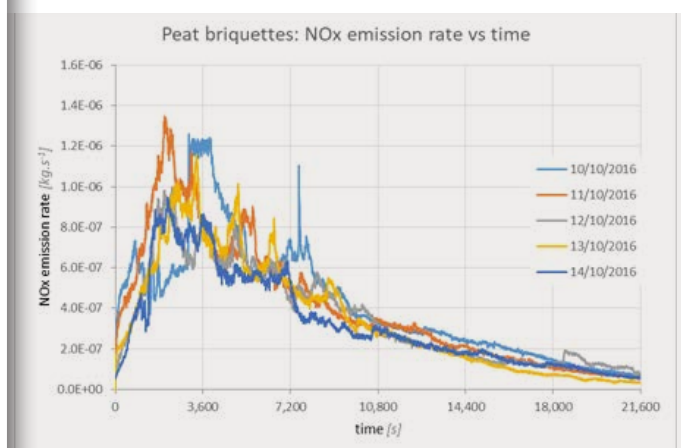


Emission Factors from Domestic-scale Solid-fuel Appliances (EFDOSOF)

Authors: W.J. Smith and C. Quinn



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EPA RESEARCH PROGRAMME 2014–2020

Emission Factors from Domestic-scale Solid-fuel Appliances (EFDOSOF)

(2011-CCRP-MS-4.5)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Dublin

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ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of Communications, Climate Action and Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors of this report gratefully acknowledge the valuable contribution and support of Mr John Gahan (School of Mechanical and Materials Engineering, University College Dublin – UCD), Dr David Timoney (Associate Professor, School of Mechanical and Materials Engineering, UCD) and Dr Raman Sharma (Postdoctoral Research Fellow, School of Mechanical and Materials Engineering, UCD).

The authors would like to acknowledge the members of the project steering committee, namely John McEntagart, Paul Duffy and Kevin Delaney (Environmental Protection Agency of Ireland), David Dodd (Climate Action Regional Office), Mícheál Young (Department of Communications, Climate Action and Environment), Professor Brian Broderick (Department of Civil, Structural and Environmental Engineering, Trinity College Dublin) and Kevin O'Rourke (Marchena Energy Management Services Ltd).

The authors would also like to acknowledge Kilian Comerford ME, Holger Marl ME, Jinliang Tong ME and Edward Healy ME for project work undertaken while postgraduate students in the School of Mechanical and Materials Engineering, UCD; Arthur Voigt and Justin Maguire (Bord na Móna); Peter Layden and Dr Robert Johnson (Arigna Fuels); Keelin Timoney (School of Mechanical and Materials Engineering, UCD); and Celia Alves (University of Aveiro).

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This report is based on research carried out/data from April 2016 to March 2017. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014–2020
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-913-0

July 2020

Price: Free

Online version

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Executive Summary

This study presents emission factors for the combustion of solid fuels in a residential stove. The fuels examined encompass the majority of solid-fuel types consumed in the Irish residential sector. The emission factors were determined using a full-cycle test protocol, which includes both the ignition and the smouldering phases. Multiple repeats of each test were performed, so that statistically robust estimates of the emission factors could be established.

All solid fuels tested, including fuels categorised as “smokeless” under Irish law, were found to generate very substantial levels of particulate emissions when tested over a complete combustion cycle. Combustion of just 2–3 kg of any of these fuels produced a mass of particulate matter (PM) equivalent to driving a typical, modern diesel car for several thousand kilometres.

Sod peat exhibited by far the highest emission factor for both PM and oxides of nitrogen (NO_x). The lowest levels of both PM and NO_x were observed when burning kiln-dried hardwood logs. Wet logs, however, generated substantially higher emissions, broadly in line with those from peat-based fuels. Firelighters contribute a disproportionately high fraction of PM emissions, relative to their energy content and mass.

Inferred emission of “volatiles” from all fuels tested, but particularly from wood and sod peat, may be a cause for concern.

However, the emission factors presented in this report were obtained using a single appliance, and it is unknown whether or not significant variations in emission factors for some or all pollutants, when burning some or all of these test fuels, would be found using other stoves or open fires. In fact, it is not clear that establishing an accurate overall emission factor for residential combustion of solid fuels is an achievable goal, because the ultimate level of emission is determined by complex interactions between many variables.

