreciably improve performance. Aspects of the heat generator performance that could be affected include turndown, capacity, efficiency, excess air, and CO emissions.

Failure to take into account all of the heat generator operating parameters can lead to increased operating and maintenance costs, loss of efficiency, elevated CO levels, and shortening of the heat generator’s life.

The following section discusses each of the operating parameters of a heat generator and how they are related to NOx control technologies.

**Turndown**

Choosing a low NOx technology that sacrifices turndown can have many adverse effects on the heat generator. When selecting NOx controls, the heat generator should have a turndown capability of at least 4:1 or more, in order to reduce operating costs and the number of on/off cycles. A boiler utilizing a standard burner with a 4:1 turndown can cycle as frequently as 12 times per hour or 288 times a day because the boiler must begin to cycle at inputs below 25% capacity (for water heaters: the outlet temperature is often constant at 60ºC, but the flowrate may differ - requiring modulation).

With each cycle, pre- and post-purge air flow removes heat from the heat generator and sends it out the stack. The energy loss can be reduced by using a high turndown burner (10:1), which keeps the heat generator on even at low firing rates.

Every time the heat generator cycles off, before it comes back on, it must go through a specific start-up sequence for safety assurance. It takes between one to two minutes to get the heat generator back on line. If there is a sudden load demand, the response cannot be accelerated. Keeping the heat generator on line assures a quick response to load changes.

Frequent cycling also deteriorates the heat generator components. The need for maintenance increases, the chance of component failure increases, and heat generator downtime increases. So, when selecting NOx control, always consider the burners turndown capability.

**Capacity**

When selecting the best NOx control, capacity and turndown should be considered together because some NOx control technologies require heat generator derating in order to achieve guaranteed NOx reductions. For example, flame shaping (primarily enlarging the flame to produce a lower flame temperature — thus lower NOx levels) can require heat generator derating, because the shaped flame could impinge on the furnace walls at higher firing rates.

However, the heat generator’s capacity requirement is typically determined by the maximum load in the hot water system. Therefore, the heat generator may be oversized.
for the typical load conditions that may occur. If the heat generator is oversized, its ability to handle minimum loads without cycling is limited. Therefore, when selecting the most appropriate NOx control, capacity and turndown should be considered together for proper heat generator selection and to meet overall system load requirements.

**Efficiency**

Some low NOx controls reduce emissions by lowering flame temperature. Reducing the flame temperature decreases the radiant heat transfer from the flame and could lower heat generator efficiency. The efficiency loss due to the lower flame temperatures can be partially offset by utilizing external components, such as an economizer. Or, the offset technique can be inherent in the NOx design.

One technology that offsets the efficiency loss due to lower flame temperatures in a firetube heat generator is flue gas recirculation. Although the loss of radiant heat transfer could result in an efficiency loss, the recirculated flue gases increase the mass flow through the heat generator — thus the convective heat transfer in the tube passes increases.

The increase in convective heat transfer compensates for losses in radiant heat transfer, with no net efficiency loss. When considering NOx control technology, it is not necessary to sacrifice efficiency for NOx reductions.

**Excess Air**

A heat generators excess air supply provides for safe operation above stoichiometric conditions. A typical burner is usually set up with 10-20% excess air (2-4% O2). NOx controls that require higher excess air levels can result in fuel being used to heat the air rather than transferring it to usable energy. Thus, increased stack losses and reduced heat generator efficiency occur. NOx controls that require reduced excess air levels can result in an oxygen deficient flame and increased levels of carbon monoxide or unburned hydrocarbons. It is best to select a NOx control technology that has little effect on excess air.

**Carbon Monoxide (CO) Emissions**

High flame temperatures and intimate air/fuel mixing are essential for low CO emissions. Some NOx control technologies used on industrial and commercial heat generators reduce NOx levels by lowering flame temperatures by modifying air/fuel mixing patterns. The lower flame temperature and decreased mixing intensity can result in higher CO levels.

An induced flue gas recirculation package can lower NOx levels by reducing flame temperature without increasing CO levels. CO levels remain constant or are lowered because the flue gas is introduced into the flame in early stages of combustion and the air fuel mixing is intensified. Intensified mixing offsets the decrease in flame temperature and results in CO levels that are lower than achieved without FGR. But, the level of CO depends on the burner design. Not all flue gas recirculation applications result in lower CO levels.

**Conclusion**

There is no contradiction between eco-design for low emissions and eco-design for energy efficiency and good performance. In fact, the most effective design measures, such as pre-mix burners, radiation burners (lower temperature), reduction of the number of cycles (e.g. through deep modulation), etc. are equally effective in lowering emissions as in increasing the energy efficiency. There are some exceptions and limitations, e.g. where there is a trade-off with CO and NOx emissions in the combustion temperature, but overall if the designer recognizes these boundary conditions and deals with them appropriately they are not problematic. Overall, there is a great deal of synergy, where intelligent design measures contribute not only to one environmental aspect, but to the whole spectrum of environmental, energy and resources impacts.
References

Cleaver-Brooks, company documentation, 2006


4 BURNERS

4.1 Introduction
This chapter gives a hands-on overview of the current EU burners sold for gas- and oil-fired CH boilers and water heaters. It discusses the trends and the main types and characteristics.

Current burner production is in the hands of both the boiler manufacturers and specialised burner-OEMs. Boiler manufacturers like Weishaupt, Viesmann, Buderus, etc. are mostly manufacturers of jet burners for floor-standing gas and oil boilers. Specialised burner-producers like Bekaert (Belgium), Worgas (Italy), etc. are mainly producing burners for wall-hung gas (combi-)boilers.

4.2 Trends
Over the last two decades there has been a development from the traditional atmospheric burners towards Low-NOx pre-mix burners, typically with lower combustion temperatures. This trend was fuelled by the ‘technology push’ of new high-temperature materials becoming available (e.g. ceramics, metal fibres) and the ‘demand pull’ of better energy efficiency (in part load and during cycling), higher heating comfort and lower (NOx) emissions.

At the moment, this trend seems to have slowed down for a number of reasons.

- In the beginning the new materials had some problems regarding fragility, a too short product life, etc. Currently this reputation is undeserved\(^{29}\) when the burners are applied properly. But it is never easy to remedy first impressions.
- Secondly, pushed by the competition and new insights burner-manufacturers found that they could meet large part—at least a sufficient part—of the legislative emission-requirements with traditional materials like perforated refractory steel\(^{30}\) plate or (half) cylindrical burners.
- Thirdly, although the in the 1990’s the legislators in some countries like Germany and Austria were very active in setting maximum emission limit values for boilers, there have been no updates since and few countries have followed, despite measures such as the EU NEC Directive. Furthermore, as already indicated in the Task 1 report, the CEN has hardly updated their emission measurement methods—which were originally meant only for safety—for a practice of environmental impact. For instance, the EN standards measure at stationary (full load) conditions, whereas in practice 80 (oil) to 95% of emissions of CO, CH\(_4\), C\(_x\)H\(_y\) occur during cycling (start/stop).
- Fourthly, regarding a possible contribution of the burner in improving the energy efficiency heat generator manufacturers have found that they could achieve this also in another, albeit more economical way at the level of the heat exchanger, e.g. recuperating latent heat of condensation.

All in all, this has made the burner into somewhat of a low-interest standard component, where pre-dominantly the most economical pre-mix perforated steel plate version is applied throughout. Prices are in the order of € 8-10, which is hardly more

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\(^{29}\) Manufacturers have solved these problems and e.g. ceramic burners are successfully being used in—mostly larger—burners

\(^{30}\) Temperature resistant, low oxidisation e.g. compare stainless steel.
than the price of an atmospheric burner. For integrated heat generators the plate or (half-) cylindrical versions are used the most.

Yet, as has been argued in e.g. the chapter on emissions, for Eco-design the burner may be far more than a low-interest product.

### 4.3 Types

For the majority of gas- and oil-fired boilers and water heaters there are two types of burners:

- Surface burners
- Jet burners

They can be fan-assisted (pre-mix) or not.

#### 4.3.1 Surface burners

A surface burner is a flat or (half)-cylindrical perforated plate or woven-fibre of metal or ceramic material. Each hole in the plate (‘burner port’) serves as a flameholder. The geometry of the holes, together with the flow and pressure of the fuel and combustion air (or their mixture), determines the shape and the size of each individual flame. Depending on the position of the flame we can distinguish:

- the flame hovers over the burner bed (**free flame**),
- the flame sits at the burner surface, i.e. at burner nozzle exit (**radiation burner**) or
- the combustion takes place inside the burner nozzles (**flameless burner**, e.g.).

All these three options—and their intermediate variations—result in a different heat transmission of the flame to the burner bed and thereby a different temperature of the resulting combustion products and a different share of the radiation energy (from flame + burner) and convection energy. E.g. For gas-fired burners some typical values are:

- the free flame burners: around 5% radiation share and flue temperatures of 1300-1500°C;
- metallic pre-mix burners: around 5-15% radiation share and flue temperatures of 1200-1300°C;
- ceramic surface burners: some 20-25% radiation and flue temperatures of 1000-1100°C and,
- flameless burners: 30-35% radiation and flue temperature of the combustion products leaving the burner bed below 1000°C.\(^{31}\)

The maximum burner load of these burners varies between <100 W/cm² for the conventional pre-mix burners, up to 300-400 W/m² for ceramic surface and flameless burners. Experiments with ceramic burners have even shown burner loads up to 1300 W/cm².

Effectively what is happening with the transition of the traditional free flame burner to the flameless burner, is that the flame is cooled by the burner surface. Or, to put it the other way around, the burner is heated. The figures on the following pages show many variations of these surface burners.

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\(^{31}\) Although inside the burner the flue temperatures may be much higher.
Figure 4-1. Selected metallic surface burners.

**Atmospheric burners, steel plate**
- **[top row]**: round, conventional [left], oval suitable for full pre-mix without fan, lower NOx [top row mid], cylindrical, optimised for use with gas-fired storage water heaters.
- **[top row left]**: round, conventional [left], oval suitable for full pre-mix without fan, lower NOx [top row mid], cylindrical, optimised for use with gas-fired storage water heaters.
- **[top row right]**: round, refractory steel pre-mix burner, modulation range 1:10, emissions akin to Gaskeur SV/Blue Angel level
- **[mid row]**: flat pre-mix burner using metal fibre media, modulation range >1:10, emissions below Gaskeur SV/Blue Angel (i.e. < 40 mg NOx/kWh), burner bed dimensions: 70 x 237, 80 x 355 or 90 x 237 mm (or custom made)
- **[mid row right]**: cylindrical pre-mix metal fibre burner, e.g. diameters 63/67, height <400mm.

**Pre-mix burner, knitted metal fibre**
Compact pre-mix burner, knitted metal fibre welded on foot, optimised for standardisation, low NOx, CO, noise (no resonance).

[source: http://www.bekaert.com/ncdheating/Home.htm]
Figure 4-2.
Ceramic radiation burner. Standard size is 250 x 250 mm. Thickness 3.2 +/- 0.5 mm. Standard perforation is 1.4/2.8 or 1.5/3.5 (other sizes and perforation on request. Operating range: Min. 10 W/cm², Max. 400 W/cm². Radiation range: 10 - 75 W/cm². Modulation range 1:35. Maximum surface temperature 1000 °C. Pictures refer to short heat-up time 2-3 s (top-left), quick cool-down 2-3 s (top right), low pressure drop +/- 10 Pa (mid left), ceramic fibre material covered with SiC through CVD/PVD-process (mid right), small burner plate height of 3.5 mm with holes 1.5 mm → permeability 95% (bottom left), front view of burner in action (bottom-right)
(http://www.schott.com/gasburnersystems/english/)

Figure 4-3.
Radiation burner Viessmann ‘off’ (left) and in operation (right). Emissions in boilers NOx: <15 mg/kWh, CO: <15 mg/kWh
Figure 4-4a.
Porous ceramic burner (SiC). Maximum load: 300 W/cm². Modulation range: 1:20. Thickness 15 mm. Low CO: <20 mg/kWh and low NOx: <20 mg/kWh, also during burner cycling operations (on/off). Picture left: www.poreos.com

Figure 4-4b.
Ceramic ‘flameless’ burners. From Left to Right: Ball burner (D. Kugelschüttung), knitted ceramics, mixing/woven burner, ceramic foam [source: Dietzinger, 2006]

Figure 4-5.
Ceramic porous burner: Propagation of temperature with a methane/air mix. The graphs show an experiment whereby the temperature is measured in the flame barrier and throughout the thickness of a 20 mm porous ceramic burner. Note that the initial temperature after ignition is close to the calculated adiabatic flame temperature and that the combustion products –while giving off their heat to the burner—cool down to a level <1000°C already 10 mm after the burner surface. Left= 1 kW; Right= 5 kW with the same burner but different flame barriers [source Dietzinger 2006]
Figure 4-6.
Components of an experimental porous ceramic burner. From left to right: Burner bed in silicium carbide (SiC) foam 10 ppi produced by fa. Erbicol, Al2O3 fibre-based insulation ring, Al2O3 fibre-based hole plate for ceramic burner.
[source: Diezinger, Stefan, Mehrstofffähige Brenner auf Basis der Porenbrennertechnik für den Einsatz in Brennstoffzellensystemen, dissertation Technical Faculty of the University of Erlangen Stuttgart, 2006 (http://www.opus.ub.uni-erlangen.de)]

Figure 4-2 shows a thin ceramic radiation burner from the German manufacturer Schott. In this design the flames typically sit on top of the burner bed (radiation burner). The graphs show that this particular ceramic fibre burner has a quick heat-up (<5-10s) and cool-down (<2s) compared to competing burners.

Another radiation burner, made of a semi-spherical mesh of stainless steel, is shown in Figure 4-3 (production Viessmann).

Figure 4-4 relates to several types of ceramic ‘flameless burners’ and in particular a burner made of porous ceramic foam, developed by the University of Erlangen and marketed by the firm Poreos in Germany. The burner can be very compact (high heat load per surface area) and have low NOx and CO emissions (< 20 mg/kWh = 12-13 ppm at 3% O2). However, because of its price and long heat up time it is probably more suited for industrial applications than for residential boilers or water heaters.

An interesting feature of the thick porous ceramic burner is the fact that the temperature curve through its 20 mm section can be studied. Figure 4-5 shows two examples of such a temperature curve, showing that —although the measured ‘combustion temperature’ at the burner exit may be as low as 1000°C— in reality inside this flameless burner much higher temperatures of around 1500°C are reached. Figure 4-6 shows the components of the porous ceramic burner.

4.3.2 Jet burners
In principle, a jet burner is nothing more than a nozzle for the fuel/air mix. In case of an atmospheric burner the nozzle and preceding induction trajectory creates a venturi effect through which the fuel sucks in a part of the combustion air (the primary air), after which the rest of the air (secondary air) is sucked in by the flame itself. In case of a full-premix burner, the fuel and all the combustion air are already fully mixed in the right proportion before they are being conducted through the nozzle. A pre-mix jet burner usually requires a fan, which —together with the gas valve, ignition and combustion controls— sits in a self-contained unit, which is then often referred to as ‘jet burner’.

Figure 4-7 gives an illustration of a jet burner. This particular jet burner is oil-fired, which means that apart from the combustion head, the fan, ignition and combustion control it also contains an oil pump and atomizer to induce the oil droplets into the air stream. Details of the oil nozzle are given in Figure 4-9.
As mentioned, jet burners are fully self-contained and can be mounted on any heat exchanger body with EN standardised attachment for the burner flange (see Figure 4-7). The units cost around €800 to €1200,- for the 15-30 kW range and around €1500,- or more for 100 kW (prices Germany, incl. VAT 16% 32).

Figure 4-7.
Jet burner assembly
1 = heat exchanger body with control unit
2 = jet burner
3 = indirect cylinder (sanitary hot water)
4-6 = options
(www.viessmann.com)

Figure 4-8.
Weishaupt oil-fired jet burner WL5. Capacity: 16,5-50 kW. Dimensions excl. combustion head 292 x 286 x 308 mm
(www.weishaupt.de)

32 www.heizungsfachshop.de
Market trends in the field of jet burners for CH boilers (also feeding separate DHW cylinders) seem to go more in the direction of aesthetics, reliability, design, electronic controls, etc. (names: Weishaupt, Buderus, Riello).

In the field of higher energy efficiency and low-emissions most innovations seem to be in the field of industrial burners in Europe. Main developments are in the use of combustion air, i.e. not only through the air factor but also by preheating the incoming air in any number of ways or by mixing the incoming air with the combustion air. These techniques are known as

- recuperator burners (preheating incoming air at burner level),
- regenerator burners (using a heat storage medium and intermittent operation to exchange heat between flue gases and incoming air),
- FLOX burners (high re-circulation rates of flue gases with flameless oxidation)
- Multi-stage combustion (below-stoichiometric pre-combustion)

Especially in the field industrial jet-burners there are new developments regarding the realisation of the cooler flame through recuperator or regenerator techniques. With *recuperator*-burners the cooler flame and the energy saving is achieved by using/pre-heating the incoming air with the combustion products.

With *regenerator* techniques the waste heat recovery is achieved through an intermediate heat storage medium that is intermittently cooled by the air and heated by...
the flue gases. This technique requires high valve activity and a very integrated construction, which is probably beyond the scope of most domestic burners/boilers.

Another technique is the re-circulation of flue gases into the combustion process. This has been explained in the chapter on emissions and entails either recirculation rates of 1 with conventional flame technology, or recirculation rates of 3 and higher with the flameless oxidation (FLOX) technology.

The flue gas re-circulation technique, subdivided between internal and external re-circulation, can also be combined with other technologies that reduce NOx emissions. One such technique is the staged combustion (D. Gestufte Verbrennung), whereby the fuel-air mixture is first combusted at below-stoichiometric conditions (air factor < 1) in a pre-combustion chamber and then brought into the main combustion chamber where secondary air is added. This also leads to a reduced flame temperature and lower NOx. This effect can be vastly increased by a combination with the FLOX operation, where the high flue-gas re-circulation is achieved in two ways: firstly by the impulse of the gas jet and secondly by a delay in mixing the combustion air with the fuel. \[^{33}\] This is shown in the Figure 4-10. \[^{34}\]

\[^{33}\] Note that in a FLOX there is no flame and therefore the conventional UV or ionisation flame sensors cannot be used. Instead the temperature in the combustion chamber is used as a parameter.

\[^{34}\] Please note that developments in this field are not concluded; especially in the field of emissions of Particulate Matter (PM) with oil-fired FLOX-burners some problems have been reported.[Ökozentrum Langenbruck]
4.4 Control of burner output (power)

4.4.1 Modulation

Controlling the burner-output between the range of 100% back to 30% of the nominal load, is already quite common for gas condensing (combi)boilers. The most common type of boiler is a 24 kW combi boiler. As a result, the minimal power input (30% of 24 kW) is around 8 kW and the boiler may still cycle on and off during low flow DHW demand.

Several companies are already developing techniques to further reduce the modulation range, preferably up to 10% of nominal load. Since most boilers that are either fan assisted or fully premix, the modulation control not only affects the gas valve, but also the fan.

4.4.2 Pneumatic ratio-control

Most commonly applied technique for modulation is the pneumatic ratio control. With this type of control the BCU (boiler control unit) sets the rotation speed of the fan, based on the requested feed temperature or heat demand. The air flow resulting from this fan speed, causes a specific air pressure that is sensed by a control membrane or venturi of the pneumatic ratio control unit. Based on this pressure-difference the gas valve opening is adjusted. These control techniques compensate for weather conditions like changes in temperature of barometric pressure.

Pneumatic ratio-control systems operate without problem to modulation ranges up until 1 : 4. At increased control ranges, the resolution of the measured pressure differences becomes too small and the control principle becomes unstable.

One way of solving this is the use of an extra diaphragm which increases the available air pressure at the pneumatic ratio control unit. With a similar device that increases the pressure over the gas valve in the same proportion, the pneumatic ratio control unit can function again, but now at higher resolutions.
4.4.3 Integrated mixing & control valve

Another technique that is being developed is the IMS control, “Integriertes Misch- und Stellventil”. This development project (by Kromschröder, Ruhrgas and Remeha) also aims at improving the modulation range to 1:10. The IMS is a system that is a combined mix- and control unit, using two valves that are both controlled by a motor. The motor adjusts the position of both valves. The position of the gas valve is based on the requested heat load, the position of the air valve is derived from that.

![Figure 4-14. Principle of the IMS-control](image)

A relatively high flow speed of the combustion air insures good system stability also in the lower regions of modulation. The fan is positioned between the IMS and the burner and if the burner is switched off, the IMS closes, which decreases convection losses over the burner in the off-mode.

![Figure 4-15. CO₂-percentages at varying power inputs](image)

More technologies are being developed for controlling the fuel/air-ratio. Main driver however is not the burner modulation, but the changing enthalpy of the fuels, due to the use of different gas-qualities.

Related techniques are discussed in the next paragraph.

---

**Pressure sensor switch**

The pressure sensing switch is sensor/actuator – combination used in gas combustion appliances in which the combustion air is fully dependant on the fan (as in premix burners). Therefore, the air flow needs to be closely monitored.
4.4.4 Fuel/air ratio control

The liberalization of the EU-gas markets forces distribution companies to allow gases from different suppliers into their networks. Already today gases of different suppliers and qualities (including tests with bio-gas and hydrogen) are mixed and supplied into the network. As a result the enthalpy or Wobbe index of the supplied gas may change, causing a shift in the air factor $\lambda$ (fuel/air-ratio). Varying gas qualities will cause higher emissions and a lower boiler efficiency, unless control systems are used that measure either the quality of the fuel or the quality of the combustion and adjust fuel/air-ratio likewise.

Figure 6-10 gives an impression of the magnitude of the air ratio shift due to gas quality variations.

A design point of air ratio $\lambda = 1.3$ for methane was taken as a reference and the resulting air ratios of some other gases used in Germany are compared. The figure shows air ratio shifts of 1.2 to 1.61 (adjusted for different gas densities).

As a result of these shifts in air factor, emissions will show large variations, flames might blow off, thermo-acoustic resonance could occur and efficiencies may drop considerably. Especially for condensing boilers, the efficiency drop is important because not only the flue gas losses increase (higher exhaust flow volumes) but also the dew-point is lowered due to a shift of the partial pressure of the water vapour.
Figure 4-18 summarizes the parameters that can be used to measure and control the fuel/air-ratio.

Parameters that can be measured **before** combustion:
- specific mass;
- viscosity;
- thermal conductivity;
- sonic speed;
- substance.

Parameters that can be measured **during** combustion:
- flame ionization;
- flame radiation;
- temperature.

Parameters than can be measured **after** combustion:
- oxygen;
- CO;
- NOx.

A lot of research has been done over the years to design, build, and test the various options. Some of these R&D activities have actually evolved in solutions that are applied today in state of the art boilers/water heaters.

**Measurement of flame ionization**

This technology is based on the measurement of the ionization voltage over flame and gas mixture. This ionization is already used for flame-control reasons (in case no ionization signal is measured, there is no flame and the gas valve is closed). With additional electronic circuitry the intensity of the ionization signal can be measured. And because the flame temperature (ionization voltage) is directly related to the air factor, the ionization signal is a indication for the quality of combustion.

For surface burners with laminar flames the relation between ionization signal and air factor is unambiguous and similar to a parabolic curve (see Figure 4-19). The maximum ionization signal is always measured at air-factor $\lambda = 1$. This point is used for the automatic calibration of the combustion control system.

![Figure 4-19. Typical curve for the ionization signal. Source: VSG](image)

Next step for a fully functional combustion control system is to use this ionization signal for an active control of the gas valve and the fan. Weishaupt uses this type of active combustion control in their wall hung gas condensing boilers called Weishaupt – Thermocondens.
Figure 4-20.
Schematic representation of combustion control system using the ionization signal. (In Germany this technology is called SCOT, meaning System Control Technology).

![Combustion Control System Diagram]

Viessmann uses this technology in the VITODENS boilers, and they gave it the name “Lambda Pro Control”.

Buderus uses the ionization signal for controlling the gas supply in their atmospheric gas fired LT-boilers.

Many of these boilers are available as combi_storage boilers (central heating boiler with integrated DHW storage).

**Measurement of O₂**

Oxygen sensors are already in use for some time now in cars and gas motors. They control the air-factor within the limits set by the catalytic reformer. The amount of oxygen in flue gases can directly be related to the combustion quality and the air factor and O₂ analysis therefore could offer proper feedback related to combustion control. However there are certain drawbacks. Heat generators are usually operated at slightly negative pressure. Any leaks cause air to be drawn in and as a result the O₂ readings in the stack will be higher than those actually found in combustion zone. Also, stratification of stack gases can make O₂ sampling at a single point inaccurate.

Several companies have tried and are trying to apply these sensors for combustion control in residential boilers / heat generators as well, but so far didn’t succeed in getting the technology beyond prototype stage. Sensor stability and price remain as the prohibitive thresholds.

Figure 4-21.
Relation between air-factor λ and CO, excess O₂ and NOₓ

![Air-factor Lambda Diagram]

For a car the sensor would need an operational lifetime expectancy of approximately 4,000 hours. For a boiler one would need 30 to 40,000 hours.
**Measurement of CO**

The other flue gas component than can be measured for combustion control purposes is CO.

CO is a product of incomplete combustion which will combine with oxygen to form CO$_2$ if sufficient O$_2$ is available. Ideally, if combustion is complete, the level off CO will drop to zero. Since complete air/fuel mixing is not possible, the practical level of CO for control purposes is usually < 160 ppm.

Using CO to trim combustion control systems offers an advantages over O$_2$/trim: the CO control point remains constant for all types of fuels.

![Construction of CO-sensor used by Vaillant.](image)

Vaillant GmbH developed together with Steinel Solutions AG a CO-sensor based on a Ga$_2$O$_3$ sensor platform.

Based on the information from the CO-sensor the also new gas valve / safety valve assembly is operated with a step controller, which again influences the fan rotation speed.

The CO-sensor can also be used to detect wear to components like the fan or pollution of the burner, resulting in more efficient maintenance schemes.

**Measurement of viscosity**

Gas quality can be expressed by the Wobbe number. The Wobbe number correlates with the dynamic gas viscosity, according to the figures given in Figure 4-23.

![The correlation between the Wobbe number and the viscosity is well known since a long period of time but so far not used for combustion control purposes. Only due to](image)
developments in micro technology a compact sensor design became possible. The Institute of Fluid Mechanics of the University of Erlangen – Nuremberg, Germany, developed a prototype of a viscosity sensor and tested the principle on a test rig.

The principle could work but additional development on the sensor part (based on capillary viscosimetry) is needed.
5 Heat Exchangers

5.1 Introduction

This section focuses on the type of heat exchangers found in (combi-)boilers and dedicated gas- and oil-fired water heaters. In principle a heat exchanger is a thermal device in which heat is exchanged between media. The three basic principles for heat transfer are:

- **Direct**
  Direct contact between two media (e.g. steam or gas through water).

- **Regenerative**
  Heat is transferred through an intermediate material that cycles between receiving and transferring heat; (e.g. electric emitters with thermal store or warmtewiel)

- **Reculperative**
  In a recuperative heater the media are always separated with a thin wall through which the heat is transferred, mainly through convection and conduction. The influencing parameters are $A$ (= size of surface), the shape of the surface, thermal conductivity of the material used, speed and flow characteristics of the media, direction of the flow (counter, cross or parallel flow).

For boiler- and water heater-applications the recuperative heat exchanger is predominantly used. However, to illustrate that a direct contact heat exchanger technically also is feasible, the principle of a prototype that achieved a constant thermal efficiency of 96% is shown below.

Figure 5-1.
Schematic diagram of the direct contact heat exchanger system. Source: Caddet Energy Efficiency projects, Result 438.

In the following paragraphs the recuperative heat exchanger will be further analysed in terms of its design aspects and application in boilers for primary, secondary and tertiary
heat exchangers. In this type of heat exchanger, heat is transferred through a combination of the three mechanisms: conduction, convection and radiation. In heat exchangers for combi boilers/water heaters, convection is the most important part in total heat transfer (appr. 60 – 80%, see chapter..). Depending on the type of burner/heat exchanger configuration, the heat transfer through radiation may vary from 5 to approximately 25%.

To give some more detail on the energy transfer processes, the general formulas mentioned in the previous chapter (Basic energy and mass balance) are elaborated on (see box below).

The total heat transfer coefficient “U” of a heat exchanger through convection can be expressed with the following formula, (calculates to total heat transfer resistance).

$$\frac{1}{U} = \frac{1}{\alpha_h} + \frac{d}{\lambda} + \frac{1}{\alpha_c} + R_f$$

In which:
- $\alpha_h$ = heat transfer coefficient on the gas side of the HE [W/(m²K)]
- $d$ = wall thickness [m]
- $\lambda$ = thermal conductivity of HE material [W/(mK)]
- $\alpha_c$ = heat transfer coefficient on the cold side of the HE [W/(m²K)]
- $R_f$ = heat transfer resistance caused by corrosion & pollution [W/(m²K)]

The total heat transferred through convection can be calculated with:

$$Q_{\text{conv}} = U \cdot A \cdot (T_g - T_c) \ [W]$$

The total heat transfer through radiation of the burner towards the HE can be expressed with the formula:

$$Q_{\text{rad}} = \psi_{b-he} \cdot A \cdot \varepsilon_{\text{res}} \cdot \sigma_s \cdot (T_g^4 - T_w^4)$$

In which:
- $Q_{\text{rad}}$ = the radiation heat energy [W]
- $\psi_{b-he}$ = exchange factor between burner surface and HE-surface [-]
- $A$ = the surface of radiating part (burner in this case) [m²]
- $\varepsilon_{\text{res}}$ = the resulting emission-factor [-]
- $\sigma_s$ = the constant of Stefan-Bolzmann: $5,67 \cdot 10^{-8}$ [W/ (m²K⁴)]
- $T_g, T_w$ = temperatures of the gas and the wall in [K]

Indications for the exchange factor $\psi_{b-he}$ can be calculated with the absorption factor method of Gebhart (not further explained here), and largely depends on whether both surfaces can “see” each other and on the emission factors of both materials.

The design parameters for optimising the heat-exchange process are:
- thermal conductivity ($\lambda$) of the material used [W/mK];
- wall thicknesses [m];
- surface area (the bigger the better) [m²];
- flow characteristics (on both sides of the heat exchanger) [turbulent, laminar, etc.];
- burner/HE – configuration [radiation / convection / conduction component].

For the overall boiler/water heater design however, other design aspects need to be integrated here, amongst which:
- HE- weight;
- HE- size;
- Reaction time HE on changing heat loads;
Corrosion / foul-up / maintenance.

For boiler/water heater manufacturers the developments in heat exchangers over the last decades can be characterized firstly by the optimization of the standard cast iron (primary) heat exchangers for floor standing LT-boilers (e.g. with with separate storage cylinder), by improving the heat exchange performance (up until the dew point of flue gas) and by improving the material resistance for corrosion. Manufacturers however, not only improved upon the floor standing standard boiler – and by doing this they prolonged the life of the cast-iron HE—, most of them also developed new light weight heat exchangers and started to apply other materials than cast-iron (being not the best process/material-combination for light weight heat exchangers). Main reason for this was the clear market trend towards wall hung modulating (combi-)boilers with efficiencies up until dew point (< 90% GCV). This represented another reason for re-evaluating and redesigning the cast-iron heat exchanger. Light-weight materials and heat-exchangers became the preference, and the application of the cast-iron heat-exchanger (non corrosive alloys) remained in the segment of floor standing LT-boilers plus the shrinking market for standard boilers.

A second important trend that characterizes the last two decades is the integration (or combination) of the sanitary hot water heat exchanger with the CH- heat exchanger. A lot of different approaches were used, varying from instantaneous appliances with a sanitary HE within a CH–HE, to combinations of both were the sanitary HE is no more than a small plate HE or tube HE in a small storage tank, to solutions were large storage tanks are used, either for CH of sanitary hot water.

The third element that is typical for the HE- development trends, is the optimization op the primary heat exchanger beyond the dew point of the flue gasses (condensing boilers). Secondary heat exchangers were integrated (gas boilers) or added (floor standing oil boilers) to the primary heat exchangers, and again non corrosive light weight materials were preferred.

More companies started to outsource the development and production of these condensing heat exchangers, mainly because –coming from cast iron primary heat exchangers— the knowledge and hands-on experience needed for the design and manufacturing of these new type of integrated light-weight and condensing heat exchangers were not always available within the company.

Boiler manufacturers without the historical burden of a foundry obviously took the lead here, because they could fully concentrate on the condensing boiler only.

