UK Government

# RAF063/2324 Methane Emissions from Domestic Boilers

## Laboratory Testing of Domestic Boilers

Department for Energy Security and Net Zero (2025)

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# Contents

# 1 Executive Summary

Laboratory testing was carried out on 5 domestic gas boilers to quantify the emissions of unburnt methane that occurred during the ignition and shutdown phases of the boiler operation.

Measurements were taken during domestic hot water (DHW) and central heating (CH) operational modes. Emissions were quantified and expressed as mass emissions, as grams per second and grams per operational cycle. These data were then extrapolated to a national scale using published typical usage data and the number of boilers in England.

A summary of the boiler data is in Table 1.1 and extrapolated data are presented in Table 1.2. Figures 1.1 and 1.2 give a graphical representation of the emissions data from the laboratory tests extrapolated to national and annual levels, based on different theoretical boiler usage scenarios.

Hydrogen blended methane fuel (80% $CH_4$, 2%$H_2$) was tested on one boiler; methane leakage was lower, but measurement limitations led to only indicative quantification of $H_2$ slippage.

The UK Greenhouse Gas Inventory (13) gives a figure for methane leakage from domestic space and water heating of 0.60 kt (600 tonnes) for the year 2023. Assuming this figure includes slippage from boiler cycling, then given the figures in Table 1.2 it appears that methane slippage emissions are higher than currently estimated, although further research is merited.

Combination boilers are estimated to emit 0.75-3.68kg of methane per year and system boilers 0.95-2.00kg. The total condensing boiler fleet in England (20.2million) is estimated to emit between 16kt and 66.5kt of methane, equivalent to 0.45Mt$CO_2$e – 1.86 Mt$CO_2$e.

The Inventory Agency should consider reviewing the data and considering how the data can be incorporated into National Atmospheric Emissions Inventory (NAEI) estimation method.

**Table 1.1: Summary of boiler specification and methane emissions data.**

| | | Boiler 1 | Boiler 2 | Boiler 3 | Boiler 4 | Boiler 5 |
|---|---|---|---|---|---|---|
| **Boiler Specification** | | | | | | |
| Central Heating power | kW | 24 | 21 | 24 | 15 | 30 |
| Boiler Type | | Combi | Combi | Combi | System | Combi |
| Burner Type | | Cylindrical | Cylindrical | Cylindrical | Flat | Cylindrical |
| Gas/Air Control Type | | Pneumatic | Pneumatic | Pneumatic | Pneumatic | Electronic |
| **Emissions Heating** | | | | | | |
| Mean Mass Emission rate | g/sec | 0.0001 | <0.0001* | 0.00006 | 0.0001 | 0.0002 |
| Total Mass emitted per test | g | 0.375 | <0.0006* | 0.434 | 0.453 | 0.927 |
| Number of cycles during test | n/a | 10 | 6 | 4 | 6 | 6 |
| Mass emitted per cycle | g | 0.0375 | <0.0001* | 0.1085 | 0.0755 | 0.1546 |
| Estimated uncertainty (k=2) | g | 0.014 | - | 0.04 | 0.027 | 0.056 |
| Mass emitted per cycle per kW | g | 0.0016 | <0.00005* | 0.0045 | 0.005 | 0.0052 |

* There were very low flow rates on boiler 2 during heating cycle tests that didn't register on the manometer. Emission concentration peaks were picked up by the FID instrument but the gas was velocity below the limit of detection of the manometer.

| | | | | | | |
|---|---|---|---|---|---|---|
| Emissions Hot Water | | | | | | |
| Overall Mean per cycle | g/cycle | 0.0781 | 0.0742 | 0.0756 | 0.0869 | 0.1454 |
| Estimated uncertainty (k=2) | g/cycle | 0.028 | 0.027 | 0.028 | 0.032 | 0.053 |
| Overall Mean per cycle per kW | g/cycle | 0.0026 | 0.0031 | 0.0025 | 0.0058 | 0.0036 |

**Table 1.2: Summary of methane emissions data extrapolated to a national and annual scale.**

| Condensing Boiler type | Methane Emissions from domestic hot water (tonnes per year) | |
|---|---|---|
| | Minimum | Maximum |
| Combi boilers | 9,856 | 29,681 |
| System boilers | 3,414 | 5,344 |
| | Methane Emissions from domestic space heating (tonnes per year) | |
| Combi boilers | 1,713 | 27,427 |
| System boilers | 1,039 | 4,036 |
| | Methane Emissions from domestic space heating and hot water (tonnes per year) | |
| Combi and System boiler total | 16,022 | 66,488 |

Based on 15,540,000 Condensing - combination boilers and 4,681,000 Condensing system boilers in England, EHS 2022-2023 (8)

**Figure 1.1: Chart of laboratory test methane emissions from domestic hot water extrapolated to an annual and national level across range of expected cycles.**

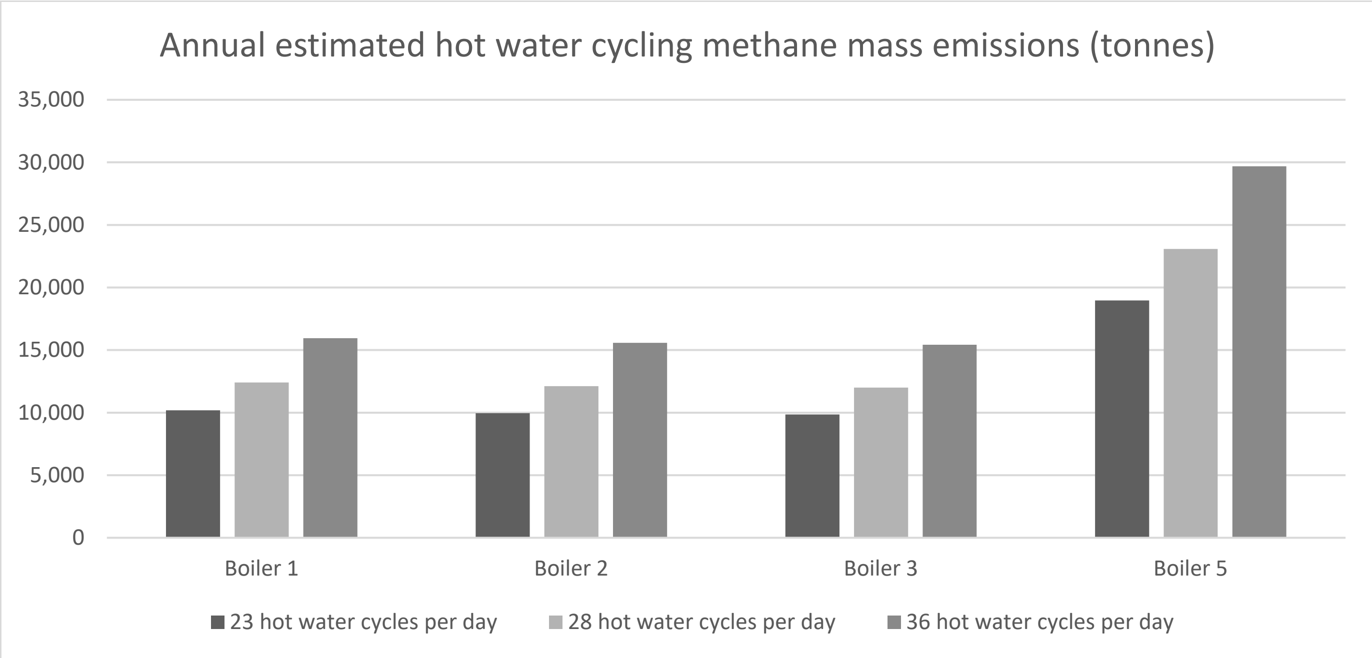
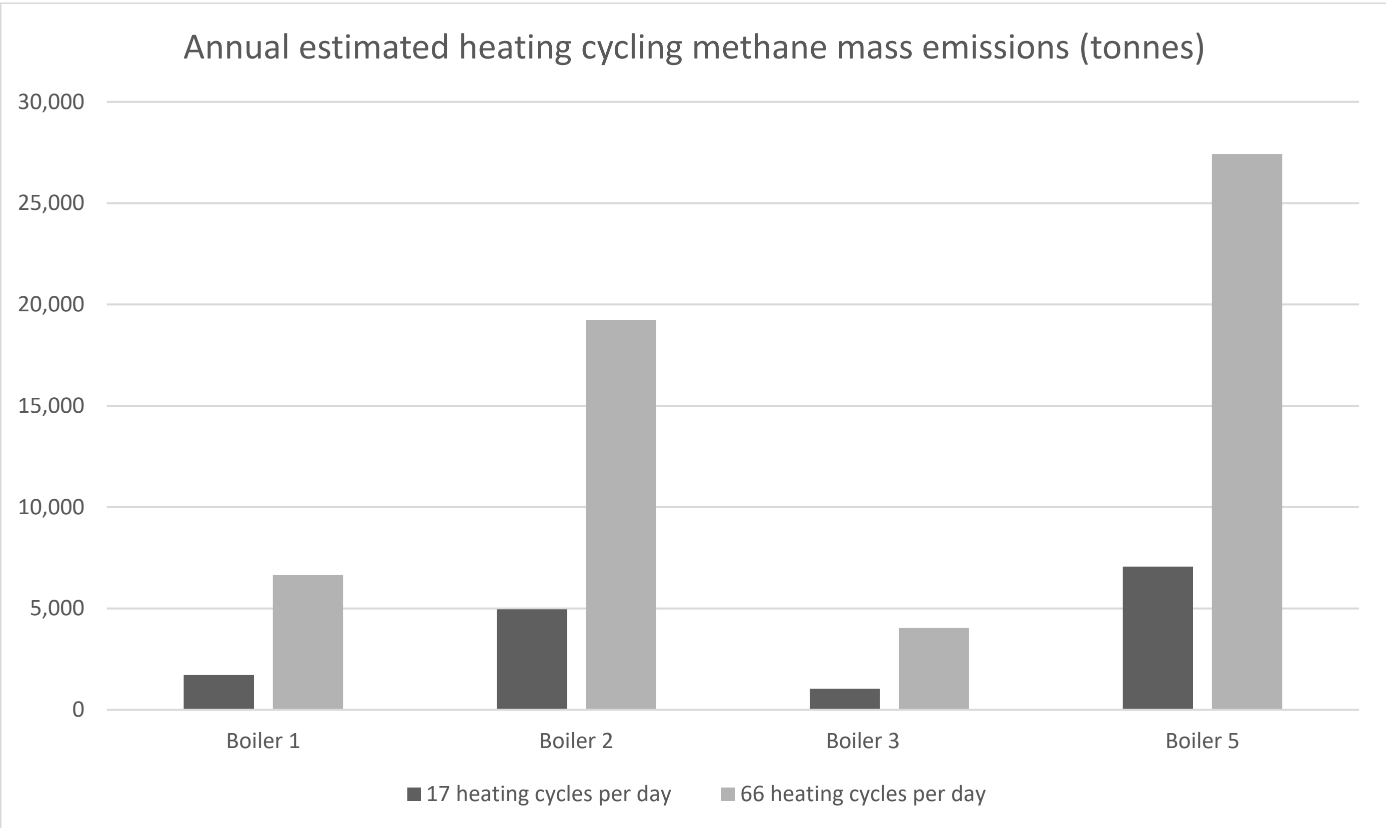