Nonetheless, the results of this study clearly show that emissions – especially particulate emissions – from this source are very significant. Because those emissions are generated in residential areas, they have the potential to impact appreciably on human health. That impact is likely to be most severe where both population density and emission source density are high.

The combustion of solid fuels in manually operated, domestic-scale appliances should therefore be discouraged in urban areas. Mandating the use of so-called smokeless fuels, while laudable in principle, is unlikely to reduce particulate emissions to an acceptable level.

1 Introduction

While the use of solid fuels in residential combustion has slowly decreased since 2000, there has been an increase in the market share of solid-fuel stoves for room heating (Dennehy and Howley, 2013). Moreover, despite the decrease in absolute demand, solid fuels have continued to supply 20–25% of the residential heating demand each year since 2003.¹ Sod peat and bituminous coal have each accounted for a little over 30% of supply, “smokeless” fuels – nuggets, ovoids and peat briquettes – accounted for a further 30% between them and the remaining 7% was split 2:1 between biomass and lignite (SEAI, 2016). It is noteworthy that biomass has almost tripled its share of that market since 2003, albeit starting from a low base.

Renewable biomass combustion makes up half of the renewable share of energy use in the residential sector (geothermal and solar energy account for 33% and 17% of the renewable share, respectively) and is viewed as an attractive option because of its near CO₂ neutrality (Williams *et al.*, 2012); there was a 13.3% increase in the use of renewable biomass in Ireland between 2006 and 2011 (Dennehy and Howley, 2013). However, there is growing concern over the potential impacts of the increased combustion of biomass fuels on air quality. The emission of fine particulate matter (PM) and oxides of nitrogen (NO_x) is of particular concern owing to their negative effects on human health (Bølling *et al.*, 2009). Naeher *et al.* (2007) reported that PM from wood smoke affects both the respiratory and cardiovascular systems, while Clancy *et al.* (2002) found that respiratory deaths in Dublin decreased by 15.5% and cardiovascular deaths by 10.3% following a ban on bituminous coal in favour of smokeless coal. Kampa and Castanas (2008) described that NO_x emissions lead to nose and throat irritation, followed by bronchoconstriction and dyspnoea; asthmatic individuals are particularly at risk. NO_x has also been seen to react with ammonia, volatile organic compounds (VOCs) and moisture to form secondary PM in the atmosphere (Squizzato *et al.*, 2013).

In comparison with mainland Europe, wood combustion for residential heating in Ireland is at a low level; in 2013, wood fuel made up 1.8% of Ireland’s residential fuel mix, compared with 24.6% in Austria and 21.6% in Denmark (Dennehy and Howley, 2013). In addition to this, the quality of wood log fuel available in Ireland varies widely, with both hard- and softwood species sold and different approaches to seasoning used. Fuel-seasoning approaches vary from kiln drying (as for the hardwood logs in this study), to air drying over an extended period (as for the softwood logs used in this study) and logs that have not undergone any purposeful drying or seasoning at all (so-called green logs). However, under the Renewable Energy Directive (2009/28/EC) (European Union, 2009), Ireland has committed to a target of 16% of the final energy consumed in the state coming from renewable sources by 2020 and the government has determined that this obligation will be met by delivering 12% of heat from renewable sources. In order to do this, Ireland will need to double biomass combustion between 2014 and 2020 (Clancy, 2015).

However, there is strong evidence that biomass combustion contributes significantly to elevated PM levels in ambient air (Fuller *et al.*, 2013; Sarigiannis *et al.*, 2015). Sarigiannis *et al.* (2015) showed elevated PM measurements in Greece during winter, attributed primarily to the increased use of biomass combustion for space heating. Wenger (2015) reported measurements that suggested that solid-fuel combustion is responsible for 50% of ambient PM with a characteristic size of 2.5 µm or less (PM_{2.5}) during winter in Cork, Ireland; it should be pointed out that not all of this is from biomass. Similar results were found for two other sites in Ireland: Killarney, County Kerry, and Enniscorthy, County Wexford. Thus, the evidence suggests that an increase in the use of renewable biomass for heating will result in higher PM concentrations in ambient air.