The last decade can be characterized by a further optimisation of the different he-solutions that were selected by the various boiler manufacturers, meaning:

- further optimisation of DHW production efficiency;
- reducing maintenance cost (by improving material specs);
- cost-price optimisation by a further integration of functions within the HE-assembly (integration with burner, air-vent, flue ducts, condensate collector and piping);
- cost-price optimisation through improvement of component commonality throughout the product range and through rationalisation of production.

5.1.1 Materials

Apart from cast-iron, the other materials that are predominantly used for primary and secondary heat exchangers in boilers and combis, are aluminium alloys, (stainless) steel and copper alloys.

The thermal conductivity \(\lambda\) varies quite a lot: stainless steel 27 [W/mK], cast iron 60 [W/mK], aluminium 237 [W/mK] and copper 390 [W/mK]. The advantage of stainless steel over cast iron is, that wall thickness can be reduced to far below 1 mm, while with cast-iron approximately 2.5 mm is the minimum. Since heat transfer also depends on the wall thickness and total surface, steel is the better material when size, weight and
cost need to be optimized. For this reason steel can also compete with cast aluminium. Another advantage of (stainless) steel is its resistance to corrosion and thermal cycling. Copper has the best thermal conductivity and can be produced – like aluminium and steel – in thin plates or strips. Copper is also commonly used for sanitary (hot water) application (including heat-exchangers); main drawback is the price per kg (approximately 3 to 4 times higher than stainless steel).

For floor standing boilers (relevant for water heaters with storage tank) the materials are cast iron or steel or a combination of both, in most cases combined with jet-burners. For the smaller and lighter wall-hung boilers (relevant for instantaneous combis) aluminium, steel (finned tubes) and copper are mostly commonly used.

5.2 Typology

Apart from the material (\(\lambda\)) that is used, the shape and surface of the HE plays an important role in the optimization of the heat transfer through convection and radiation.

Shape and overall design however strongly depends on the basic (semi finished) material that is used. This can be tubes, plates or the raw material being casted in the requested shape.

An overview of types of heat exchangers in gas-/oil-fired water heaters, including combi-boilers can be structured according:

- heat transfer media (flue gas, CH water, DHW, combustion air),
- material/shape combination (cast iron, fin-tube, etc.)
- application (HEs for heating only boilers, instantaneous combis, etc.)

Please note this overview does not include heat exchangers found specifically in separate storage cylinders, although the same materials and shapes may apply (like for boilers with integrated storage).

The overview shows that multiple types of heat exchangers can be found in a single appliance (i.e. a combi-boiler with primary fin-tube heat exchanger and a plate heat exchanger for DHW production). Also the same heat exchange principle can be found in various product groups (the shell-tube HE is applied in large heating only boilers as well as gas storage water heaters).

<table>
<thead>
<tr>
<th>Table 5-1. Heat exchangers - an overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common description</td>
</tr>
<tr>
<td>Material (for conventional DHW)</td>
</tr>
<tr>
<td>Typical application</td>
</tr>
<tr>
<td>boilers with separate DHW storage</td>
</tr>
<tr>
<td>combi-boilers with DHW storage (\geq 15\ l)</td>
</tr>
<tr>
<td>combi-boilers with DHW storage (&lt; 15\ l)</td>
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<tr>
<td>combi-boilers without DHW storage</td>
</tr>
<tr>
<td>gas storage (no CH)</td>
</tr>
<tr>
<td>gas instantaneous (no CH)</td>
</tr>
<tr>
<td>Heat transfer direction</td>
</tr>
<tr>
<td>flue gas to CH water</td>
</tr>
<tr>
<td>CH water to DHW</td>
</tr>
<tr>
<td>flue gas to DHW</td>
</tr>
<tr>
<td>flue gas to comb. air</td>
</tr>
</tbody>
</table>

Eco-design Water Heaters, Task 4, Final | 30 September 2007 | VHK for European Commission
Primary heat exchangers are designed to transfer heat up to the dew point of the flue gases, secondary heat exchangers are designed to extract heat beyond the dew point and thus create the condensing mode of gas/oil combi-boilers and water heaters. The tertiary heat exchanger is purely intended as an efficiency booster, to extract even more heat from the flue gases. It can only be applied in conjunction with a primary and secondary heat exchanger.

It is of course very likely that there are heat exchangers applied in gas/oil water heaters or combis that are not described above. However to indicate ALL possible variations would not help to structure the main trends as intended in the table above. The table is not exhaustive.

The following sections describe aspects of heat exchangers as applied in DHW systems. Since the design of a (combi)boiler or water heater is usually centered around the heat exchanger as the main component the overview also functions as a first introduction into types of (combi)boilers / water heaters available.

### 5.2.1 Cast iron heat exchanger

As described above the cast-iron heat exchanger is among the oldest principles/designs of heat exchangers. It is still applied in heating-only boilers with DHW supplied by an external cylinder equipped with a CH to DHW heat exchanger.

Boilers with cast-iron HE can be characterised as heavy, slow responding types of boilers with high primary water content (lots of water in the primary flue gas to CHW heat exchanger) which also adds to its weight.

![Figure 5-2](image1.png)

Vitogas 100 kW22. Floor standing atmospheric gas fired LT-boiler with cast-iron heat exchanger; Viessmann. Part load eff. 85% (GCV), Net weight: 119 kg. Water content: 9.7 l.

In the UK and Ireland there has been a market for cast-iron wall hung boilers. Nowadays these boilers often do not meet the demands of Part L of the Building Regulations.

![Figure 5-3](image2.png)

Buderus Logano G125 21kW. Floor standing oil fired LT boiler with cast iron heat exchanger. Part load eff.: 90% (GCV), Net weight: 175 kg. Water content 33 l.
5.2.2 Shell-tube heat exchanger

The “Shell & Tube” heat exchanger is based upon a tube- or pipe-arrangement placed within a shell that contains the connections for the two flows. Shell-tube HEs can function both as water-to-water HEs or as flue gas-to-water HE and are applied in many industrial applications. Here - for residential use - the main application is flue gas-to-water heat exchange.

Flue gasses are guided through the tubes, while boiler water circulates between the outer shell and the tubes. In the industry, this still is the most applied type of heat exchanger since it is very robust, especially towards flows containing particles. But also for small scale heat generators for residential applications, all kinds of variations on this type of HE are commonly used.
Heat exchangers based on plates
A variant of the shell-and-tube heat exchanger is the "shell-and-plate" heat-exchanger. Instead of tubes the flue gases are led to a construction with a (broadly speaking) flat plate surface (the plate can be circular or butted so that three-dimensional shapes are present).

Also for shell-and-plate heat exchangers it is possible to add fins to the surface and achieve higher heat transfer coefficients. Plates and corrugated fins (deformed plates) are then collated together in a sandwich construction.
Shell-tube heat exchangers are also redesigned to function as dual heat exchangers, for CH and DHW.

A special configuration of the “Shell & Tube” principle in the concentric tube-in-tube HE. In the boiler industry this type of HE is used for instantaneous combi appliances. This HE can both be used as a separate secondary HE for hot water production, or as a combined primary HE in the burning-chamber, heating both flows (CH- and sanitary water) at the same time (flue gases heating the outer tube which is used for CH operation. The inner tube is used as CH to DHW heat exchanger and is essentially a sort of submerged coil HE).

![Figure 5-9](image)

Figure 5-9
Tube-in-tube heat exchanger (as variant of shell-in-tube)

Another variation is the Daalderop Combifort which has a burner located at the top of a storage tank which directs flue gases through a shell-tube type heat exchanger to the bottom of the tank. The heat is first transferred to the CH circuit and from there to the DHW storage.

![Figure 5-10](image)

Figure 5-10: Daalderop Combifort

The figure above even shows a third coil-type heat exchanger that functions as a heat exchanger for a secondary CH circuit.

5.2.3 **Fin-tube heat exchanger**

Finned tube heat exchangers are probably the most commonly applied for light-weight wall-hung boilers and combis and probably represents the archetypical heat exchanger applied for DHW. The fins are added to the tube/pipe to increase the heat transfer through convection on the gas-side (outside) of the tubes. To improve the heat transfer on the inside of the tube (water-side) grooves can be applied.
Figure 5-11. Most commonly applied finned tube heat exchanger for wall-hung non condensing boilers, combis and water heaters. Fins or plates are brazed unto the copper pipes, the surface is hardened by shot blasting and painted with a silicone-aluminium mixture. This subassembly is placed within a casing (shell) on top of the burner (source: Fugas Italy).

Figure 5-12. Heat generator of instantaneous dedicated gas-fired water heater exposed (Picture: eBay)

Figure 5-13. Viessmann Vitopend 200 (24 kW). Wall-hung premix modulating fan assisted gas boiler, with light-weight finned tube heat exchanger. Part load eff.: 85% (GCV). Net weight: 48 kg. Water content: 0,55 l.

Several techniques are used to manufacture the finned pipes, like brazing, welding (high frequency /resistance), rotary extrusion (in case of aluminium) etc.
Other options to apply fins are illustrated below.

**Figure 5-14.**
Solid fin, in the form of a metal strip: The fin is helically wound around the specified pipe/tube and continuously fillet welded to the tube using the M.I.G. weld process (source: Tex-Fin, USA).

**Figure 5-15.**
Longitudinal fin: Fin in the form of a U-shaped fin channel, is resistance welded along the tube’s longitudinal axis (source: Tex-Fin, USA).

**Figure 5-16.**
Serrated Fin: A metal strip that has been serrated or cut and then helically wound around the specified tube. The fin is welded to the tubular base using a high frequency weld process (source: Tex-Fin, USA).

**Figure 5-17.**
Extruded fin: This finned surface is formed as a thick walled aluminium tube is put through cold rotary extrusion, forming fins that are much longer in diameter than the original tube. This process hardens the aluminium so the fins are very strong, resulting in good heat transfer efficiency and high durability. It can be applied to single aluminium tubes (mono aluminium) or with the addition of a liner tube within the original aluminium tube (bi-metal) (source: UniFin, Canada).

**Figure 5-18.**
Twisted Tubes™: It is also possible to twist the whole tube, causing a turbulent flow both inside and outside the tube. According to the manufacturer heat transfer increases with roughly 40% (source: Brown Fintubes).

To improve the heat transfer coefficient on the inside of a tube the following options are available.

**Figure 5-19.**
Inner grooves: Inner grooved cooper tubes achieve a high energy transfer coefficient inside the tube at low pressure drop.

**Figure 5-20.**
Inserts: Another way to improve heat transfer on the inside of the tube is to add inserts into the tube that influence the flow characteristics of the boiler water. The left picture is an illustration of an internal wire matrix and the right picture is an example of a “twisted tape” insert.
The fin-tube configuration is not only used in the traditional kitchen water heater (geiser), but also in the latest high efficient condensing boilers, however without the fins, but with a flattened tube to increase surface area.

The condensing mode (at low temperature of primary water) is achieved by an extra coil which functions as the secondary heat exchanger. This coil is divided from the primary coil and burner by a well insulated deflector disc. The cold return primary water enters the HE in the last segment of this secondary coil and exits the HE at the first segment of the primary coils close to the burner. Because of its configuration and material, a relatively large part of the radiation heat is transferred to the boiler water, which can reduce the amount of material needed compared to a heat exchanger with mainly convective heat transfer.

This type of heat exchanger is being applied by several condensing boiler manufacturers, to name a few: Remeha (Avanta en Aquanta), Vaillant ecoTEC, Viessmann Vitodens.

Another variant of the fin-tube principle is the combination of fin-tube with an internal coil HE. This type of heat exchanger is able to simulatneously produce both CH and DHW.
5.2.4 Aluminium die-cast heat exchanger

Various boiler manufacturers use their own integrated casted heat exchanger. Some manufacturers still use cast iron as base material (floor standing boilers) but the many companies already changed to aluminium alloys. The advantage of this approach is that casing and heat-exchanger and all necessary connections can be integrated into the castings, reducing the number of components and assembly times.

Another advantage of this integrated approach is that heat exchanger design can be further optimised for radiative heat transfer, by creating a configuration where the burner surface is fully surrounded by the water containing heat exchanger surface.

A few design- and engineering companies are specialised in this field.

Figure 5-24. Ferroli Dual Heat Exchanger as found in the Domitop range.

Figure 5-25. Integrated aluminium HE by Aluheat.
The company Aluheat (taken over by Bekaert may 2006) designed a new family of condensing heat exchangers. This new product line is available for all boiler manufacturers.

Characteristics
+ available in capacity of 28 kW, 36 kW and 46 kW
+ monobloc casting, so no internal weldings or couplings
+ low water content
+ low hydraulic resistance
+ small compact design
+ fire chamber water cooled, so no ceramic insulation required
+ water channels in full serial water flow
+ smoothened heat transfer through optimised flue and water geometry
+ aluminium; good anti corrosion properties, high heat conductivity, low weight

(source: Aluheat)
An innovation regarding die-cast aluminium heat exchangers was introduced by Dutch company Intergas in 1996. They combined the primary CH heat exchanger and the DHW heat exchanger in one integral component by inserting copper tubes in the die-cast mould and then pressure cast the aluminium around the tubes. The integral heat exchanger is capable of achieving condensing modes for both CH and DHW mode. Furthermore this solution could do without the 3-way valve or other components needed in traditional combis to transfer the heat from the primary CH heat exchanger to the DHW.
5.2.5 Tank-in-tank heat exchanger

In the case of a separate DHW cylinder the heat exchanger is not positioned in the heat generator, but in or onto the cylinder itself. One version is the tank-in-tank heat exchanger where a tank is positioned inside (often only partially) another tank. The outside area of the inner tank forms the heat exchange area with the outer tank.

A major difference with conventional coil-shaped heat exchangers in a tank is that the primary water volume is much larger.

5.2.6 Coil heat exchanger

The coil heat exchanger is a typical water-to-water heat exchanger and is applied mostly as CH-to-DHW heat exchanger in DHW storage tanks.

Probably the best known application of a coil heat exchanger is in a storage tank filled with DHW in which the coil supplies heat from a CH circuit. The reversed configuration is also applied, where the tank is filled with CH water and for the coil extracts heat for DHW purposes (allowing a sort of instantaneous DHW production possible).
Both principles are applied throughout the market for combi-boiler (or similar set-ups based upon solo-boilers), in small to very large variants.

The application in DHW storage means that most coil heat exchangers operate at temperatures (well) above 60 °C in order to maintain a safe, legionella-free DHW system. The drawback is that it is difficult to use latent heat from combustion (condensing mode). The recent years have shown development of storage configurations which do allow the use of heat below 55-60°C. In this report they are referred to as "Schichtladenspeicher" - and are further described in the paragraph further down.

**Performance**

A 80 liter tank can be equipped with 8 meter coil heat exchanger of 22 mm outer diameter copper tube. The heat transfer surface is in that case 0.55 m² and with a feed temperature of 90 °C and a storage temperature of 10°C the power transferred is 29 kW. Such a boiler can produce 710 liters of water per hour or 11.8 l/min at 45°C continuously.

---

**Figure 5.30.**

Nibe boiler, type PCU

<table>
<thead>
<tr>
<th>Type</th>
<th>PCU 80/8</th>
<th>PCU 100/10</th>
<th>PCU 120/12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boilerinhoud (liter)</td>
<td>80</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>Netto gewicht (kg)</td>
<td>47</td>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>Hoogte/breedte/diepte (mm)</td>
<td>816/475/480</td>
<td>978/475/480</td>
<td>1140/475/480</td>
</tr>
<tr>
<td>Diameter (Ø mm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Spirallengte warmtewisselaar (m)</td>
<td>8</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>VO warmtewisselaar (m²)</td>
<td>0.55</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Continu tepcapaciteit 90/10-45°C (l/min)</td>
<td>710</td>
<td>810</td>
<td>960</td>
</tr>
<tr>
<td>Warmte overdracht 90/10-45°C (kW)</td>
<td>29</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>Aanwarmtijd tot 60°C (min)</td>
<td>16</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>kW/kW knielkoppelingen (Ohm)</td>
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<td>15</td>
<td>22</td>
</tr>
<tr>
<td>Aansluiting CV A+R (Ohm)</td>
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<tr>
<td>Artikelnummer</td>
<td>088354</td>
<td>088310</td>
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</tr>
</tbody>
</table>
5.2.7 Plate heat exchanger

These types of compact plate heat exchangers are mainly used for liquid media or media with similar heat transfer coefficients (α). In the boiler industry this type is widely applied for sanitary hot water production, where heat from primary CH-water is transferred to sanitary water.

A plate heat exchanger consists of several rectangular plates (with a flow pattern pressed into them) that are mounted on top of each other. Between two plates a compartment is created through which the flows are guided. Each plate contains four openings (one in each corner) to allow the flows to enter and leave a compartment. Each medium only flows through half of the total number of compartments, each time skipping one compartment. As a result the two media always flow next to each other, with a heat-transferring plate in between. For this purpose, plate heat exchangers are considered the most compact and cost-efficient solution.

This type of compact plate HE is not suited for the heat-exchange of flue-gas to water.
Plate heat exchangers are also the main component in substations for collective heating (and district heating).

The water-to-water heat exchanger is usually of the plate heat exchanger type. These are very compact and ideally suited for transferring heat from media with similar fluid characteristics.

The output of heat exchanger can range from a few kW up to 500 kW and should be dimensioned to satisfy the maximum hot water demand.

The output of a plate heat exchanger is primarily a function of heat transfer surface, which follows from the dimensions of the stack of plates. Other design issues are the pressure drop (pressure loss) over the component (or the whole system), the build up of lime and scale and materials used.

The build up of limescale is in some types of substations prevented by a fast responsive valve, shutting down the supply when the hot water demand stops - this way hot water
is only allowed to enter the heat exchanger when there is a demand to transfer the heat to. In general plate heat exchangers are less susceptible to limescale because the flow is very turbulent when compared to tube-in-tank type of heat exchangers.

The materials used in the PHE determine its longevity and how it affects other components. Some larger plate heat exchangers (like the AlfaLaval TSN range) are gasketed (each plate is separated from the other by a leak-proof gasket), the stack is compressed by a series of fasteners. Others are copper brazed or fusion bonded (like the all stainless steel AlfaNova plate heat exchangers by AlfaLaval). Each types comes with its specific pro's and con's:

- Gasketed PHE: Has limited resistance to high temperature and certain fluids. Needs maintenance. Capacity can be modified on site, at will.
- Copper brazed PHE: High resistance, but limits due to copper ion exchange (can incurr corrosion in nickel plated steel);
- Nickel brazed PHE: Limited mechanical strength due to chemical changes in braze area;
- (Laser) Welded PHE: Fulfills most demands but is costly
- AlfaFusion PHE: Patented technology by AlfaLaval, applied in AlfaNova PHE. Providing high tensile strength and temperature resistance. Its 100% steel composition prevents copper ion leakage which may cause corrosion in galvanised piping networks. In some District Heating areas the use of copper brazed PHE is not allowed anymore.

Most PHE can easily withstand temperatures of 120 °C and 16 bar pressure.

The heat transfer efficiency of plate heat exchangers is very high: The flow is counterflow and turbulent, the stacks are made from very thin steel sheet thus ensuring high thermal efficiency in the range 80 to over 90 %. Heat that is not transferred to the secondary circuit is not essentially "lost", it is only retained in the primary circuit. The effect however is a somewhat higher return temperature which in most cases reduces the efficiency of the primary heat generating process. Radiation losses of the plate heat exchanger are "real", non-recoverable losses. These losses depend on the siting of the heat exchanger (in or outside the heated area), the insulation and the number of cycles.

35 http://svk.ch/Kalteforum/2006/Buendelrohraustauscher.pdf
36 Stainless steel chemically bonded by thermically hardened paste, without changing the chemical properties of the base material.
5.2.8 Secondary and tertiary heat exchangers

Secondary and tertiary heat exchangers are applied to extract latent energy from flue gases. Materials used are corrosion resistant: Stainless steel (forged, welded, brazed), Aluminium (die-cast), copper (forged, welded, brazed).

Figure 5-37.

Figure 5-38.

For tertiary heat exchangers (flue-gas/combustion-air he) plastics can be used because temperatures of flue gases are below 90°C. Since with plastic the wall-thickness of the material between the two flows can be reduced to below 0.3 mm, the heat transfer between flows becomes less dependent on the thermal conductivity of the material itself. Plastics (e.g. PP) are then a good option, because they have a very good chemical resistance.

HE-manufacturer Giannoni SAS integrated a tertiary heat exchanger in its condensing HE-design, and uses only plastic for the casing. The tertiary HE itself is made off metal strip.
The air to air heat exchanger is positioned between the combustion air intake and the flue gas outlet. It provides continuous condensing operation, regardless of the water temperature regime used. The company claims that fume temperatures are always lower than 55°C, and that it also reduces plume production at the outlet.

The German company Götz Heizsysteme GmbH, uses a thermoformed plastic heat exchanger for its floor standing oil or gas boiler, carrying the name “ProCondens”.

With this plastic tertiary HE the combustion air is preheated to approximately 60°C and the flue gasses are cooled down to around 40 – 50°C. As a result flue gasses will condensate also with higher boiler water return temperatures.
SECTION TWO - WATER HEATERS, GAS-/OIL-FIRED AND ELECTRIC
6 SUBSTATIONS

Note: District Heating networks rely on substations to distribute DHW to dwellings. District Heating is however outside the scope of the underlying study. This Section (and Task 2 Market Analysis) includes substation water heaters to complete the overview of water heating technologies, but substations will not be part of further investigation in the subsequent Tasks.

6.1 Product description

Substations transfer heat from a collective hot water circulation loop to a DHW circuit and/or the space heating circuit of a dwelling or building. The collective loop can be part of a district heating circuit or the central heating circulation loop from a collective boiler in a multi-family building.

The space heating function of a substation can be directly fed (meaning the distributed hot water is fed directly to the radiators for space heating) or with mixing facility (hot water is injected / mixed into a circuit for space heating) or indirect (the space heating circuit is hydronically separated from primary hot water).

The water heater function is always indirect, producing DHW on demand from mains cold water. It is possible to connect the substation to a storage tank which is referred to as a semi-instantaneous system. In combi-substations the DHW overrules the space heating function.

As a result various types of substations exist, but the main components are more or less the same:

- heat exchanger (water-to-water);
- regulating valves (thermostatic, pressure regulated or motorised);

Certain types of substations include circulators for the space heating circuit or for the DHW circuit (in case the substation feeds a DHW storage tank).

Figure 6-1. Substation internal lay-out (picture: AGH Centurion)
Larger substations, serving multiple dwellings, hospitals, hotels or service flats, etc. are available at least in sizes ranging from 75 up to 500 kW (example AlfaLaval TSN range).

![Figure 6-2. Large substation, available up to 500 kW (picture: Alfa Laval TSN)](image)

Major manufacturers of substations are: Alfa Laval (Sweden), Danfoss (Denmark), AGH (Netherlands - using Danfoss components) and Agpo-Ferroli (Italy/Netherlands).

**Materials**

In most cases, copper and/or copper brazed heat exchangers are used in district heating substations. In some district heating areas copper brazed heat exchangers are not allowed because of potential copper ion leakage. Copper ions may introduce the risk of corrosion of galvanised pipework - the copper ions break down the galvanic surface thus exposing the steel. A stainless steel heat exchanger can be used to avoid the problem.

### 6.2 DHW performance

#### 6.2.1 Flow rate

The DHW flow rate produced by substations depends on the size of the heat exchanger and feed temperature (assuming a constant flow rate and a predefined allowable temperature drop of the feed circuit).

Typically a substation is designed to produce DHW for an entire dwelling, e.g. function as a primary water heater. The flowrates are thus in the area of 8 l/min at 60ºC or higher. This corresponds to heat exchanger capacities of 24kW and higher.

Example: The maximum flow rate of the URS Elegance (two options) is 8 or 12 l/min at 60ºC indicating a heat output of 25 or 38 kW 37, which is comparable to standard sized combi-boilers (providing the heat supply is also large enough).

#### 6.2.2 Temperature control

The substation keeps the DHW temperature at the outlet constant independent of flow rate fluctuations (draw-off valves opening/closing, pressure loss, etc.). through passive (hydraulic) or active (electronic) control components.

An example of ‘passive’ control (without auxiliary energy use) is the Alfa Laval Villa Station pictured below, which uses a ‘self-acting’ thermostatic valve in the ‘primary’ supply side and a the temperature gauge placed in the DHW circuit. The gauge may be pre-set to (for example) 55ºC and allows the thermostatic valve to remain open until the DHW has reached the set temperature. When this temperature is reached the thermostatic valve closes. This way a fairly steady temperature of DHW can be attained, although there is some delay due to the response time of the thermostatic valve.

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37 The flow of 8 l/min equals 0.13 l/s and with a water inlet temperature of 15 degrees the temperature rise is 45 ºC. The specific heat capacity of water is 4.18 kJ/l*K. The output of the plate heat exchanger is 0.2*45*4.18 is 25 kW. 12 l/min results in 38 kW.
An example of a substation with 'active' components is the AGPO URS Elegance which uses an electronic controller connected to a flow sensor to sense DHW draw-off, temperature sensors to sense DHW and feed temperature and a motorised valve to control DHW temperature. The temperature control is more accurate under varying circumstances. The responsiveness is still subject to the speed of the motor valve (may take 2-3 seconds to open).
6.3 Energy

6.3.1 Steady-state efficiency

Substations do not have a heat generator. The efficiency of the primary heat generator (collective boiler or district heating station) and heat distribution should be considered in a system approach and should include an allocation of these losses to DHW heating and space heating functions when applicable.

When looking at the heat transfer efficiency of the plate heat exchanger only, one may assume this is very high, possibly over 95% (turbulent, counter flow). Heat not transferred to DHW is returned to the distribution loop. It can be argued that such 'unused' energy raises the return temperature and reduces the efficiency of the primary heat generation process (at district heating plant or collective boiler) and reduces the overall efficiency of the system. This is however outside the scope of the study.

6.3.2 Standby energy consumption

Comfort switch

Most substations experience some delay in heating up DHW. Partly this is due to the thermal mass of components involved and to overcome this delay substations may be equipped with a "comfort switch" that offer faster DHW delivery times, especially during periods of low heat demand. It is during these periods (summer operation) that no heat is transported through the appliance for extended periods and the heat exchanger stays relatively cool.

Substations with an active (electronic) control offer a 'comfort switch' that activates a setting to periodically open the 3-way valve and send some heat over the plate heat exchanger.

Other, 'passive', substations can use a thermostatic valve to continuously feed the supply side of the DHW heat exchanger with water of a certain pre-set temperature (often limited to max. 45ºC to avoid scaling). See #3 in the picture below (thermostat for by-pass/circulation).

The comfort switch thus adds to envelope losses or standing losses.
6.3.3 Start-stop losses

Start-stop losses are mainly related to repeated heating up and cooling down of the thermal mass. The mass (product weight) of the URS Elegance is 25 kg. The AkvaLux pictured above weighs 15 kg, which gives an indication of the weight range for domestic use.

6.3.4 Auxiliary energy

Hydraulic controlled (‘passive’) substations using a thermostatic valve to regulate DHW temperature do not require auxiliary electric energy and are controlled by passive components only (example by Danfoss, AGH).

Electronic controlled (‘active’) substations need electrical power for electronic controls. In case the substation also provides space heating an ‘active’ 3-way valve or two 2-way valves (to open/close the DHW or CH circuit) are needed. The power consumption of the Agpo URS Elegance for example with two motorised valves is 5VA minimum and 30VA maximum (excluding circulator). The circulation pump may use some 50 to 65W to feed the space heating circuit (but is essentially not part of the DHW system). A benefit of the system with a central controller and motorised valves is that it can be connected to a standard room thermostat for easy control of room temperature.
(modulating). The control-unit itself may consume a few Watts continuously (the AGPOFerroli URS Elegance has a minimum power consumption of 5W, Rendamax units with a capacity of 15 to 500kW require 15W for the control unit).

![Figure 6-9. Features of the AgpoFerroli URS Elegance (picture: www.agpoferroli.nl)](image)

The AgpoFerroli URS Elegance 12 l/m features options that are typical for combi-boilers:
- Can be combined with on/off and modulating room thermostats (Open Therm possible);
- Can be combined with solar water heater storage;
- Hot water production overrules space heating;
- There is an comfort-option that periodically heats up the heat exchanger in periods of low space heating demand - thus ensuring that the supply lines are filled with warm water.

![Figure 6-10. Substation without cover, placed in metering cupboard (picture: www.aqua-tech.nl)](image)

### 6.3.5 Alternative energy sources
Certain manufacturers claim their substations to be ready for connection to solar storage (or heat pump) systems. This assumes the substation is capable of handling inlet of water at high temperatures (e.g. 90°C) which should not be a problem given the existence of space heating and district heating circuits with a feed temperature of 90°C. The thermostatic feedback-loop reduces the outlet temperature to 60°C (or other preset value).

### 6.4 Infrastructure

#### 6.4.1 Combustion air / flues
Substations do not require combustion air nor flues.

#### 6.4.2 Envelope / noise / position
Important factor in envelope losses is the ambient temperature, which depends on the position in the dwelling. Substations for single-family households are relatively modest in size and are placed within the insulated shell of the dwelling but out of sight in cupboards, metering closets or storage spaces. The presence of district heating pipework often raises ambient temperatures.

Larger substations (like the Alfa Laval TSN of 75-500 kW) that provide DHW for a whole building can be placed in the boiler rooms or equivalent spaces, that are probably but not necessarily within the insulated shell of the building.

The product size of normal domestic substations differs per model type but is approximately 0.03 to 0.06 m³.
Noise is not really an issue (below 30 dBA)

### 6.4.3 Drains

Some substations are equipped with a safety relief valve (blow off pipes) and require a connection to waste water drains. This is not a standard feature.

### 6.4.4 DHW infrastructure

Substations generally provide enough capacity to act as primary water heater, serving multiple draw-off points. Realisation of a DHW recirculation loop is possible.

It is possible to link substations to individual primary (space heating) boilers and/or storage tanks and produce (and store) DHW this way. In such cases the substation acts as an external DHW heat exchanger and from technical point-of-view the difference with a boiler plus internal heat exchanger is minimal (see chapters on combi-boilers - instantaneous and storage).

![Substations linked to DHW circulation or storage boiler (here fed by a local boiler)](picture: www.alfalaval.com)

### 6.5 Prices

Substations streetprices are close to that of gas fired combi-boilers. Below are some street prices for substations found for the Netherlands and Austria:

The AGH Centurion costs € 1.130,00 (incl. VAT) in the Netherlands. To this has to be added some € 380,00 for standard installation costs and a monthly maintenance charge of € 4,03. This includes servicing and repair (excluding € 15,50 upfront costs for each visit). The unit can also be rented for € 20,34 / month, including installation, maintenance/repairs. ([http://www.e-s-a.nl/producten.php?id=73](http://www.e-s-a.nl/producten.php?id=73))

The Danfoss Akva Lux 26 substation costs € 1199,52 (incl. 20% VAT) in Austria and the Akva Lux 40 costs € 1578,78 (incl. 20% VAT) ([http://shop.smuk.at](http://shop.smuk.at)).
7 GAS/OIL-FIRED INSTANTANEOUS COMBIS

7.1 Product description

The gas- or oil-fired instantaneous combi-boiler is one of the most successful water heater products in Europe today. It combines production of space heating and DHW in one, relatively small package. Gas-fired wall-hung models are the most popular (see also Task 2 Report - Market Analysis). Oil-fired instantaneous combis do exist but are rare.

In this study the instantaneous combi is defined as a boiler with an internal DHW storage of zero to maximum 15 L. The latter (micro-storage or micro-accumulation) was introduced primarily to boost instant hot water delivery (better comfort) and minimise burner cycling during small draw-offs. A large DHW draw-off however provokes a burner action and therefore these combis are considered to be ‘instantaneous’ water heaters.

Gas-fired combis are available in an immense variety of designs, shapes, features, specifications, and so on.
As regards the way the heat from the flames and flue gases are transferred to DHW there can be significant differences. There are two main principles:

- The burner heats a primary (CH) circuit which feeds a DHW circuit through a DHW heat exchanger (requires 3-way valve);
- The burner heats a combined CH / DHW heat exchanger, with separate circuits for CH and DHW.

Either of these principles can be combined with micro-DHW storage (< 15 l). The following figures are examples of the approaches sketched above.

**Figure 7-2.**
Typical wall-hung atmospheric modulating gas combi-boiler, with lightweight finned primary CH heat exchanger and DHW plate heat exchanger.
(picture: www.vaillant.com atmoTEC VC194, 22kW, net weight: 37 kg)

**Figure 7-3.**
Combi-boiler with 1 ltr integrated DHW storage (detail below)
(picture: www.nefit.nl - Smartline)
The gas burners are either free flame, radiation or flameless burners. Oil burners (not really applicable) are jet burners (atomising).