**Figure 1.2: Chart of laboratory test methane emissions from central heating extrapolated to annual and national level across range of expected cycles.**



# 2 Introduction

Natural gas (NG) is widely used due to its abundance and high specific energy; and is easily transportable and generally cleaner than other types of fossil fuels (1). NG is a popular fuel in various industrial and domestic processes, such as for residential combustion appliances (e.g., water heaters, cookers, ovens). The major constituent of NG is methane (CH4), which is a potent greenhouse gas (GHG) with a global warming potential value of 82.5 times that of CO2 on a 20-year timescale or 29.8 on a 100-year timescale, values from Intergovernmental Panel On Climate Change (IPCC), AR6, (2). It is thus important to reduce methane emissions as much as possible. Recent studies have observed that fugitive methane emissions can occur as the results of leakage (or slippage) of unburned NG from the use of residential appliances (1). In the USA, measurements have been made to estimate methane leakage rate from appliances such as water heaters with the leakage rate of about 0.35-0.44% (3) and cookers with about 0.8-1.3% leakage rate (4).

With the UK's target of achieving Net Zero by 2050 (5), decarbonising household appliances plays an important role. There are numerous top-down and bottom-up methods that can be used to quantify domestic methane emissions. However, most of these methods, in general, could only focus on the processes and distribution infrastructure of NG (1). As a result, methane emissions from end users have been potentially underestimated or excluded, and therefore it is imperative to understand the emissions of fugitive and unburned methane from NG-consuming appliances. Boilers are an example of such appliances, which are widely used in home heating in the UK and are a major source of the UK's carbon emissions, accounting for around 14% of the total (6), primarily through CO2 emissions from combustion. However, this number was derived from the provisional inland energy consumption statistics, which does not take into account fugitive emissions from leakages. Currently, there are not many studies in the UK that focus on methane emissions from residential appliances, particularly boilers. This project drew on the results of relevant studies that measured GHG emissions from residential appliances to design a measurement strategy for laboratory testing of domestic boilers.

Testing was carried out in November 2024 and January 2025.

# 3 Scope of work

The aim of this phase of the project was to obtain methane emissions data from a range of commonly used domestic boilers under laboratory conditions.

It was understood at the outset that results of the laboratory testing would in no way be conclusive, given the small sample size and the time limitations of the project.

The planning and execution of the laboratory testing was carried out in collaboration with Kiwa Energy.

Kiwa Energy informed the selection of appropriate boilers for testing and the formulation of an appropriate test schedule. They also provided the test facilities and personnel at their test labs at Bishops Cleeve, Cheltenham.

# 4 Laboratory Testing

## 4.1 Objectives

The principal aim of the boiler operation methodology designed was to make the boilers react as they would under normal operation in a dwelling in the UK. The main fuel used was methane. A limited amount of testing was undertaken using 20% hydrogen in methane.

All testing was undertaken at KIWA Energy's test facility at Bishops Cleeve, Gloucestershire.

## 4.2 Boiler selection

Five current models were selected,1 system and 4 combination boilers, from a range of manufacturers. This selection was designed to be representative of boilers currently available in the UK. They provided nominal outputs ranging from 15kW – 40kW and this was expected to result in a range of methane slippages so that relationships between fuel flow and methane slippage could be investigated. Two types of burner control were represented by these boilers, pneumatic gas air ratio control and electronic gas air ratio control.

Table 4.1 presents the boilers selected for the study together with their specifications including Central Heating (CH) and Domestic Hot Water (DHW) output. The boilers were selected with expert input from KIWA Energy. All selected appliances are condensing appliances available in the UK market at the time. Focus on combination boilers (combi) reflects the installed base and trend on replacement types as recorded in the English Housing Survey [1]

**Table 4.1: Domestic boilers used in the laboratory tests**

| Reference | Type | Burner Configuration | Burner Control | CH output | DHW output |
|---|---|---|---|---|---|
| Boiler 1 | Combi | Cylindrical | Pneumatic | 24 kW | 30 kW |
| Boiler 2 | Combi | Cylindrical | Pneumatic | 21 kW | 24 kW |
| Boiler 3 | Combi | Cylindrical | Pneumatic | 24 kW | 30 kW |
| Boiler 4 | System | Flat | Pneumatic | 15 kW | - |
| Boiler 5 | Combi | Cylindrical | Electronic | 30 kW | 40 kW |

[1] English Housing Survey - GOV.UK

## 4.3 Installation

The boilers were installed according to the manufacturer’s installation and commissioning instructions. The water flow temperatures were set for Central Heating to 55 °C and for DHW to 65 °C. A testing flue was connected to enable sampling and measurements to be consistent between boiler models. This was the only deviation from the manufacturer’s instructions. All testing was conducted in a controlled laboratory environment at an ambient temperature of 20 ± 5 °C.