This study examines emissions from common peat or biomass solid fuels burned in Ireland (peat briquettes,

¹ Authors’ calculations, based on SEAI (2016).

sod peat and wood logs) and compares these with emissions from bituminous (Polish) coal and from manufactured “smokeless” nuggets. Emissions from peat-based fuels, in particular, have received very little attention in the literature to date; Mitchell *et al.* (2016) have produced a recent study on peat briquettes, but there is little else reported. In order to produce statistically robust estimates for emission factors (EFs), the inherent inhomogeneity of solid fuels means that controllable test parameters must be identical test to test, e.g. the fuel stacking and ignition method, and a significant number of burns must be completed. This work specifically presents EFs for PM, NO_x, CO and CO₂.

1.1 Quantifying Emissions of Particulate Matter

Quantifying and characterising the emissions of PM from solid-fuel combustion is inherently challenging, and the values obtained depend on both the details of the combustion process and the measurement technique employed. Figure 1.1 (Nussbaumer, 2017) provides an indication of the myriad processes and factors that govern the ultimate mass and characteristics of the PM.

It can be seen from Figure 1.1 that the reactions leading to PM formation can be associated with four distinct, physical locations:

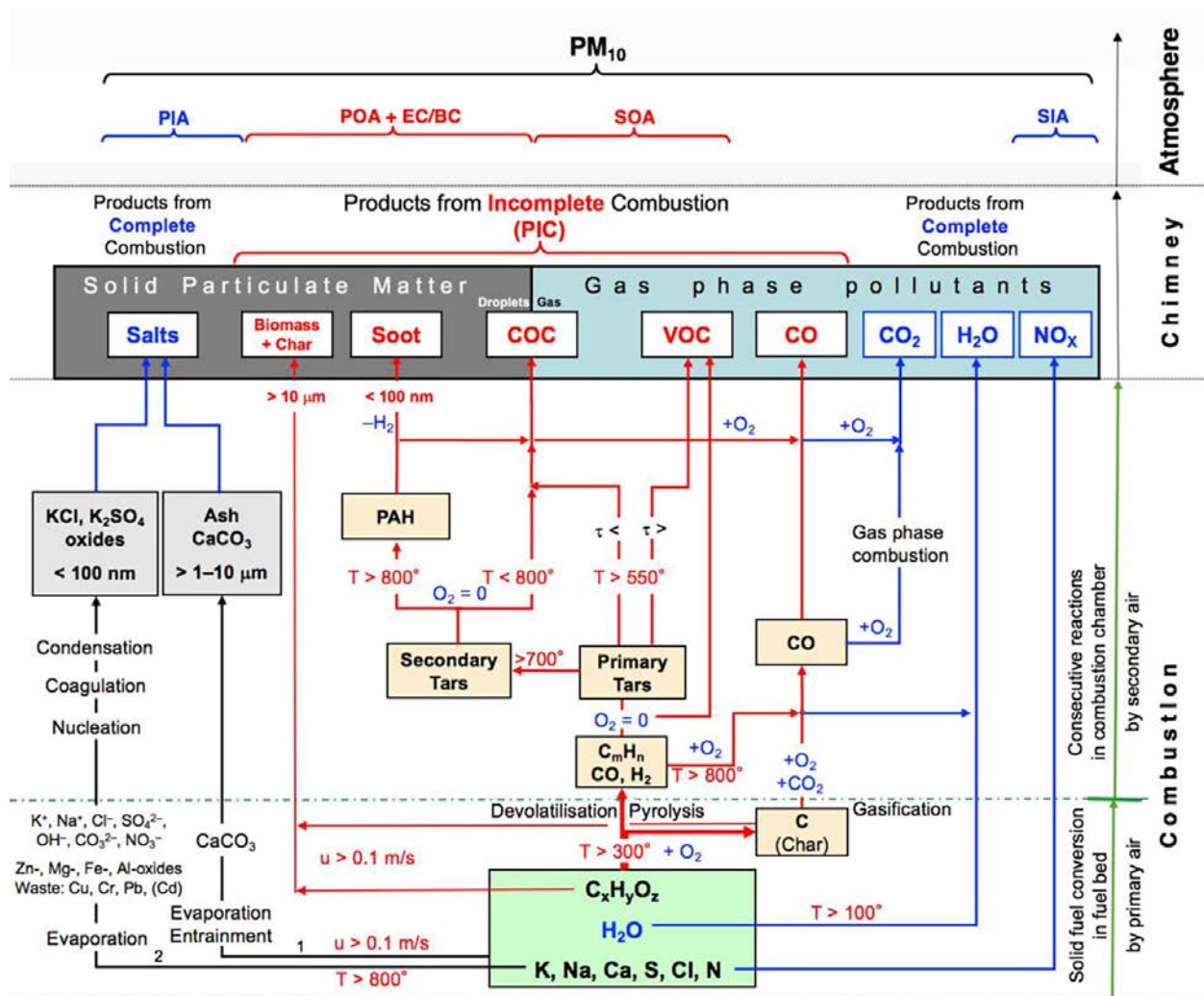


Figure 1.1. An outline of the principal features of PM formation, and subsequent secondary aerosol formation in the atmosphere, in biomass combustion. *u*, gas velocity; *τ*, residence time (< denoting short residence time, > denoting long residence time); 1, solid particle path; 2, solid vapour particle path. COC, condensable organic compounds; EC/BC, ratio of elemental carbon to black carbon; PIA, primary inorganic aerosol; PM₁₀, particulate matter with a characteristic diameter of 10 μm or less; POA, primary organic aerosol; SIA, secondary inorganic aerosol; SOA, secondary organic aerosol. Source: Nussbaumer (2017).

1. in the fuel bed itself;
2. within the combustion chamber of the stove;
3. in the flue or chimney;
4. in the atmosphere, following emission from the stove.

The reactions depend on the physical conditions – such as temperature and oxygen concentration – within those zones. Conditions within the first three zones depend, in turn, on a varying number of factors including:

- the size, shape, arrangement, moisture content and chemical composition of the fuel elements;
- the availability of combustion air;
- the design of the stove;
- the quality of the flue and the flue installation.

It is significant that, while a consumer may choose to purchase a well-designed stove, and even to ensure that it is connected to an appropriate flue, the combustion of low-grade fuel and/or inappropriate control of the inlet air supply can lead to substantial quantities of PM still being emitted.