Primary CH heat exchangers applied in instantaneous combis are of the (improved) fin-tube type (e.g. Nefit), bare tube (no fins) (Auer Gianola) or aluminium die-cast (e.g. Weishaupt). Secondary circuit DHW heat exchangers are either of the plate heat exchanger type or submerged coil.

The number of manufacturers and brand names is numerous. The leading manufacturing groups are Vaillant, Baxi, MTS and BBT (in random order and many more to add - see also the Task 2 Report on water heaters market analysis).

7.2 DHW Performance

7.2.1 Flow rate

Most combis have a heat output of 18 to 30 kW in DHW mode with the typical combi hovering around 24 kW. The table below gives an overview of theoretical (100% efficiency) power output for various flow rates.

<table>
<thead>
<tr>
<th>l/min</th>
<th>l/sec</th>
<th>T_in</th>
<th>T_out</th>
<th>delta_T</th>
<th>spec.heat</th>
<th>kW needed</th>
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<tr>
<td>2</td>
<td>0,03</td>
<td>15</td>
<td>60</td>
<td>45</td>
<td>4,18</td>
<td>6,3</td>
</tr>
<tr>
<td>4</td>
<td>0,07</td>
<td>15</td>
<td>60</td>
<td>45</td>
<td>4,18</td>
<td>12,5</td>
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<tr>
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<td>0,10</td>
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<td>60</td>
<td>45</td>
<td>4,18</td>
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</tr>
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</tr>
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<td>15</td>
<td>60</td>
<td>45</td>
<td>4,18</td>
<td>62,7</td>
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</table>

The maximum flow rate at a given temperature lift is defined by the maximum power output in DHW operation. The values in the table above presume 100% heat exchange efficiency, which is usually not the case: In real life a typical 24 kW combi produces some 6 l/min at 60°C which requires 19 kW (see above). Dividing output by input (19/24 LHV) gives an efficiency of around 80% (LHV).

38 The formula applied is : flow [l/sec] * temp.diff [K] * spec.heat water [4.18 kJ/kg*K] = power [kW] (density of water is kept constant at 1 kg/l)
7.2.2 Temperature control

Most combis are factory-set to a DHW outlet temperature of 60°C (to avoid scalding and reduce legionella counts). In order to maintain a constant 60°C at the outlet the combi has to be able to adjust the burner output in accordance with the flow rate (and temperature of incoming water).

The minimum flow rate is related to the modulation range of the burner and heat exchange characteristics. If the boiler operates below the minimum flow rate 'boiler cycling' will occur. The temperature control mechanisms are described in Section One - Chapter 4 Burners.

Lower flow rates are becoming a necessity with the advent of low flow water saving shower heads, thermostatic mixing valves and -recently- waste water heat recovery.

For example a water saving showerhead pinches the flow to approximately 5.5 l/min. If T\text{shower} is 40°C and T\text{cold} is 15°C then the boiler must deliver a flow of 3 l/min of 60°C (9.6 kW). This is close to minimum flow rate of many boilers; the Vitodens 200 (25.7 kW) for example has a minimum flow rate of 3 l/min. Some combis offer even lower minimum flow rates such as the Intergas KombiKompakt HR 36/30 (32.7 kW LHV, 2 l/min) and the Vaillant HRV30C (23.1 kW LHV, <1.4 l/min). A solution to reduce minimum flow rates to 'zero' is the application of a (small) DHW storage tank (for as long as the DHW storage lasts).

7.2.3 Responsiveness

Most instantaneous combis are relatively slow starters because of their thermal mass. The speed with which a combi can produce hot water at the desired temperature (measured at the boiler DHW outlet) is determined to a large extent by:

- Whether or not the combi has a DHW storage;
- The control settings (pre-purge time, keep hot facility / comfort switch on/off);
- The thermal mass of the heat exchangers and components;
- The responsiveness of mechanical components directing DHW flow.

The 'keep-hot facility' or 'comfort switch' makes the boiler periodically send some heated CH water over the DHW heat exchanger. This adds some 50 to 100 kWh annually to the overall energy consumption.

Many combis employ three-way valves to direct primary (CH) water over the DHW heat exchanger. Solenoid valves allow a rapid response, motorised valves take a few seconds to change position. Another variant is a two-directional pump.

Figure 7-5.
Left: Solenoid 3-way valve from AWB Thermomaster (picture: www.getprice.de)
Right: Parts of solenoid 3-way valve from Nefit VR combi (picture: www.technischeunie.nl)

Solenoid valves use power when in "on" position.
7.3 Energy

7.3.1 Energy efficiency

The energy performance of combi-boilers for DHW production is assessed through test standard EN 13203 (limited to combis of max. 70kW and 300 l storage). The recent finalisation of this test standard (2006) means that little information based upon EN 1320 made its way to product brochures yet 39.

The energy assessment covers a period on 24 hrs per tapping cycle of which at least two must be executed. The result thus includes losses in on-mode, off-mode and start-stop.

Without going into too much detail (modelling is part of the next Task) some aspects that influence the energy efficiency in on-mode are:

39 In the Netherlands a test standard exists for energy efficiency of gas water heaters / combi's. Water heaters exceeding certain minimum values can be awarded the "gaskeur HRww" label.
- The surface area of the primary heat exchanger and associated condensing operation;
- The outlet temperature. Many countries require an outlet temperature of minimum 60°C;
- Minimum modulation / flow rate. At a given output temperature the power input is determined by the flow-rate at the draw-off point. If the flow rate drops below the minimum modulation cycling will occur.

Condensing combis with integrated DHW heat exchangers (exposed to burner) are able to (partly) operate in condensing mode since incoming water of 10 to 15°C is well below the dew point (around 57°C for natural gas). Total recovery of latent heat is not possible with outlet temperatures of minimum 60°C. Most combis however avoid such thermal stress at the primary heat exchanger and use a secondary DHW heat exchanger.

The steady-state efficiency is an important parameter for larger tappings (shower, bath) and many national (building) standards use default values for ‘on-mode’ efficiency. Previous studies (SAVE study on water heating 2001) note the following steady-state efficiencies:
- > 90% hhv for condensing combi-boilers;
- 78 - 83% hhv for improved efficiency combi-boilers;
- < 78% hhv for combis with conventional efficiency.

7.3.2 Off-mode

Energy losses in off-mode (standing losses) are mainly envelope-losses and flue duct losses if no flue damper is used. Some combis still use pilot flames for ignition that also contribute to off-mode losses. These are covered in EN 13203.

The envelope losses depend on the placement of combis and the ambient temperature. Most combis are wall-hung and installed within the insulated perimeter of the dwelling. The preferred position is close to the main tapping point (the kitchen, as is customary in UK and Italy) but national Building Regulations regarding the position of flues do not always allow this and lead to combis being tucked away in corners of the dwelling (attic, basement, scullery, den, airing cupboard) or even outside the insulated / heated perimeter of the building (balcony, patio, conservatory, etc). Obviously the latter solution contributes to envelope losses (also depending the local climate).

Envelope losses are also increased when using the keep-hot facility or comfort switch offered by most (instantaneous) combis and if the combi has a micro-storage of DHW. A small DHW tank of say 5 l. has standing losses varying from 0,2 to 0,4 kWh/day (or 75-150 kWh/year). The ‘keep-hot facility’ or ‘comfort switch’ makes the boiler periodically send some heated CH water over the DHW heat exchanger. This adds some 50 to 100 kWh annually to the overall energy consumption.

The pilot flame is believed to consume some 75 to 125 m³ natural gas per year (or 750 to 1212 kWh/year) (SAVE WH). However not all the heat from the pilot flame should be treated as a loss, since some of it pre-heats the appliance (reducing start-stop-losses)

7.3.3 Start-stop losses

Instantaneous production of DHW means many boiler cycles (start-stops) per day. Repeated heating and cooling down of the thermal mass of the boiler, plus pre- and after-purges introduce energy losses and is covered in EN 13203: Standby-losses are measured in a separate 24hr cycle without draw-offs.

Instantaneous combis without micro-storage are heated up and cool down again at each draw-off. The SAVE WH study calculated that a 40 kg instantaneous combi loses some 0,53 kWhperc per cool-down cycle. Depending on the number of cycles and the thermal characteristics of the appliance (level of insulation etc.) the annual loss could be 1865 kWhperc (for 7 draw-offs per day, no benefit form CH operation included). In winter time
the combi is often already heated up for central heating operation and the annual start-stop losses for DHW operation may be reduced by say 40 or 50%.

**7.3.4 Auxiliary energy**

 Auxiliary energy is also taken into account in the EN 13203.

Modern combi-boiler control systems measure several parameters in order to operate and control combi-boiler functions such as automatic ignition, fuel/air-ratio control, power input control, inlet temperature sensors, 3-way valve control.

For these purposes a low voltage system is applied for the operation and communication of sensors, microprocessor and actuators. A schematic representation of components controlled by the BCU and input sensors is shown below.

The power consumption in operation can range from 100 to 200 Watts, depending on size of pumps and fans (the main power consumers). In standby (only electronic controls active) power consumption is 5 to 15 Watts.

The 2005-2006 stude SAVELEC investigated the power consumption of combi-boiler components.\(^{40}\)

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### Table 7-2. Power consumption of electric components in (combi)boilers

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
<th>Time (hours)</th>
<th>Ownership (%)</th>
<th>Stock (millions)</th>
<th>GWh</th>
<th>%</th>
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<td><strong>Gas Boilers</strong></td>
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<tr>
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<td>114,4</td>
<td>60</td>
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<td>4955</td>
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<td>100</td>
<td>80,2</td>
<td>1156</td>
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<td>100</td>
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<td>0,6</td>
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<td>Solenoid valve</td>
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<td><strong>GRAND TOTAL OIL + GAS</strong></td>
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</table>

The columns regarding operating time, ownership/stock and GWh in the table above are related to space heating and are not relevant from DHW perspective - they are however part of the original table and shown here for informative purposes only. In general the electricity consumption of boilers (in space heating - not DHW- operation) is split up as follows: pump 57%, fan 34%, control 9% 41.

### 7.3.5 Alternative energy

Many modern combis are able to cope with high inlet temperatures of 85-90°C and can be connected (retro-fitted) to solar storage cylinders. In the Netherlands these boilers carry the Label "Gaskeur NZ". Such boilers must also have a facility to reduce the outlet DHW temperature to max. 60°C to prevent scalding.

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41 Schweitzer, Jean, Electricity consumption of central heating appliances, Joint workshop GERG-SAVE, Horsholm, 4 April 2001
In principle the *Gaskeur NZ* combis can be connected to (pre-heated water storage) from heat pumps as well, but this is rarely applied in practice.

There are heat pump applications that use a (gas)boiler as emergency / back-up heater but these heaters are usually not instantaneous combis.

### 7.4 Infrastructure

#### 7.4.1 Chimney and supply air

Instantaneous combis are available in both B- and C-type flue/air configurations.

Combis that are designed to operate under condensing conditions require a suitable (gast-tight / condensate proof) flue duct, even in case the combi doesn’t condense during DHW production. See the Task 3 Report (section on chimneys) for strategies and solutions available for applying condensing boilers in existing dwellings and buildings.

#### 7.4.2 Drains

All combis are equipped with a pressure relief valve, for the CH part and/or for the connection to the drinking water mains, and are thus connected to a drain. In case the combi is condensing (even only in CH mode) the condensate can be discharged through this drain (provided discharge is allowed and the diameter is sufficient). For oil-fired combis a neutralisation box may be required.

#### 7.4.3 DHW piping

Most instantaneous combis are primary water heaters, serving multiple draw-off points, and are thus connected to a potentially lengthy DHW circuit.

Such pipe lengths introduce energy and water losses due to waiting times. These losses will be calculated in the technical model that is constructed in the subsequent tasks. Relevant input parameters are: the length, diameter and R-value of the piping and the supply- plus ambient temperature. Also the response time of the water heater itself is a factor.

Especially the distance from the water heater to the most frequently used draw-off point (usually the kitchen) is an important factor in determining waiting time losses.

Connection of instantaneous combis to DHW recirculation systems is not a realistic option: The instantaneous combi lacks the DHW buffer to feed the recirculation loop.

### 7.5 Prices

For combi-boiler prices see the Task 2 Report.
8 GAS/OIL-FIRED INTEGRATED STORAGE COMBIS

8.1 Product description

This group comprises gas-/oil-fired combis with integrated DHW storage of more than 15 litres. "Integrated" in this context means that the heat generator and storage tank are sold as one unit. In practice the unit can be delivered in two parts (a boiler part and storage part) to ease transport and installation and to be assembled on site. The groups comprises wall-hung combi-boilers (with heat generator hung above or aside the DHW storage) as well as floor standing models (with the heat generator placed on top or beside the DHW storage).

Storage-combis offer high DHW performance by definition, although many variants exist in how the storage is charged.

The traditional combi with integrated storage is based upon a heating only boiler with a matched storage cylinder equipped with a DHW coil heat exchanger.

More recent storage combis use an external (plate) heat exchanger to produce DHW and inject this directly in the top half of the storage. This type of storage is called "Schichtenspeicher" (thermal layer storage) and offers faster reheat times and eliminates the 'empty-boiler'-effect (DHW injected can be extracted immediately, giving instantaneous combi-like operation).

Figure 8-1.
Oil-fired storage combi (155 l) by Wolf Heiztechnik
(picture: www.wolfheiztechnik.de)
A third route to integrated storage combis is based upon gas storage heaters that are equipped with a heat exchanger for space heating operation. An example of this is the Daalderop CombiFort.

Major manufacturers (groups) are a.o. Vaillant, Baxi, BBT, MTS, Viessmann, etc. (overview incomplete - see also the Task 2 Report, Market Analysis).

8.2 DHW performance

8.2.1 Flow rate and temperature stability

The storage component offers very high initial flow rates in the range of 12 to 30 l/min or more. The question is however how long the desired flow-rate can be maintained at a given temperature difference. In other words: what is the recovery rate (in l/hr at a given T_diff).
One way to increase recovery rates is to increase storage size. Another approach is introduced above, by creating a thermal layer storage, increasing the power input and make sure this power output is delivered at the DHW outlet. Such storage combis function like an instantaneous combis during large tappings, but offer fast response and high initial flow rates as well.

To indicate the performance of modern storage combis the following comparison is made: An instantaneous combi like the 26 kW Viessmann Vitodens 200 produces 803 l/hr (with T-diff. at 30K). The 24 kW storage combi by Auer Gianola Lelia with a 130 l storage tank produces a comparable 840 l/hr. Depending on the size of the storage, the capacity of the boiler and the design of CH to DHW heat transfer boilers can produce from 450 l/hr (100 l storage, 20 kW) to 1500 l/hr (300 l storage, 60 kW).

Figure 8-4. Combi-boiler schematic, with 20 l storage (picture: www.agpoferroli.com - MegaLux6)

This boiler has a 20 l storage cylinder contained in its casing. During small -low flow- draw-offs DHW is taken from the storage tank and as long the temperature doesn't drop below a certain set-point the burner will not ignite and the boiler functions as a boiler with external storage. At large -high flow- draw-offs the setpoint will be reached within a short time period and the boiler will ignite. Due to the proximity of the storage feed loop (follow 39) next to the storage outlet tube (follow 8) most of the feed water will directly flow to the outlet: the boiler acts as an instantaneous boiler. After such draw-offs the burner will continue to operate to fill the storage tank with hot water, circulation provided through a DHW circulator (130).

Figure 8-5. Saunier Duval F35E ISOTWIN 33kW (picture: SaunierDuval F35E product brochure)

Once the 200l. tank is depleted the ISOTWIN continues to operate in normal combi mode producing 14 l/min of hot water @ 35°C rise.
8.2.2 Responsiveness

The availability of a (fully charged) DHW storage ensures instant DHW production at the appliance outlet. The figure below present an example of responsiveness of a storage combi compared to an instantaneous combi.

Figure 8-6.
Responsiveness of combi-boiler with 25 l storage ("Ecomline Classic") compared to traditional instantaneous combi-boilers ("conventioneel doorstroom-toestel").
(picture: www.nefit.nl - from product brochure Ecomline Classic)

In case of a 'cold-start' (the DHW tank is depleted) conventionally heated tanks with coil heat exchanger in bottom half of tank need more time to reach the required temperature than thermal layer storage tanks. The reheat time depends on the storage volume, the capacity of the burner and the heat exchanger efficiency.

Figure 8-7.
Reheat times of conventional and thermal layer DHW storage tanks.
(picture: Vaillant ecoCOMPACT brochure)

8.3 Energy

8.3.1 On-mode

Most storage combis are heated by conventional burners and heat exchangers (spiral in storage). The average efficiency lies in the range of that of instantaneous combis. Previous studies (SAVE study on water heating 2001) note the following steady-state efficiencies:

- >90% hhv for condensing combi-boilers;
- 78 - 83% hhv for improved efficiency combi-boilers;
- < 78% hhv for combis with conventional efficiency.

The availability of thermal layered storage opens up the possibility for increased efficiency of water heating; Thermal layer storage combis can create a loop in which the coldest water is send to the primary heat exchanger, which creates the highest heat exchange efficiency (condensing). Mixing of hot and cold water is postponed until the
storage is almost completely full. Only to fully charge the storage tank the boilers switches to a higher supply temperature. This two-stage heating process makes the most use of the thermal stratification in the storage tank and the benefits of the coldest return temperatures that allow condensation. Part of the water heating thus may take place with an efficiency above 100% LHV (Vaillant calls this their "AquaKondensSystem", a.o. applied in the ecoCOMPACT models).

8.3.2 Off-mode

During off-mode the storage combi loses energy through the envelope (mainly the through the thermal DHW storage), flue duct and pilot flame (if present).

The standing losses of the storage tank are significant and may vary from 0.96 kWh/day for a 30 l storage to 2.65 kWh/day for a 300 l storage. For a 75 l storage combi this is approximately 471 kWh/year. Combining this with an estimated average hot water consumption of 105 l/day at ∆T of 50ºC (translates to 2222 kWh/year) the standing losses are 21% of the total usable energy content of the DHW water (471/2222) (SAVE WH).

An important factor determining standing losses through the envelope is of course the ambient temperature of the appliance. Many boilers will be placed within the insulated perimeter of the dwelling or building, whereas others will be placed in unheated area’s such as the attic, den, loft.

Also contributing to these standing losses are thermal bridges and thermosiphon effects. Insulation and careful design minimises the first and application of heat traps (a small riser in a pipe or a strainer - ball type - in horizontal streches of pipe) reduce the latter.

The pilot flame losses (if applicable) are in the range of 75 to 125 m³ natural gas per year (or 750 tot 1212 kWh/year) (SAVE WH). However not all the heat from the pilot flame should be treated as a loss, since some of it pre-heats the appliance (reducing start-stop-losses).

8.3.3 Start-stop

The actual energy use per cool-down cycle is probably in the range of instantaneous combis. The big difference however is the number of start-ups: Storage combis will only start-up if the storage sensor senses a reduced capacity (say half full) and will then fire for a prolonged period to completely charge the storage again.
SAVE WH calculated annual cool-down losses of 1332 kWh\textsubscript{pr}/year for a storage combi compared to 1865 kWh\textsubscript{pr}/year for an instantaneous combi or 70\% compared to 100\%. (SAVE WH). These figures are indicative only.

### 8.3.4 Auxiliary energy

The storage combi consumes electricity when in standby and in operation. The standby power consumption is often 10 Watts or less for normal sized boilers (below 35 kW).

The power consumption when in operation depends to a large extent of the power output of the burner (a more powerful boiler requires more powerful fans, circulators, controls, etc.) and ranges from 100 to 200 W.

Some models employ a dedicated DHW feed pump instead of a 3-way valve plus a double duty (CH plus DHW) circulator.

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**Figure 8-9.**

This combi (Isotwin condens) has a separate central heating and DHW circulator (picture: Saunier Duval F35E product brochure)

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The 2005-2006 stude SAVELEC investigated the power consumption of combi-boiler components\textsuperscript{42}.

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Table 8-1: Power consumption by boiler components (source: SAVELEC study)

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<th>Component</th>
<th>Power (W)</th>
<th>Time (hours)</th>
<th>Ownership (%)</th>
<th>Stock (millions)</th>
<th>GWh</th>
<th>%</th>
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<td></td>
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</tbody>
</table>

The columns regarding operating time, ownership/stock and GWh in the table above are related to space heating and are not relevant from DHW perspective - they are however part of the original table and shown here for informative purposes only. In general the electricity consumption of boilers (in space heating - not DHW- operation) is split up as follows: pump 57%, fan 34%, control 9% \(^{43}\).

8.3.5 Alternative energy sources

Whether a (combi-)boiler is able to cope with solar (or heat pump) pre-heated water is mainly determined by its components at the DHW water inlet side. The Dutch Gaskeur NZ prescribes a maximum inlet temperature of 85°C.

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\(^{43}\) Schweitzer, Jean, Electricity consumption of central heating appliances, Joint workshop GERG-SAVE, Horsholm, 4 April 2001
Most (storage) combi-boilers produced after 1999 are able to use pre-heated water. In fact, many manufacturers that also market solar systems make sure their combi-boilers can be connected to their solar systems.

The text above explains that (for this model):
- the flow restrictor needs to be removed from the boiler inlet and installed before the solar storage;
- the installer has to make sure the boiler has a thermostat switch - to prevent the boiler from firing if water is already hot enough;
- installation of a thermostatic mixing valve to limit the DHW temperature to max. 60°C to prevent scalding.

Systems that integrate solar storage and (combi)boilers in one casing are also available, but these fall outside the intended scope of this chapter.
8.4 Infrastructure

8.4.1 Chimney / drains
The storage combi requires a chimney/flue gas system and a combustion air supply. If the boiler is able to operate in condensing mode the chimney needs to be airtight and moisture proof - see also Task 3.

Another requirement is a waste water drain to be used by the pressure relief valve. The same drain can be used for condensate if applicable.

8.4.2 Draw-off point
Most storage combis are the primary water heater in the dwelling and serve multiple draw-off points and are thus connected to a lengthy DHW circuit.

It is very well possible to use the storage combi in a DHW recirculation system thereby reducing waiting times at the point-of-use. This price comes at a loss: There are heat losses of the piping system and energy consumption for circulation.

8.5 Prices
For combi-boiler prices see the Task 2 Report.
9 SEPARATE CYLINDERS

9.1 Product description

Although separate cylinders aka external storage tanks, like substations, lack an internal heat generator and thus cannot function as an independent water heater they are included in the scope of the study.

The heat source of external DHW storage tanks or cylinders (also referred to as calorifiers) is CH system water. The heat input is via a heat exchanger (coil or tank-in-tank), sometimes in combination with an electric heater. Features characterising external storage tanks are: heat exchanger, tank material, insulation (plus jacket/casing).

Most cylinders in mainland Europe are pressurised (under water pressure). In the UK many external cylinders are ‘unpressurised’ but fed by a feed tank located above the cylinder. Unpressurised storage cylinders can also be applied as a primary store with the DHW heat exchanger under mains pressure.

Coil heat exchanger

The heat exchanger generally applied in external storage tanks is a coil heat exchanger (spiralled tube), usually of the same material as the cylinder itself. The diameter, length and surface-features of the coil determine the heat transfer surface and are designed for the desired performance.

A 22 mm diameter coil heat exchanger (no fins) offers a heat transfer surface of approximately 0.07 m²/m length. With a feed temperature of 90ºC and a hot water production of 45 ºC (cold water in at 10ºC) the coil transfers 3 to 3.6 kW heat/m coil.

Figure 9-1.
Example typical external storage cylinder
(picture: www.nibe.com - Nibe PCU)

Table 9-1. Specifications of range of external storage cylinders

<table>
<thead>
<tr>
<th>Nibe PCU/DDS</th>
<th>single-wall</th>
<th>double-wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>volume (l)</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>coil length (m)</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>heat transfer surface (m²)</td>
<td>0.55</td>
<td>0.7</td>
</tr>
<tr>
<td>heat transfer 90/10-45ºC (kW)</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>kW/m</td>
<td>3.6</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Some countries require cylinders with a certain heating capacity (Netherlands: over 45 kW, see BRL K656) to be fitted with double-walled heat exchangers. Double-walled heat exchangers are also applied in case cross-contamination has to be avoided (f.i. if the heat exchanger is placed in a toxic environment, like in certain solar systems where the collector fluid contains toxic anti-freeze fluids). The space between the walls is vented to the outside so that leakages can be noticed. Disadvantage is that the double-wall heat exchanger performance is much less compared to single-walled versions.

Example: Nibe PCU 120 with double-wall HE performance is 42% of single-wall version (39 kW for single-wall version vs. 16.5 kW for double-wall version).

The price of the double-wall HE is 143% of the single-wall (list price: 615 versus 880 euro).

**Double-coil/bi-valent**

Double-coil cylinders are applied in bi-valent systems or in systems that apply feeding with low- and high-temperatures, possibly from different energy sources. The coils are vertically oriented to use the effect of thermal stratification. The ‘colder’ bottom HE is used for low-temperature heat sources (e.g. solar collector, heat pump or boiler in condensing mode). The ‘hotter’ upper HE can be used for DHW production (in case the boiler is filled with CH water and the bottom coil is for solar), or CH heat input (in case the tank is filled with DHW and the bottom coil serves a solar collector). With ratings of 39 kW per coil continuous tapping is possible when the top coil is fed by a boiler with such capacity.
Tank-in-tank

The tank-in-tank HE is characterised by its low pressure drop and relatively large water content of the heat exchanger. Extra-large heat exchanger versions are available to minimise cycling of boilers and are recommended for heat pumps. The water content of the enlarged version is triple the amount of a standard version: 66 l versus 22 l for a 200 l storage tank.

Figure 9-4. Nibe VPA

Table 9-2. Specifications of tank-in-tank cylinders

<table>
<thead>
<tr>
<th>Example Nibe tanks</th>
<th>SP standard</th>
<th>VPA tank-in-tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHW storage volume (l)</td>
<td>110 150 200 300</td>
<td>200 300 450</td>
</tr>
<tr>
<td>HE volume (l)</td>
<td>12 18 22 22</td>
<td>66 190 145</td>
</tr>
<tr>
<td>Heat transfer 90/10-45°C (kW)</td>
<td>13 14 22 25</td>
<td>8.2 10 14.1</td>
</tr>
<tr>
<td>Heat transfer 55-45/10-45°C (kW)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pressure loss coil HE vs. tank-in-tank HE

At 1000 l/h the coil HE has a pressure loss of 10-17 kPa, the tank-in-tank (double mantle) has a pressure loss of around 0.2-0.3 kPa.
External storage cylinders without HE

In some applications external storage cylinders are fed directly with heated DHW (possibly by instantaneous combi-boilers) and thus do not require a heat exchanger for CH/solar/other to DHW heat transfer. In such cases they are practically no more than a thermal DHW store. An example is the "boost-boiler" introduced by Itho in 2006 and designed to operate in combination with a medium performance combi-boiler in order to 'boost' the hot water performance. The tank stores hot water produced by the combi-boiler and, when emptied, activates a dedicated feed circuit connected to this boiler, to refill the store. For that purpose the boost boiler comes equipped with a feed-pump, sensors and control circuit.
**Unpressurised primary stores**

In the UK and Ireland one can also find unpressurised primary stores: the storage tank is filled with unpressurised CH water system (tank is connected to feed and expansion cistern on top of the primary store). Such tanks can be equipped with a coil or (external) plate heat exchanger for DHW production.

Claimed advantages are reduced start-stop losses and smaller boilers possible.

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**Figure 9-9.**
Thermal store principle
(picture: http://www.gledhill.net > water-storage)

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**Materials**

Materials used for DHW external storage tanks and heat exchangers are:

- copper
- stainless steel
- enamelled (glass lined) steel

Copper cylinders (i.e. by Nibe) and coils are not recommended for areas with high chloride or calcium content in water or prolonged feeding with high temperatures. In such cases a tank-in-tank cylinder is recommended (less susceptible to calcium deposits or scaling and corrosion pitting). In aggressive waters an aluminium rod can be specified to provide corrosion protection. Sometimes copper is avoided in the circuit since copper ions can attack metals further downstream.

Stainless steel tanks (i.e. by Nibe, Viessmann) are gaining popularity. Provided the stainless steel grade is sufficiently high (AISI 316L, Duplex 2304) the tanks are virtually maintenance free and have very long life.

Enamelled tanks (glass lined) (i.e. by Buderus) have also high corrosion resistance, but do need protection against corrosion since the base material is steel-sheet and minute cracks in the enamel layer may induce corrosion. Two methods are applied generally: The first is insertion of a magnesium anode which is a less precious metal than steel and sacrifices itself. The dissolved products are not dangerous for one's health but the sacrificial rods need to be replaced periodically. Traditionally the anode needs to be removed in order to inspect it (requiring removal of mains pressure). Nowadays there
are anodes that provide a (colour) signal when it’s time to replace them. Street prices per anode range from 10-50 euro (incl. VAT) depending on brand, fitting and size.

A second method is applying a tiny current that prevents discharge of ions that contribute to corrosion (DE: "Fremdistromanode"). Such elements can cost up to 130 euro for cylinders up to 300 l and 180 euro for cylinders larger than 300 l (street price, incl. VAT). The anodes can be supplied by 230 V and consume some 2.5 kWh/year. In normal working conditions they do not need replacement.

Insulation materials

A very common method of insulation of (external) DHW storage cylinders is by placing the cylinder in sheet metal casing and filling the space with PUR foam. The method is simple, reliable and cheap but hinders easy separation of the materials after product life. Another method is to cover the tank in an insulating sleeve (can be flexible PUR, expanded PE or PS foam), with or without a external liner, and cover the top and bottom with a rigid plastic lid.

Common insulation materials applied are:

- Polyurethane foam (PUR);
- Expanded polyethylene (EPE) or polypropylene (EPP);
- Expanded polystyrene (EPS) - open cell foam, expanded beads;
- Extruded polystyrene (XPS) - closed cell foam;
- Mineral wool (only used for large > 500 l cylinders)

Common thickness of insulating PUR jackets is 30 mm or higher. See some examples on the next page.
Overview of characteristics of several insulation materials (VIPS are treated in a separate chapter as well):

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Thermal Conductivity (W/m*K)</th>
<th>Foaming agents</th>
<th>Prices (eur/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral wool</td>
<td>28 - 55</td>
<td>0.041* - 0.045</td>
<td>n.a.</td>
<td>45-52</td>
</tr>
<tr>
<td>Glass wool</td>
<td>15 - 28</td>
<td>0.041* - 0.045</td>
<td>n.a.</td>
<td>43-48</td>
</tr>
<tr>
<td>EPS</td>
<td>25</td>
<td>0.040* - 0.045</td>
<td>pentane, water or CO₂</td>
<td>35-60</td>
</tr>
<tr>
<td>XPS</td>
<td>27</td>
<td>0.034* - 0.040</td>
<td>may be HFC</td>
<td>220</td>
</tr>
<tr>
<td>PUR/PIR</td>
<td>30-40</td>
<td>0.028* - 0.035</td>
<td>pentane, water or CO₂</td>
<td>170-185</td>
</tr>
<tr>
<td>VIP</td>
<td>162 - 192</td>
<td>0.002 - 0.009</td>
<td>depends on core material</td>
<td>5000 - 10000</td>
</tr>
</tbody>
</table>

1) Values indicated with * have been certified by ATG-BUTGb. Source: Bewust Duurzaam Bouwen, text Vibe for Vlaamse Provincies

2) Prices are street prices indicative for building applications, excluding VAT and depend on geometry, quantity, etc. Prices have been recalculated to euro/m³. Source: Richtprijzen, Cobouw.nl.
9.2 Performance

The hot water performance of external storage tanks is essentially identical to that of integrated storage tanks. See section 11.2.

9.3 Energy

9.3.1 On-mode

The heat generator is by definition an external (heating only) boiler and does not form part of the product. On-mode efficiency is defined by the external boiler.

Part of the efficiency is however influenced by the external storage tank design and especially the heat exchanger.

9.3.2 Off-mode

Energy losses in off-mode (standing losses) are the main loss factor for external storage tanks. A few examples of standing losses:

- 150 litre (120mm insulation): 65-70W, 600 kWh/year;
- 350 litre solar (110mm insulation): 100 W, 870 kWh/year.

Please note that these values are already much lower (ca. factor 3) than the maximum values suggested by e.g. EN 303-6. Actual standing losses naturally depend on insulation level, storage temperature, stratification effects, etc. but the general calculation of standing losses (verage tank) is "45*0.16*volume^{0.5} ".