## 4.4 Operation

The testing was carried out under two operating modes of the combi boilers, domestic hot water (DHW) production and Central Heating (CH) and only CH on the system boiler.

### Domestic Hot Water

To test the DHW side the boilers were connected to the mains water line from the laboratory and exited the boiler straight to drain. The valve at the supply would be opened to allow a water flow to induce a start from the boiler, this enabled a controlled duration of operation and non-operation. Timing intervals of 1, 3, 5 and 10 minutes were selected to cover a broad range of timings for which a boiler in a dwelling could operate during daily use from tapping (i.e. showers, washing hands, washing up). The 1 and 3 minute durations were repeated 10 times and the 5 and 10 minutes received 5 repeats per boiler. This was to allow comparison of the impact different running times and so different boiler combustion chamber temperatures at shutoff.

For the system boiler to have some comparative data, a switch thermostat was used to simulate these timings. The boiler was connected to a plate-to-plate heat exchanger and pump to remove heat from the system, simulating heating a DHW cylinder. This was only run for the 5- and 10-minute intervals.

### Central Heating

To test the central heating, boilers were connected to an Efficiency test rig. This rig controls the temperature of the system water after exiting the boiler and before returning it, along with the water flow rates around the system. This allowed the control of the rate at which the system was heated up or cooled down thus enabling increases in the rate of cycling from the boiler to allow timely repeats. The temperatures and gas consumption during the cycling period were monitored. This was achieved by the rig having a plate-to-plate heat exchanger connected to a chiller unit which can control the flow to increase or decrease cooling. It also had an immersion heater inside the water tank to allow an increase in the rate of system heat-up (this was required on boiler 3 which had a very low turndown). The heat loss of the test rig was approximately 4 kW.

The aim was to see how the boilers reacted at and around the target temperature (55 degrees C). The rig allowed the observation of the extent of turn down on each boiler to see the impact larger turn down has on the measurable methane slippage. The second possible factor was the impact of hot and cold starts, so testing was conducted at both conditions. The initial aim was to obtain 10 repeats of the ignition/shutdown cycle for each boiler in order to obtain a representative average. However, due to the variation in boiler operation and turndown ratios, this was not always achievable within the allotted time.

## 20% Hydrogen in Methane mixture

Although use of blends of 20% hydrogen in methane have shown similar overall performance to methane alone in other test work, details of the combustion and flame may differ. A limited investigation of the potential impact of the presence of hydrogen with methane was carried out using this blend. A combination boiler (Boiler 2) was operated on the blend in DHW production mode. The operating method was the same as described above. Five operations of 3 minutes each were carried out.

**Table 4.2: Schedule of operation cycles under test.**

| **Mode** | **Duration** | **Boiler 1** | **Boiler 2** | **Boiler 3** | **Boiler 4** | **Boiler 5** |
|---|---|---|---|---|---|---|
| DHW (Domestic Hot Water) | 1 minute | x 10 repeats | x 10 repeats | x 10 repeats | NA | x 10 repeats |
| | 3 minute | x 10 repeats | x 10 repeats | x 10 repeats | NA | x 5 repeats |
| | 5 minute | x 5 repeats | x 5 repeats | x 5 repeats | x 5 repeats | Not tested |
| | 10 minute | x 5 repeats | x 5 repeats | x 5 repeats | x 5 repeats | x 5 repeats |
| | 20%H2/80% CH4 fuel 3 minute | Not tested | x 5 repeats | Not tested | Not tested | Not tested |
| CH (Central Heating) | Dependant on boiler cycle | 10 Cycles | 6 cycles | 5 cycles | 6 cycles | 6 cycles |

## 4.5 Measurement equipment

The aim of the project was to determine methane slippage occurring during boiler operation. The level of slippage was quantified in units of mass of methane emitted per unit time (in grams per second) and mass per boiler operational cycle (in grams).

To determine mass emission, two parameters must be measured in the boiler exhaust – namely methane emission concentration (in milligrams per cubic metre – mg/m3) and exhaust gas volumetric flow rate (in metres cubed per second – m3/sec).

### 4.5.1 Methane emission concentration measurement - FID gas analyser

A heated Flame Ionisation Detector (FID analyser) was used to measure methane emissions in the boiler exhausts. The FID measures total organic carbon over a wide range of concentrations (0 – 10000 ppm). The instrument was chosen for its rapid response time and its operational range. The instrument used was a SICK model 3006, calibrated on methane.

Gas was extracted from via a heated sample line. A heated catalyst was used to remove any organic species other than methane. The catalyst efficiency was checked prior to testing using a test gas containing methane and ethane. During the testing we had an Aeris methane/ethane analyser for the first set of tests and a Gasmet FTIR for the second set of tests - as well as the FID. The Aeris detected insignificant levels of ethane (<5ppm) during the methane peaks at startup/shutdown. Similarly, the FTIR registered no other organics or any significant residual absorbance.

Previous research had indicated that methane slippage was evident as very short sharp emissions peaks during start up and shutdown of the boiler. For this reason, real-time data from the instrument were electronically logged every second.

Calibration checks of the instrument were carried out at the beginning and end of each measurement day and the instrument was operated in accordance with BS EN 12619 – Determination of mass concentration of total gaseous organic carbon – Continuous FID method (7). The gain on the FID was adjusted so it gave a 1 to 1 reading on methane. This eliminated the need to convert from ppm propane to ppm methane. The instrument was calibrated at the beginning of each measurement day - including a full system check - and checked for drift at the end of the day as per the standard requirements. All of the sample system was heated to 180C except for the small (3cm long) probe in the exhaust duct - the duct was too small to fit any sort of heated probe.

### 4.5.2 Exhaust gas volumetric flow measurements.

Determination of exhaust gas volumetric flow was achieved by multiplying the gas velocity by the duct cross sectional area.

Gas velocity was derived from differential pressure and gas temperature measurements taken continuously during each test. A calibrated ‘L’ type pitot tube and digital manometer were used for the differential pressure measurements; calibration of the pitot was by an external lab prior to measurement. The pitot selected was the smallest diameter ‘L’ type we could practically use (3mm) to minimize its impact on the exhaust gas flow. A calibrated thermocouple and digital thermometer were used to measure the temperature. Barometric pressure was also measured, in order to correct readings to reference conditions.

The same section of ducting was used for testing on each boiler. The internal diameter was measured as 0.0548m. Mean of measurements across 2 axes at the velocity measurement plane were taken to account for non-uniformity of the plastic duct an ensure an accurate cross sectional area calculation since it was fundamental to the mass emission calculations. Measurement carried out using a calibrated set of callipers.

The flow measurement plane was located approximately halfway along the ducting at least 5 hydraulic diameters downstream of the boiler exit. The sampling position for the methane measurement was located downstream of the flow measurement plane to ensure that the methane sampling probe didn’t affect the flow profile.

Prior to testing each boiler, a 20 point velocity traverse was conducted across the exhaust duct during normal operation. This was to establish the acceptability of the flow profile and to determine the appropriate velocity measuring point closest to the mean velocity value.

### 4.5.3 Additional measurement equipment

Measurement for additional organic species was also carried out. The combustion gas data was logged continuously.