From a measurement perspective, even greater significance is attached to the fact that particulate emissions continue to evolve even after they have exited the flue and entered the atmosphere; PM emissions differ completely from gaseous emissions such as NO_x in this respect. Although the concentration of gaseous emissions decreases as the gases mix with atmospheric air, the total mass and physico-chemical characteristics of the gaseous emissions remain invariant. That, unfortunately, is not the case with PM.

As the exhaust gases are cooled and diluted in the atmosphere, VOCs and condensable organic compounds (COCs) may form liquid droplets, adsorb onto the surface of solid carbonaceous particles and/or react with CO , H_2O and other compounds. The rate and the extent of these processes depend on the composition and temperature of the gases leaving the stack and on the rate and degree to which they are cooled in the atmosphere. That rate of cooling and dilution depends in turn on exogenous factors, such as wind strength and ambient air temperature, while the rate and extent of chemical reaction also depend on the local concentration of compounds such as the

OH radical and non-methane organic gases in the ambient air.

Hence, the mass, chemical composition and physical characteristics of PM observed in ambient air may differ substantially from those observed in the exhaust flue. However, it is clear that the total mass of PM formed following dilution and cooling in the atmosphere exceeds that emitted from the flue.

This is significant because published data on PM emissions (and EFs) are sometimes derived from measurements in the flue gas (typically referred to as “hot filter” measurements) and sometimes from measurements taken in dilution tunnels. Estimates in the literature put the ratio of PM mass obtained using these two methods at between 2 and 10 (e.g. Robinson *et al.*, 2010; Bruns *et al.*, 2016) for biomass fuels; Olesen (2016) points out that the ratio can be substantially influenced by the moisture content of the raw fuel.

Although the use of a dilution tunnel may yield results closer to those found in ambient air, the “hot filter” method was used throughout this project, for the following reasons:

- It is simpler, less expensive and requires less laboratory space.
- It sidesteps the additional uncertainty and variability introduced with dilution and therefore allows a more straightforward comparison to be made between the various fuels tested.
- Even using a dilution tunnel, the mass and other characteristics of the PM captured are still unlikely to accurately reflect the true mass and composition of PM formed in the atmosphere, since those factors remain highly sensitive to the rate and extent of dilution and to the composition of the dilution air.