9.3.3 Auxiliary energy

Although most if not all separate cylinders are delivered without a power chord there is some auxiliary energy consumption - this however occurs in the boiler itself which needs to operate at least a circulator and a three-way valve (to send primary CH water over the coil), fans and gas-valves for the combustion process and some electronic controls (that monitor the need for burner action). This energy consumption depends on the type and make of the boiler that supplies the heat and cannot be influenced by the manufacturer of the cylinder itself.

9.3.4 Alternative energy

"Thermal layer tanks" (DE: Schichtenspeicher) can use heat produced in condensing mode but also low-temperature heat from sources like solar collectors or heat pumps. By maintaining a relatively "cold" spot in the bottom half of the tank even the low temperature solar heat can be transferred to the contents of the tank.
Figure 9-15.
Solus II (www.consolar.de)

An example of the use of solar heat is shown above (by Consolar, Germany): The left side shows the transfer of heat from solar collectors through a coil heat exchanger positioned at the bottom of the storage tank. The surrounding storage water is heated, expands and rises to the top half of the tank through a dedicated riser. Thus the tank is filled from the top down, while still achieving maximum heat transfer between the relatively warm solar collector fluid and relatively cold storage water at the lower part of the tank.

The right side shows the extraction of heat for DHW purposes. In the top half a coil heat exchanger (shape: inverted umbrella) is positioned which extracts heat from the storage for DHW. The cooled down storage water sinks to the bottom half of the tank through a dedicated shunt.

The principle shows that the aim is to prevent mixing of thermal layers and to keep the heat at the top half of the tank for better DHW performance and keep the bottom half relatively cold (for optimum solar heat transfer).

9.4 Infrastructure

9.4.1 Chimney / drains
Pressurised storage cylinders require a pressure relief valve discharging into a waste water drain.

Chimneys, flues and combustion air supply are not applicable to external storage cylinders.

9.4.2 Draw-off point
Most storages are the primary water DHW source in the dwelling and serve multiple draw-off points and are connected to a lengthy DHW circuit. Some unpressurised systems however cannot meet the desired flow rates and multiple points and are sometimes only servicing a bathroom (or even bathtub only).

Connection of external storage cylinders to DHW circulation systems is very well possible. Such systems greatly reduce waiting times at the point-of-use and minimise wastage of heated water. At the downside there are heat losses of the piping system and energy consumption for circulation.
9.4.3 Distribution losses

Separate cylinders are typically used as primary water heaters, serving DHW for the whole dwelling. The distribution of this DHW water throughout the dwelling causes energy losses that can be calculated using different approaches, described in the relevant standards (see also the Task 1 Report on Standards & Legislation).

9.5 Prices

The figure below presents list prices from Nibe of several types of external storage tanks: Copper tanks with a coil (single or double-walled), tank-in-tank or no heat exchanger, Copper tanks with an electric heater (3 or 6 kW rods) and Steel tanks without heat exchanger [source: Nibe list prices].

![Figure 9-16.](image)

Table 9-4. List price vs. street price, examples

<table>
<thead>
<tr>
<th>Description</th>
<th>List price</th>
<th>Street price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nibe PCU External cylinder, Copper tank, 20 kW Copper HE (single wall) 100 L</td>
<td>€495,-</td>
<td>€510,59</td>
</tr>
<tr>
<td>(single wall) 120 L</td>
<td></td>
<td>(103% of list price)</td>
</tr>
<tr>
<td>Nibe PCU External cylinder, Copper tank, 28 kW Copper HE (single wall) 120 L</td>
<td>€615,-</td>
<td>€634,37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(103% of list price)</td>
</tr>
</tbody>
</table>
10 GAS/OIL STORAGE WATER HEATER

10.1 Product description

This group comprises gas-/oil-fired water heaters with integrated DHW storage. The difference with storage combis being that these are dedicated water heaters - not designed to supply heat for space heating although in practice some construction similarities may exist.

Storage-water heaters offer high DHW performance (l/min) and recovery rates (l/hr at given temp. difference). Most storage water heaters are essentially storage cylinders with a burner / heat exchanger built into the appliance. The basic principle is fairly simple and robust and the product may last for decades with adequate maintenance (ie. corrosion protection for storage tank).

Gas- and oil-fired storage water heaters are produced with atmospheric or fan-assisted burners, in open or closed configurations and a wide range of burner output power (from < 5 kW to > 180kW) and storage volumes. Some examples are listed below.

Figure 10-1.
Left: single pipe AO Smith NGT gas-fired storage water heater.
Right: multi-pipe AO Smith ADMR gas-fired storage water heater
(picture: www.aosmithinternational.com)
Figure 10-2.
Merloni-Ariston "Micro". 42 l volume, 4.4 kW power
(picture: www.mtsgroup.com)

Figure 10-3.
Gas fired water heater, available in 90, 125 and 250 gallons (340, 475 and 950 l)
(picture: www.pvi.com)

Figure 10-4.
"Platinum" Gas fired condensing water heater, available in 70 gallons (277 l)
(picture: www.pvi.com)

PLATINUM Condensing Water Heater
A. Completely submerged, vertical, 2-pass firetube heat exchanger with solid copper firetubes and steel combustion chamber with copper / PTFE composite for corrosion protection on waterside
B. Flange connection allows complete removal of heat exchanger
C. 316L stainless steel condensate and flue collector. Vents as a category IV appliance through PVC or CPVC when water temperatures are at sanitizing levels
D. Fan-assisted, pre-mix surface burner with electronic sequencer and flame safeguard (capable of connection to direct inlet air)
E. ASME pressure vessel for hot water storage lined with POLYSHIELD or fabricated of 439 stainless steel
Maxxflo condensing gas water heater. This type of water heater can operate at 109% efficiency until the tank is charged for 80%.
[picture: www.andrews waterheaters.co.uk]

The Maxxflo series is a direct fired condensing storage water heater which has a stainless steel tank that is heated by up to four burner modules placed outside the tank, providing 30 to 120 kW. The burner module has a stainless steel heat exchanger in which the burner is placed. The water heater works according to the loading principle: The water in the bottom of the tank is led directly through the heat exchanger, heated up and carried back to the top of the tank. The temperature of the water at the bottom of the tank (return temperature) is representative of the input heat; the burner modulates on the basis of this return temperature. The temperature at which the water is supplied to the tank from the heat exchanger (supply temperature) is kept at the set water heater temperature using pump modulation.

An important advantage of bringing the heat transfer from outside the tank is that the output is not influenced by the temperatures that prevail in the tank. As long as draw off occurs the water from the bottom of the tank to the heat exchanger is almost the same as the supply cold water temperature. This means the maximum output is maintained during the heating up period. On the final heating period, when the tank is almost completely heated up, the return temperature will increase and the burner modulates.

Because the water is pumped round from the lowest point in the tank, the whole tank is heated up and there are no cold spots.

This Itho / vanderbeyl GGBB is technically a gas-fired water heater - the main components (boiler, external storage) clearly visible.
[picture: www.itho.nl]

The GGBB is 54 kW, 300 or 500 l storage, auxiliary energy 180W
For safety reasons some storage water heater are equipped with a thermally operated valve in the flue. This valve shuts down the gas supply in case the flue gases do not leave the appliance in the correct way.

Manufacturers are among others Andrews Water Heaters (UK, part of the Baxi Group), Vaillant (atmoSTOR range), Junkers (StoraFlam range), ACV (HM models) and MTS Group (under the Ariston / Radi / Simat brand). Many North-American brands are also active in Europe such as A.O. Smith and Lochinvar.

10.2 DHW performance

10.2.1 Storage capacity

The performance of storage water heaters is primarily determined by the storage capacity and the research indicates this capacity ranges from approximately 40 l to over 500 l.

Another performance parameter for gas storage water heaters is the recovery rate which links storage capacity and the power of the heat generator. The recovery rate is defined as the amount of hot water the device can produce in a specified period and a specified temperature raise. A large storage capacity with a relatively modest burner may achieve similar recovery rates (for a specific time period - not continuously) as a smaller storage with larger capacity burner. The efficiency of the heat transfer is also a factor in this.

The table below gives an indication of recovery rates for some gas fired storage water heaters: from 140 to almost 1800 l/hr (temp. difference 50°C). Oil fired storage water heaters produce even up to almost 2800 l/hr (also temp. difference 50°C).

| Table 10-1. Recovery rates of gas/oil fired water heaters (Andrews Water Heaters) |
|---------------------------------|----------------|------------------|
| Gas fired | Heat input (kW) | Recovery rate (l/hr) at delta_T 44/56°C |
| Standard series | | |
| 12 | 178 / 142 |
| 19 | 278 / 222 |
| 26 | 397 / 316 |
| HiFlo series | | |
| 42,8 | 649 / 517 |
| 50 | 786 / 829 |
| 80 | 1199 / 959 |
| 102 | 1549 / 1239 |
| 128 | 1899 / 1520 |
| 139 | 1988 / 1598 |
The average recommended storage temperature is 60ºC, although higher temperatures can be supported. Generally manufacturers advise not to keep temperatures higher than 80ºC for risk of scalding.

### 10.2.2 Temperature control

A typical low-cost gas storage water heater uses an aquastat as temperature control - at a preset temperature the aquastat switches the burner on and off. The simplest form requires a pilot flame so the burner ignites automatically as the gas valve is opened. The burners are atmosferic burners with ‘open’ (type B) combustion air supply.

More sophisticated gas storage water heaters are equipped with an ionisation control module and self-ignition and those equipped with fans usually employ a boiler-like gas control unit (also ionisation). These gas storage water heaters can be type C (‘room sealed’) although non-fan assisted (balanced flue) heaters are also available.

Furthermore several safety thermostats apply (to limit max. temperature etc.).

### 10.2.3 Responsiveness

Storage water heaters produce hot water with virtually no time delay.

### 10.3 Energy

#### 10.3.1 On-mode

Historically the heat generator is placed inside the storage tank, with the burner chamber and flue gas duct surfaces functioning as heat exchangers (see figures in section 13.1). Burners range in capacity from 5 kW to over 180kW.

The trend towards condensing operation also reached the gas storage water heaters and several models are available nowadays. Condensing heat transfer is achieved by enlarging the heat exchange surface, preferably combined with burner modulation (see figure 13.3 and below as example).
Another strategy to achieve condensing mode is pursued by Andrews' Maxxflo that features a heat generator placed outside the storage tank, creating a dedicated filling loop. The external burner extracts the coldest water from the bottom of the tank and inserts this at the top. Condensing modes can be maintained until the tank is approximately 80% full. This set-up is very much alike combi-boilers with storage, except for the space heating functionality of those.

By the way, even non-condensing storage water heaters can produce condensate during "cold" starts (tank is filled with cold water). Instruction manuals prepare users for 'hissing sounds' of water condensate droplets falling onto the burner - and that these should dissapper once the water is heated up further.

The efficiency (lhv) for conventional heaters is 85% and may reach 95-96% for condensing models.

10.3.2 Off-mode

Standby losses are the thermal losses from the storage tank. In fact these losses occur continuously and not only when the water heater is in standby (burner not ignited) - therefore "standing losses" are a better description.

The losses depend on the storage temperature, the insulation applied and edge losses like standing feet or connections to rest of DHW system. Gas- and oil-fired water heaters also have a flue gas system and air supply that may contribute to standing losses.

Common measures applied to reduce standing losses are: improved insulation (including the standing feet / bottom part / connections), flue dampers (reduce draught when not ignited), non-return valves in system connections (reduce heat transfer through internal flow), connections aimed downwards (also reduce heat transfer through internal flow) and lower system temperatures (this strategy should be aligned with anti-legionella measures).

10.3.3 Auxiliary energy

Simple gas storage water heaters equipped with a pilot flame (ignited manually) and a gas valve operated by the thermostat require no electrical power. The burner is atmospheric and the construction is open (B...) (example: A.O.Smith BT range).
Electric / electronic components typical for fan-assisted, sealed gas fired storage water heater are:

- Burner control, including connection to ionisation electrode (to detect ignition);
- Gas valve (operates gas supply, works with solenoid valve);
- Pressure differential sensor (checks airflow);
- Fan (controlled by burner control);
- Thermostat (temperature thermostat and safety thermostat);
- Switches, control lights, etc.

The power consumption of this set-up (5 kW heat input for 75 or 110 l storage) is 26 W of which 10 W by the gas valve and 16 W by the fan\textsuperscript{44}. 

Fan-assisted gas water heaters of a different brand, with more capacity (190 l), may use ten times as much energy: the Andrews RFF 190 (190 l storage) consumes 236 W. The extra consumption can partly be explained by a more powerful fan (the RFF range is a 19.5 or 23kW heater with open configuration intended for longer/difficult flues). More advanced models (the sealed CSC range of 44 to 104kW by Andrews) also consume up to 236W. Apparantly the fan and controls are designed for the maximum power model and are throttled to fit less powerful models.

Highest electricity consumption is recorded for condensing boilers. The A.O.Smith BFC Cyclone condensing gas water heater consumes 275W (30 to 60kW models), 625W (80kW) or 710W (100kW). The Andrews Maxxflo consumes 170W (30kW model), 340W (60kW), 510W (90kW) and 680W (120kW).

Models equipped with a timer may consume 10 to 15 W for this option (example Baxi/Sentry EBW: 14W).

Oil-fired storage water heaters require auxiliary electricity for feed and dosage pumps and other controls (no data).

\subsection*{10.3.4 Alternative energy sources}

Since most storage water heaters can be connected to DHW circulation loops there should no real problems with handling incoming pre-heated DHW water from a solar system (if needed a thermostatic valve may be used to limit inlet temperatures). The gas-/oil-fired storage water heater acts as a re-heater.

Total integration of the solar storage into the DHW storage is problematic the DHW storage temperature of minimum 55 to 60ºC reduces the solar contribution (solar heat of less than 55ºC cannot be transferred).

\subsection*{10.4 Infrastructure}

\subsubsection*{10.4.1 Drains}

All UNVENTED - ie mains pressure - storage water heaters have to have a facility that handles the pressure build-up by the expanding heated water. A pressure relief valve (usually combined with a non-return valve and stop-cock in one component) is a mandatory item and sometimes is combined with an expansion vessel (as indicated in some UK installation manuals)\textsuperscript{45}. The pressure relief valve must be connected to a waste water drain. Vented storage water heaters can expand through the cistern located in the loft.

\textsuperscript{44}The appliance described here is the WFF 80 / 120 by A.O.Smith. This boiler produces 164 l/hr at a delta_T of 25ºC. The efficiency is 94% (calorific value and test standard not indicated, most likely EN89).

\textsuperscript{45}ACV also recommends expansion vessels to prevent extreme pressure build-up due to water hammer effects (induced by rapid closing of valves).
Condensing gas-/oil-fired storage water heaters also need a drain for condensate. This drain can be combined with the waste water drain provided it is allowed to dispose of the condensate in the general sewage system and includes an air-break. For gas-fired water heaters this is usually allowed, for oil-fired systems a neutralisation box may be required.

**10.4.2 Chimney**

Gas-/oil-fired storage water heaters require a chimney/flue gas system and a combustion air supply. If the boiler is able to operate in condensing mode the chimney needs to be airtight and moisture proof - See also Task 3.

Many dedicated gas-fired storage water heater are equipped with a thermally operated valve in the flue. This valve shuts down the gas supply in case the flue gases do not leave the appliance in the correct way.

**10.4.3 DHW piping**

Most storage WH's are the primary water heater in the dwelling and serve multiple draw-off points and are thus connected to a lengthy DHW circuit. It is obvious that frequent small tappings and large pipe lengths contribute to waiting time losses. These losses will be modelled in other Chapters of this Task.

It is also not uncommon for large storage water heaters to be applied in circulation loops. This requires extra circulation energy and compensation of heat losses of the circulation pipes.

**10.5 Prices**

In general gas storage water heater product price increases with storage volume and output power of the burner. However (the combination of) features like open or sealed configuration, automatic flue diverters, storage tank materials, temperature control features and special precautions for 'agressive' water quality may cause sharp price increases over the standard product price.

The table below gives an indication of list- and street prices for several storage volume / kW combinations for four countries.

| Table 10-2. Product price of gas storage heaters (first column: volume/kw, second column: price) |
|---|---|---|---|---|---|
| UK | GBP/euro (street) | FR | euro (street) | IT | euro (list) | NL (list) |
| 1) | 2) | 3) | 4) |
| 120 / 6.9 | 652 / 978 | 115 / 7.5 | 537 | 80 / ... | 895 | 75 / 4.7 | 740 |
| 150 / 7.2 | 679 / 1018 | 155 / 8.4 | 580 | 100 / 5.5 | 968 | 115 / 4.7 | 893 |
| 200 / 8.0 | 693 / 1040 | 195 / 10.1 | 852 | 120 / 5.6 | 1066 | 109 / 7.5 | 500 |
| 200 / 28.5 | 1890 / 2835 | 115 / 4.3 | 716 | 80 / 2.9 | 605 | 144 / 9.1 | 600 |
| 300 / 31 | 2090 / 3135 | 155 / 4.7 | 799 | 100 / 2.9 | 624 | 181 / 10 | 986 |
| 195 / 5.2 | 1085 | 50 / 3 | 320 - 340 | 265 / 18 | 1669 |
| 80 / 5.4 | 739 | 80 / 4.4 | 320 - 380 | 355 /18.5 | 2284 |
| 100 / 5.4 | 817 | 100 / 4.4 | 360 - 380 | 217 / 30.1 | 5430 |
| 111 / ... | 980 | 120 / 4.4 | 412 | 368 / 32.8 | 5715 |
| 142 / ... | 1076 | 120 / 3.6 | 740 | 368 / 48.6 | 6407 |
| 185 / ... | 1722 | 150 / 4 | 834 | 368 / 59.6 | 6935 |
| 200 / 4.5 | 928 |

1) www.discountedheating.co.uk (streetprices)
2) www.brosette.fr (listprices)
3) Ariston list prices for Italy (listprices)
4) www.technishceunie.nl (wholesaleprices)
11 GAS/OIL INSTANTANEOUS WATER HEATER

11.1 Product description
Gas- and oil-fired instantaneous water heaters are available in a wide capacity range, ranging from small 'geysers' of less than 10 kW, to bath water heaters of 40 kW, to very large industrial type water heaters of over 1000 kW. The lower end of the range is intended for "kitchen-sink only" whereas the higher end is found in washdown and process use in the food industry, hotels, sports and leisure centres, universities, colleges and hospitals, etc.

Figure 11-1.
Nefit kitchen-sink geyser 4.7 - 9.4 kW (picture: www.nefit.nl)

Figure 11-2.
Merloni Fast 14 FIMET 9-24.3 kW (Picture: http://www.mtsgroup.com)

Figure 11-3.
Andrews SupaFlo R18 range 481-1002 kW (picture: www.andrewswaterheaters.co.uk)
Most instantaneous water heaters on the market today are gas-fired. Oil-fired instantaneous water heaters do exist but are rare in Europe (the Toyotomi TO 148 is mainly aimed at the Canadian and US market).

Most gas-fired instantaneous water heaters are wall hung, with fin-tube type heat exchangers. (Small gas-fired) Instantaneous water heaters are still available in type A configuration (open flue - emits flue gases in installed space), although type B or C are recommended by legislators and installers for health, safety and efficiency reasons.

Some brand names of manufacturers of (gas-fired) instantaneous water heaters are Vaillant, Bosch, Nefit, Chaffoteaux, Ariston, Main, Andrews Water Heaters, Vokera, Rinnai, etc.

### 11.2 DHW performance

#### 11.2.1 Flow rate

The maximum flow rate of DHW by instantaneous water heaters depends foremost on the capacity (and efficiency) of the burner. The amount of power to produce 1 litre per minute however remains fairly constant over the range (some 3.4 to 3.5 kW per l/min).

Some examples are listed below.

<table>
<thead>
<tr>
<th>Max. power output</th>
<th>Max. flow ((\Delta T) 50°C)</th>
<th>constant</th>
<th>Brand, model series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen sink</td>
<td>9.4 kW</td>
<td>2.4 l/min</td>
<td>3.9 kW per l/min</td>
</tr>
<tr>
<td>Shower + sink</td>
<td>17.5 kW</td>
<td>5 l/min</td>
<td>3.5 kW per l/min</td>
</tr>
<tr>
<td>Bath, shower + sink</td>
<td>27.1 kW</td>
<td>8 l/min</td>
<td>3.4 kW per l/min</td>
</tr>
<tr>
<td>Bath, shower + sink</td>
<td>42 kW</td>
<td>11.9 l/min (1)</td>
<td>3.5 kW per l/min</td>
</tr>
<tr>
<td>Bath, shower + sink</td>
<td>55.8 kW</td>
<td>16.5 l/min (1)</td>
<td>3.4 kW per l/min</td>
</tr>
<tr>
<td>Collective/commercial</td>
<td>70 kW</td>
<td>20.25 l/min (1)</td>
<td>3.5 kW per l/min</td>
</tr>
<tr>
<td>Collective/commercial</td>
<td>274 kW</td>
<td>79.6 l/min (1)</td>
<td>3.4 kW per l/min</td>
</tr>
<tr>
<td>Collective/commercial</td>
<td>481 kW</td>
<td>139.7 l/min (1)</td>
<td>3.4 kW per l/min</td>
</tr>
<tr>
<td>Collective/commercial</td>
<td>1002 kW</td>
<td>291 l/min (1)</td>
<td>3.4 kW per l/min</td>
</tr>
</tbody>
</table>

(1) Original data interpolated for \(\Delta T\) 50°C
Temperature stability partly depends on the minimum flow rate. Below the minimum flow rate the appliance will start to 'cycle' (DE: *Takten*). The minimum flow rate for the smaller water heaters (up to 30 kW or so) is in the range of 2.4-2.5 l/min (at ΔT 50ºC). For the larger models (40-60 kW) it can be 3.5 l/min. The Andrews Supaflo range (70 to 1000 kW) is stated to be able to modulate down to 20% of burner output, all within a 1% temperature accuracy. The Lochinvar IntelliFin featuring extended electronic controls is said to be accurate within 0.5ºC.

Responsiveness of gas- (and oil-) fired instantaneous water heaters is generally quite fast due to low thermal mass (mainly fin-tube heat exchangers with little thermal mass) and simple controls. The room sealed appliances (mainly type C configuration) apply pre-purging of the burner chamber. Water heaters with a pilot flame have a little advantage in terms of waiting time.

## 11.3 Energy

### 11.3.1 On-mode

The heat generator is in most cases a burner with a fin-tube heat exchanger arrangement.

![Figure 11-5. Stereotypical domestic instantaneous water heater, apparently type B (not room sealed, with flue) (picture: eBay)](image)

Net efficiency is in the range of 85-90%, although condensing water heaters are available (at least from Andrews and Lochinvar) with net efficiencies up to 110% (depending on temperatures and flow). The figures below present efficiency data from the Andrews and Lochinvar condensing water heaters, also indicating the dependance of efficiency from supply-send temperatures. Other energy losses in on-mode are due to envelope losses.

![Figure 11-6. Graph representing the efficiency of the Andrews R300 series over a range of supply-send temperatures. (picture: Brochure Andrews Water heaters SupaFlo)](image)
The dual heat exchanger arrangement preheats return water to control condensate formation. Using a pumped bypass, a portion of the heated supply water is recirculated to raise inlet temperature to a point where condensation on the primary heat exchanger is avoided. The secondary heat exchanger allows condensing operation (103% ncv) even if the supply temperature is over 70°C.

11.3.2 Off-mode

In off-mode envelope losses also occur, especially if a pilot flame is present. Another factor is the placement of the appliance (several manufacturers offer models in both indoor and outdoor versions). Appliances without a pilot flame may be equipped with a flue damper to prohibit downdraughts of cold outside air.

In case the appliance is connected to a DHW circulation loop extra system losses are introduced (heat losses and power needed for circulation).

11.3.3 Start-stop

Start-stop losses are mainly due to pre- and post purging (heating/cooling of thermal mass, unburnt fuel losses).

In case the flow is below the minium flow rate frequent start-stops occur (even within a tapping cycle).
11.3.4 Auxiliary
The simplest gas-fired water heaters (open configuration: Type A or B, with pilot flame and hydraulic control) do not use auxiliary energy (pilot flame left aside). More advanced (closed: type C) water heaters use electronic (piezo) ignition and require electric mains connection or batteries to ignite.

Fan-assisted water heaters are always connected to the electric mains: by example the Ariston Fast 14 FFI (27 kW) consumes 55W at maximum.

An Australian-led study\(^{46}\) gives the following values, based upon a survey of 20 mains powered gas water heaters:

- On-mode: 40-120W;
- Cool down-mode: 10-40W;
- Passive standby mode (off-mode): 4,5-12W, average 10W and newer models between 6-8W;
- Frost protection-mode: Either zero (drain down type) or 50-120W.

Some types of gas instantaneous water heaters can operate without being connected to an energy source: AquaStart water heaters by Nefit are powered by a small water turbine, driven by the flow of the water. The principle is applied by Vaillant and some other brandnames too. The technology however is not suited to power flue fans or electronic controls requiring constant power and as such limited to atmosferic, type B heaters.

11.3.5 Alternative sources
No gas- or oil-fired instantaneous water heaters have been found to use pre-heated DHW from alternative energy sources (solar of heat pump).

11.4 Infrastructure

11.4.1 Drains
Condensing models are equipped with condensate drains. Depending on local requirements a neutralisation kit may be needed.

11.4.2 Chimney/ air supply
As stated earlier instantaneous water heaters are available in all flue/supply air configurations: Type A, B and C.

Some models are equipped with safety provisions that monitor correct flue functioning, eg. Ondea with S.P.O.T.T. (Système Permanent d'OBServation du Tirage Thermique).

11.4.3 Single, multiple or circulation draw-off points
Smaller kitchen-sink models can be equipped with a faucet and can be hung directly over the sink - these are typical single-point appliances. Larger models can be connected to conventional DHW piping and can facilitate multiple draw-off points.

Appliances producing up to 5 l/min (at ΔT 50ºC) are often indicated for kitchen use only, up to 8 l/min could facilitate a shower and more than 8 l/min could facilitate a bath.

Connection to a storage tank is a possibility, just as connection to a DHW circulation loop - even in cascade configuration if required.
11.5 Prices

Street and list prices of some small to medium sized appliances were retrieved:

<table>
<thead>
<tr>
<th>Model</th>
<th>l/min at ΔT 50°C</th>
<th>DE 2)</th>
<th>IT 1)</th>
<th>FR</th>
<th>UK 2)</th>
<th>NL 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosch W135-TZ1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>287</td>
</tr>
<tr>
<td>Nefit F1400</td>
<td>2,4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>284</td>
</tr>
<tr>
<td>Chaffoteaux Celt Star</td>
<td>2,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>242</td>
</tr>
<tr>
<td>e.l.m. leblanc LM5</td>
<td>2,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(243)</td>
</tr>
<tr>
<td>Vaillant atmoMAG 9</td>
<td>2,7</td>
<td>340-345</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nefit F2555HE</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Bosch 250-1AM</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>737</td>
<td></td>
</tr>
<tr>
<td>e.l.m. leblanc LM10</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>(359-426)</td>
<td></td>
</tr>
<tr>
<td>Vaillant atmoMAG 9</td>
<td>5,5</td>
<td>449-516</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ariston Fast 11</td>
<td>5,5</td>
<td>(244/330/544)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pilot/electronic</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chaffoteaux Britony IIT</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>505</td>
<td></td>
</tr>
<tr>
<td>Bosch 325-1AM</td>
<td>6,5</td>
<td></td>
<td></td>
<td></td>
<td>844</td>
<td></td>
</tr>
<tr>
<td>Nefit F3255HE</td>
<td>6,5</td>
<td></td>
<td></td>
<td></td>
<td>649</td>
<td></td>
</tr>
<tr>
<td>Vaillant atmoMAG 9</td>
<td>7</td>
<td>551-625</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ariston Fast 14</td>
<td>7</td>
<td>(320/396/594)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pilot/electronic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>e.l.m. leblanc LC17</td>
<td>8,5</td>
<td></td>
<td></td>
<td></td>
<td>(510-586)</td>
<td></td>
</tr>
<tr>
<td>Andrews FastFlo 42</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td>819</td>
<td></td>
</tr>
<tr>
<td>Andrews FastFlo 56</td>
<td>16,5</td>
<td></td>
<td></td>
<td></td>
<td>1087</td>
<td></td>
</tr>
</tbody>
</table>
12 ELECTRIC STORAGE WATER HEATER

12.1 Product description

Electric storage water heaters are relatively easy installed (no flues, combustion air or fuel supply needed, just electricity and hot/cold water piping, possibly a drain) and offer relatively high water comfort (depending on recovery rate).

The principle design is a storage tank with one (or more) electric immersion heater(s). The size of the storage tank may vary from just a few liters (for single point use) to several hundreds of liters (for multi-point use). The power of the electric immersion heater increases as the size of the storage increases but electric power exceeding 6 kW is rare, given the average maximum size of a household fusebox (20 A). Larger tanks (over 200 l.) are often floor standing.

Electric storage heaters may be pressurised (with the storage at mains pressure) or unpressurised. The latter is either an open vented storage or cistern (more common in the UK) or a vented tap (more common in Germany, in small storage heaters (max 5 l.) placed above a washbasin). Such unpressurised heaters can be equipped with plastic tanks, whereas pressurised heaters are made of metal (enamelled steel, copper or stainless steel). And there are versions with an electrically heated primary store, producing DHW through a (plate) heat exchanger (like the Gledhill PulsaCoil).

A special group of electric storage water heaters is the boiling water heater, intended to supply (almost) boiling hot water for consumption (tea, soup, etc.). Again here we have pressurised and unpressurised systems.

The table below tries to group electric storage water heaters by application and volume.

<table>
<thead>
<tr>
<th>Application</th>
<th>Storage volume</th>
<th>pressurised</th>
<th>unpressurised</th>
</tr>
</thead>
<tbody>
<tr>
<td>boiling water (point-of-use by definition)</td>
<td>1,5 to 40 liter</td>
<td>up to 7 l.</td>
<td>up to 40 l.</td>
</tr>
<tr>
<td>small DHW storage</td>
<td>5 - 30 l.</td>
<td>whole range</td>
<td>whole range</td>
</tr>
<tr>
<td>medium sized DHW storage</td>
<td>30-200</td>
<td>whole range</td>
<td>up to 125 l. (cistern)</td>
</tr>
<tr>
<td>large DHW storage</td>
<td>&gt;200</td>
<td>whole range</td>
<td>not found (for primary stores see External Storage cylinders)</td>
</tr>
</tbody>
</table>

The figures below give a (not comprehensive) overview of the product group electric storage water heaters.

Figure 12-1.
Boiling water heaters.
(pictures left: ZIP hydrotap (1.5 to 4 l boiling water)
(picture mid: Clage KA range, 1.5 to 40 l.)
(picture right: HeatraeSadia Supreme range 10-40 l)
Figure 12-2. Combined boiling and/or hot water heater

The Quooker combi combines a boiling water heater with a hot water heater in one package (volume 7 l, 2.2 or 3kW), pressurised.

Price range 1200 euro

The Vaillant VEK can manually be set to produce water from 30°C to boiling point (unpressurised). The pipe on the left is the overflow pipe.

Figure 12-3. Small storage water heaters (< 30 l), available in pressurised and unpressurised versions for either above or under-sink installation.

(picture left: Stiebel Eltron 10-15 l)
(picture right: Ariston - unpressurised, 10 to 30 l)

Figure 12-4. Medium sized storage (30 to 200 l), pressurised.

(picture left: Vaillant VEH, 50, 80 and 100 l)
(picture right: Ariston TI TRONIC BEST 80 VR/5)

Figure 12-5. Large sized, pressurised (> 200 l).

(picture: Vaillant VEH)
(picture: Stiebel Eltron SHO, 1000 l, up to 18 kW element)

Figure 12-6. Unpressurised 25 to 125 l. storage

(picture: HeatraeSadia Cistern, direct fed)
(picture right: Gledhill PulsaCoil, indirect storage)
There are numerous manufacturers of electric storage water heaters. Brandnames are Stiebel Eltron, Heatrea Sadia, Clage, Vaillant, Ariston, Inventum, Daalderop, Bosch, Junkers, Blomberg, A.O.Smith, etc.

**Heat generator**

The electric heater applied in electric storage water heaters is a tubular heater which consists of a spiral-wound resistive wire perfectly centred in a tubular metal sheath filled with a powdery insulator (electro-fused magnesium-oxide MgO). The type of metal sheath (or its surface finishing) is optimised for the working conditions (susceptibility against scaling, water conditions, temperature range, etc.).