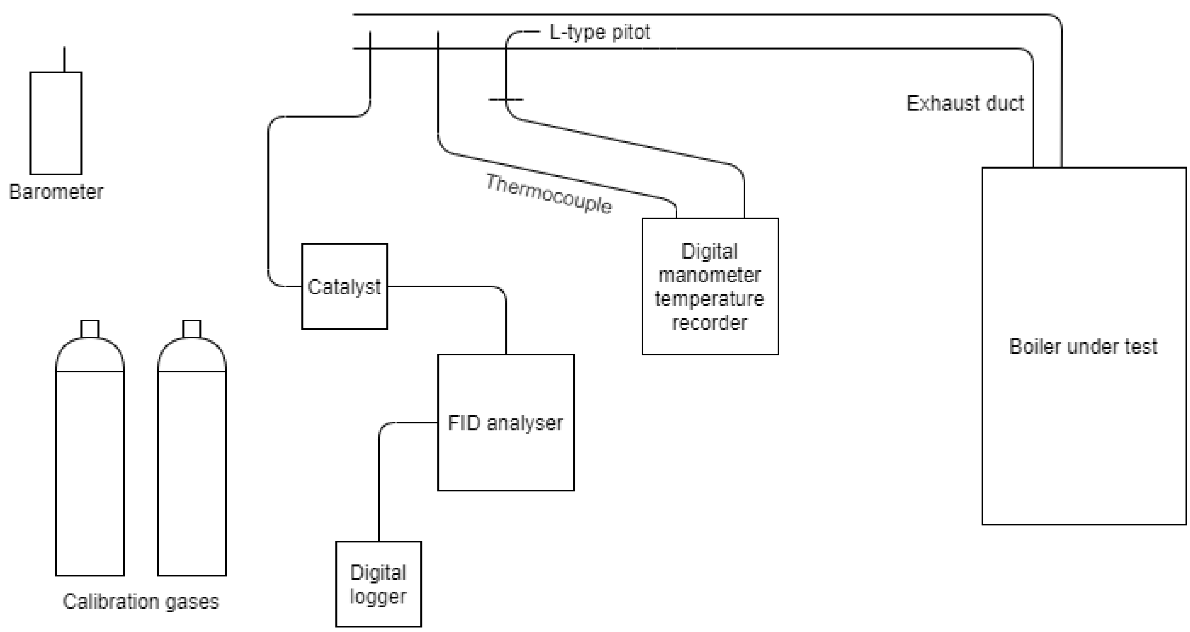
Additional measurements were carried out to determine the presence of other organic species resulting from the partial combustion of methane.

A mid – infra red LAS (Laser Absorption Spectroscopy) gas analyser was used during the November 2024 testing to determine the presence of ethane. For the testing carried out in January 2025, a Gasmet Fourier Transform Infra-red (FTIR) analyser was used for this purpose. An FTIR analyser can analyse up to 50 infra red absorbing compounds at a time including organics and combustion gases.

## 4.6 Laboratory setup

Figure 3.6.1 shows a diagram of the laboratory setup that was used to conduct the boiler tests, including measurements of methane using the FID analyser, and measurements of temperature and pressure inside the exhaust duct using the manometer. The exhaust duct was constructed from a typical plastic pipe, modified for attaching the inlet of the analyser, pitot, and thermocouple required for the above-mentioned measurements.  A digital datalogger was used to record the methane data (Analogue signal (0 - 10V) into digital data logger), while a digital camera was set up to record the temperature and pressure of the exhaust duct manually every second due to a lack of logger for the manometer. Calibration gas cylinders were also setup to perform daily calibration of the FID analyser.

**Figure 3.6.1 Laboratory setup diagram for the boiler tests**



# 5 Test results

Methane emissions results from each boiler are expressed in terms of mass emission in grams – both as an emission per unit time (g/second) and per operational cycle (grams). An operational cycle is defined as one boiler operation including ignition and shutdown.

Test data were logged every second for each test, to capture the short duration peaks in methane emissions and the rapid changes in gas velocity and temperature during the startup and shutdown phases of the boiler operation. To facilitate this, all data logger clocks were synchronized to within a second.

Readings for differential pressure and temperature of the exhaust gas were instantaneous, with no lag time. Measurements of methane concentration were subject to a delay in instrument response due to the time taken for the gas to pass through the sample system to the analyser. Furthermore, the lag time between the ‘flame on’ indication on the boiler display and ignition taking place varied from boiler to boiler. To ensure consistency across the sample boilers and ensure the correct data points were averaged, the start of each test was taken to be the first positive velocity reading. The methane raw data log was then aligned so that the first data point indicating an increase in concentration was aligned with this point.

Figure 5.1 shows a typical boiler ‘startup – run – shutdown’ cycle. There is an initial short sharp peak in methane concentration at startup as the gas valve is opened and a small pulse of unburnt gas is forced out of the vent prior to ignition. The methane emission drops rapidly to zero once the gas is fully ignited. There is then a similar but smaller peak immediately after shutdown – after the gas valve has closed and ignition ceases, a small pulse of unburnt gas is released through the vent before the exhaust flow drops to zero.

Figure 5.2. shows the same cycle in terms of methane mass emission (in grams/second).

The mass emission figure is derived by multiplying the volume flow rate in m3/second (at standard temperature and pressure) with the emission concentration in grams/m3, also at standard temperature and pressure (273K and 101.3kPa for both concentration and flow. The FID system is a hot wet system and therefore no correction for stack gas moisture content is required for the calculation of mass emission). The gap in the velocity data occurs when the methane concentration is effectively zero at this point as the boiler is on therefore no impact on the mass emission figures occurs then this is recorded.

**Figure 5.1 Time series of typical ignition and shutdown cycle – Boiler 2, 3 minute domestic hot water test.**

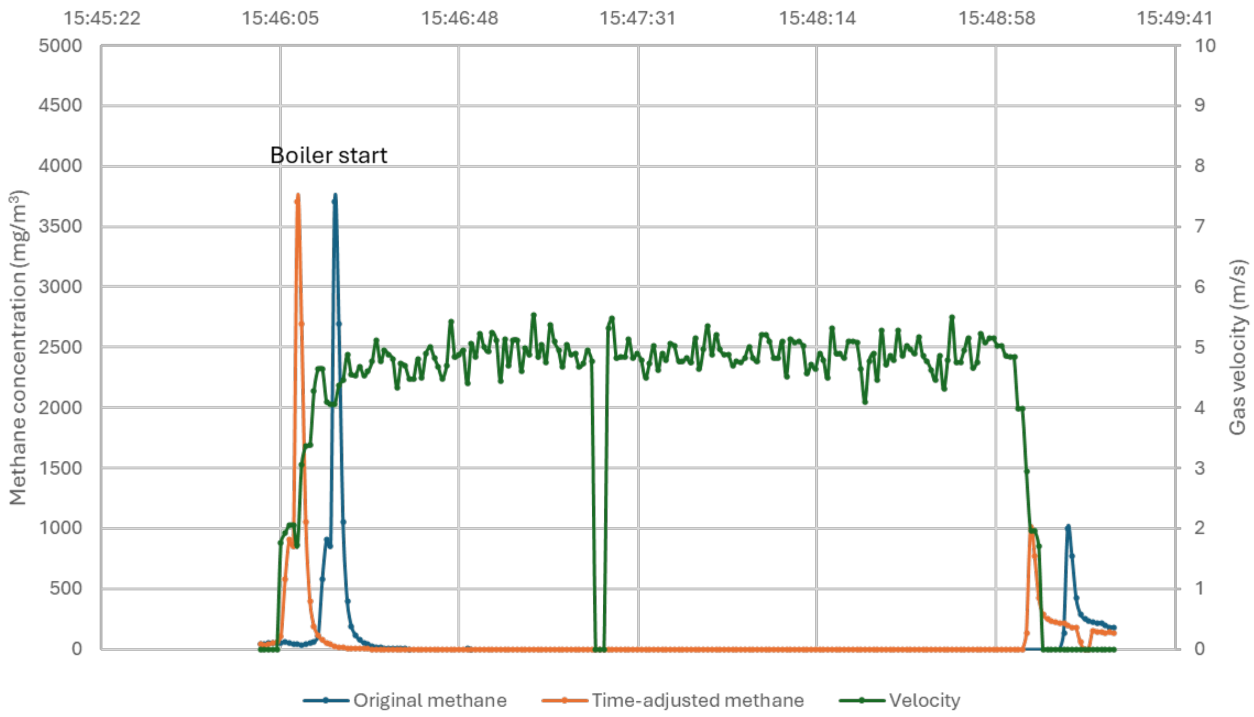
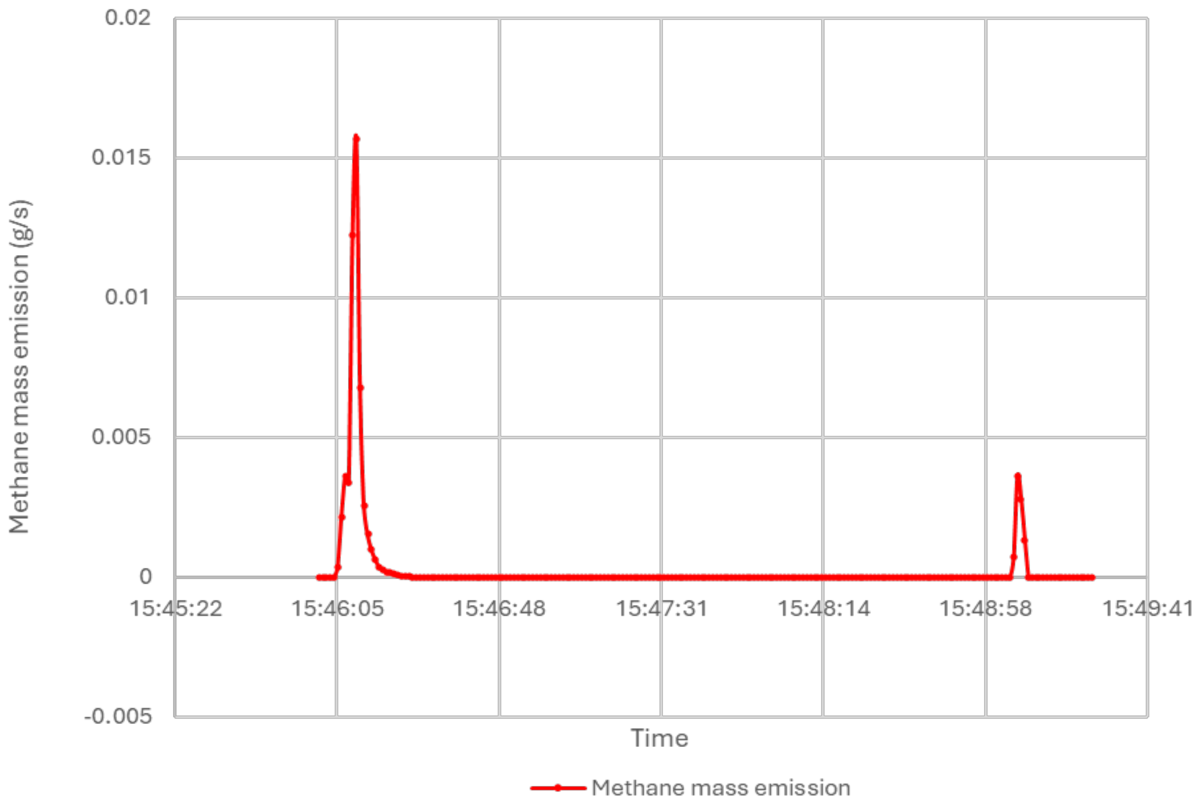