The authors also note that prEN 16510, currently under development by CEN TC 295 as a harmonising standard for PM emission measurement in stoves and boilers, is also likely to recommend non-isokinetic, hot-filter sampling of in-stack gases, albeit at a slightly higher filter temperature (140°C) and with parallel sampling of VOCs using a heated flame-ionisation detector (HFID). This seems to be an excellent approach, since it offers good repeatability while also providing additional insight into the nature of the emissions from a stove.

2 Experimental Programme

Over 300 combustion tests were carried out in the course of this project. The data from the 80+ tests presented in this report were gathered between April 2016 and March 2017 by Dr Cian Quinn, a post-doctoral researcher employed by the project, and the data represent a very substantial body of experimental and analytical work.

2.1 Test Fuels

Six distinct fuels were assessed during this project:

1. bituminous coal (doubles);
2. “smokeless” coal nuggets;
3. peat briquettes;
4. sod peat;
5. air-dried softwood logs;
6. kiln-dried hardwood logs.

As will be discussed, a seventh fuel – “wet wood” – was also included. However, time constraints limited the number of tests that could be done using wet wood, so those results are indicative only.

Each fuel was purchased from standard consumer outlets and consumed in the “as received” condition. The sod peat was purchased in bags of about 5 kg each, the wood in bags of about 7–10 kg, the coals in bags of 40 kg and the peat briquettes in bales of approximately 12 kg.

The kiln-dried hardwood represents “best in class” firewood fuel. Air-dried softwood is a cheaper alternative, with the potential for greater variation in quality and moisture content. It is noted, however, that each batch of the air-dried softwood purchased in this project was commendably dry. In general, both classes of log were ~25 cm in length and each log had been split into approximate quadrants; each quadrant weighed approximately 0.5–0.7 kg and was not debarked.

A crude estimate of the impact of moisture content on the performance of wood logs was sought by soaking approximately 10 kg of each wood type in water for 18–36 hours. These samples are referred to as “wet wood” in this report. Although intended to provide insight to the performance of fresh, or “green”, logs – wood that has not been seasoned sufficiently to reduce its moisture content below 20% – it should be noted that green logs dry from the outside in and the moisture content is therefore likely to be highest in the centre. In contrast, the “wet wood” used in this study had absorbed water from the outside in and was therefore likely to be wettest on the outside.

Proximate and ultimate analysis of the fuels was carried out by Environmental Scientifics Group (ESG), a UK-based laboratory service. Based on its analyses, the principal thermal and chemical properties of the various fuels are summarised in Tables 2.1 and 2.2. The full analyses supplied by ESG are presented in Appendix 3.

Table 2.1. Thermal properties of the fuels tested, as determined by ESG

Thermal property	Bituminous coal	Smokeless coal	Softwood (air-dried)	Hardwood (kiln-dried)	Peat briquette	Peat sod
Total moisture (as received) (%)	4.6	17.3	14.3	6.2	13.1	40.2
Ash fraction (as received) (%)	3.4	3.2	0.8	0.5	11.3	1.5
Volatile matter (dry, ash free) (%)	34.6	52.3	80.6	85.4	67.9	67.2
Gross calorific value (dry, ash free) (MJ kg ⁻¹)	34.0	26.8	21.2	20.0	23.0	23.0
Net calorific value (dry, ash free) (MJ kg ⁻¹)	32.8	25.2	19.6	18.6	21.6	20.9

See Appendix 3 for further details.

Table 2.2. Chemical composition of the fuels tested, as determined by ESG

Mass fraction of chemical element (dry, ash free)	Bituminous coal (%)	Smokeless coal (%)	Softwood (air-dried) (%)	Hardwood (kiln-dried) (%)	Peat briquette (%)	Peat sod (%)
Carbon	84.2	68.8	53.3	50.8	58.1	59.7
Hydrogen	4.8	4.3	5.7	5.8	4.3	1.8
Oxygen	8.9	25.7	40.7	43.1	35.7	37.1
Sulfur	0.47	0.33	0.02	0.02	0.32	0.24
Nitrogen	1.5	0.8	0.3	0.2	1.6	1.2
Chlorine	0.21	0.04	0.01	0.00	0.08	0.03

See Appendix 3 for further details.