The magnesium powder is compacted by a laminate, also necessary to obtain good thermal conductivity and good mechanical and dielectric strength.

The extremities are sealed with a resin (silicone, epoxy, polyurethane, etc., according to the application) and terminated by a ceramic plug. The electric connections and the mechanical attachment accessories required can be specified by the manufacturer. Several types of flanges or other fastening methods can be applied.

Manufacturers of electric heater elements: Cetal (France), Caloritech (US), Cotherm (France), Electrowatt (France), RICA (Italy), Thermowatt (Italy), NIBE (Sweden, several trademarks), etc.
Figure 12-9.  
Cut-out tubular heater (Electrowatt)

Screw-plug (Electrowatt)

Flanged heater (Electrowatt)

Specialty flange (Electrowatt)

Figure 12-10.  
Stéatite (FR) heaters are not immersed in the water but contained in cylindrical shaped hollow rods enable heating element replacement without emptying the boiler. The immersion type is called Blindée (FR).

(picture: www.brossette.fr)
**Anti-corrosion**
Like all external storage cylinders (Chapter 12) the electric storage water heater has to be protected from corrosion. Copper and stainless steel cylinders are corrosion resistant by themselves (although there are differences in type of quality of stainless steel) and enamelled steel tanks have to be equipped with self-sacrificing (magnesium) anodes that dissolve over time. Small unpressurised vessels may also use a plastic (polyolefine) tank.

**Temperature settings and safety**
Most electric storage water electric heaters allow setting of the storage temperature in the range from approximately 40 - 50ºC to 80 - 90ºC (some models support operating temperatures in the range of 7ºC to 85ºC). User manuals warn against the risk of scalding when using higher temperatures. Higher temperatures (above 60ºC) also contribute to scaling of the electric element and sediment formation.

In case of thermostat failure the heaters have a thermal sensor/switch to prevent overheating. Usually at temperatures of 95ºC or above the sensor switches off the electric supply, which can only be turned on again through manual intervention (after a check for correct operation and repair if needed).

Some heaters have frost-protection ie. they switch on if the storage temperature drops below 7ºC. Please note that fittings and piping leading to and from the heater need frost protection too.

Boiling water heaters are designed to produce water up to the boiling point.

### 12.2 DHW performance

#### 12.2.1 Flow/recovery rate and temperature stability
The performance of electric storage water heaters is best expressed through their recovery rates: the amount of hot water the device can produce in a specified period and with specified temperature raise. The main determinant for the (continuous) recovery rate is the capacity of the electric heaters. The recovery rate starting with a fully charged storage is of course higher than the continuous recovery rate.

The table below presents some data for typical electric storage water heaters over 25 litter (AO Smith EES range).

#### Table 12-2. Technical specifications electric storage water heaters

<table>
<thead>
<tr>
<th>AO Smith EES range</th>
<th>Volume l</th>
<th>Electric power kW</th>
<th>Current A</th>
<th># Elements</th>
<th>Electrical supply VAC/Hz</th>
<th>Max. set temperature °C</th>
<th>30 min. ∆T=28°C l</th>
<th>60 min. ∆T=28°C l</th>
<th>90 min. ∆T=28°C l</th>
<th>120 min. ∆T=28°C l</th>
<th>Continu ∆T=28°C l/h</th>
<th>Full ∆T=28°C min.</th>
<th>30 min. ∆T=50°C l</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>25</td>
<td>1,8</td>
<td>8</td>
<td>1</td>
<td>230 (-15/+10%) /50 Hz</td>
<td>77</td>
<td>63</td>
<td>91</td>
<td>119</td>
<td>148</td>
<td>56</td>
<td>27</td>
<td>35</td>
</tr>
<tr>
<td>15</td>
<td>55</td>
<td>1,8</td>
<td>8</td>
<td>1</td>
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<td>77</td>
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<td>166</td>
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<td>1</td>
<td></td>
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<td>40</td>
<td>155</td>
<td>2,7</td>
<td>11-13</td>
<td>1</td>
<td></td>
<td>77</td>
<td>271</td>
<td>313</td>
<td>355</td>
<td>398</td>
<td>85</td>
<td>80</td>
<td>152</td>
</tr>
<tr>
<td>52</td>
<td>190</td>
<td>2,7</td>
<td>11-13</td>
<td>1</td>
<td></td>
<td>77</td>
<td>323</td>
<td>366</td>
<td>408</td>
<td>450</td>
<td>85</td>
<td>81</td>
<td>181</td>
</tr>
<tr>
<td>66</td>
<td>250</td>
<td>2,7</td>
<td>11-13</td>
<td>1</td>
<td></td>
<td>77</td>
<td>413</td>
<td>456</td>
<td>498</td>
<td>540</td>
<td>85</td>
<td>80</td>
<td>212</td>
</tr>
<tr>
<td>80</td>
<td>300</td>
<td>2,7</td>
<td>11-13</td>
<td>1</td>
<td></td>
<td>77</td>
<td>488</td>
<td>531</td>
<td>573</td>
<td>615</td>
<td>85</td>
<td>80</td>
<td>231</td>
</tr>
<tr>
<td>120</td>
<td>450</td>
<td>2,7</td>
<td>11-13</td>
<td>1</td>
<td></td>
<td>77</td>
<td>713</td>
<td>756</td>
<td>798</td>
<td>840</td>
<td>85</td>
<td>80</td>
<td>319</td>
</tr>
</tbody>
</table>
For electric water heaters of less than 25-30 liters the recovery rate is often not indicated in product brochures, only the reheat time. The example below gives reheat times (and standing losses) for some smaller electric storage water heaters.

### Table 12-3. Reheat times of electric storage water heaters

<table>
<thead>
<tr>
<th>Volume (l)</th>
<th>10</th>
<th>10</th>
<th>15</th>
<th>15</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reheat time (from 10°C to 60°C with 2 kW element)</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Standing losses (kWh per 24 hr at 65°C)</td>
<td>0.57</td>
<td>0.43</td>
<td>0.69</td>
<td>0.53</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Another aspect defining the performance of a storage water heater is its useful volume, which is indicated by the mixing efficiency factor V40 and a.o. depends on the placement and shape of sensor and heater in the storage tank.

For example:

- a hot water need of 150 l at 40°C can be covered by:
  - a 100 l storage at 65°C (V40 = 1.5N);
  - or 86 l at 65°C (V40 = 1.75)
  - or 100 l at 56°C (V40 = 1.75)

A better mixing efficiency thus increases the nominal capacity with the same storage volume, or enables the same nominal capacity with a smaller storage at the same temperature or a similar sized storage with a lower temperature. The table below gives the mixing efficiency for several base case storage volumes.

### Table 12-4: V40 mixing efficiency

<table>
<thead>
<tr>
<th>Storage Volume</th>
<th>V40</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 l</td>
<td>1.60 * nominal capacity</td>
</tr>
<tr>
<td>80 l</td>
<td>1.60 * nominal capacity</td>
</tr>
<tr>
<td>100 l</td>
<td>1.65 * nominal capacity</td>
</tr>
<tr>
<td>200 l</td>
<td>1.70 * nominal capacity</td>
</tr>
</tbody>
</table>

## 12.3 Energy

### 12.3.1 On-mode

The immersed electric heater element transfers virtually all energy to the storage content: the transfer efficiency therefore reaches 100%. The primary efficiency (and CO₂ emissions) depends on grid characteristics.

More important for overall energetic performance are the standing (off-mode) losses.

---

47 CECD presentation, 14.02.2007
12.3.2 Off-mode

The off-mode describes the status of the electric storage water heater with the electric element turned off, also referred to as standing losses (heat losses through envelope and connections).

Standing losses are an important energetic loss of electric storage water heaters and are determined by the temperature difference between the water and the surroundings and the insulation level (radiation, convection and conduction losses).

In a presentation by CECEG on 14.02.2007 regarding electric storage water heaters the standing losses of a basecase 200 l storage heater were calculated as 37% of the total energy consumption. Increasing insulation thickness would improve standing losses to 31% of total.

Table 12-5: Standing losses of basecases

<table>
<thead>
<tr>
<th>CECED basecase</th>
<th>standing losses (65°C)</th>
<th>standing losses of total (useful energy 1246 kWh/yr, 400 kWh for 30 l model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 l storage volume</td>
<td>244 kWh/yr</td>
<td>244 / (400+244) = 38%</td>
</tr>
<tr>
<td>80 l storage volume</td>
<td>487 kWh/yr</td>
<td>487 / (1246+487) = 28%</td>
</tr>
<tr>
<td>100 l storage volume</td>
<td>500 kWh/yr</td>
<td>500 / (1246+500) = 29%</td>
</tr>
<tr>
<td>200 l storage volume</td>
<td>743 kWh/yr</td>
<td>743 / (1246+743) = 37%</td>
</tr>
</tbody>
</table>

Even small details like insulated standing feet help to reduce standing losses. Also the surface/volume ratio is a factor in this (the 5 l model loses 0,05 kWh/24hr*ltr and the largest 400 l model 0,0065 kWh/24hr*ltr: roughly 1/8th).

Table 12-6: Standing losses of modern electric storage water heaters

<table>
<thead>
<tr>
<th>Storage volume (l)</th>
<th>Standing losses (kWh/24 hr at 60°C)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0,25</td>
<td>91</td>
</tr>
<tr>
<td>10</td>
<td>0,35</td>
<td>128</td>
</tr>
<tr>
<td>15</td>
<td>0,40</td>
<td>146</td>
</tr>
<tr>
<td>30</td>
<td>0,49</td>
<td>179</td>
</tr>
<tr>
<td>50</td>
<td>0,54</td>
<td>197</td>
</tr>
<tr>
<td>80</td>
<td>0,66</td>
<td>241</td>
</tr>
<tr>
<td>100</td>
<td>0,79</td>
<td>288</td>
</tr>
<tr>
<td>120</td>
<td>0,92</td>
<td>336</td>
</tr>
<tr>
<td>150</td>
<td>1,07</td>
<td>391</td>
</tr>
<tr>
<td>200</td>
<td>1,8</td>
<td>657</td>
</tr>
<tr>
<td>300</td>
<td>2,2</td>
<td>803</td>
</tr>
<tr>
<td>400</td>
<td>2,6</td>
<td>949</td>
</tr>
</tbody>
</table>

These examples are from the Vaillant electric storage water heater line and concern basic models ("classic") if applicable.

As the storage temperature is an important factor in determining standing losses, optimisation of storage temperatures can further reduce these losses. An intelligent management of storage temperature would take into account peak demands, night-time tariffs, legionella risks, seasonal impact on needs, etc. to achieve the least standing losses (night-time operation is already standard in a.o. France and Belgium).

12.3.3 Start-stop

Start-stop losses of the electric storage water heater are not a significant loss factor: The thermal mass of the electric element is minimal and pre-heated by the volume of DHW in which it is immersed.
Start-stops are regulated by an aquastat sensor-switch. The hysteresis of the sensor-switch determines the deviation from the set temperatures (overshoot, responsiveness). The better this control the less energy is consumed unnecessarily.

### 12.3.4 Auxiliary energy

The simplest electric storage water heaters (whether they are 5 or 400 liters) do not use auxiliary electrical energy: The temperature sensors (aquatstats) are capillary tubes operating the on/off switches of the heating element.

However, more sophisticated models may be equipped with a control panel with signal lights or an electronic (LCD) display indicating the settings and temperature. These added functions require some power (generally < 1 watt).

Electric storage water heaters equipped with a electric anode for corrosion protection (DE: *Fremdstromanode*) may require less than 0.5 Watt electric power (some 2.5 kWh/year).

And there are electric storage water heaters that heat and store primary (non potable) water. DHW is produced via a plate heat exchanger which is fed by a circulation pump circulating the stored primary water. The pump of the Gledhill PulsaCoil (Grundfos UPR 15-50) consumes some 50 W max.

12.3.5 Alternative energy

Combination of solar heat with electric storage water heaters is quite often applied in solar storage tanks where the electric element is used to charge the system during periods of low solar energy. Such systems are primarily solar water heaters and the electric elements are only used for back up e.g. during the winter months or to boost DHW if solar irradiation is low.

Systems where the electric element is the main heater and solar heat functions as an extra energy source are less common. A few products on the market do combine the two heat sources. In such systems great care is taken to avoid conflicts between heating in electric or solar mode. The electric heater is only turned on when there is no chance of solar contributions (night-time) and then only heats the upper part of the tank. The bottom part remains 'cold' (stratification) and this is where the solar heat exchanger is placed. Mixing of solar pre-heated water occurs through natural convection. Conflicts between the two sources cannot be avoided in all circumstances since the electrically heated part of the tank reduces the available capacity for storing solar heat. Legionella is not a problem in the PulsaCoil-Sol solution since DHW is produced via a plate heat exchanger.
The combination of an electric heater with intermittent solar heating only makes sense if the electric heater uses off-peak electricity / night-tariff, charging the system overnight when no solar contribution is expected. Another feature of this product is the mains pressure DHW delivery through the plate heat exchanger, eliminating the need for pressure relief valves and reducing risk of legionella. The store itself has a feed/expansion cistern. An advantage is that scaling is less of a problem, since the storage water is not renewed.

Heat pumps and electric heating are often combined a similar fashion as solar and electric heating: Many heat pumps storage systems employ an electric heater as back-up or to periodically raise the temperatures to 60ºC and above. However one cannot categorise these appliances as electric heaters since the heat pump is always the dominant heat generator.

The combination depicted below of a (vented primary storage) electric water heater with a heat pump could also be regarded as a (heat pump) boiler with an external cylinder, equipped with an electric heating element as booster / back-up during off-peak hours.
12.4 Infrastructure

12.4.1 Water pressure
Pressurised boilers are usually tested to 8 to 12 bar maximum pressure. The minimum pressure is often not stated but should be enough to fill the boiler, regardless its placement in the house.

Small (max 30 l) unpressurised cistern-fed storage heaters may require a minimum pressure of 0.4 bar (so the feed tank, if applicable, should be located over 4 m above the appliance). Most of the unpressurised storage heaters without cistern (using vented taps) are not rated at all as they are designed to relieve any excess pressure through the tap or an overflow pipe.

Figure 12-14. Vented tap systems (picture: Junkers EHU Untertisch / Obentisch)

Large unpressurised cistern-type vented storage tanks are equipped with float valves, capable of withstanding 7 bar. The cistern itself is under atmospheric pressure only.

The open vented indirect storage water heater with a plate heat exchanger accepts water pressure from 1 bar minimum to 5 bar maximum. The cistern (open vented feed tank) should not be placed over 10 m above the storage tank (1 bar).

12.4.2 Electrical supply
The power of a single electric heater element is usually in the range of 2 to 3 kW. Some small heaters operating on night-time tariff may use a 0.4 kW heater (longer heat-up times allowed). Large heaters may use up to 6kW or more for faster heat-up times. High power heaters exceeding 6 kW are often supplied by a 3-phase 400V electric supply.

Many electric water heaters, especially the larger ones, offer the possibility to connect the heating elements to a night-time tariff electrical supply (DE: Zweikreisbetrieb) to reduce running costs.

12.4.3 Chimney / drains

Chimney
Chimneys, flues and supply air are not applicable to electric storage water heaters.

Drains
Pressurised systems always need a relief valve to let off pressure from expanding water. The valve is usually set a 3 bar and should be allowed to feed into a waste water drain.

Unpressurised systems can either be open vented or connected to a vented tap.
12.4.4 **Single- or multi-point**

Depending on the storage volume the electric storage water heater is connected to either a single-point or multi-point DHW system.

Since every electric storage water heater is connected to some sort of pipework, extra heating losses are introduced if the hot water is allowed to circulate in this pipework (by convection). These losses can be reduced/prevented by measures like heat traps in attached pipework (U-shaped or angular fittings that prohibit convection) and ball valves that prevent circulation.

Unpressurised, cistern-fed storage boilers may need a venting pipe rising from the appliance to the cistern located in the loft of the dwelling. This may introduce considerable piping losses since the vent-pipe may act as a large heat-emitter: Heated water rises to the top of the vent pipe, introducing extra piping losses in often unheated areas. (see figure 12.14)

Other piping losses are introduced by the repeated heating up and cooling down of pipe contents. of course this factor is smaller for single-point water heaters (over- or under-sink position). For multi-point systems with 8 meter pipework of 22mm, filled by 65°C hot water with 10 tappings/person/day the losses are around 140 kWh/year.

At the final section of the system, the draw-off point, losses are introduced by inefficient tapping. A contributor to this are single-lever taps with a middle position producing 50/50 hot and cold water. The aesthetically pleasing neutral position may induce unnecessary hot water tappings. Assuming 5 unintentional tappings/day at 1 min each at 6 l/min with 30% DHW “content” supplied at 65°C (cold water is 15°C) the energy loss is 450 kWh/year. For single-point storage water heaters the effect is likely to be less.
### 12.5 Prices

In general electric storage water heater product price increases with storage volume. However (the combination of) features like day- and/or night-tariff heating elements, 400V/3-phase elements, pressurised/unpressurised, storage tank materials, temperature control features and special precautions for 'aggressive' water quality may cause a price increase over the standard product of 100% or more.

**Table 12-7: Overview of list- and street-prices electric storage water heaters**

<table>
<thead>
<tr>
<th>Type of electric storage water heater</th>
<th>UK streetprices</th>
<th>DE streetprices</th>
<th>FR streetprices</th>
<th>IT listprices</th>
<th>NL listprices</th>
</tr>
</thead>
<tbody>
<tr>
<td>unpressurised cistern 25 - 125 l</td>
<td>1000 - 1800</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>boiling water</td>
<td>&gt;150 to &gt;1500 (multi-tap)</td>
<td>5: 129 - 217</td>
<td>n.a.</td>
<td>n.a.</td>
<td>5: 170 - 190</td>
</tr>
</tbody>
</table>

**Figure 12-16. Electric storage EU prices [BRGConsult, 2007]**

![Electric storage EU prices](image-url)
13.1 Product description

Electric instantaneous water heaters (or "inline" water heaters, DE: *Durchlauferhitzer*) are very versatile in installation (requires no flue) and mostly used as point-of-use water heaters. The main determinant for their application is the flow rate at a certain outlet temperature: For wash basin use 2 liters per minute of max 40ºC is satisfactory, for shower use one would prefer minimum 6 l/min of 40ºC and for kitchen use (eg. dishwashing) a temperature up to 60ºC is preferred.

The flow rate that can be achieved at a certain temperature lift is determined by the electric power of the electric heating element. The table below presents the range available.

<table>
<thead>
<tr>
<th>Application</th>
<th>Electric power (kW)</th>
<th>Flow rate</th>
<th>ΔT 25K</th>
<th>ΔT 45K</th>
</tr>
</thead>
<tbody>
<tr>
<td>hand-wash sink</td>
<td>3 - 6,5 kW</td>
<td>1,7 - 4 l/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kitchen sink (small shower)</td>
<td>6 - 12 kW</td>
<td>3,4 - 6,9 l/min</td>
<td>1,9 - 3,8 l/min</td>
<td></td>
</tr>
<tr>
<td>kitchen / normal shower</td>
<td>12 - 27 kW</td>
<td>7 - 15,5 l/min</td>
<td>3,8 - 8,6 l/min</td>
<td></td>
</tr>
</tbody>
</table>

Besides electric power there are also differences in type of electric heating element (coil immersion or bar-wire), temperature/flow rate control (hydraulically or electronically) and whether the heat exchanger is 'pressurised' or 'unpressurised'. 'Unpressurised' can mean that either the product is connected to a low-pressure feed (e.g. less than 0,8 bar) or that the heat exchanger is protected from mains pressure by a stop-valve located before the heat exchanger.

Versions that are designed for use as electric showers often include a matching shower head and hose.
Figure 13-1. 2.8 to 3 kW instantaneous hand washer (Heatrea Sadia) - 2.8 kW, 230 V - flow rate: 1.7 l/min @ ΔT25K (estimate by VHK) - inlet pressure: min. 1 bar, max. 7 bar - vented tap

Figure 13-2. Pressurised water heater (Clage MDX-range)

<table>
<thead>
<tr>
<th>kW</th>
<th>3.5</th>
<th>4.4</th>
<th>5.7</th>
<th>6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow (l/min. (ΔT25K))</td>
<td>2</td>
<td>2.5</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>on/off flow (l/min.)</td>
<td>1.2/1.0</td>
<td>1.5/1.3</td>
<td>1.5/1.3</td>
<td>1.5/1.3</td>
</tr>
<tr>
<td>A/V</td>
<td>15/230</td>
<td>19/230</td>
<td>25/230</td>
<td>2*16/400</td>
</tr>
<tr>
<td>max. inlet temp</td>
<td>60°C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 13-3. Electric instantaneous water heater (Vaillant VEDe)

<table>
<thead>
<tr>
<th>power (kW)</th>
<th>13</th>
<th>18</th>
<th>21</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow (ΔT 28K)</td>
<td>6.7</td>
<td>9.2</td>
<td>10.7</td>
<td>12.3</td>
</tr>
<tr>
<td>on/off (l/min.)</td>
<td>3.6/6.5</td>
<td>4.0/7.0</td>
<td>4.6/8.0</td>
<td>5.0/9.0</td>
</tr>
<tr>
<td>current (400V)</td>
<td>3*19 A</td>
<td>3*26 A</td>
<td>3*30 A</td>
<td>3*35 A</td>
</tr>
</tbody>
</table>

Figure 13-4. Mira Zest electric shower (Mira Zest)

Mira Zest electric shower
Produces 4 l/min at 38°C at 8.5 kW (240V) and inlet temp. of 10°C.

An important technical feature is whether the heater is controlled hydraulically or electronically. Newer electronically controlled water heaters all use a "bar wire" (DE: Blankdraht) heating element which allows very fast response times. The conventional hydraulically controlled models (including most electric showers) may use a coil-shaped element, immersed in a small quantity of water.
A third type of electric instantaneous water heater is the *Verbundheizkörper* (DE), a special version of a tubular heating system with an outside lying heating element. The heating element is not immersed in water, but is soldered laterally to a water pipe and all together is wound up to a spiral. This is probably the most simple and robust heating system for an electric instantaneous water heater: The enlarged heat transfer surface allows a lower heating surface temperature and is as such better suited for sections of the water grid with aggressive water quality (above average level of chlorine and/or acids present, like in certain areas in Spain). It is however not as responsive as other types due to its high thermal mass (higher start-stop losses).

![Figure 13-5. Conventional coil immersion and improved bar-wire heating element](image1)

![Figure 13-6. Verbundheizkurper. The spiral wound coil clearly visible.](image2)

| Table 13-2. Comparison of three heating element types for instantaneous DHW production (VHK 2007) |
|-----------------|-----------------|-----------------|-----------------|
| robustness      | bar wire        | tubular immersed| tubular laterally|
| start/stop-losses| good            | good            | best            |
| dynamic temp. control | lowest        | medium          | worst           |
| calcination     | best            | medium          | worst           |
| costs           | lowest          | worst           | medium          |
| water quality   | lowest          | medium          | medium          |
| min. water pressure | standard      | standard        | not important   |
| preferred used in | Germany and Poland | England and worldwide | special environments |

Brand names (mainly UK and Germany) are among others: Stiebel Eltron, Vaillant, Junkers, Clage, Siemens, Zanker, Ariston, Hyco, Redring, Santon and Heatrea Sadia. For electric showers some brand names typical for the UK can be added: Mira, Triton, Aqualisa.
13.2 DHW performance

13.2.1 Flow rate and temperature stability

The temperature lift is linked to the flow rate and the electric power of the heater. The table below gives the maximum flow rate produced at a certain electrical power and two temperature lifts (assuming 100% efficient heat transfer at all flow rates).

<table>
<thead>
<tr>
<th>kW</th>
<th>l/min at delta_T 45°C</th>
<th>l/min at delta_T 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>4</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>6</td>
<td>1.9</td>
<td>3.4</td>
</tr>
<tr>
<td>8</td>
<td>2.6</td>
<td>4.6</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
<td>5.7</td>
</tr>
<tr>
<td>12</td>
<td>3.8</td>
<td>6.9</td>
</tr>
<tr>
<td>16</td>
<td>5.1</td>
<td>9.2</td>
</tr>
<tr>
<td>18</td>
<td>5.7</td>
<td>10.3</td>
</tr>
<tr>
<td>21</td>
<td>6.7</td>
<td>12.1</td>
</tr>
<tr>
<td>24</td>
<td>7.7</td>
<td>13.8</td>
</tr>
<tr>
<td>27</td>
<td>8.6</td>
<td>15.5</td>
</tr>
<tr>
<td>30</td>
<td>9.6</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Two temperature control mechanisms are applied in electric instantaneous water heaters: hydraulically and electronically. Both are described below.

**Hydraulic control**

The conventional hydraulically controlled water heater simply turns on/off heating elements depending the flow rate (or: the water pressure to be more exact, hence hydraulic control). Below a certain pressure the device does not actuate the heating elements and the water stays cold.

Above this pressure point the heating element will be activated and the water is heated. The outlet temperature then depends on the flow rate. In figure 13-7 the appliance is equipped with two stage power control. This option is often marketed as 'summer/winter' switch to accommodate the drop in temperature of the incoming water during winter times.
The dependence of outlet temperature on flow rate / water pressure also means that if elsewhere in the house a tap is opened (a toilet is flushed) the available pressure and flow rate drops, leading to an increase in outlet temperature (and vice versa if a running tap is closed).

**Electronic control**

The electronically controlled electric instantaneous water heater is able to maintain a set temperature throughout a certain range in flow rate, and in addition to this, offers the possibility of temperature pre-sets and flow rate presets (depending on the actual model).

The picture below shows the main components of an electronic water heater and the outlet temperature in accordance with flow rate (output volume). It shows the
minimum flow rate needed before the appliance switches on. The vertical line indicates the possibility of restricting the flow rate to a maximum 6 l/min (example).

The temperature is maintained constant by powering the electric heating elements (barwire type) in steps of approximately 100 Watts. If the flow rate increases to beyond the point where the water heaters is using its maximum power the outlet temperature will drop just like for hydraulically controlled water heaters.

**Minimum flow rates**

Both hydraulic and electronic controlled appliances need a minimum flow rate before the heating elements are activated. This helps to protect the heating elements (ensures that enough heat is transferred for safe operation). The electronic controlled water heater with bar-wire heating elements is a much faster responding device and can thus operate from lower minimum flow rates.

As an example: The Vaillant VED range needs a minimum flow rate of 3 l/min before the appliance switches 'on'. The minimum flow rate below which the appliance switches off is 2,5 l/min.

**Accurate temperature setting**

In hydraulic controlled water heaters in case the water becomes too hot, the desired outlet temperature is realised by mixing in cold water (reducing the flow of warm water has counterproductive effects). In electronically controlled water heaters the temperature can be set with 1 to 0.5K accuracy, displayed on the appliance user interface.

Advanced electronic models offer preset buttons for specific temperatures. Remote control of temperature setting (from multiple draw-off points) is also a possibility.
13.2.2 Responsiveness

The response speed of electric instantaneous water heaters is seldom documented in brochures. However, some delay in reaching operating temperatures can be expected during heat up of the heat exchanger (heating elements and water contents).

Important determinants here are the type of heater elements: conventional coil immersion heaters are submerged in a tank of approximately 0.6 l, whereas a water heater with a bar-wire heating element may have a water content of 0.3 l.

Due to the lower thermal mass and less water content the bar-wire heating elements reach their operating temperature must faster than the powder and metal encapsulated coil immersion heaters: A 'waiting time’ of 20 seconds is deemed indicative for coil-immersion / hydraulically operted water heaters. 5 Seconds is indicative for bar-wire, electronic heaters.
13.3 Energy

13.3.1 On-mode
The immersed electric heater element transfers virtually all energy to the water: the on-mode heat transfer efficiency therefore reaches 99-100%. The primary efficiency (and CO₂ emissions) depends on grid characteristics.

13.3.2 Off-mode
Most if not all electric instantaneous water heaters are installed close to or are integrated with the draw-off points, within the heated area of the dwelling / building.

There is no DHW storage kept at temperature, nor a pilot flame. Residual heat in the heat exchanger is part of 'start-stop losses'.

During off-mode electronic heaters may use some power to operate the circuit board and display, which is covered at 'Auxiliary energy'.

13.3.3 Start-stop losses
At 'start-up' from cold start the thermal mass of the electric heating element and the water contained in the heat exchanger chamber have to reach operating temperatures. The typical water content of the heat exchanger chamber varies from 0, 1 l (2 kW system) to 0,4 or 0,6 l (27 or 24 kW).

Assuming a flow rate of 3 l/min the water content of a conventional hydraulic / coil immersion heater (0,6 l.) is replaced in 12 seconds during which the heater also heats up. The electronic / bar-wire heat exchanger has its contents replaced in 6 seconds (0,3 l.) during which the heating elements reaches its operating temperature.

At 'stop' the residual heat is lost to the environment (also depending on the tapping pattern). A temperature drop of 25K (from 40 ºC to 15 ºC) causes losses of some 31 kJ/8Wh (0,3 l) to 63 kJ/17Wh (0,6 l).

13.3.4 Auxiliary energy
Hydraulically operated electric instantaneous water heaters can operate without auxiliary power.

Electronically controlled heaters use auxiliary power for the controller (PCB) and the user interface display (if applicable). The power consumption is rarely documented in product literature/brochures but experience learns this is probably in the range of 1 Watt or less.

13.3.5 Alternative energy sources
Many instantaneous electric water heaters can be combined with solar pre-heating (certain models by Clage for instance allow inlet temperatures of up to 70 ºC).

For the installation of solar pre-heated water a mixing valve is often prescribed to limit the maximum outlet temperature and prevent scalding accidents (solar pre-heated water may reach very high temperatures, 80 to 90 ºC is not uncommon. The electric water heater itself is not designed by default to reduce outlet temperatures).

For water pre-heated by heat pumps the same principle applies (although in most cases the heat pump will also be a primary water heater, supplying the whole house with DHW).
13.4 Infrastructure

13.4.1 Water pressure

For both hydraulic and electronic instantaneous water heaters designed for connection to mains water pressure (‘pressurised’) the minimum / maximum water pressure is 0.8 / 10 bar (with small deviations depending on model and manufacturers). This ensures enough flow over the heat exchanger (minimum flow rate).

Products connected to a vented tap (like the Clage MH range) are called unpressurised (DE: Drucklos) and a min/max pressure is not indicated, but the minimum flow rate of 1.6 l/min also assumes a minimum pressure.

In case of very low (like DHW storage cisterns in the UK) or no water pressure, specialised products need to be applied: An example is the HeatraeSadia SureFlowPlus electric shower with an integrated booster pump.

13.4.2 Electrical supply

The type of electrical supply needed, depends on the electric power of the appliance and the (local/national) regulations applicable to electrical installations. Almost all electric instantaneous water heaters are connected by a fixed terminal (no plug socket).

In many countries exceeding 4,5kW (20 Ampere @ 230 V) electric power requires a dedicated three-phase, 400 V supply (like applied for electric hobs).

In other countries (the UK for instance) higher currents are allowed (up to 45 A) provided the cabling and routing support this. With 45A@240V 10,8 kW can be realised, which is the maximum rating for most electrical showers. In such cases the cable diameter (4, 6 to 10 mm²) is chosen depending on power, cable lenght and other aspects (ambient temperature, bunched with others or not, behind insulation, etc.).
13.4.3 Chimney / drains

Chimney
Chimneys, flues and supply air are not applicable to electric instantaneous water heaters.

Drains
A pressure relief valve is not a must for these water heaters. The heat exchanger of pressurised systems can withstand mains water pressure (plus a safety margin). After closing the tap no heat build up takes place, in fact the water cools down thereby reducing internal pressure.

Some models (e.g. witnessed on electric showers and/or equipped with slower responding coil immersion heating elements) do have a pressure relief valve to cope with abnormal pressures. Electric showers may also allow the handset to drip for 7 seconds or so to cool down the heating elements before the next user uses the shower.

Unpressurised models can be connected to a vented tap.

13.4.4 Single- or multi-point
Electric instantaneous water heaters that produce maximum 6 l/min at $\Delta T$ 25K (corresponding with 12kW electric power) are in general considered single point water heaters. Examples are the electric showers in the UK and 'above' or 'under the sink' water heaters in the rest of Europe, Germany in particular. Although 12kW in principle suffices for hot water to a kitchen sink or a small shower, such multi-point use (and simultaneous use in particular) is not advised.

Water heaters above 12 kW are more often used for multiple draw-off points. In Germany the 24kW water heater is a popular product, providing hot water for the whole bathroom (shower, washbasin) and sometimes the kitchen as well (proximity provided).