**Figure 5.2 Time series mass emissions during one cycle – Boiler 2, 3 minute domestic hot water test.**




## 5.1 Results Calculations

Detailed emissions results for all boilers tested are given in Tables 5.1 to 5.11.

As stated above, mass emissions results are calculated from emissions concentration and exhaust volumetric flow data. Both components of this calculation must be expressed at the same temperature and pressure conditions to ensure a correct result. Emission concentration and volumetric flow data were both corrected to standard temperature and pressure – STP - (temperature: 273 Kelvin, pressure:760mm Hg) through the following calculations.

Emission concentration:

Analyser raw data: parts per million (volume) methane (ppmv), wet gas

Conversion to mass/volume at STP (in mg/Nm3) = ppmv x (molecular weight/molar volume)

Molecular weight of methane : 16

Molar volume at STP: 22.414 litres.

Volumetric flow rate:

Gas velocity measurement at exhaust vent conditions derived from differential and static pressure measurements and temperature measurements conducted with the calibrated pitot, thermocouple and digital manometer/temperature reader (Manometer provided differential pressure readings. Velocities were the calculated from these.).

Conversion to volumetric flow rate (m3/sec) = gas velocity (m/sec) x exhaust CSA (m2)

CSA: Cross sectional area.

Correction to STP = Volumetric flow rate x (273/(273+T)) x ( P/760)

Where:

T = exhaust temperature

P = absolute exhaust pressure (exhaust static pressure + barometric pressure in mmHg).

Note: The generally accepted minimum gas velocity that can be accurately measured by a pitot tube is 3 metres/second. Several of the boilers tested exhibited gas velocities below this for at least some of their operational cycle. These data have been included in the calculations of average emissions however they add an additional uncertainty to the measurement. For this reason the measurement uncertainties associated with each measurement have been estimated rather than calculated.

Emission rate and emission per cycle

Mass emission rate (g/sec) = (emission concentration/1000) x volumetric flow rate at STP.

For each test, emission concentration and gas velocity were logged every second and the mass emission rate was calculated per second.

The average emission rate and the total emission (in grams/cycle) were calculated on a test by test basis, the emissions by output are calculated on the basis of the boiler rated output. Both average and total were calculated based on the duration of each cycle. As presented in the tables the average decreases as the test duration increases as the proportion of the test with the boiler on and zero emission increases.

The minimum and maximum values represent the range for complete cycles not the instantaneous maximum or minimum within each test, In the following tables the maximum, minimum and mean values are calculated from all of the tests carried out for each duration/operational mode.

One set of tests was carried out (on Boiler 2) using a mixed fuel – 20% hydrogen/80% methane – Table 5.3.

This was to see how the addition of hydrogen to the fuel reduced methane slippage.

Boiler 2 was selected as it was able to burn the mixed fuel without modification.

Time constraints meant testing was restricted to one set (5 tests) carried out in domestic hot water mode.

## 5.2 Results tables

Table 5.1: Test results for Domestic Hot Water – Boiler 1

| Test type | | Boiler 1 (30kW) | |
|---|---|---|---|
| | | Mass Emission rate | |
| | | g/second | g/cycle |
| 1 minute | Maximum | 0.0016 | 0.1311 |
| | Minimum | 0.0012 | 0.0935 |
| | Mean | 0.0014 | 0.1113 |
| 3 minute | Maximum | 0.0006 | 0.1254 |
| | Minimum | 0.0005 | 0.0992 |
| | Mean | 0.0006 | 0.1097 |
| 5 minute | Maximum | 0.0002 | 0.0679 |
| | Minimum | 0.0001 | 0.0347 |
| | Mean | 0.0002 | 0.0527 |
| 10 minute | Maximum | 0.0001 | 0.0730 |
| | Minimum | 0.0000 | 0.0255 |
| | Mean | 0.0001 | 0.0388 |
| Overall Mean per cycle | | | 0.0781 |
| Estimated uncertainty (k=2) | | | 0.028 |
| Overall Mean per cycle per rated kW | | | 0.0026 |

Table 5.2: Test results for Domestic Hot Water – Boiler 2

| Test type | | Boiler 2 (24kW) | |
|---|---|---|---|
| | | Mass Emission rate | |
| | | g/second | g/cycle |
| 1 minute | Maximum | 0.0013 | 0.0805 |
| | Minimum | 0.0011 | 0.0702 |
| | Mean | 0.0012 | 0.0753 |
| 3 minute | Maximum | 0.0005 | 0.0868 |
| | Minimum | 0.0003 | 0.0497 |
| | Mean | 0.0004 | 0.0640 |
| 5 minute | Maximum | 0.0003 | 0.0985 |
| | Minimum | 0.0002 | 0.0581 |
| | Mean | 0.0003 | 0.0802 |
| 10 minute | Maximum | 0.0002 | 0.1112 |
| | Minimum | 0.0001 | 0.0574 |
| | Mean | 0.0001 | 0.0773 |
| Overall Mean per cycle | | | 0.0742 |
| Estimated uncertainty (k=2) | | | 0.027 |
| Overall Mean per cycle per rated kW | | | 0.0031 |

Table 5.3: Test results for Domestic Hot Water – Boiler 2, comparison of methane emissions when running on methane and 20% H2/80% CH4.

| Test type | Fuel type | Boiler 2 CH4 Mass Emission rate | | | |
|---|---|---|---|---|---|
| | | 80% CH4/20% H2 | | CH4 | |
| | | g/second | g/cycle | g/second | g/cycle |
| 3 minute | Maximum | 0.00029 | 0.0533 | 0.00048 | 0.0868 |
| | Minimum | 0.00017 | 0.0309 | 0.00027 | 0.0497 |
| | Mean | 0.00025 | 0.0455 | 0.0004 | 0.0640 |

Note: The instrument used to measure hydrogen emissions was unable to log data at intervals less than one minute, therefore peaks in hydrogen emissions were not logged electronically. Peaks in hydrogen emissions were observed and logged manually during testing. The mean startup peak was 500 ppm H2 and the mean shutdown peak was 377 ppm H2, due to the frequency limitation, no meaningful mass emission could be calculated.