It is worth noting that the smokeless coal nuggets – and, to a lesser extent, peat briquettes – are manufactured fuels: the manufacturer can therefore control, to a greater (smokeless nuggets) or lesser (peat briquettes) extent, the chemical composition of the fuel elements. It is notable that the peat briquettes used for all tests covered by this report exhibited a substantially higher ash fraction (11.3%) than nominally identical briquettes analysed 3 years previously (6.4%) – see Appendix 3, Table A3.1. The smokeless coal nuggets, on the other hand, exhibited a significantly higher oxygen content (25.7% by mass) than in previous analyses (6.3% by mass), implying perhaps the use of higher levels of biomass in its manufacture. One consequence of the increased oxygen content is a substantial reduction in the lower heating value (LHV) of the fuel: 25.2 MJ kg⁻¹ for the fuel used in this report versus 30.5 MJ kg⁻¹ for the nuggets analysed in 2014. Full details of the analyses are available in Appendix 3.

2.2 Test Protocol

The objective of the protocol was to simulate the real-world operation of domestic stoves in Ireland, while minimising the number of independent variables and trying to maintain consistency between tests of an individual fuel and between fuels.

In order to simulate real-world operation, it is essential that the ignition phase be incorporated, as previous studies and preliminary tests in this project have shown that this phase contributes a disproportionate fraction of total emissions. It is also essential that the fuels used are representative of the fuels actually consumed by Irish households.

Unfortunately, these requirements could not be met by following an existing national or international standard: the British and German standards omit the ignition phase, while the Norwegian standard (which is focused on solid biomass fuels) requires the use of fuel elements that are completely unrepresentative of the Irish market. The Norwegian standard also requires the use of a dilution tunnel. Although this approach has many merits (and some drawbacks), the hardware required is expensive and bulky, and was not available to this project.

A new protocol was therefore developed, the primary characteristics of which are as follows:

1. In total, 3.5 kg of test fuel² was used for each test (similar to BS EN 3841), plus 100 g of firelighters. This mass of firelighters was sufficient to ensure consistent, successful ignition for all fuels except sod peat. A single brand of firelighters – readily available in supermarkets – was used for all tests.
2. The fuel was arranged so that fuel elements were positioned both above and below the firelighters. The physical arrangement of the fuel and firelighters was made as consistent as possible between tests.
3. In the case of sod peat, satisfactory ignition could not be guaranteed with 100 g of firelighters. A separate ignition charge was therefore employed, comprising 100 g of firelighters plus 500 g of kiln-dried kindling. This ignition charge was lit and once it was burning strongly (about 8–12 minutes after ignition), the sod peat was added to the fire. The mass of sod peat added was 3 kg, rather than the 3.5 kg used for all other fuels, so that the total

² Except for sod peat – see item 3.

mass of combustibles in the stove at the start of the test was approximately 3.5 kg.

4. No refuelling was permitted during the test.
5. The air inlet to the stove was held in the fully open position throughout the test.
6. The start of the test was defined as the moment immediately prior to ignition of the test fuel. In the case of sod peat, this corresponds to the moment that the peat is added to the stove. For all other fuels, it corresponds to the moment that the firelighters are lit.
7. The end of the test was defined as the time when the fuel consumption rate was asymptotically approaching zero: in general, the absolute consumption rate was below 1 g min^{-1} at the end of the test. Each test typically lasted between 4 and 7 hours.
8. Gaseous emissions were sampled from a port 100 cm above the top of the stove and recorded at 10-second intervals throughout the test. With the exception of PM emissions, all other test parameters were also recorded at 10-second intervals.
9. The PM emissions were determined using a “hot filter” method. A sample of exhaust gas was extracted, from a location about 100 cm above the roof of the stove, at a fixed rate of 3.5 g min^{-1} ; this corresponds to about 1.5% of the total exhaust mass flow. (On account of the large variations in flue gas velocity across the various stages of the test, isokinetic sampling was deemed impractical.) The filter housing and sampling tube were maintained at a temperature of 120°C .
10. Sample gas was drawn through the PM filters continuously for 4 hours,³ beginning at the start of the test. This allowed sufficient time for the housing to cool to a safe level prior to removal of the filters. Although some tests continued for more than 4 hours, PM emissions during the final phase of combustion are generally very low.⁴

Although developed completely independently, the authors were pleased to discover subsequently that the European Union FP7 project “BeReal” had settled on a similar protocol, including the use of “hot filtering” to determine PM emissions (Schmidl, 2015). On the other hand, because of differences in consumer behaviour, fuel properties and stove size in the BeReal study region, their protocol expressly incorporates refuelling.