Most electric instantaneous water heaters are used as secondary water heaters, parallel to primary systems: Over 32% of the EU22 households own a secondary water heater, 7.9% of which are electric instantaneous. The main markets where electric instantaneous water heaters are used as primary heaters are Germany, UK, Ireland, Poland and Slovakia (where 5% of households have electric instantaneous as primary water heaters).

One particular advantage of electric instantaneous water heaters is the reduction (and quite often elimination) of pipeline losses. When compared to circulation systems that also promise instant hot water the pipeline losses of circulation systems become relevant and may amount to 60 kWh/m*year. This comes down to 34 to 50% of total energy consumption for hot water at 10 to 20m length of circulation pipes (15 mm Cu with insulation). Positioning the appliance close to the point-of-use also reduces waiting time (water and energy losses). This is further investigated in the modelling Task.

13.5 Prices
At the expert meeting of 15 March 2007 BRGConsult presented retail selling prices of electric instantaneous water heaters. The figures below present the average prices for hydraulic and electronic heaters per power category, and the average prices per country for electronic and electronic instantaneous water heaters in two categories (<12kW and 24 kW).

---

50 CECED Presentation on Electric Instantaneous Water Heaters, Brussels, 14.02.2007
The purchase price of electric instantaneous water heaters depends on the electric power, type of control and extra features of the product and ranges from some 41 euro (bottom price range, hydraulic heater < 12 kW) to over 650 euro (top end price range 27 kW heater, electronic). Electronic heater pricing is 150 to 200% as much as hydraulic versions (prices are sales weighted).
In addition VHK looked at (street)prices of other types of instantaneous water heaters like electric showers (in the UK) and hand washers (unpressurised, vented through tap).

Table 13-4. Prices for electric instantaneous water heaters (streetprice)

<table>
<thead>
<tr>
<th>Product</th>
<th>UK (<a href="http://www.plumbworld.co.uk">www.plumbworld.co.uk</a>)</th>
<th>DE (<a href="http://www.getprice.de">www.getprice.de</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric shower</td>
<td>55 GBP / 83 euro to 280 GBP / 420 euro, depending on features</td>
<td>n.a.</td>
</tr>
<tr>
<td>unpressurised / vented tap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressurised / hydraulic</td>
<td>Average hydraulic (max. 12kW): 80-100 euro, 3.5 to 6.5 kW = 110 to 130 euro</td>
<td>13 to 24 kW is 230 to 250 euro</td>
</tr>
<tr>
<td>pressurised / electronic</td>
<td>Average electronic (max. 12 kW): 150-200 euro, 9,5 / 10,8 / 12kW = 162 / 184 / 189 GBP</td>
<td>3.5 to 6.5 kW = 150-200 euro, 11 to 27 kW = 250 to 550 euro</td>
</tr>
</tbody>
</table>

The overall picture is that in Germany (large EU market for instantaneous water heaters) electronically controlled water heaters are almost double the price of hydraulically controlled heaters. An investment most consumers are willing to make since it saves them some 60 \(^{51}\) to 120 \(^{52}\) euros per year, resulting in a payback time of approximately 2

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\(^{51}\) http://www.durchlauferhitzer.info

\(^{52}\) From http://www.heisswasser.de/, citing a calculation by Clage:

Comparing DSX oder DEX electronic water heaters with a flow rate 8l/min at exact 38 °C to a hydraulic water heater of 21 kW with a flow rate of 11,6l/min (to achieve 38 °C mixed water temperature) in a 3-person household with following parameters: Shower duration: 4 min/person, inlet temperature: 12 °C, showers: 330 days/year, electricity price: 0,15 €/kWh, water-/sewage rate: 4.– €/m³.
to 4 years. In 2006 the sales of electronic water heaters surpassed the sales of hydraulic water heaters \(^5^3\).

The installation costs can be a significant part of the total price for an installed product. Connection of high electric power devices to the electrical mains most often requires trained personnel, especially if a 3-phase/400V connection is to be made. In certain EU countries DIY (do-it-yourself) is illegal, although enforcement of such laws is difficult. In the UK installation costs (for an electric shower) are in the range of 150 to 200 euro\(^5^4\), which is probably also the price range for the remainder of Europe. This means that the installation costs are in the same order of magnitude as the product costs.

\(^{53}\) personal information from CECED spokesperson, 14.2.2007.

\(^{54}\) personal information from CECED spokesperson, 14.2.2007
SECTION THREE - ALTERNATIVE TECHNOLOGIES
14 SOLAR SYSTEMS

14.1 Product description

In many parts of Europe solar thermal systems are applied as DHW pre-heater or as stand-alone DHW system. Literature regarding solar DHW systems often makes the distinction between split (pumped) systems and thermosiphon systems. The Integrated Collector Storage (ICS) is presented as third technology.

Another categorisation can be made by the application: DHW only or combined with heating systems. A third categorisation could be on basis of components of which a vast array has been developed that differ in techniques applied to collect, transport, store and heat the collected solar energy (components like glazed/unglazed, flat-plate or evacuated tube collectors, pressurised or unpressurised storage vessels, low-flow or high-flow pumps, etc.).

When looking at components only, a solar DHW system basically consists of three main parts: The collector that collects solar thermal energy, a thermal storage unit that transfers solar heat to DHW and stores this and a heat generator that heats up the DHW to required outlet temperatures. In some parts of Europe the heat generator is omitted and DHW outlet temperatures of 60ºC can not be guaranteed / less than 60ºC is accepted.

Table 14-1. Typology of solar systems

<table>
<thead>
<tr>
<th>Collector</th>
<th>Store</th>
<th>Heat generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermosiphon</td>
<td>Flat plate - glazed</td>
<td>On roof</td>
</tr>
<tr>
<td></td>
<td>Evacuated tube</td>
<td></td>
</tr>
<tr>
<td>Pumped</td>
<td>Flat plate - glazed</td>
<td>Indoors</td>
</tr>
<tr>
<td></td>
<td>Evacuated tube</td>
<td></td>
</tr>
<tr>
<td>ICS</td>
<td>Storage tank is collector</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

14.1.1 Collectors

Sales of collectors by type seem to indicate a regional or national preference: In Germany evacuated tubes are popular, in neighbouring country the Netherlands the glazed flat plate is most sold, in Greece the unglazed flat plate collector is wide-spread - mainly in the form of thermosiphon systems. There is of course a link between collector type and outdoor temperatures: The lower this temperature the more benefit from well-insulated solar collectors and/or collectors that work well even under overcast sky conditions (read: evacuated tubes).

Two main types of collectors can be considered. The integrated collector storage is treated in a separate paragraph:

- Flat plate (glazed, unglazed)
- Evacuated tubes.

Within these two types many variants are possible, each with slightly different principles or designs. Common for all is the application of a spectral selective layer which enhances absorption of infrared and visible solar radiation and reduces emissivity of infrared radiation - the heat is retained in the material.
**Flat plate collectors**

Flat plate collectors vary in type of glazing (non-, single- or double-glazed), fin-tube arrangements (serpentine fin-tube, register type, cushion type). A few collectors are designed to operate using potable DHW water (which requires reliable controls to prevent overheating and freezing). Furthermore there are endless variations in size and design of the box and insulation, etc.

Heart of the collector is the absorber which connects the part that collects the solar heat with the part that transports this heat to some form of storage. Many techniques are applied.

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**Figure 14-1.**

Fin-tube absorbers
A: Ultrasonic weld
B: Cold formed
C: Laser welded (Sun Laser)
D: Point weld

---

**Figure 14-2.**

"Cushion" or "sandwich" type absorber
E: (Energie Solaire)
F: (Solahart)

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**Figure 14-3.**

The cushion-type absorber is fully irrigated Source: www.energie-solaire.ch

G: VDM-Evidal
H: Solar-Graubunden
Evacuated tubes
Evacuated tubes also come in variety of designs. Each is briefly discussed below.

Fin-tube arrangement
Fin-tube collector uses a pipe-in-pipe arrangement with the inner pipe transporting the fluid to the outer end of the tube and an outer pipe transporting it back to the manifold thereby absorbing heat from the fin attached to it. This type of collector needs to be oriented towards the sun to use the optimal aperture.

The second version employs a U-shaped tube, attached to a flat fin. The tubes can be rotated within their structure for optimal aperture exposure.
A third version uses a curved fin which results in maximal aperture throughout the day.

The table below gives some general data for evacuated fin-tube collectors.

<table>
<thead>
<tr>
<th>Table 14-2. Evacuated Fin tube data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solamax</strong></td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Net Absorber Area</td>
</tr>
<tr>
<td>Overall Dimensions</td>
</tr>
<tr>
<td>Manifold Capacity</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Absorption</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Vacuum</td>
</tr>
</tbody>
</table>

**Tube-in-tube**

Here the absorber is formed by the outer tube of (again) a tube-in-tube arrangement, coated with a spectral selective layer. The working fluid is injected at the bottom end of the outer tube and absorbs the solar heat on its way up to the manifold at the top.

An even simpler design is applied in low-cost asian collectors where the transportation of the working fluid is wholly based on the thermosiphon principle. This is a unpressurised systems sold mainly in China. This principle is not (or rarely) applied in Europe, probably because of the risk of freezing and lesser comfort (unpressurised).
Heat-pipe

A third principle applied in evacuated tubes is the heat-pipe. This collector combines high performance with high reliability. The heat-pipe functions as a sort of heat diode - it only transports heat from the aperture area to the manifold, not the other way around. Risk of freezing is low, since the amount of fluid in the heat pipe is very small and characterised by a very low boiling point (and very low freezing point as well).

The heat-pipe absorbs the solar heat either through a flat fin-tube absorber or a curved absorber design. The flat fin-tube design needs to be oriented towards the sun, the curved version already exposes maximum aperture.
The table below gives some general data for evacuated heat pipe collectors.

<table>
<thead>
<tr>
<th></th>
<th>Thermomax</th>
<th>Heat pipe with fins</th>
<th>MS20 Manifold</th>
<th>MS30 Manifold</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Absorber Area</strong></td>
<td>2 m²</td>
<td>3 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Overall Dimensions</strong></td>
<td>1960 x 1420 mm</td>
<td>1960 x 2120 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Manifold Capacity</strong></td>
<td>3.4 litres</td>
<td>5.1 litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>45 Kg</td>
<td>68 Kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Absorption</strong></td>
<td>Better than 96%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>$n_0 = 0.81$, $k_1 = 1.2$, $k_2 = 0.007$ W/m²K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vacuum</strong></td>
<td>Better than 10^{-5} mbar</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Integrated collector storage**

The third main type of solar collectors integrates the storage tank in one housing. The definition of Integrated Collector Storage (ICS) is rather diffuse in the sense that some consider all products that combine a collector (absorber) surface and a storage tank in one housing and is put on top of the roof are ICS. In this sense the popular thermosiphon systems in Greece with a storage tank placed above a flat plate collector are also ICS.
Other people restrict the definition of ICS to products where the storage is completely integrated (or wrapped up inside) the collector. This interpretation includes the simple batch collectors (US term) - simple drums with black paint on them, placed on top of the roof.

ICS systems are simple, reliable solar water heaters. However, they should be installed only in climates with mild freezing because the collector itself or the outdoor pipes could freeze in severely cold weather. Furthermore the heat loss (also during cold clear nights/kisses) is significant and measures should be taken to prevent this (e.g. through transparent insulation, heat pipes).

More sophisticated ICS systems are often heralded as offering the best price-performance ratio, mainly due to ease of installation and simple, rugged construction (no moving parts) and improvements in this price/performance ratio are still being made.

Examples are the Dutch Econok and the ICS developed by Ecofys.
Collector fluids

Most flat plate systems on sale today use a water-glycol mixture to prevent freezing. A drawback is that the mixture is toxic.

Other systems use pure (drinking) water as working fluid. Most of these systems are designed as a drain-back system where the collector is emptied in case of risk of freezing. Naturally these systems rely on pumps for circulation.

Freezing of the water-filled collector of the "AquaSystem" by Paradigma is prevented by linking the collector circuit to the DHW or CH heat exchanger of a boiler and, in case of risk of freezing, supply some of the DHW or CH heat to the collector (thereby in fact cooling the storage contents).

Integrated Collector Storage systems may also use drinking water as collector fluid. In the design of these systems particular attention is paid to preventing damage by freezing and overheating (boiling).

14.2 DHW performance

Assessing the DHW performance of solar water heaters is hindered by the fact that most solar systems are not designed to deliver DHW at a constant temperature. Most systems sold and in use in Europe are DHW pre-heaters, ie. the final heating up to required temperatures is done by some other water heating device.

There are however lots of solar water heaters, mainly thermosiphon systems, that include an electric element in the storage tank. This heater is used to boost the DHW performance and consequently these heaters may be able to achieve

14.3 Energy

14.3.1 Performance of collectors

The thermal performance of unglazed, glazed and evacuated tube collectors does not differ that much. The typical collector produces some 0.7 kW/m².

The performance of solar collectors depends on a many variables and should ideally not be seen separate from the system it forms part of. However collectors can be tested as separate items and the main aspects determining performance are: How much solar
energy is absorbed and retained in the absorber? How well does the absorber transfers its energy to the working fluid? What thermal losses occur in the collector?

These properties are described in the test method for thermal solar systems and components (EN 12975-2:2006 - Solar collectors - Part 2: Test methods).

The Swiss institute for Solartechnik-Prüfung-Forschung (SPF) publishes on its website a database of performance of flat plate and evacuated tube collectors, tested according EN12975.\(^{55}\)

The collector efficiency is calculated as:

\[
\eta = F'(\alpha \tau)_{\text{e}} - a_1 \left( \frac{T_m - T_o}{G_k} \right) e - a_2 \left( \frac{T_m - T_o}{G_k} \right)^2 / G_k
\]

and \( \eta_0 = F'(\alpha \tau)_{\text{e}} \)

and \( x = \left( \frac{T_m - T_o}{G_k} \right) / G_k \) (where \( x \) = reduced temperature coefficient)

\[
\eta = \eta_0 - a_1 x - a_2 G_k x^2
\]

With:

- \( F' \) [-] Kollektorwirkungsgradfaktor:
- \( G_k \) [W/m²] Globale Bestrahlungsstärke in die Kollektorebene
- \( T_o \) [K] Umgebungstemperatur
- \( T_m \) [K] Mittlere Kollektortemperatur \( T_m = (T_i + T_o) / 2 \)
- \( T_i \) [K] Kollektor Eintrittstemperatur
- \( T_o \) [K] Kollektor Austrittstemperatur
- \( (\alpha \tau)_{\text{e}} \) [-] Effektives Absorption-Transmissionsprodukt
- \( \alpha \) [-] Absorptionskoeffizient
- \( \tau \) [-] Transmissionskoeffizient
- \( \eta \) [-] Kollektorwirkungsgrad
- \( \eta_0 \) [-] Optischer Wirkungsgrad, Kollektorkennwert
- \( a_1 \) [W/m²K] Kollektorkennwert
- \( a_2 \) [W/m²K²] Kollektorkennwert

These SPF test reports for solar collectors include an indication of annual solar contribution (in kWh) to 1) DHW, 2) DHW pre-heating and 3) space heating alone. The overview below presents the values for of the best and worst collectors in the SPF database of which information was available (some models did not indicate the performance), assessed on basis of their annual contribution to DHW production.

\(^{55}\) http://www.solarenergy.ch/spf.php?lang=de&fam=1&tab=1
Table 14-4. Performance of solar collectors [Source: SPF, Switzerland]

<table>
<thead>
<tr>
<th></th>
<th>kWh DHW</th>
<th>$\eta_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best</td>
<td>570</td>
<td>0.823</td>
<td>3.02</td>
<td>0.0125</td>
</tr>
<tr>
<td>Worst</td>
<td>244</td>
<td>0.765</td>
<td>7.31</td>
<td>0.051</td>
</tr>
<tr>
<td>(difference)</td>
<td>43%</td>
<td>93%</td>
<td>242%</td>
<td>408%</td>
</tr>
<tr>
<td>Evacuated tube</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best</td>
<td>669</td>
<td>0.813</td>
<td>1.32</td>
<td>0.0035</td>
</tr>
<tr>
<td>Worst</td>
<td>455</td>
<td>0.571</td>
<td>2.1</td>
<td>0.0067</td>
</tr>
<tr>
<td>(difference)</td>
<td>68%</td>
<td>70%</td>
<td>159%</td>
<td>191%</td>
</tr>
</tbody>
</table>

The best/worse ratio for $\eta_0$, $a_1$ and $a_2$ of individual collectors can be even larger than indicated above.

The table shows that large variations exist, both in solar absorption/transmission properties as thermal losses. The differences for evacuated tubes however appear less prominent than for flat plate collectors. Also noteworthy and consistent with general rule of thought is that evacuated tubes have better performance (the worst evacuated tube is still 186% better than the worst flat plate in the database). Please note that these values relate to standardised test conditions (according SPF corresponding to European averages - see figure below).
Storage systems can either positioned on the roof (thermosiphon or ICS) or indoor. The following types are identified:

- On roof as in Integrated collector storage (see also above);
- On roof, storage only;
- Indoor, storage only;
- Indoor, combined with heat generator.

As far as heat generators for solar DHW go they can be either integrated in the storage cylinder or be external (either separate or combined in a single casing):

- Internal - combined with storage
- External - feeds storage with heat supplied by non-integrated boiler (this includes storage and heat generator in one casing and storage with electrical element)
Storage

Atag O-Solar:
1. CH heat exchanger 
   stainless steel
2. Control management
3. Three-way valve
4. CH circulator
5. Load storage (by CH) 
   heat exchanger
6. DHW sensor
7. Solar circuit sensor
8. DH heat exchanger
9. Modulating three-way 
   valve (solar circuit)
10. DH return temperature 
    sensor
11. Solar heat exchanger
12. Fill/draw-off valve solar 
    circuit
13. Solar collector 
    circulator and flow control
14. Solar collector storage
15. Solar activating sensor
16. Solar feed temperature 
    sensor
17. Storage draw-off valve
18. DHW safety valves
19. Thermostatic mixing 
    valve
20. Connections for DHW 
    circulation

14.3.2 (Auxiliary) Heaters

Circulation

Considering the pumped systems there are two options: A system which drains itself if 
the pumps stops - this is to prevent freezing or boiling of the working fluid. Another 
option is to use a working fluid which does not need to be drained (often filled with 
glycol anti-freeze). The non-drain system can do with a less powerful circulator.

The popular thermosiphon systems employ a electrical (emergency) heater in the 
horizontal tank placed upon the roof. There is some discussion that the use of such 
electric elements brings down the efficiency of the system, since it heats up the whole 
tank thereby frustrating heat transfer from the collector. In systems that use a vertical 
storage tank and position the heater in the top part the heat transfer of the collector in 
the bottom part is not hindered by what happens in the top half.

Most split systems (collector on roof, storage tank inside) use a drain-back system

Some solar systems are equipped with a form of frost-protection that uses electric 
heaters. Econok says 20W, PER is 0,03 GJ which converts to 0,012GJ_d (40% eff. 
assumed) or 3,3 kWh_d.
14.4 Infrastructure

The installation and operation of solar systems can be limited or influenced by several infrastructural and system constraints. Solar exposed areas, azimuth and orientation of collectors as well as structural integrity and weatherproofing of the roof are obvious aspects of the installation. The vertical distance between collector and storage of pumped systems depends on the head of the circulation pump. Thermosiphon systems are critical as regards position of storage tank.

Aesthetic considerations can limit the feasibility of solar systems, as well as the legal infrastructure (tenant in practice experiences great great difficulties

In case of integrated or ICS systems the storage is also positioned on the roof, near the collector. In case of pumped systems (or thermosiphon systems with storage positioned above the collector) the collector is positioned indoors.
14.5 Prices

The German Stiftung Warentest published a solar system test in 2003, which included prices with and without installation. These solar systems were sized to assist in space heating as well and are therefore much higher priced than dedicated solar water heater systems.

Table 14-5. Solar systems in Stiftung Warentest 4/2003

<table>
<thead>
<tr>
<th></th>
<th>Price w/o. installation</th>
<th>Price with installation</th>
<th>savings on ann. heat demand (%)</th>
<th>aperture (m²)</th>
<th>collector (type / quantity)</th>
<th>Storage volume: sanitary / system (l)</th>
<th>Electricity cons. (kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>separate boiler required</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wagner Solarpaket SH1440AR</td>
<td>8890</td>
<td>11430</td>
<td>29</td>
<td>14,22</td>
<td>Flatplate/6</td>
<td>200/977</td>
<td>84</td>
</tr>
<tr>
<td>Paradigma Kombipaket CPC Optima</td>
<td>12510</td>
<td>15190</td>
<td>24</td>
<td>10,47</td>
<td>Vacuumtube/3</td>
<td>250/794</td>
<td>74</td>
</tr>
<tr>
<td>Buderus Logasol Diamant Classic H750/6U-B+FM443</td>
<td>11010</td>
<td>13550</td>
<td>25</td>
<td>13,03</td>
<td>Flatplate/6</td>
<td>250/750</td>
<td>80</td>
</tr>
<tr>
<td>Consolar TUBO-SOLUS 6/560L Komplettpaket</td>
<td>10390</td>
<td>13050</td>
<td>18</td>
<td>5,74</td>
<td>Vacuumtube/6</td>
<td>100/530</td>
<td>100</td>
</tr>
<tr>
<td>Nau Variolux Vakuun-Röhrenkollektro mit Schichtspeicher BS800</td>
<td>22660</td>
<td>25160</td>
<td>21</td>
<td>8,80</td>
<td>Vacuumtube/8</td>
<td>300/788</td>
<td>149</td>
</tr>
<tr>
<td>Viessmann Solarsystem mit 4 Vitosol 100 Aufdachmontage</td>
<td>8380</td>
<td>10920</td>
<td>22</td>
<td>9,98</td>
<td>Flatplate/4</td>
<td>150/723</td>
<td>143</td>
</tr>
<tr>
<td>Ikarus Powerröhre mit Schichtspeicher HSK</td>
<td>8750</td>
<td>11410</td>
<td>21</td>
<td>8,04</td>
<td>Vacuumtube/12</td>
<td>100/795</td>
<td>72</td>
</tr>
<tr>
<td>UFE Solar Solarpaket Ecoplus Gold K4/518 Aufdach</td>
<td>7310</td>
<td>9850</td>
<td>17</td>
<td>7,90</td>
<td>Flatplate/4</td>
<td>125/546</td>
<td>73</td>
</tr>
<tr>
<td>internal gas burner - condensing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solvis max-Paket SX 6.Max 950 und Fera Flachkollektor</td>
<td>18040</td>
<td>19690</td>
<td>28</td>
<td>12,81</td>
<td>Flatplate/2</td>
<td>225/923</td>
<td>55</td>
</tr>
<tr>
<td>Rotex Solaris</td>
<td>10330</td>
<td>11980</td>
<td>11</td>
<td>7,00</td>
<td>Flatplate/3</td>
<td>150/447</td>
<td>78</td>
</tr>
<tr>
<td>internal gas burner - non-condensing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solatherm Solamax + Multibag 500 RW</td>
<td>not available anymore</td>
<td>not available anymore</td>
<td>15</td>
<td>6,45</td>
<td>Vacuumtube/2</td>
<td>275/517</td>
<td>116</td>
</tr>
</tbody>
</table>

The overview above is therefore expanded by an inventory of streetprices of solar water heaters (different designs and sizes, indicative prices only).

Figure 14-21. Several streetprices of solar systems throughout Europe

Complete set: evacuated tube collector, indoor storage, pump + control. Street price Spain: 2319 euro

Schuco system with 2 collectors, 300L storage etc. costs 4200 euro (excluded installation)

ProSun H 403 HighLine (Artikel-Nr. 65010006) bestehend aus:
2 x Kollektor PS2400 HighLine 2 (Kollektorfläche: 4,6 qm) 1 x MP 2 HighLine SDZ HN (2N) 1 x Ausdehnungsgefäß Solar AG18S 1 x Haltebügel AGHB 1 x Frostschutzkonzentrat FS10 1 x Solarspeicher 300L Integrale 1 x Montageanleitung ProSun Integrale
Streetprice: from 4,023,00 to 2,599,00 Euro
[www.oeko-energie.de/Sonderangebote.htm#SOLARWÄRME]

ProDuo 7/540 HighLine (Artikel-Nr. 65030004) bestehend aus:
3 x Kollektor PS2400 HighLine 2 (Kollektorfläche: 6,9 qm) 1 x MP 3 HighLine SDZ HN (3N) 1 x Pumpstation PS10 Duospeicher 1 x Ausdehnungsgefäß Solar AG25S 1 x Haltebügel AGHB 1 x Frostschutz L 16KG 1 x 1-Kreissteuerung PS C104 1 x Duospeicher 540/150 ISO+BW-SET 1 x Montageanleitung ProDuo 06/04. Streetprice: from 5,908,00 to 3,999,00 Euro
[www.oeko-energie.de/Sonderangebote.htm#SOLARWÄRME]

Streetprices systems:
2,4 m², 200L: 2573 euro (incl.)
4,8 m², 300L: 3330 euro
7,2 m², 500L: 4269 euro
[www.okuonline.de]

Solar system, Greek system, double collector, 180L storage (ICS) costs 2000 euro (streetprice). A pumped system would cost up to 2500 euro.
www.elitherm.com
Integrated evacuated tube system: Street price Spain: 1319 euro

Copper collector 144 to 230 euro (1.8 m²) and 198 to 300 euro (2.45 m²) difference in coating, insulation, glass.
[www.isteksolar.com.tr]

Solar storage cylinder only: Street price Spain: 885 euro

ICS collector / batch collector: 895 EUR (min. order 27) http://www.alphasolar.com

ICS collector / batch collector (US dollar)
PT-20-CN, 20 Gallon, 84 x 20 x 7. 65 $998.97
PT-30-CN, 30Gallon, 97.4 x 35.4 x 7.75 $1279.97
PT-40-CN, 40 Gallon, 97.4 x 47.4 x 7.75 $1579.97
PT-50-CN, 50 Gallon, 97.4 x 47.4 x 7.75 $1729.97
http://www.thesolar.biz/Progressive%20Tube%20Water%20Heaters.htm
15 HEAT PUMP SYSTEMS

15.1 Product description

This section is limited to heat pumps for water heating that extract heat from either plain outside air or air extracted from the house (usually ventilation air). Heat pumps using other heat sources (soil, rock or ground-/surface water) and heat pumps providing space heating as well (sometimes combined in one appliance, but mostly a solo boiler with indirect storage) are not covered in this section. A typical air source DHW heat pump is pictured below.

Figure 15-1.
Techneco / Blomberg
WPB closed

Compressor 385 W (230 V)
Electric back-up 1.5 kW
Refrigerant R134A, 0.9 kg
Temp. 58°C
COP 2.34
Standing losses 45,2 W
Insulation 50mm PUR
Fan max. 350 m³/hr, 73W
Noise: Type E 59dbA (at Tair 15°C and Twater 45°C)
Reheat time 10-55°C: 160 l 10 hr, 300 l 16 hr (w.o. el.back-up, at Tair 20°C and 150 m³/hr)

Figure 15-2.
(picture: Nibe Fighter 100 installation manual)

1 - electric heater 1.5 kW
3 - thermostat 51°C
4 - thermostat 60°C
6 - temperature cut-out switch
8 - switch, position 0-1-2-3
10 - power chord
22 - connections controlling fan speed
27 - compressor
28 - start capacitor
29 - starting relais
30 - relais
36 - fan
37 - control light
38 - temp.switch
41 - low pressure pressostat
48 - expansion valve
49 - high pressure pressostat
54 - power supply fan
57 - operating capacitor
61 - condensor
62 - evaporator
63 - air filter
65 - filter dryer
73 - cold water in
74 - hot water out
78 - filter hatch
84 - ventilation hose
90 - air in
91 - air out
92 - condensate hose
95 - condensate container
96 - type / model plate
97 - sump heater
99 - drain container
103 -serial number
105 - overflow outlet condensor
Heat pumps are considered very efficient electric storage water heaters: one unit of electrical energy is "lifted" to 3 or 4 units of useable heat.

The storage volume is in the range of 150 to 300 l. The average heat pump is electric compressor driven.

Manufacturers are Stiebel Eltron, Blomberg / Techneco, Nibe, Siemens, etc. (incomplete).

15.2 DHW performance

15.2.1 Flow rate and temperature stability
Heat pumps are storage DHW systems hence the flow rate and temperature stability of the heat pump are identical to any DHW storage system.

A major difference however can be the re-heat time since the heating power is often limited, especially at lower source temperatures and dependent on heat sink conditions. To boost charging times most electric heat pumps have an electric back-up heating element on board, usually in the range of 1.5 to 3 kW.

15.2.2 Responsiveness
Starting with a fully charged storage the response (measured at the appliance outlet) is very fast.

15.3 Energy

15.3.1 On-mode
The efficiency of a heat pump (in steady state conditions) is indicated by its Coefficient of Performance (COP), which indicates the ratio of electric power input and thermal output. For most DHW heat pumps the COP is in the range of 2.5 to 4. A heat pump with a 350 W compressor and a COP of 3.5 thus produces 1.2 kW of heat.

To date the only official test method for DHW heat pumps is EN255-3:1997 which measures (a.o.):

- heating up time and energy input;
- standby power input (includes energy for fans/pumps);
- COP (procedure includes tapping 50% of contents twice and measuring energy input);
- maximum quantity of usable hot water in a single tapping;
- reference hot water temperature.

The COP not always includes all auxiliary energy, e.g. the energy to power the fans for transport of air and the electronic controls. In EN 255 some of the auxiliary energy is included through corrections for fan and pump operation: For fans corrections are applied to even out differences between appliances designed to operate without an air pressure difference or with an air pressure difference but with or without a fan. The corrections for pumps concern the circulation of heat transfer media to outdoor heat exchangers.

The heat pump with a 350 W compressor indicated in the pages before uses a 73 W fan, although more efficient (direct current) fans use less than 50% of that (31 W). This is still some 2.6 to 6% of heat output (1.2 kW) or 10 to 20% of compressor power consumption.

The COP is also highly dependent on heat source and heat sink conditions. Since both change in time (the DHW storage -heat sink- is emptied and refilled throughout the day, outside air conditions change throughout the day and seasonally, indoor/ventilation may be limited in supply since every m³ extracted is replaced by un-
pre-heated cold outside air) a measurement method was developed to take into account these variations: The seasonal performance factor.

The IEA Annex 28 workgroup undertook the task to come up with a test method to develop a standard that includes a seasonal performance factor. They did so for space heating and combi-appliances and on this the current prEN15316-4-2:2005 has been developed. The SAVE WH study also mentions the effect of the tapping pattern on appliance efficiency: A pattern with very small draws reduces seasonal performance to 145% whereas a pattern with some large draws achieves 225%.

The efficiency on primary fuels is also influenced by the type of electricity generation and the grid characteristics (in short: "grid efficiency").

### 15.3.2 Off-mode

Off-mode or standby / standing losses are a significant loss factor for all storage systems, including DHW heat pumps. The heat pump presented as example on the first pages of this chapter has standing losses of 45,2W (probably the 160 l. version at 55°C).

EN 255 describes a measurement of standby power consumption, which includes a few on-off cycles of the compressor to compensate for storage losses. prEN15316-4-2:2005 Annex B4 contains references to DHW heat pumps and provides some default values for COP and storage losses. It shows that storage losses are a significant part of the heat input (55W of 1200W is 4,6%).

<table>
<thead>
<tr>
<th>Testing point</th>
<th>Storage temperature</th>
<th>Pe [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0/*</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>B0/*</td>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td>B0/*</td>
<td>45</td>
<td>42</td>
</tr>
</tbody>
</table>

### 15.3.3 Start-stop

Start-stop losses for (electric compressor driven) heat pumps are relevant since frequent on-off switching reduces the overall energy efficiency (during every cycle a equilibrium of optimal energy transfer has to be reached which takes time). This is the reason that a DHW storage is applied - this allows for long(er) run times.

Start-up losses are included in the EN255-3 test for COP and standby and are through this also considered in the prEN15316-4-2:2005 test standard on efficiency of heating systems. The prEN15316-4-2 contains a host of equations to calculate efficiencies of heat pumps for space heating and/or DHW production and refers to values from EN255 tests.

The dutch test directive for DHW heat pumps (R 98/463 November 1998) includes a tapping pattern over a 24 hr period, but it depends on the appliance whether any or frequent start-stops are included.

### 15.3.4 Auxiliary energy

In this section auxiliary energy is defined as all energy consumed by the heat pump except the energy required to drive the vapor compression cycle. EN 255 doesn’t define auxiliary energy, but does make corrections for fan and pump energy (see above). Controls are also included in measurement of COP and standby energy consumption.