Table 5.4: Test results for Domestic Hot Water – Boiler 3

| Test type | | Boiler 3 (30kW) Mass Emission rate | |
|---|---|---|---|
| | | g/second | g/cycle |
| 1 minute | Maximum | 0.0009 | 0.0744 |
| | Minimum | 0.0004 | 0.0367 |
| | Mean | 0.0007 | 0.0615 |
| 3 minute | Maximum | 0.0004 | 0.1065 |
| | Minimum | 0.0003 | 0.0497 |
| | Mean | 0.0004 | 0.0725 |
| 5 minute | Maximum | 0.0004 | 0.1348 |
| | Minimum | 0.0002 | 0.0778 |
| | Mean | 0.0003 | 0.0928 |
| 10 minute | Maximum | 0.0001 | 0.0922 |
| | Minimum | 0.0001 | 0.0578 |
| | Mean | 0.0001 | 0.0765 |
| Overall Mean per cycle | | | 0.0756 |
| Estimated uncertainty (k=2) | | | 0.028 |
| Overall Mean per cycle per rated kW | | | 0.0025 |

Table 5.5: Test results for Domestic Hot Water – Boiler 4

| Test type | | Boiler 4 (15kW) Mass Emission rate | |
|---|---|---|---|
| | | g/second | g/cycle |
| 1 minute | Maximum | n/a | n/a |
| | Minimum | | |
| | Mean | | |
| 3 minute | Maximum | n/a | n/a |
| | Minimum | | |
| | Mean | | |
| 5 minute | Maximum | 0.0003 | 0.0888 |
| | Minimum | 0.0002 | 0.0686 |
| | Mean | 0.0003 | 0.0814 |
| 10 minute | Maximum | 0.0002 | 0.1041 |
| | Minimum | 0.0001 | 0.0863 |
| | Mean | 0.0002 | 0.0924 |
| Overall Mean per cycle | | | 0.0869 |
| Estimated uncertainty (k=2) | | | 0.032 |
| Overall Mean per cycle per rated kW | | | 0.0058 |

Note: Boiler 4 is a system boiler – as opposed to a combi - designed to heat a tank. 5 and 10 minute cycles were judged to be more realistic for this boiler type.

Table 5.6: Test results for Domestic Hot Water – Boiler 5

| Test type | | Boiler 5 (40kW) | |
|---|---|---|---|
| | | Mass Emission rate | |
| | | g/second | g/cycle |
| 1 minute | Maximum | 0.0024 | 0.1805 |
| | Minimum | 0.0019 | 0.1475 |
| | Mean | 0.0021 | 0.1599 |
| 3 minute | Maximum | 0.0009 | 0.1695 |
| | Minimum | 0.0006 | 0.1211 |
| | Mean | 0.0007 | 0.1419 |
| 5 minute | Maximum | n/a | n/a |
| | Minimum | | |
| | Mean | | |
| 10 minute | Maximum | 0.0002 | 0.1490 |
| | Minimum | 0.0002 | 0.1145 |
| | Mean | 0.0002 | 0.1343 |
| Overall Mean per cycle | | | 0.1454 |
| Estimated uncertainty (k=2) | | | 0.053 |
| Overall Mean per cycle per rated kW | | | 0.0036 |

Note: Time restrictions prevented completion of 5 minute domestic hot water tests

Table 5.7: Test results for Heating cycle – Boiler 1

| Boiler 1 (24kW) | | | |
|---|---|---|---|
| Boiler Heating Cycle | Boiler starts at 17.8kW, immediately ramps up to 27kW until system is approaching 50 C. Boiler then ramps steadily down to 7.5kW until burner off at 58C. Re ignition when system temperature has dropped to around 50C. Boiler starts at 18kW and then ramps down to 7.5kW within a minute. | | |
| | Mean Mass Emission rate | g/second | 0.00010 |
| | Total Mass emitted | g | 0.375 |
| | Number of cycles during test | n/a | 10 |
| | Mass emitted per cycle | g | 0.0375 |
| | Estimated uncertainty (k=2) | g | 0.014 |
| | Mass emitted per cycle per rated kW | g | 0.0016 |

Table 5.8: Test results for Heating cycle – Boiler 2

| Boiler 2 (21kW) | | | |
|---|---|---|---|
| Boiler Heating Cycle | Boiler starts at 12kW, immediately ramps up to 22kW until system is approaching 50 C. Boiler then ramps steadily down to 5.3kW until burner off at 60C. Re ignition when system temperature has dropped to around 50C. Boiler starts at 18kW and then ramps down to 5.3kW within a minute. | | |
| Heating | Mean Mass Emission rate | g/second | <0.0001 |
| | Total Mass emitted | g | <0.0006 |
| | Number of cycles during test | n/a | 6 |
| | Mass emitted per cycle | g | <0.0001 |
| | Mass emitted per cycle per rated kW | g | <0.00005 |

Note: In duct velocities were below the detection limit of the velocity measuring equipment. Peaks in methane emissions concentrations were recorded, however the gas velocity measurement equipment registered zero flow. This means a mass emission could not be calculated.

Table 5.9: Test results for Heating cycle – Boiler 3

| Boiler 3 (24kW) | | | |
|---|---|---|---|
| Boiler Heating Cycle | Boiler starts at 10kW, ramps up to 28kW until system reaches approximately 45 C. Boiler then ramps steadily down to 3.5kW and maintains this, keeping system at close to 60C. Boiler shutdown only occurs if demand is switched off. Re ignition when system temperature has dropped to around 50C. Boiler starts at 18kW and then ramps down to 3.5kW within a minute. | | |
| | Mean Mass Emission rate | g/second | 0.00006 |
| | Total Mass emitted | g | 0.434 |
| | Number of cycles during test | n/a | 4 |
| | Mass emitted per cycle | g | 0.1085 |
| | Estimated uncertainty (k=2) | g | 0.040 |
| | Mass emitted per cycle per rated kW | g | 0.0045 |

Table 5.10: Test results for Heating cycle – Boiler 4

| Boiler 4 (15kW) | | | |
|---|---|---|---|
| Boiler Heating Cycle | Boiler starts at 17kW, and maintains this until 50 - 55C. Boiler then ramps steadily down to 10kW and maintains this until boiler switches off at 62C. Re-ignition when system temperature has dropped to around 48C. Boiler then starts at 10kW , maintaining this until setpoint reached. | | |
| | Mean Mass Emission rate | g/second | 0.00014 |
| | Total Mass emitted | g | 0.453 |
| | Number of cycles during test | n/a | 6 |
| | Mass emitted per cycle | g | 0.0755 |
| | Estimated uncertainty (k=2) | g | 0.027 |
| | Mass emitted per cycle per rated kW | g | 0.0050 |

Table 5.11: Test results for Heating cycle – Boiler 5

| Boiler 5 (30kW) | | | |
|---|---|---|---|
| Boiler Heating Cycle | Boiler starts at 30kw, maintains this until approximately 50C system temp then ramps down to 5.3kW until switch off at set point. Restarts at around 50C and 20kW, immediately ramps down to 5kW until switch off at setpoint. | | |
| | Mean Mass Emission rate | g/second | 0.00021 |
| | Total Mass emitted | g | 0.927 |
| | Number of cycles during test | n/a | 6 |
| | Mass emitted per cycle | g | 0.1546 |
| | Estimated uncertainty (k=2) | g | 0.056 |
| | Mass emitted per cycle per rated kW | g | 0.0052 |

## 5.3 Results summary

Table 5.12 gives a summary of the emissions results for all five boilers. The mean mass emitted per cycle for each operational mode (heating and hot water) is used as the basis for the extrapolation calculations (using total boiler numbers and typical usage data) detailed in section 6.