2.3 Experimental Setup

2.3.1 Stove

A schematic of the experimental setup used in this investigation is shown in Figure 2.1. A fixed bed, multi-fuel stove with a nominal heat output of 11 kW was used for all tests. The internal dimensions of the combustion chamber are $40 \times 50 \times 30 \text{ cm}$; a deflector plate lies across the top of the chamber.

Three modifications were made to the stove for the purposes of this study:

1. The existing ash tray and grate were removed from the stove and replaced with a fuel basket and a tray to catch the ash produced during combustion of the test fuel (Figure 2.2).
2. A small hole was drilled through the floor of the stove, so that the combined basket and ash tray assembly could be supported externally.
3. The inlet to the stove glass air curtain was sealed closed, so that all combustion air would enter the stove through the primary air inlet below the grate/basket. This was done so that the mass flow rate of air into the stove could be accurately determined on a continuous basis.

The basket and tray arrangement rests on a single-point load cell (Tedea Huntleigh, 1042) in order to continuously measure the mass of fuel in the stove. This required a hole to be drilled through the floor of the stove, so that the weight of the ash tray, basket and fuel could be transferred to the load cell. To

3 The pressure drop across the filter housing was monitored continuously, to ensure that blockage did not occur. If the pressure drop exceeded $\sim 0.3 \text{ bar}$, the sample was diverted through a second filter housing, in parallel with the first, so that sampling could continue uninterrupted.

4 Because of the high PM loadings associated with combustion of sod peat, both filter housings were employed for all tests involving this fuel. Gas was sampled through filter housing “A” for the first 30 minutes of the test and then diverted through filter housing “B” for the remaining 3.5 hours of sampling. Analysis of these data reveals that the PM emission rate during the first 30 minutes of the test was, on average, 10 times greater than during the subsequent 3.5 hours.