Some heat pumps use an electric heater for defrosting the evaporator, which may be necessary during very cold inlet temperatures. This energy is not considered in EN 255. And then an unknown number of (outside placed) heat pumps use a sump heater to

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57 The appliance is forced to charge the storage completely by making two draw-offs of 50% of the content - One can assume that the heat pump runs continuously during charging.
pre-heat the compressor sump (oil carter of compressor) in cold conditions. This reduces wear and tear on the compressor during start-up. Both forms of energy consumption are not included in the EN 255 test method and little is known about their actual energy consumption.

15.3.5 Alternative energy
Heat pumps are an application of alternative energy. Combination with the other main alternative energy source, solar heat, is possible but rarely applied since it would introduce two heat sources fighting to transfer their low temperature heat to a storage.

15.4 Infrastructure

15.4.1 Chimney / drains
The electric compressor heat pump requires no flues nor chimneys to operate. Condensate may occur at the evaporator-side, since this element is colder than ambient air. Depending on the model the condensate may be pumped away to a drain or is collected in a small container where it is allowed to evaporate.

A water drain is also needed to relieve pressure build up from the boiler and to facilitate filling and draining.

15.4.2 Air ducts
In case extraction air from the dwelling is used as heat source an air duct system is used to guide air towards the heat pump. These ducts can be quite voluminous (for a domestic heat pump Ø 125mm) and usually lead from extraction points in the kitchen and bath-room to where the heat pump is situated (air from the cooker hood is usually not used as heat source).

No ducts are required in case outdoor air is used and the heat pump is positioned outside as well. In case an outside-air heat pump is placed indoors it is usually placed next to an outdoor wall and only a short duct is required.

The flow rate of air is usually between 75 to 400 m³/hr and thus may exceed the ventilation requirements of the dwelling at times. Persons commissioning the installation need to be aware that if the extraction rate increases more cold supply air is drawn into the dwelling. The heating system must be designed to cope with this. The minimum flow rate should be maintained while in operation.

An important aspect in heat pump operation is cleaning and maintenance of the air duct system and the filters in it. Blocked or seriously hindered airflow could damage the heat pump. Therefore the supply air filters should be checked and cleaned preferably 4 times per year. Vents or grilles that extract the air should be checked and cleaned annually. Finally, if an outside-unit is used, the evaporator should be checked and cleaned periodically as well.

15.4.3 Draw-off point
Heat pump water heaters are the primary water heater in the dwelling, serving multiple draw-off points. The length of DHW piping introduces extra waiting time and loss of energy and water.

Recirculation of DHW by the heat pump storage tank is possible but not often applied since the continuous supply of cooled down water (water is cooled in the recirculation pipes) may cause the heat pump to switch on-off frequently. Much depends on the settings of the DHW storage sensor/control.
15.5 Prices

Average costs for a completely installed exhaust air heat pump with a 225 l storage tank (sanitary hot water only and excluding costs for the ventilation ducting system in the house) varies from 2000 to 3500 euro.

More recent prices (wholesale or street-price excl. installation costs, excl. VAT) are given below:

Table 15-2. Prices of heat pump water heaters (and some combis)

<table>
<thead>
<tr>
<th>Manufacturer 'A'</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation air heat pump, COP 3 (heat up to 65°C), Compressor 300W, fan 150W, electric element 1500W, timer control 5 W, 100 - 225 m³/hr</td>
<td></td>
</tr>
<tr>
<td>Without electric element: 75 euro reduction</td>
<td></td>
</tr>
<tr>
<td>80 L: 1911 euro</td>
<td>[1]</td>
</tr>
<tr>
<td>(streetprice 2454 euro)</td>
<td>[2]</td>
</tr>
<tr>
<td>120 L: 1982 euro</td>
<td>[1]</td>
</tr>
<tr>
<td>(streetprice 2538 euro)</td>
<td>[2]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer 'B' [1]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation air heat pump, compressor 300W, fan 150W, electric element 1500W, timer control 5 W, 72 - 350 m³/hr</td>
<td></td>
</tr>
<tr>
<td>225 L: 2427 euro</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer 'C' [1]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation air heat pump, COP 3.45 (heat up to 65°C), nom.power 400W, electric element 1500W, Air: 75 - 350 m³/hr</td>
<td></td>
</tr>
<tr>
<td>300L: 2336 euro (2493 for &quot;solar ready&quot;)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combi's [1]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation air-to-water, 303L storage, nominal power 375W, 6.6kW electric element, 50-280 m³/hr</td>
<td></td>
</tr>
<tr>
<td>4276 euro</td>
<td></td>
</tr>
<tr>
<td>Ventilation air-to-water, 303L storage, nominal power 575W, 6.6kW electric element, 100-280 m³/hr</td>
<td></td>
</tr>
<tr>
<td>4286 euro</td>
<td></td>
</tr>
<tr>
<td>Water/brine-to-water, (source/system 0°C /35°C)</td>
<td></td>
</tr>
<tr>
<td>5.8kW: 4600 euro</td>
<td></td>
</tr>
<tr>
<td>7.7kW: 4650 euro</td>
<td></td>
</tr>
<tr>
<td>10.1kW: 5095 euro</td>
<td></td>
</tr>
<tr>
<td>13.4kW: 5495 euro</td>
<td></td>
</tr>
<tr>
<td>Water/brine-to-water (modular - cascade of max. 6)</td>
<td></td>
</tr>
<tr>
<td>13.4kW: 4300 euro</td>
<td></td>
</tr>
<tr>
<td>17.4kW: 4850 euro</td>
<td></td>
</tr>
<tr>
<td>Seperate storage tanks</td>
<td></td>
</tr>
<tr>
<td>100L: 354 euro</td>
<td></td>
</tr>
<tr>
<td>200L: 452 euro</td>
<td></td>
</tr>
<tr>
<td>700L: 905 euro</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer 'D' [3]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>heat pump 'model X' - 6 kW 3-phase 400 V</td>
<td>streetprice 5303 euro</td>
</tr>
<tr>
<td>separate storage cylinder 250 L</td>
<td>streetprice 1791.34 (excl. heat pump adaptation 470 euro)</td>
</tr>
</tbody>
</table>


The installation costs depend very much according the local situation. For ventilation air heat pumps these costs are comparable to installation of an electric boiler plus the connection to the (exhaust air) ventilation system. An (anecdotal) indication of product plus installation costs is 2600 euro all in. If one allows 2000 euro for the heat pump itself some 600 euro can be attributed to the installation (in standard circumstances).

Important aspects to consider during installation are:

- vibration free installation: flexible connections to existing pipework/ductwork;
- reduce sound pressure to environment;

[58] From www.actieenergiezuinigwonen.nl, at 19-3-2007, for a 300L storage, COP 4.4 and nominal power 410W ventilation air heat pump water heater in standard situation.
- for ventilation air heat pumps: balancing of ventilation components, check airtightness of connections;
- for combi-heat pumps: balancing of heat flow from source/to sink (check circulator speed).

Re-occurring costs besides maintenance/servicing are filter replacement (indicative costs 10–20 euro per filter) and costs for cleaning the evaporator, condensate drain and fan (blades).
SECTION FOUR - WATER HEATER SYSTEM COMPONENTS
16 ANTI-LEGIONELLA SYSTEMS

16.1 Introduction
An important aspect of water heating systems is the prevention of infection with Legionella bacteria. In Task 1 Legislation & Standards, Chapter 4, several methods for preventing or combating growth of Legionella bacteria in water heating systems have been listed:

- Thermal prevention;
- Thermal disinfection;
- Physical or chemical-physical disinfection:
  - UV disinfection;
  - Micro- / Ultra membrane filtration;
  - Anodic oxidation;
  - Copper/silver ionisation;
  - Electrical pulses;
- Chemical disinfection.

In those situations where thermal techniques cannot properly be applied physical and chemical techniques are applied. Physical techniques are techniques that do not introduce foreign elements or substances into the water, examples are UV and filtration techniques. Chemical, physical and thermal techniques can be combined and sometimes have to be combined since some techniques only have a local or temporarily effect.

This Chapter will discuss those methods applied in water heating systems other than thermal prevention and disinfection in the water heater / storage tank itself.

16.2 Thermal prevention
Thermal prevention of legionella growth in hot or cold water systems is most of all a matter of good design. Prevention measures focus on aspects such as 59:

- Avoid dead ends: in older systems certain pipe segments may have been disconnected due to changes in the system lay-out - these should be corrected. Pipe segments leading to fire hoses are equipped with stop valves - these should be located at the beginning of the segment. If the valves are at the end of the pipe, close to the fire hose, a large dead end segment is created in the supply piping.
- Avoid hot/cold spots: known problems are central heating pipes heating up cold water pipes (in shafts, under floor and even in crawlspace where heat may be transferred by condensation). Cold spots can cool down hot water pipes (or storage) to temperatures that promote legionella growth.
- Ensure circulation: especially in circulation systems with pressure boosters (pumps that maintain desired water pressure, often applied in high-rise buildings) dead ends may be created in the expansion vessels. This can be overcome by special valves that maintain the flow through the expansion vessels. Another measure is applying modulating booster pumps. Traditional pumps are on/off type which may

cause stagnant pipe segments and un-even temperature distribution. Modulating pump control maintains circulation and temperature. Another effect is that expansion vessels may be smaller since the variations in pressure are much smaller.

- Not really a thermal prevention measure but nonetheless relevant are the materials used in the system. Some materials (like gaskets from organic materials) have been known to promote bacteria growth. Materials also differ in their effects on the formation of biofilms: e.g. plastic pipes are more susceptible than e.g. stainless steel. Last but not least sediment (usually formed at the bottom of storage tanks) also functions as a breeding ground for legionella bacteria.

Thermal prevention measures are now considered 'good design practice' for new buildings. Owners of existing buildings in which legionella is more likely or more risky to occur (e.g. buildings for elderly, health care) can be ordered to make changes to their system if on-site samples indicate legionella risks.

In many cases thermal prevention measures are combined with other prevention or disinfection measures, especially if these other measures are 'gatekeeper'-type methods.

16.3 Thermal disinfection

Thermal disinfection of DHW pipes is aimed at eradicating legionella bacteria in systems through a combination of high temperatures and residence time.

Disinfection measures ideally not only aim to disinfect the water in the pipes but also the biofilm on the inside of the pipes. Standard procedures are weekly pipe flushing with water of 60°C (20 minutes), 65°C (10 minutes) or 70°C (5 minutes) or water reheating at 60°C (10 minutes), 65°C (1 minutes) or 70°C (10 seconds). Also steam cleaning of spas and aqua centres is used (60 - 70°C at longer times).

Special care should be taken that during flushing with hot water (and immediately after, when there is still hot water in the pipes) the water system is not used. In shower areas for instance the flushing takes place outside visiting hours and after flushing the showers are (electronically) 'blocked' to avoid scalding.

16.3.1 (Automated) Flushing

Flushing of pipes with hot water from the water heater(s) can be done manually but this is cumbersome and requires adequate management. Installation of automated valves makes operation and control a lot easier.

For systems with less than 1 ltr mixed water content (typically < 5m) behind the thermostatic mixing valve a solenoid operated valve in combination with a central control unit ensures periodic (daily) flushing. The system is combined with electronic controls for the showers that prevent use of the showers during flushing.

---

60 In the Netherlands this is regulated in "Waterleidingbesluit Art. 4.1" and ISSO publication 55.1 and 55.2.
Systems with more water content (longer distances) behind the thermostatic mixing valve are flushed regularly with hot water by having a motorised three-way valve shut off the cold water inlet of the thermostatic valve and connect this to the DHW circulation. The system is also combined with electronic controls for the showers.

16.3.2 Reaction chamber
A second option involves the use of a reaction chamber in which the cold incoming water is heated and stored in a reaction chamber. The temperature (> 60°C) and residence time (> 6 minutes) in this chamber ensure that the cold water is disinfected. A unique feature of this application is that during draw-offs the hot water is cooled down to useable temperatures. The extracted heat is transferred to the cold incoming water and is not lost - and no cold water (possibly with bacteria) reaches the mixed pipes. The application shown below is patented by AlfaLaval.
16.3.3 Local heating

A third option is the local heating of water in the pipes followed by flushing the pipes with clean cold water. The pipe contents are heated by a heating wire (stainless steel chord) that has been inserted into the pipes and heats up the water to up to 70°C. The pipes are then flushed with clean water by opening of automated valves\(^\text{61}\).

The system promises minimum energy costs and minimum water costs and is patented by Legiofreewater systems. Legiofreewater claims an energy saving (compared to flushing with hot water for 20 minutes) of 98%\(^\text{62}\).

\(^{61}\) Manufacturers information on the website www.legiofreewater.nl
\(^{62}\) Source: http://www.senternovem.nl/energietransitie/over_energietransitie/koplopersloket/legio_free_water.asp
16.4  UV lamp

UV radiation, or more particular UV-C radiation of wavelength between 200-280 nm, breaks down the DNA structure of the Legionella bacteria. The effectiveness depends on the radiation intensity and the exposure time. The product of intensity * exposure is the dosage which is expressed in MJ/cm².

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Dosage (MJ/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cholera</td>
<td>0.5</td>
</tr>
<tr>
<td>E. coli</td>
<td>0.6</td>
</tr>
<tr>
<td>Legionella pneumophila</td>
<td>3.8</td>
</tr>
<tr>
<td>Salmonella</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The heart of a UV disinfection system is the UV lamp, mounted in a quartz tube. This lamp produces UV-C of 254 nm wavelength which is very effective for disinfection. The tube is placed in the direction of the water flow, the chamber is called the reactor chamber. Depending on the features of the system a UV-sensor, time counter, alarm and temperature sensor are included.

The lamp has a life span of approximately 9000 hours after which efficacy reduces to below 80% of the specified value. The bulb is a low-pressure sodium discharge type, that emits some 30% of its power in the UV-C range where it is effective as disinfectant.
Most manufacturers advise replacement of filter and lamp of twice a year. The lamp operates on 12 V implying use of a power supply to enable connection to the 230 V mains.

The overall water quality must meet certain minimum standards in order for the unit to function properly. The recommended water quality is:

- Iron < 0.3 mg/l
- Manganese < 0.05 mg/l
- Turbidity < 1 NTU
- Tannin < 0.1 mg/l
- Hardness < 120 mg/l
- UV transmission > 75%

Very important when using UV light disinfection is the combination with filtration. Substances in the water (legionella may ‘hide’ in amoebae or floating biofilm) may block the UV light from reaching the legionella bacteria. Filtration of at least 1 micron is recommended.

The operating range of most UV units is 2-40°C. In case the water may be stagnant for longer periods the lamp will heat up the water. In such cases an automated vent can be applied, letting off water in case the temperature gets too high.

### 16.4.1 Point-of-use

In this application the UV light (and filter) is placed less than 5 meters from the outlet. The products can be relatively simple in-line lamps and filters or more elaborate, completed products like the "life shower". Examples:

![Figure 16-9. Lifeshower](picture: www.uvlifeshower.nl)

1: thermostatic mixing valve,
2: 1 micron pass Dupont Microfree filter
3: physical anti-scaling device
4: UV-C lamp
5: electronic control device with LED signal light.

![Figure 16-10. Single faucet UV unit](picture: www.thewaterexchange.net)

Model PUV-6Watt, maximum flow rate 1 gallon/min (3.8 l/min). Power supply included. Filters are recommended but not included in the shipment.
**Street Prices**
The Lifeshower costs 1140,- euro in the Netherlands 63 (consumer price, excl. VAT / transport).

The single faucet purifier has a suggested sales price of 149 dollar / 113 euro including shipping within the USA 64 (1 USD = 0,76 EUR). A replacement bulb (6W) costs 85 dollar / 65 euro and, depending on use, may need annual replacement.

**16.4.2 Gatekeeper**

In larger water systems often a central gatekeeper or point-of-entry' disinfection system is applied, situated after the main water meter and before the rest of the installation. As with other central point measures the rest of the water system needs to be disinfected and properly designed and serviced to avoid legionella growth behind the central UV disinfection unit.

The range in capacity of the UV units from a specific supplier:

<table>
<thead>
<tr>
<th>Flow (l/min)</th>
<th>Power consumption (W, at 30 MJ/cm²)</th>
<th>Dimensions (mm)</th>
<th>Filter cartridges (#, 7.5l/min per cartridge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>smallest</td>
<td>4 12 (1 * 10W lamp)</td>
<td>310<em>52</em>52</td>
<td>1</td>
</tr>
<tr>
<td>medium</td>
<td>90 95 W (2 * 39W lamp)</td>
<td>940<em>178</em>241</td>
<td>12 (3 rows of 4 pcs)</td>
</tr>
<tr>
<td>largest</td>
<td>375 375 (8 * 39W lamp)</td>
<td>970<em>250</em>330</td>
<td>48 (4 rows of 12 pcs)</td>
</tr>
</tbody>
</table>

The overview shows that the electricity consumption varies from 3 W per l/min (small system) to 1 W per l/min (larger systems). The difference lies in that lamps are available in a restricted number of Wattages (10, 14, 17, 24, 36, 39 W) which also influences the dosage in the reactor chamber. Furthermore, there are differences in number of features incorporated in the electronic controls which cause extra electricity consumption.

<table>
<thead>
<tr>
<th>simple</th>
<th>elaborate</th>
</tr>
</thead>
<tbody>
<tr>
<td>power on</td>
<td>yes</td>
</tr>
<tr>
<td>lamp failure</td>
<td>yes</td>
</tr>
<tr>
<td>9000 hr signal</td>
<td>yes</td>
</tr>
<tr>
<td>elapsed time (days)</td>
<td>yes</td>
</tr>
<tr>
<td>remaining time (days)</td>
<td>yes</td>
</tr>
<tr>
<td>UV monitor signal</td>
<td>yes</td>
</tr>
<tr>
<td>contact for aux.eq.</td>
<td>yes</td>
</tr>
<tr>
<td>alarm at distance</td>
<td>yes</td>
</tr>
<tr>
<td>temp. of control unit</td>
<td>yes</td>
</tr>
<tr>
<td>temp. of reactor</td>
<td>yes</td>
</tr>
</tbody>
</table>

---

64 Source: www.thewaterexchange.net
Specifications:
Max. 1100 ltr/hour = 18 l/min
HxLxB = 66x50x18cm
230V - 50Hz - 26W
Life time filters: 6 months
Life time UV lamp: 12 months
UV reaction chamber RVS 304
Max. 5 bar working pressure
Pressure loss max. 0.5 bar
Water temp. 2 - 40ºC
1x active carbon filter
Micron filters: 2 pcs., choice 10, 5 of 1 micron
Connections 3/4" (inlet/outlet)

Figure 16-12.
Elektrospekt Point of entry system (picture: www.elektrospekt.nl)

Shown is a filter (upright), UV unit (horizontal) and control units (wall). This unit serves a school and sports facility (picture: www.elektrospekt.nl)

Figure 16-13.
Point-of-entry system (picture: www.uvidis.nl)

(Street)Prices
The complete Purex UV system is 775,- euro, excl. VAT / shipping. For maintenance (replacement filters 6 months, lamp 12 months) 180,- euro (excl. VAT/ shipping) has to be added every 6 month.
Prices of UV units for swimming pools (mainly intended to break down ammonium to avoid typical chlorine smell) are:

- 10m³/hr, 630,- euro (excl. VAT/shipping)
- 15m³/hr, 998,- euro (excl. VAT/shipping)
- 20m³/hr, 1398,- euro (excl. VAT/shipping)

It is not known whether these units offer the required performance (mJ/cm²) to eradicate legionella.

16.5 Micro-/Ultra Filtration

Micro-filtration is filtration with a pore size of approximately 0.1 µm to 1 µm. The required pressure is in the range of 0.1 to 4 bar. Ultra-filtration requires a pore size of approximately 0.01 µm to 0.1 µm and a pressure of 0.2 to 5 bar. The figure below indicates the types of organisms and particles retained by several filtration techniques.

The mains water pressure (3-5 bar) is often enough to drive the water through the membranes.

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65 Source: www.pomaz.nl
66 Source: Scheffer, W., Membraanfiltratie voor bestrijding van legionella, intech K&S, May 2003
67 Source: Scheffer, W., Membraanfiltratie voor bestrijding van legionella, intech K&S, May 2003
Often two-stage filtration is applied in which a first membrane stops the largest particles that may damage the expensive micro- or ultra-filtration membrane.

Gatekeeper or Point-of-entry filtration does not prevent (re)contamination with Legionella further ‘downstream’. When point-of-entry filtration is applied this should always be combined with legionella control and prevention techniques for the rest of the system.

Over time the surface of the filtration membrane is clotted / covered with sediments and bacteria etc. There are techniques that prolong the life of membranes. The first is called cross-flow where water circulates violently just before the membrane. Part of the water then enters the membrane. The violent water motion prevents deposition of bacteria and other sediments. Another method is the semi-dead end in which all the water is led through the membrane. After a while the membrane is clotted and a back-flush is performed freeing most of the sediments. Sometimes this can also be achieved by a forward-flush - a short violent forward motion of the water.

Other types of contamination of the membrane, like biofilm and scaling deposits, can be removed by chemical treatment. If chemicals are applied great care has to be taken that these cannot contaminate the municipal water supply nor that end-users come into contact with these sometimes toxic substances.

16.5.1 Point-of-use

Filtration at point-of-use is made possible through the introduction of in-line filters, shower sets with filters and filters for faucets.

Advantages are easy application (especially in retrofit situations) and little to no changes to the existing system. Disadvantages are the need for periodic replacement (re-occurring costs), aesthetics and reduced flow rates.
### Table 16-3: Specifications AQL3 (source: www.pall.com)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane area</td>
<td>1100 cm²</td>
</tr>
<tr>
<td>Membrane rating</td>
<td>0.2 µm Supor incorporating pre-filtration layer</td>
</tr>
<tr>
<td>Flow rate at 3 bar</td>
<td>See graph</td>
</tr>
<tr>
<td>Maximum operating pressure</td>
<td>5 bar</td>
</tr>
<tr>
<td>Normal operating pressure</td>
<td>2 - 4 bar</td>
</tr>
<tr>
<td>Maximum temperature exposure</td>
<td>70°C for 30 min.</td>
</tr>
<tr>
<td>Maximum operating temperature</td>
<td>60°C</td>
</tr>
<tr>
<td>Length (excluding connector)</td>
<td>Approx. 240 mm</td>
</tr>
<tr>
<td>Maximum duration of use</td>
<td>One calendar month</td>
</tr>
</tbody>
</table>

The filter reduces the flow rate by approximately 50% and limits it to effectively 14 l/min at 5 bar maximum (the unfiltered version achieves over 30 l/min at 5 bar). At 2 to 3 bar the filtered showerhead produces some 8-10 l/min, which is somewhat higher than water saving low flow showerheads.

**(Street)Prices**

The Ster-O-Tap inline filter is claimed to cost less than 0.02 dollar/l for 3000 ltr which converts to less than 60 dollar per cartridge (some 45 euro) \(^{68}\).

16.5.2 **Gatekeeper**

Larger capacity membrane filters can be used in the gatekeeper concept, where all incoming water is filtered before entering the sanitary water system. The filters in such systems are flushed regularly (3 to 6 times a day) and the residue is directed to the waste water drain.

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Manufacturers / suppliers

One of the largest manufacturers/suppliers of filter materials is Pall (www.pall.com), also supplier of point-of-use filter cartridges. In Belgium there is Prime Water (www.primewater.com) producing filters.

16.6 Copper-/silver ionisation

This technique involves the formation of charged copper (100-400 mg/l) and silver ions (10-40 mg/l) by way of ionisation (electrolysis of copper and silver electrodes). The positively copper-ions attack the negatively charged membrane of the bacteria and the silver-ions stops the reproduction of the bacteria. The system is electronically controlled to ensure a correct dosage of ions.

The introduction of substances (like ions) in (drinking) water is heavily regulated. When copper/silver ionisation is applied the relevant authorities must have approved the application and the status of the electrodes and the level of ions in the water must be carefully monitored.

Advantages of copper/silver ionisation is that the ions spread throughout the whole water system, even the dead ends. Also the biofilm is attacked by the ions. Disadvantages are the purchase costs of the system and the costs associated with control of dosage and maintenance.
Manufacturers
Holland Milieutechniek (Netherlands) Bifipro, http://www.hollandmilieu.nl
Ateca (Netherlands) (www.ateca.nl)

(Street) Prices
Prices of copper-/silver ionisation equipment for swimming pools are 69:

- pool capacity 75m³, 2 electrodes, 620,- euro (excl. VAT/shipping);
- pool capacity 150m³, four electrodes, 731,- euro (excl. VAT/shipping);
- replacement electrode Cu/Ag, 43.50 (excl. VAT/shipping).

It is not known whether these swimming pool applications offer the same performance (i.e. adjustment of current depending the flow rate) as those for sanitary water systems.

16.7 Anodic oxidation

This technique involves the production of oxidising and disinfecting substances from minerals and salts already present in the water by means of anodic oxidation. No new substances are introduced to the water. Low voltage is applied to electrodes in the water which converts minerals to ‘free chlorine’ and salts to hypochlorite. Chlorine and hypochlorite attack the bacteria and are reconverted to harmless salts after treatment. Also some ozone and hydrogen peroxide is produced.

In order to work properly there must be a minimum chloride-content of 20 mg/l. Also the temperature of the water must be lower than 60ºC to prevent damage to the electrodes. Other process parameters are the residence time in the reaction chamber (where the electrodes are positioned) and the voltage and current applied to the electrodes.

Frequent checks and maintenance is important for correct operation of the installation. An important consideration is that the free chlorine can promote corrosion of metals that form part of the water system itself. This very much depends on the chlorine content of the water.

According the manufacturer the hypochlorite is active throughout the whole water system. The hypochlorite also attacks the biofilm, preventing growth and—if the chlorite level is raised temporarily— helps to remove the biofilm.

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69 Source: www.vanremmen.nl
Belgian manufacturer Ecodis claims an energy consumption of 20 to 50 Watt per m³ treated water.

Figure 16-22.
(left): Anodic oxidation system
(picture: www.brightspark.nl).
Figure 16.23 (right): The electrodes in close-up, placed in a plastic tube segment
(picture: www.brightspark.nl)

Manufacturers
- Bright spark (Netherlands) (www.brightspark.nl)
- Ecodis (Belgium) www.ecodis.nl

(Street) Prices
Bright spark developed the system originally for disinfection of drinking water storage tanks on ships. The current applied in these systems is 100 mA. The prices listed below are for such applications (incl. VAT, excl. shipping).

<table>
<thead>
<tr>
<th>Capacity fresh water storage</th>
<th>2B Sure Standard</th>
<th>2B Sure Luxe (with control panel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 100 litre</td>
<td>€ 385,-</td>
<td>€ 475,-</td>
</tr>
<tr>
<td>101 - 120 litre</td>
<td>€ 435,-</td>
<td>€ 525,-</td>
</tr>
<tr>
<td>121 - 150 litre</td>
<td>€ 435,-</td>
<td>€ 525,-</td>
</tr>
<tr>
<td>151 - 250 litre</td>
<td>€ 550,-</td>
<td>€ 640,-</td>
</tr>
<tr>
<td>251 - 500 litre</td>
<td>€ 675,-</td>
<td>€ 765,-</td>
</tr>
<tr>
<td>501 - 2000 litre</td>
<td>ask for price</td>
<td>ask for price</td>
</tr>
</tbody>
</table>

Application of anodic oxidation in water systems (in the supply pipe, with bypass option) will require much more installation work and will result in higher prices.

16.8 Electric pulse
Electric pulse is reported as effective for bacterial inactivation, with UV and plasma effects responsible for disinfection. Inadequate information was available to assess this technology as it appears to be in experimental stage still.

70 Source: www.ecodis.be
71 Oemcke, D., The Treatment of Ships’ Ballast Water, EcoPorts Monograph Series No. 18, March 1999 (citing Blatchley & Isaac, 1992)
16.9 Chemical disinfection

Legionella bacteria are killed by a certain dosage of ozone or chlorine. These chemical treatment methods are heavily regulated since (normally) it is not allowed to add substances to sanitary water.

Legionella is killed at an ozone concentration of 1-2 mg/l. Ozone however decomposes in hot water so that maintaining the correct level of ozone is difficult. Furthermore high concentrations of ozone may damage the piping.\(^{72}\)

Addition of chlorine to sanitary water reduces the Legionella count, but low dosages do not kill all the bacteria present since some may have developed some resistance towards chlorine. A chlorine treatment starts with high dosage (2-6 ppm) of chlorine and the system is flushed until a chlorine smell is detected at all draw-off points. The system is kept in this state for 2 hours and then taken into use with water with a low dosage of chlorine (1-2 ppm) - fit for human consumption. Disadvantage of chlorine treatment is the risk of corrosion and resulting leakage and the taste/smell of the water. Continued monitoring of chlorine levels is necessary. Discontinuation of the chlorine treatment of water would lead to recolonisation with legionella.\(^{73}\)

Chemical treatment methods are typically applied in (public) swimming pools and not in residential installations.

\(^{72}\) Source: Vos, M.A., Troelstra, A., Legionella, diagnose en preventie, Infectieziekten Bulletin, year 12, nr. 12

\(^{73}\) Source: Vos, M.A., Troelstra, A., Legionella, diagnose en preventie, Infectieziekten Bulletin, year 12, nr. 12
17 SCALDING

17.1 Introduction
To complete the overview of water heater products and systems this chapter focuses on techniques to prevent scalding.

17.2 Scalding
Scalding is a specific type of burning that is caused by hot fluids or gases. The burning can lead to first, second or third (full thickness) degree burns on the skin (or internal organs if ingested) also depending on the temperature of the fluid, skin area exposed and exposure time.

Table 17-1. Exposure time to scalding injury by temperature (source: Wikipedia - scalding)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Max duration until injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>155F (68.3C)</td>
<td>1 second</td>
</tr>
<tr>
<td>145F (62.9C)</td>
<td>3 seconds</td>
</tr>
<tr>
<td>135F (57.2C)</td>
<td>10 seconds</td>
</tr>
<tr>
<td>130F (54.4C)</td>
<td>30 seconds</td>
</tr>
<tr>
<td>125F (51.6C)</td>
<td>2 minutes</td>
</tr>
<tr>
<td>120F (48.8C)</td>
<td>5 minutes</td>
</tr>
</tbody>
</table>

Tap water scald injuries can be very severe, even fatal, if they cover a large part of the body and are especially likely to occur in certain populations, particularly children and elderly. Both children and elderly have a thinner skin, leading to faster and/or deeper burns. Elderly also have a slower reaction time and together with persons with handicaps such as sensory neuropathies may be less sensitive to heat.

In the UK alone some six hundred people a year suffer severe bath water scalds, three quarters of whom are children. This means that every day a child under five is admitted to hospital with serious injuries resulting from scalding hot bath water. Many of such accidents lead to lengthy and painful treatments and permanent scarring. In the UK alone fifteen pensioners a year die from burns from bath water.74

17.3 Prevention
Water temperature may be kept high for a number of reasons a.o. prevention of Legionellosis, increase hot water capacity, for cleaning purposes (washing up). Therefore most actions to prevent scalding are aimed at the bathroom only and focus on the temperature of the water at the outlet.

In Germany the maximum temperature at the draw-off point is limited to 45ºC and similar legislation was introduced in Scotland on 1 May 2006, where new building regulations require that the temperature of all bath water in new build and extensively refurbished domestic properties be controlled to a maximum of 48ºC. Similar legislation is under review in England and Wales (see also the task 1 report for Water Heaters, Chapter 4.3).

74 http://www.marycreagh.co.uk/index.php?id=411 "hot water burns like fire" campaign, tabled a bill (ten minute rule) at 29 March 2006
In the UK a certification scheme for TMVs exists (based upon EN1111 and EN 1287) which prescribes valves certified to Buildcert TMV3\textsuperscript{75} must be fitted in healthcare institutions. For most other premises valves to the domestic TMV2 standard are deemed acceptable but a risk assessment should be carried out to determine if the facilities are used by vulnerable people, such as the elderly, young children or the mentally or physically disabled. If so, manufacturers and installers recommend to install TMV3 valves to provide the maximum safety level.