**Table 5.12: Summary of boiler specification and methane emissions data.**

| | | Boiler 1 | Boiler 2 | Boiler 3 | Boiler 4 | Boiler 5 |
|---|---|---|---|---|---|---|
| **Boiler Specification** | | | | | | |
| Central Heating power | kW | 24 | 21 | 24 | 15 | 30 |
| Boiler Type | | Combi | Combi | Combi | System | Combi |
| Burner Type | | Cylindrical | Cylindrical | Cylindrical | Flat | Cylindrical |
| Gas/Air Control Type | | Pneumatic | Pneumatic | Pneumatic | Pneumatic | Electronic |
| **Emissions - Heating** | | | | | | |
| Mean Mass Emission rate | g/sec | 0.0001 | <0.0001 | 0.00006 | 0.0001 | 0.0002 |
| Total Mass emitted | g | 0.375 | <0.0006 | 0.434 | 0.453 | 0.927 |
| Number of cycles during test | n/a | 10 | 6 | 4 | 6 | 6 |
| Mass emitted per cycle | g | 0.0375 | <0.0001 | 0.1085 | 0.0755 | 0.1546 |
| Estimated uncertainty (k=2) | g | 0.014 | - | 0.04 | 0.027 | 0.056 |
| Mass emitted per cycle per rated kW | g | 0.0016 | <0.00005 | 0.0045 | 0.005 | 0.0052 |
| Emissions - Hot Water | | | | | | |
| Overall Mean per cycle | g/cycle | 0.0781 | 0.0742 | 0.0756 | 0.0869 | 0.1454 |
| Estimated uncertainty (k=2) | g/cycle | 0.028 | 0.027 | 0.028 | 0.032 | 0.053 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Overall Mean per cycle per rated kW | g | 0.0026 | 0.0031 | 0.0025 | 0.0058 | 0.0036 |

# 6 Extrapolation of test results

Methane emissions data were derived on a per cycle basis – for domestic hot water and central heating – for each boiler under test. The test results have been extrapolated to allow comparison with previous estimates of methane slippage.

To extrapolate these results to a national and annual level, further information is required, the number of boilers of each type installed in England and the typical number of starts /cycles per day.

## 6.1 Basis for the calculations

### 6.1.1 Number of boilers

The 2022-2023 English Housing Survey (8) gives the following figures for English boilers numbers.

| | |
|---|---|
| Standard boilers: | 1,455,000 |
| Combination boilers: | 674,000 |
| Condensing boilers: | 4,681,000 |
| Condensing - combination boilers: | 15,540,000 |

Figures are for 2022 and based on a sample of 11,270 dwellings.

### 6.1.2 Domestic hot water cycles (tappings)

There is no definitive information for the typical number of boiler starts for domestic hot water per day.

BS EN 13203-2 : 2022 (9) defines standard cycles for the assessment of boiler energy efficiency when producing hot water. Each cycle is based on 24 hours of usage and defines a number of short and longer hot water tappings over that period depending on dwelling occupation and boiler size. There are seven cycles defined, from small to 4XL. The Medium cycle is defined as typical for a European family and specifies 23 hot water tappings per day.

Research has been carried out into real life boiler usage cycles. The results are tabulated below.

Table 6.1.1: Domestic hot water daily tappings.

| Source | Mean number of tappings per day |
|---|---|
| BS EN 13203-2 Medium Cycle (9) | 23 |
| Energy Saving Trust (10) | 28 |
| Bennett et al (11) | 36 |

Emissions data from boilers 1,2,3 & 5 have been extrapolated to an annual and national (English) level using the usage scenarios outlined above.

Boiler 4 is a system boiler, designed to heat a hot water tank, and therefore will not respond to hot water demand in the same way as a combination boiler. Boiler 4 emissions were calculated based on central heating demand only.

### 6.1.3 Central heating cycles

Testing of the sample boilers on the central heating test rig revealed quite different behaviours to central heating demand. Boilers 1, 4 & 5 cycled in response to heat demand – igniting, heating the system and them turning off at the temperature setpoint. Re ignition was then triggered when the system had cooled below another set point. Boiler 2 cycled in a similar way but re-ignited at a much lower output. Consequently the exhaust gas velocity was below the detection limit and an emission rate could not be calculated with the measured data. Boiler 3 was able to turn down its heat output to a very low level, therefore minimising cycling.

To obtain a sufficient number of repeat tests, the heating test rig was force cooled once the set temperature had been reached so that re-ignition could be triggered. The frequency of boiler starts during testing is therefore not representative of ‘normal’ operation.

Determining a representative number for central heating boiler starts/cycles is therefore challenging.

Bennett et al (11) give a mean value of 93 for total boiler starts per day (DHW and CH) with a median of 53. They also quote a mean value for domestic hot water of 36 starts. Subtracting DHW starts from the total, this gives a mean value for central heating only of 57 (with a median of 17). Jörg Ramin (referenced in 11) gives a mean value of 66 starts for central heating, in his study.

Based on the above, the lowest and highest theoretical mean values (17 and 66 starts/cycles) were used to calculate total emissions from central heating.

Central heating systems are not operated continuously throughout the year, there is a 'heating season' from October to April. The Energy Follow up Survey commissioned by BEIS (12), interviewed several thousand households between 2017 and 2019 and determined the mean length of the heating season to be 5.7 months (173 days).

Boiler 2 has not been included in these calculations as there was no measurable emission during central heating tests.

Example results are given below for Boiler 1. Results for all boilers are given in Appendix 1

Table 6.1.2: Boiler 1 – Extrapolated results, Domestic Hot Water

| Boiler 1 - Domestic Hot Water | | Boiler Usage Scenario | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Mean mass emission per cycle (g/cycle) | 0.0781 | | | |
| Number of cycles (per day) | | 23 | 28 | 36 |
| Mass emission per day (g/day) | | 1.80 | 2.19 | 2.81 |
| Mass emission per year (kg/year) | | 0.66 | 0.80 | 1.03 |
| Estimate of Condensing - combination boiler numbers in England: | 15,540,000 | | | |
| Extrapolated annual mass emission (kg) | | 10,190,824 | 12,406,221 | 15,950,856 |

Table 6.1.3: Boiler 1 – Extrapolated results, Central Heating

| Boiler 1 - Central Heating | | Boiler Usage Scenario | |
|---|---|---|---|
| | | 1 | 2 |
| Mean mass emission per cycle (g/cycle) | 0.0375 | | |
| number of cycles (per day) | | 17 | 66 |
| Mass emission per day (g/day) | | 0.64 | 2.47 |
| Heating season (days) | | 173 | 173 |
| mass emission per year (kg/year) | | 0.11 | 0.43 |
| Estimate of condensing - combination boiler numbers in England | 15,540,000 | | |
| Extrapolated annual mass emission (kg) | | 1,713,125 | 6,650,956 |

# 7 Results discussion

## 7.1 Test results

All boilers exhibited the same pattern of methane emissions – a short sharp peak in methane concentration immediately prior to ignition with another smaller peak immediately after shutdown, with effectively zero emission in between.

For the DHW testing, Boiler 1 exhibited a decrease in methane emissions per cycle as the tapping duration increased. This may have been due to the boiler warming up over longer duration operational cycles. This behaviour wasn't witnessed in the other three combination boilers (Boilers 2, 3 and 5) where the per cycle emission was relatively consistent regardless of the length of tapping. Boiler 5 had greater per cycle emissions than the rest of the sample, however this is to be expected given its greater output (40kW). When the boiler output is factored in, the emission per cycle per kW is broadly similar to the rest of the combination boilers.

Boiler 4 is a more basic system boiler and therefore has the same output (15kW) for hot water and heating. This is reflected in the similarity between the emissions results for both operational modes.

Results from the central heating tests were broadly similar to those for the hot water testing for all but Boiler 1. Heating cycle emissions for Boiler 1 were half of those for domestic hot water. Boilers 2, 3 and 5 have a lower output for heating than hot water, however, the ignition settings may be the same for both operational modes, hence the similarity in methane emissions.

## 7.2 Limitations

The test program was designed to obtain repeatable emissions data over a range of boiler operations that broadly reflect real life usage. They did not however accurately replicate real life usage. For example, during domestic hot water testing, it was observed that the initial methane startup spike was greater when the boiler was first started from cold. Subsequent repeat tests were carried out when the boiler was warm – due to time limitations. This might not reflect real life operation, where hot water may be required infrequently and therefore more of the boiler starts will be cold starts.

During central heating testing, it was found that the rate of heat loss from the test rig was too low to trigger a sufficient number of boiler starts within the available timeframe. The test rig was force cooled to increase the rate of temperature loss and trigger re- ignition. This may mean that the emissions measured during central heating testing may not truly represent real boiler operation.

Measurement of exhaust gas velocity was carried out using a calibrated ‘L’ type pitot tube, calibrated thermocouple and a digital manometer/temperature indicator. During testing this measurement was made from a single point within the exhaust duct. Prior to testing each boiler, the velocity profile was determined across the duct on two axes and 20 measurement points. A representative measurement point was then determined for each boiler. The velocity profile measurement was carried out during steady state boiler operation. The flow profile of each boiler during steady state operation may be different during the start up and shutdown phases when peaks in methane emission occur and there is a possibility that the chosen measurement point for each boiler may not have been representative. This adds an additional level of uncertainty that cannot be quantified.

# 8 Conclusions

The overall aim of the project was to determine whether methane slippage measured from domestic boilers is in line with current estimates or whether further research – both in the laboratory and in the field – was required.

The laboratory test results have been extrapolated to a national (English) and annual level to allow comparison with exiting estimates. A summary of the range of extrapolated emissions is given in Table 8.1

Table 8.1: Extrapolated emissions summary (details in appendix)

| **Boiler type** | **Methane Emissions from domestic hot water (tonnes)** | |
|---|---|---|
| | Minimum | Maximum |
| Combination boilers | 9,856 | 29,681 |
| Standard boilers | 3,414 | 5,344 |
| | Methane Emissions from domestic space heating (tonnes) | |
| Combination boilers | 1,713 | 27,427 |
| Standard boilers | 1,039 | 4,036 |

The UK Greenhouse Gas Inventory (13) gives a figure for methane leakage from domestic space and water heating of 0.60 kt (600 tonnes) for the year 2023 Assuming this figure includes slippage from boiler cycling, then given the figures in Table 8.1 it appears that further research is merited.

Combination boilers are estimated to emit 0.75-3.68kg of methane per year and system boilers 0.95-2.00kg.  The total condensing boiler fleet in England (20.2million) is estimated to emit between 16kt and 66.5kt of methane, equivalent to 0.45MtCO2e – 1.86 MtCO2e.

The Inventory Agency is recommended to review the data and consider how the data can be incorporated into National Atmospheric Emissions Inventory (NAEI) estimation method.

# Appendix 1 – Extrapolated emissions results

## A.1 Extrapolated results – Domestic Hot Water

Table A.1.1: Boiler 1

| Boiler 1 - Domestic Hot Water | | Boiler Usage Scenario | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Mean mass emission per cycle (g/cycle) | 0.0781 | | | |
| Number of cycles (per day) | | 23 | 28 | 36 |
| Mass emission per day (g/day) | | 1.80 | 2.19 | 2.81 |
| Mass emission per year (kg/year) | | 0.66 | 0.80 | 1.03 |
| Estimate of Condensing - combination boiler numbers in England: | 15,540,000 | | | |
| Extrapolated annual mass emission (kg) | | 10,190,824 | 12,406,221 | 15,950,856 |

Table A.1.2: Boiler 2

| Boiler 2 - Domestic Hot Water | | Boiler Usage Scenario | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Mean mass emission per cycle (g/cycle) | 0.0763 | | | |
| number of cycles (per day) | | 23 | 28 | 36 |
| Mass emission per day (g/day) | | 1.75 | 2.14 | 2.75 |
| mass emission per year (kg/year) | | 0.64 | 0.78 | 1.00 |
| Estimate of Condensing - combination boiler numbers in England: | 15,540,000 | | | |
| Extrapolated annual mass emission (kg) | | 9,954,269 | 12,118,241 | 15,580,595 |

Table A.1.3: Boiler 3

| Boiler 3 - Domestic Hot Water | | Boiler Usage Scenario | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Mean mass emission per cycle (g/cycle) | 0.0756 | | | |
| number of cycles (per day) | | 23 | 28 | 36 |
| Mass emission per day (g/day) | | 1.74 | 2.12 | 2.72 |
| mass emission per year (kg/year) | | 0.63 | 0.77 | 0.99 |
| Estimate of Condensing - combination boiler numbers in England: | 15,540,000 | | | |
| Extrapolated annual mass emission (kg) | | 9,856,329 | 11,999,009 | 15,427,297 |

Table A.1.4: Boiler 5

| Boiler 5 - Domestic Hot Water | | Boiler Usage Scenario | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Mean mass emission per cycle (g/cycle) | 0.1454 | | | |
| number of cycles (per day) | | 23 | 28 | 36 |
| Mass emission per day (g/day) | | 3.34 | 4.07 | 5.23 |
| mass emission per year (kg/year) | | 1.22 | 1.49 | 1.91 |
| Estimate of condensing - combination boiler numbers in England | 15,540,000 | | | |
| Extrapolated annual mass emission (kg) | | 18,963,157 | 23,085,582 | 29,681,463 |

# A.2 Extrapolated results – Central Heating

Table A.2.1: Boiler 1

| Boiler 1 - Central Heating | | Boiler Usage Scenario | |
|---|---|---|---|
| | | 1 | 2 |
| Mean mass emission per cycle (g/cycle) | 0.0375 | | |
| number of cycles (per day) | | 17 | 66 |
| Mass emission per day (g/day) | | 0.64 | 2.47 |
| Heating season (days) | | 173 | 173 |
| mass emission per year (kg/year) | | 0.11 | 0.43 |
| Estimate of condensing - combination boiler numbers in England | 15,540,000 | | |
| Extrapolated annual mass emission (kg) | | 1,713,125 | 6,650,956 |

Table A.2.2: Boiler 3

| Boiler 3 - Central Heating | | Boiler Usage Scenario | |
|---|---|---|---|
| | | 1 | 2 |
| Mean mass emission per cycle (g/cycle) | 0.1085 | | |
| number of cycles (per day) | | 17 | 66 |
| Mass emission per day (g/day) | | 1.84 | 7.16 |
| Heating season (days) | | 173 | 173 |
| mass emission per year (kg/year) | | 0.32 | 1.24 |
| Estimate of condensing - combination boiler numbers in England | 15,540,000 | | |
| Extrapolated annual mass emission (kg) | | 4,956,806 | 19,244,072 |

Table A.2.3: Boiler 4

| Boiler 4 - Central Heating | | Boiler Usage Scenario | |
|---|---|---|---|
| | | 1 | 2 |
| Mean mass emission per cycle (g/cycle) | 0.0755 | | |
| number of cycles (per day) | | 17 | 66 |
| Mass emission per day (g/day) | | 1.28 | 4.98 |
| Heating season (days) | | 173.00 | 173.00 |
| mass emission per year (kg/year) | | 0.22 | 0.86 |
| Estimate of condensing standard boiler numbers in England: | 4,681,000 | | |
| Extrapolated mass emission (kg) | | 1,039,449 | 4,035,508 |

Table A.2.4: Boiler 5

| Boiler 5 - Central Heating | | Boiler Usage Scenario | |
|---|---|---|---|
| | | 1 | 2 |
| Mean mass emission per cycle (g/cycle) | 0.1546 | | |
| number of cycles (per day) | | 17 | 66 |
| Mass emission per day (g/day) | | 2.63 | 10.20 |
| Heating season (days) | | 173 | 173 |
| mass emission per year (kg/year) | | 0.45 | 1.76 |
| Estimate of condensing combination boiler numbers in England | 15,540,000 | | |
| Extrapolated annual mass emission (kg) | | 7,064,505 | 27,426,900 |

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