The BuildCert Thermostatic mixing valve Scheme offers two approval Schemes, these being:

a. Type 2 approval (TMV2) certifying Thermostatic Mixing Valves against the requirements of BS EN 1111 and or BS EN 1287 and the additional requirements of the Scheme (details required in the information and maintenance document (I&M), marking and audit).

b. Type 3 approval (TMV3) certifying Thermostatic Mixing Valves against the requirements of the NHS Estates Model specification D 08.

| Table 17-2. Type approval requirements for thermostatic mixing valves (British Standards) |
|---------------------------------------------|------------------|------------------|------------------|------------------|
|                                             | Low Pressure TMV2 | High Pressure TMV2 | Low Pressure TMV3 | High Pressure TMV3 |
| Maximum Static Pressure (Bar)               | 10               | 10               | 10               | 10               |
| Flow Pressure, Hot & Cold (Bar)             | 0.1 to 1         | 0.5 to 5         | 0.2 to 1         | 1 to 5           |
| Hot Supply Temperature (°C)                 | 55 to 65         | 55 to 65         | 52 to 65         | 52 to 65         |
| Cold Supply Temperature (°C)                | £ 250            | £ 250            | 5 to 20          | 5 to 20          |

The TMVs do not necessarily need to be fitted at the draw-off point. In general 'mixer taps' and 'in-line mixing' is distinguished

Extra safety is added by TMV’s that cut off the hot water inlet automatically if the cold supply fails. A lockable safety cap displays the temperature set point and prevents unauthorised adjustment.

Some manufacturers of TMVs are Rada, Honeywell, Grohe (to name a few).

\textsuperscript{75} The TMV Scheme is an independent third party approval scheme administered by Buildcert. The TMV Scheme certifies Type 3 thermostatic mixing valves manufactured to meet the highest specifications required by the NHS Estates D08 standard for mixing valves for use within health care premises in the United Kingdom. The TMV Scheme also certifies Type 2 thermostatic mixing valves for the domestic market and is working with the Child Accident Prevention Trust to promote the safe use of hot water in domestic premises. (www.buildcert.com)
### Table 17-3. Example list prices mixing valves (source: Reliance controls, www.rwc.co.uk)

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Price (GBP excl.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in-line mixer</td>
<td>Heatguard LS2</td>
<td>55.50</td>
</tr>
<tr>
<td>in-line mixer valve</td>
<td>Promix 22-2</td>
<td>497</td>
</tr>
<tr>
<td>surface mount</td>
<td>Thermomix</td>
<td>105</td>
</tr>
<tr>
<td>concealed</td>
<td>Heatguard CS</td>
<td>274.30</td>
</tr>
</tbody>
</table>

### Table 17-4: Examples retrofit installation costs (source: [http://www.reactfast.co.uk/htm/thermostatic_mixing_valve.htm](http://www.reactfast.co.uk/htm/thermostatic_mixing_valve.htm))

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost (GBP excl.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bath (22mm pipe)</td>
<td>From £130 / 188 EUR</td>
</tr>
<tr>
<td>basin (15 mm pipe)</td>
<td>From £90 / 130 EUR</td>
</tr>
</tbody>
</table>
18 **WASTE WATER HEAT RECOVERY**

Drain water (or waste water eq. greywater) Heat Recovery (DHR) devices are able to recover (part of) the heat contained in used DHW water that is flushed down the drain into the sewer. The DHR is a very simple device, requiring little or no maintenance and can be used in retrofit situations provided there is enough space (either as vertical tube or as shower floor).

### 18.1 Drain water heat recovery

The first commercial product to recover heat from shower water is probably the GFX Drain Heat Recovery System, developed in the USA in 1993. The GFX uses a copper pipe of 2 to 4 inch diameter for the drain which is tightly wrapped with a pipe carrying the incoming cold water. Graywater flows through the drain pipe, forming a thin film of water on the walls. This thin film is essential in cleaning the walls from grease, detergents and other graywater contaminants. The system is in fact a double walled heat exchanger with a counter-flow aspect to it.

![GFX Drain Heat Recovery System](picture: gfxtechnology.com)

In the Netherlands several companies have come up with a variant based upon a tube-in-tube principle. The cold incoming water flows through the space between an inner tube (which carries the waste water on the inside) and an outer tube. The space can withstand mains pressure. Again the thin film of flowing water keeps the inner surface clean and helps to maintain the performance over extended time periods. The use of calcium-containing detergents may reduce this self-cleaning ability and is discouraged.

The first versions were single-walled and (according to Dutch Regulations) needed an air-breaker before connecting it to the drain (to prevent sewage ever reaching the DHR part carrying cold water). More recent models are double-walled and feature a small air gap over the length of the pipe that will flood if the cold incoming water side is leaking. These can be connected to drains without use of an air-breaker.
A third type of DHR is integrated into the shower floor. This type simply directs the drain water over a pipe-heat exchanger carrying the incoming cold water. The efficiency of this system is somewhat lower than the vertical pipe systems. Furthermore it is likely a bit more susceptible to fouling because the speed of the water flow is lower. For cleaning the user can easily lift up the top floor and clean the heat exchanger. This type of DHR is especially fit for renovations and retrofitting.
18.2 Application

18.2.1 Installation

There are essentially three different ways to connect a DHR to the water heater:

- The heated water is directed to both shower valve and water heater (A);
- The heated water is directed to shower valve only (B);
- The heated water is directed to the water heater only (C).

Studies have shown that installation according A results in the highest recovery rates. (see "performance/savings" further on). The water heater can either be an instantaneous water heater, but storage systems are also possible. In the latter case the preheated water enters the storage cylinder.

A fourth installation option is the combination of a DHR with a dedicated storage system to overcome the time disparity between availability of hot drain water and the need for DHW (like happens when emptying a bathtub). Such a storage system has been introduced by GFX Technology for the US market, called the GFX-Star system (Figure 18-7). Sensors register the availability of hot drain water and activate a circulation pump to recover this heat and store it in a storage tank. Of course the maximum temperature in this storage tank will seldom reach over 30°C (considering the average temperature of the return line is around 25-26°C). The pre-heated water is led to 'any type of water heater' for further heating.
Figure 18-6. Installation scheme of DHR.

Configuration 'A'

Configuration 'B'

Configuration 'C'

Figure 18-7. GFX-Star (picture: www.gfxtechnology.com)

Larger systems

Although the single-family household appears to be the primary target group of DHR sellers the same principle can be applied in large DHW consuming environments as well, with often very short pay-back times. Such installations are applied in for instance health spa's, hotels, swimming pools, etc. Care should be taken to avoid legionella...
growth in pipes carrying pre-heated water, especially if the water in the pipes is stagnant for longer periods.

**Figure 18-8.**
Large scale solution by Hei-tech (picture: www.hei-tech.nl)

**Figure 18-9.**
Installation of 16 GFX DHRs in a fitness club in Toronto, Canada (picture: gfxtechnology.com)
18.2.2 Other installation issues

The vertical DHR water systems have a length of 76 cm (small GFX) to 2,1 m (Hei-tech DoucheBooster). The larger vertical pipe-type DHR will not always fit in the crawlspace or basement which leaves only shower drains located at least one floor above ground floor suited for these DHRs. The shower-floor version and larger versions with a feed pump can be applied on the same level as the shower itself.

Bries recommends installation of the DHR parallel to (existing) vertical drains (DHR exclusively for shower, other-existing-drain for the rest). The DHR does not necessarily need to be directly under the shower drain - displacement is allowed but larger displacements will introduce more thermal loss. Some manufacturers discourage connecting the DHR to especially washbasin drains since deposits from toothpaste or shaving crème can cling to the inner surface and reduce the efficiency.

The use of a DHR is associated with a pressure loss in the cold water piping. This could lead to problems when showering at high flow (double shower heads). The pressure loss is dependent on the water flow and differs per type and dimension of the DHR.

![Figure 18-10. Pressure loss in pipe-DHR - horizontal: flow (l/min), vertical: pressure loss (bar) (picture: www.hei-tech.nl)](image)

18.2.3 Regulations

The installation of DHR must follow local/national Regulations concerning drain water and domestic (cold) water systems.

In the Netherlands this means that installation of cold water pipe-segments that contain more than 1 ltr. in environments that heat up the cold water to over 25ºC is prohibited\(^{76}\). Placement of the DHR in a metering cupboard that also holds a substation of a collective or district heating system is therefore not allowed (Dutch standard NEN 2768) and connection to a bath drain could also heat up the cold water.

However if the water content is less than 1 ltr. the requirements are less strict. Most DHR systems contain 0.3 to 0.5 ltr and can legally be fitted to a bath drain\(^{77}\). It is however necessary to refrain from insulating the DHR and allow the pipe to cool down rapidly. Still, connection of a DHR to a bath drain could also heat up the cold water.

In order to avoid the possibility of contamination of the cold water supply with greywater the Dutch government required either an "air-breaker" (an open vented connection to the drain to avoid internal spills and contamination) for single-walled DHRs or a double-walled heat exchanger (relevant standard NEN 1717).

If the DHR is single-walled and contains an air-breaker this breaker must be situated at least 150mm above street level (to avoid overflow/ spills of sewage in case of blockades in the general sewage system) (Dutch standard NEN3215).

\(^{76}\) ISO/UNETO-VNI-Richtlijn 30.4

\(^{77}\) Modelbeheersplan Legionella-preventie inleidingwater, Ministerie van VROM
It is essential that the drain water enters the DHR-pipe correctly, e.g. forms a film over the total surface of the inner pipe. To ensure this Hei-tech recommends installation of a ‘rotator’: A small pipe-segment with a curve, that forces the water to swirl along the sides of the inner pipes for better efficiency.

The cold water inlet of the DHR must be equipped with a non-return valve an a stop-cock. The DHR (and air-breaker if applicable) should be accessible at all times. Usually it takes a while, some 2 minutes or so, before the thermal inertia of the DHR is overcome and the DHR returns the maximum of heat to the cold incoming water. This means that (assuming installation according ‘A’ or ‘B’) the cold incoming water increases in temperature in a two-minute period. The use of an thermostatic mixing valve is advised for optimum comfort and highest savings.

**18.3 Performance / Savings**

According Dutch sources an average shower consumes some 60 litres of water of 38 to 40ºC. Most of this water is flushed away at a temperature level 3 to 4ºC lower than the initial temperature. This means that some 80 to 90% of the shower water energy is washed away.

**18.3.1 Testing**

The performance of a DHR can be described by its output (energy transferred to cold incoming water, in MJ) or by its efficiency (the amount of heat recovered from drain water, in %). The method for measuring these parameters has been developed by Gastec Certification in 2003 and essentially describes a steady-state measurement. The table below shows data from brochures for models by two manufacturers.

<table>
<thead>
<tr>
<th>Table 18-1. DHR output and efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer A</td>
</tr>
<tr>
<td>Single-wall pipe</td>
</tr>
<tr>
<td>Double-wall pipe</td>
</tr>
<tr>
<td>Single-wall floor</td>
</tr>
<tr>
<td>Double-wall floor</td>
</tr>
</tbody>
</table>

The output is often the basis for taking into account the effect of a DHR in the DHW or whole building energy performance. For this the manufacturer can ask an independent third party to certify the performance of the product. The declaration mentions the amount of energy recovered in standard situations.

**18.3.2 Real-life savings**

A third performance parameter can be the (gas) savings realised by the DHR, but this value is very much dependent on the system the DHR forms part of.

Factors influencing the performance of the DHR are:

- the temperature of the cold incoming water (may vary between 5 to 20ºC according measurements);
The temperature of the grey water at DHR entry point. In tests this is usually defined as 40ºC (shower temperature), but practice shows that on the way down some 3 ºC are lost. A sharp shower beam with much spray cools down more than a soft beam with larger water droplets. The average DHR inlet temperature is likely closer to 37ºC;

There are heat losses at the DHR drain inlet side (tiled shower floors absorb more heat than enamel or plastic floors) and at the DHR pre-heated water outlet side (if the DHR is installed at long distance from the water heater more heat is lost).

Experiments have shown that DHR with larger diameter inner pipes show larger variations in performance. One suspects that with larger diameter inner pipes the formation of an even water flow film is less easy to achieve. The way the drain water enters the DHR is also of much importance to the creation of an evenly distributed water film;

The flow through the DHR has an effect on the efficiency: The same DHR has an efficiency of 54.1 % at 5.5 l/min and 49.3 % at 7.5 l/min;

And the system configuration has various effects on the DHR performance and overall system performance:

- In configuration 'A' the grey water flow and the DHW water flow are equal. This results in the highest efficiency for the DHR.
- In configuration 'B' and 'C' the grey water flow is higher than the DHW flow through the water heater. This reduces the efficiency of the DHR.
- Considering the highest efficiency is achieved by configuration 'A' this configuration also has the smallest heat demand.
- If the heat demand in configuration A is lower, the water heater efficiency will also be lower (generally speaking), especially if the heat demand is below what is achieved by the minimum modulation range of the water heater. Furthermore the inlet temperature is higher than 'C', reducing water heater efficiency.
- In configuration 'B' the water supplied to the water heater is the coldest, thus contributing to higher efficiencies in DHW production.

Tests have shown that if a normal shower requires 15 kW the DHR can produce some 5 kW of this. For similar shower performance the size of the boiler thus can be lower, a modern house could do with a boiler of 10kW, even without DHW storage.

Summarising, the various configurations have different effects on overall DHW water heater efficiency regarding the balance of flows through the DHR (influencing overall DHR efficiency), the temperature of the water supplied to the water heater (colder water results in higher water heater efficiency) and the flow through the water heater (beware of minimum flow rate required).

A tube-in-tube DHR has been tested by GASTEC for a year in four households and resulted in average gas savings of 30% 80. This prototype has been further optimised by at least Hei-tech and Bries (Itho also sells a DHR but the actual producer is probably linked to Hei-tech), a.o. by increasing the heat transfer surface and optimising flows. Laboratory test have shown efficiencies of 50%. In real-life an efficiency of 40% should be feasible.

Considering that in the Netherlands an average person consumes some 60 m³ natural gas during showering savings of 24m³ per person per year should be possible 81.

A shower floor version was tested by Gasunie Research and showed average gas savings in the area of 28%. The table below presents the outcome of this study 82.

---

80 Peereboom, P. W. E., Het terugwinnen van douchewaterwarmte – Een praktijkproef in nieuwbouwwoningen Gastec; januari 2001
81 Quote from Itho website and brochures.
Table 18-2. DHR test results

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to DHW</td>
<td>kW</td>
<td>14.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Share of DHR</td>
<td>%</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>Boiler power (DHW side)</td>
<td>kW</td>
<td>14.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Boiler power (gas side)</td>
<td>kW</td>
<td>16.0</td>
<td>11.3</td>
</tr>
<tr>
<td>Boiler efficiency 1)</td>
<td>%</td>
<td>89</td>
<td>87</td>
</tr>
<tr>
<td>Gas savings 2)</td>
<td>%</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>Effective efficiency 3)</td>
<td>%</td>
<td>89</td>
<td>134</td>
</tr>
</tbody>
</table>

1) Boiler power (DHW side) \* 100
   Boiler power (gas side, lhv 31.7MJ)
2) diff. WH power (gas side) ‘B’ or ‘C’ vs. ‘A’
   Boiler power (gas side) for ‘A’
3) Power to DHW
   Boiler power (gas side)

The boiler efficiency calculated above includes first time start-up losses (boiler fires up to maximum power to heat up the heat exchanger, then turns down to maintain a constant 65°C at required flow - essentially a cold start situation as opposed to steady-state). The test was based upon shower routine with the following parameters:

Table 18-3. DHR test set-up

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>7.5 min</td>
</tr>
<tr>
<td>Flow</td>
<td>7.5 l/min</td>
</tr>
<tr>
<td>DHW temperature from thermostatic valve/tap</td>
<td>40°C</td>
</tr>
<tr>
<td>DHW temperature from boiler</td>
<td>65°C</td>
</tr>
<tr>
<td>Distance shower head to shower floor</td>
<td>2 m</td>
</tr>
<tr>
<td>Other</td>
<td>un-manned shower, no soap, shampoo, etc.</td>
</tr>
</tbody>
</table>

No information was provided on other system aspects like the thermal losses of the pipes from the DHR to the boiler.

Other studies by GasUnie regarding a pipe-DHR concluded in possible gas savings of 30 to 49%, depending on the type of shower beam and floor (tiled or enamel)\(^\text{83}\). In this set-up the pre-heated water was directed to both the mixing valve and the water heater. In a similar set-up another shower-floor model resulted in gas savings of 28.5%. If the pre-heated water of the shower-floor DHR is only made available to the mixing valve the gas savings are 27.7%\(^\text{84}\).

For calculation of whole building energy performance the Dutch institute Vereniging Stadswerk Nederland (representing the Dutch communities, responsible for checking compliance with building regulations) allows a reduction of Energy for hot water of 15.8% if flow is 5.5 l/min and 28% if flow is 7.5 l/min.

\(^\text{83}\) Darmeveil, J.H., Afvoerbuis met warmteterugwinning (voor docuhes), Gasunie, 25 September 2003
\(^\text{84}\) Darmeveil, J.H., Douchebak met warmteterugwinning, Gasunie, 11 April 2003.
## 18.4 Manufacturers

### 18.4.1 Prices

The table below lists prices from known manufacturers / re-sellers of DHRs.

<table>
<thead>
<tr>
<th>USA</th>
<th>Price</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFX technologies</td>
<td><strong>G3/S3-60: 540 - 560 USD (410 - 425 euro, incl. VAT, excl. shipping)</strong></td>
<td>1 USD = 0.76 EUR this is for a 60 inch pipe</td>
</tr>
<tr>
<td>Netherlandse</td>
<td><strong>475,- excl. VAT, incl. transport in NL</strong></td>
<td>for 1670 mm version</td>
</tr>
<tr>
<td>Bries (<a href="http://www.bries.nl">www.bries.nl</a>)</td>
<td><strong>475,- excl. VAT/shipping</strong></td>
<td></td>
</tr>
<tr>
<td>Hei-tech (<a href="http://www.hei-tech.nl">www.hei-tech.nl</a>)</td>
<td><strong>387 (excl. VAT, transport and fittings)</strong></td>
<td>sales through Technea (<a href="http://www.technea.nl">www.technea.nl</a>) who supplies installer</td>
</tr>
<tr>
<td>Itho (<a href="http://www.itho.nl">www.itho.nl</a>)</td>
<td><strong>(unknown)</strong></td>
<td>developed by Itho together with Heatex Waterheating</td>
</tr>
<tr>
<td>Nefit (<a href="http://www.nefit.nl">www.nefit.nl</a>)</td>
<td><strong>(unknown)</strong></td>
<td>re-seller of Bries products</td>
</tr>
</tbody>
</table>

### 18.4.2 Payback

Taking an average consumer price of 565 euro (475 plus 19% VAT) and gas prices of 13 euro/GJ or 0.46 euro per m³ (see Task 2 report) the device must produce gas savings of at least 1230 m³ over its life to repay itself.

Assuming an overall gas consumption of 60 m³ gas per person per year and gas savings of 30% some 18 m³ is saved per person per year. For a four person household this is 72 m³ or 33 euro per year. Assuming constant energy prices and no interest on investment the payback time is 17 years for this family.

If the DHR has a real-life efficiency of say 50% (120 m³ gas saved per family) the payback for this family becomes 10 years. In manufacturers brochures savings of 86 to 175 m³ gas per household are mentioned.

For electric water heaters one can assume savings of around 4500 MJ (typical output, see table in section 7.3.2, corresponds to 142 m³ gas lhv). With an electricity tariff of 0.15 euro/kWh (and 1 kWh is 3.6 MJ) annual savings are 1250 kWh or 187.50. The payback time becomes 3 years.

Assuming the DHR has a product life of 15 years and a street price of 565 euro the device costs (565/15) 37.67 euro per year (no interest accounted for). Considering the DHR may save some 4500 MJ per year (for a household) the cost price of saved MJ is in the range of 0.84 eurocent per MJ.

Please note that real-life gas or electricity savings depend heavily on the assumed efficiency or output of the DHR, which in turn are dependent on actual DHW consumption patterns and DHW system parameters.
ANNEX A - VACUUM INSULATION PANELS

Introduction

Vacuum insulation panels are very efficient thermal barriers, having a thermal conductivity 3 to 10 times lower than conventional thermal insulators (0.002 to 0.009 W/m²K). This makes them interesting for achieving a similar level of insulation (as with conventional materials) but with less thickness or achieve a higher level of insulation with equal thickness.

VIPs are produced by vacuum packaging an open-celled, micro-porous insulating core in a gas barrier bag. Due to high costs commercial applications of VIPs are still rare and limited to deep freezers and some small electric water heaters (besides several non domestic, professional uses).

Properties of the core materials

The core is what provides stiffness to the panel and prevents it from collapsing under atmospheric pressure. Current commercial VIP core materials include polystyrene and polyurethane foams, precipitated silica, fumed silica and silica (aero)gel. The best insulation values are achieved with silica cores, even at higher pressure levels, although "micro-fleece" also performs very well.

All vacuum insulation panels rely on high vacuum to provide their low thermal conductivity values: the better the vacuum the lower the thermal conductivity. VIPs do not maintain a “perfect vacuum”. Most vacuum panels are initially evacuated to an internal pressure of 1 torr (1.3 mbar) to 0.05 torr (0.067 mbar). A better vacuum would cost significantly more while not contributing to insulation value that much.

What does make a difference is the core material. The relationship between internal pressure rise and increasing thermal conductivity varies tremendously with different core materials.

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Much of this text has been sourced from the Porextherm website (www.porextherm.de) which provides an excellent overview of VIP properties. Other text is based upon information from Glacierbay and Va-Q-tec. Higher pressure” for vacuum panels means “less vacuum”.
Gas molecules can enter through the barrier film and the sealant material that bonds the film envelop together. The larger the VIP the greater the film surface area vs. seal area and the smaller the VIP the greater the seal area vs. film surface area. Therefore, selecting a suitable barrier material requires that both the barrier film and sealant properties are appropriate for the type and size of panel.

Thickness also has much effect on panel performance. Halving the thickness of a panel will halve the lifetime of a panel because the surface and seal areas remain almost constant whereas the insulation volume is halved. So although the transfer rates through the seal and barrier will be almost the same the gas pressure will be doubled because of the smaller volume.

The performance during product life thus depends on the quality of the barrier/seal (how long is vacuum maintained) the core material (what happens to conductivity if vacuum is lost, gradually) and the dimensions of the panel.

**Membrane and Seal Permeation Rates**

The membrane film is the material that forms the walls of the VIP. All membrane films in use today permit some molecules of gas and moisture to pass through over time. The amount of permeation through a particular membrane film will depend on the material of its construction and the resistance of this material to degradation during handling in the production process. Some films contain of a very thin metal film (usually aluminium) which is reinforced by laminating a plastic film to each side. These films can have excellent barrier properties but can conduct significant heat around the edges.
These “edge effects” can significantly reduce the effective performance of a VIP. In order to reduce the unwanted “Thermal Edge Effects” to a minimum, some films are based on a thin film deposition technique which builds the metal layer even thinner. The membrane films are sealed at the edges to form an envelope for the core material. A thin layer of low temperature plastic is laminated to the inside of the film so than it can be sealed using heat and pressure. These layers of heat-sealing plastic do not have the same resistance to gas and moisture permeation as does the rest of the film. To minimize the negative impact of permeation of the sealing layer, manufacturers use as thin a film layer as possible combined with a wide seal lip.

Most barriers consist of layers PE, PET and Aluminised PET foils. Application of pure aluminium film is possible but increases edge losses.

**Outgassing, Getters and Desiccants**

Most materials release gases (outgas) when placed in a low pressure environment. The kind and quantity of gas released, as well as the length of time the outgassing will continue, varies from material to material. The released gases can contribute substantially to the rise in internal pressure (i.e. loss of vacuum) of a VIP. In some cases, the rate at which gas released from the core and membrane materials exceeds
that at which it permeates through the membrane. Silica-based cores do not outgas, while some foam based cores may never stop. The core and membrane materials used by a particular manufacturer will determine what, if any, impact outgassing will have on the life of their product.

Getters are chemicals that absorb gases; desiccants are chemicals that absorb moisture. Getters and desiccants are used to extend the life of VIPs by absorbing unwanted gases and moisture that promote heat transfer within the evacuated space. To be effective, the getters and desiccants must be carefully matched to the kind and quantity of gas/moisture they will be expected to absorb. Besides that getters and desiccants must also be capable of effectively absorbing and holding the gases and moisture at the low pressures inside the VIP. It is, therefore, important that the quantity and type used be selected in accordance to the core material, membrane film and required life expectancy. Foam-based panels have no absorbent capacity at all. It is, therefore, necessary to add these chemicals into the VIP envelope. Getters can add significant cost to a panel and because of their heavy metal composition create major safety and environmental concerns.

A popular type of getter is the COMBOGETTER by the Italian company SAES. SAES claims that the combo getter is a non-evaporable getter made of alloys based on metals such as zirconium, vanadium or titanium. The getters are made from fine powders of these alloys either compressed into the form of pills, granules, pellets or strips, or coated and deposited with proprietary techniques onto suitable surfaces and which act as metal “sponges” for the remaining gas molecules present within an evacuated device. The COLD II study mentions that COMBOGETTERS constitute of a Barium-Lithium alloy. When calcium oxide and Cobalt oxide are added it can absorb

SAES also produces desiccants under the trade names COMBOdryer and SAESdryer. Precipitated silica and silica aerogel acts as their own getters/desiccants.

Also opacifiers may be added to the core material to reduce losses through infra-red radiation.

**Operating conditions**

Operating conditions are important for both usability and lifetime. Usability refers to a panel’s suitability for a given operating environment. Foams being plastics have a limited temperature range over which they can be used. Most panels can be applied in environments of -20 to 80ºC. Outside of this range shrinkage and deformation occur which can render a panel practically useless. For example the upper limit for polystyrene foams is 88°C (190°F) which rules out their use in applications such as hot water heaters and hot food delivery systems. Silica based core material can be used at temperatures up to 950°C (1742°F) with appropriate barrier films like e.g. a stainless steel envelope.

Operating conditions effect lifetime because the transfer rates of water vapour and gases through the barrier film and seals change with temperature. Higher temperatures promote increased transfer rates and lower temperatures slow down molecular movement. In addition, the higher the concentration of a gas surrounding the panel the higher will be it’s concentration in the panel and consequently the greater it’s effect on heat transfer. In general the smaller the gas molecule the faster it will penetrate into the panel and greater will be it’s effect on thermal conductivity. So for example encasing a panel in polyurethane foam, the preferred method of application in refrigerators helps to prolong panel life because the heavy gas molecule of the foam blowing agent take longer to penetrate into the panel and when inside are not as good conductors of heat as nitrogen or oxygen because of their larger molecular sizes. Similarly for water vapour; the higher the humidity of the air around the panel the faster the transfer into the panel and the higher the final water concentration in the panel when equilibrium is reached.
Shapes

The simplest shape of the VIP is a rectangular panel. Depending on specifications the edges can be folded or left "as is". Most manufacturers are bound by maximum panel sizes (often in the range of 80 - 100 cm per side).

A little bit more complicated is the production of non-rectangular panels or panels with holes or other cut-outs. These are more costly since they require manual handling and preparation of the foam core. Much attention is given to avoiding and removing dust specks or other "contaminants". Tiny speckles of dust can easily damage the barrier film, reducing the lifetime of the panel. Some damages occur only after a some time has elapsed (creep of plastics).
By removing some material from the foam core in the form of long grooves the core can be bend. Depending on the type of core and the evacuation method the panel with grooved core assumes a curved shape during evacuation. Such panels allow some bending or stretching to be fit into place. Again the manual labour involved in producing such cores makes them very costly with current production techniques.

The technique of non-rectangular shapes and curving can be combined resulting in shapes as shown below that are used in experimental water heaters.

Manufacturers

Production of VIPs is still costly. Especially the handling and processing of panels with a powdery core is more expensive than that of foam cores. The creation of non-rectangular and cylindrical shapes requires manual efforts and thus adds to the costs. Furthermore the quality of the panel depends on the level of vacuum applied and the working environments: Even tiny speckles of dust can damage the barriers when
vacuum is applied. Some defects may occur only after some time has elapsed. Prices for VIPs range from 5000 to 10000 euro per m³.

The table below presents some cost price information (street prices, excl. VAT) of VIP manufacturers in Germany and the United States (SeasGetters from Italy does not provide general price information). These prices include getters and desiccants.

**Table A-1. Prices of vacuum insulation panels**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Core Material</th>
<th>Prices</th>
<th>Size (mm)</th>
<th>Thickness (cm)</th>
<th>Price (excl. VAT)</th>
</tr>
</thead>
</table>
| Glacier Bay "Barrier Ultra-R™" | Silica aerogel | Prices: | Size up to 76*89 cm | 400 euro/m² | 35 mm "small" panel: 400 euro/m² (excl. VAT)
|                         |                        |        | Size up to 152*178 cm | 264 euro/m² | Other: 25 years warranty |
| Porextherm "Vacupor NT"  | Fumed silica           | Price: | Series of 10,000 pcs | 60 euro/m² | 10 mm is 60 euro/m² (70 euro/m² if taped)
|                         |                        |        |                      | 64 euro/m² | 13 mm is 64 euro/m² (74 euro/m² if taped) |
| Va-Q-Tec panels         | Silica powder          | Price: | 10 mm is 100 euro/m² | Prices are for a series of 10,000 pcs (status 2004, excl. VAT) |
| RP Parts                | DOW Instill (EPSM foam) | Price: | 25.4 mm is 200 euro/m² | Max. size is 81*81 cm, excl. VAT |
| Seasgetters "saesINSULA" | Probably foam, possibly EPS | Prices: | No price information available | Shapes: plane, cylindrical and customised |

**Savings**

Reports indicate reduction of daily standing losses of water heaters of up to 25% when compared to conventional insulation. For refrigerators/freezers savings of up to 35% have been recorded using metal film barriers. Metalised plastic film barriers should result in even fewer edge losses.

**Figure A-11.** Improved Vacuum Insulated Panel Design for Water Heaters, 5th Annual Vacuum Insulation Symposium, May 2001, P. Di Gregorio, E. Rizzi, and M. Urbano.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Expected Value (kWh/day)</th>
<th>Average (kWh/day)</th>
<th>Calculated (FFA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 with VIP</td>
<td>0.795</td>
<td>0.784</td>
<td>0.780</td>
</tr>
<tr>
<td>2 with VIP</td>
<td>0.703</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 with VIP</td>
<td>0.801</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 with VIP</td>
<td>0.776</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 w/o VIP</td>
<td>0.969</td>
<td></td>
<td>1.050</td>
</tr>
<tr>
<td>6 w/o VIP</td>
<td>1.130</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Improvement: 25%**

**Alternatives**

Besides conventional insulation materials there are also advanced alternatives to application of vacuum insulation panels.

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The first example is the application of completely evacuated vessels, e.g. the "thermos" flask (Dewar flask). Only a few products in the realm of water heaters apply this principle. There is the small kitchen countertop boiling water dispenser "Quooker" applies this principle in the 7 ltr. combi-version.

**Figure A-12.**
"Quooker Combi" with vacuum insulation. This application is interesting since it involves a commercial application of an evacuated cylinder. Standby loss is 10 Watt
(picture: www.quooker.com)

Another application is found in solar collectors: Evacuated tubes are a well-known type of solar collector. And the larger ICS type solar water heater "Econok" applies an evacuated storage tank for minimising heat losses and the application of the heat-pipe heat transfer principle.

**Figure A-13.**
Evacuated tubes
(picture: www.radiantcompany.com)

**Figure A-14.**
Eco-nok by Inventum / Lafarge
(picture: www.dakweb.nl)

A major design attention point is the minimisation of heat losses through edges/flanges.

Another alternative insulation method relies on the lower thermal conductivity of special gases such as Argon, Krypton and Xenon when compared to air. LBNL (USA) has conducted research for the application of "gas-filled panels"(GFP)\(^89\). Some results are shown below. GFP have been subject to study since 1995 but the first commercial applications still have to be developed.

\(^89\) http://gfp.lbl.gov/performance/default.htm
Figure A-15.
Gas-filled panels in comparison with conventional and vacuum insulation
(picture: http://gfp.lbl.gov)

Figure A-16.
Picture of gas-filled panel (cross-cut)
(picture: http://gfp.lbl.gov)

Table A-2. Properties of GFP - center of panel measurements

<table>
<thead>
<tr>
<th>Gas Fill</th>
<th>U-value Effective conductivity per Inch (W / m.K)</th>
<th>R-value Effective Resistance per Inch (hr.ft² °F / Btu . in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon</td>
<td>0.0074</td>
<td>19.5</td>
</tr>
<tr>
<td>Krypton</td>
<td>0.0116</td>
<td>12.5</td>
</tr>
<tr>
<td>Argon</td>
<td>0.0199</td>
<td>7.2</td>
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<tr>
<td>Air</td>
<td>0.0281</td>
<td>5.1</td>
</tr>
</tbody>
</table>