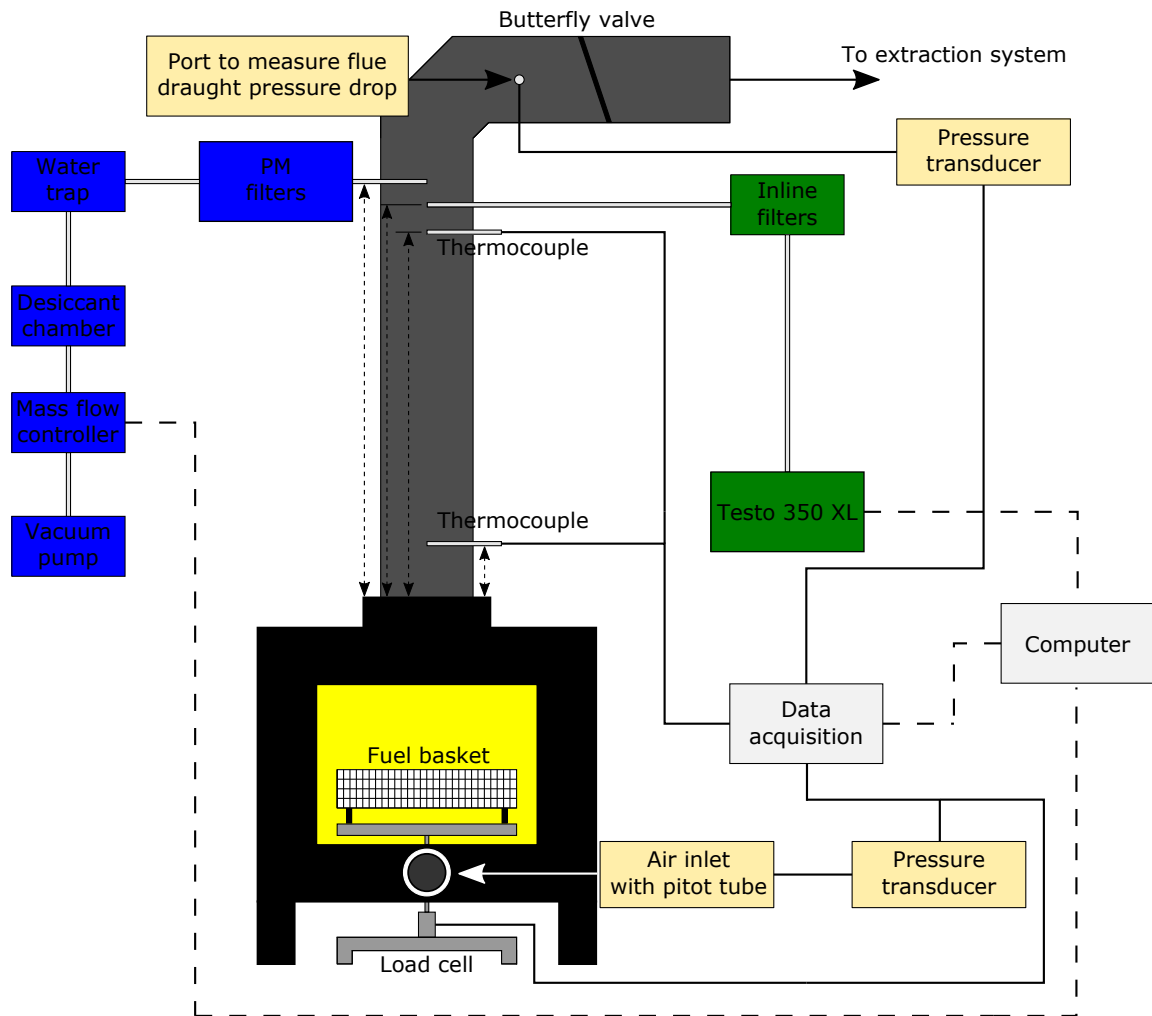


Figure 2.1. Schematic of the experimental setup used in this investigation.



Figure 2.2. Stove as purchased with grate and ash tray installed (left), and with fuel basket and modified ash tray (right).

confirm that this hole did not permit air leakage into or out of the stove during operation, a series of smoke tests was performed. In these tests, the inlet and exhaust opening of the stove are sealed, a smoke bullet is placed in the stove and ignited, and the door of the stove is closed. The slight over-pressure resulting from the large volumes of smoke produced will force smoke out through any faulty seals. As can be seen in Figure 2.3, no such leakage was observed.

An uninsulated flue with an inner diameter of 15 cm and length of 110 cm was fixed to the stove outlet. This was then connected to the laboratory's existing flue gas extraction system. A butterfly valve in the exhaust duct was modulated to maintain a pressure differential of 12 ± 2 Pa between the top of the flue and the ambient pressure in the laboratory. Two k-type thermocouples, 9 and 95 cm above the stove, respectively, measured the temperature of the flue gas at each location (Figure 2.4).

2.3.2 Inlet air flow

Primary inlet air is supplied through an inlet below the tray; this has been fixed fully open for all tests performed. To measure the flow rate of air into the stove, a circular duct with an inner diameter of 5 cm was attached to the air inlet. A pitot tube was



Figure 2.3. The smoke test provided no evidence of leakage.

mounted inside the duct and was connected to a relative and differential pressure transducer (Huba Control, type 694). A k-type thermocouple measured ambient air temperature in the laboratory; ambient pressure was determined using a mercury manometer and this was assumed to remain constant throughout a given test.

2.3.3 Particulate matter sampling equipment

All PM emissions data presented in this report are based on measurements obtained using a so-called "hot filter" method. The PM measurements were obtained by drawing a sample of raw (undiluted) flue gas from a PM sampling port located 107 cm above the top surface of the stove, through a pair of heated (120°C) filters arranged in series. The filters are held in an insulated, stainless-steel housing – designed and manufactured within the School of Mechanical and Materials Engineering, University College Dublin – and connected to the flue via a stainless steel tube approximately 20 cm in length. The PM sampling head extends to the centre of the flue and is oriented in the downstream direction, i.e. away from the stove, in the direction of the flue exit.

For the majority of fuels tested, sample gas passed through a single filter housing containing these two filters. The high PM loading observed during some tests, however, required the use of a second filtering pair. To accommodate this situation, two filter housings were positioned in parallel, as shown in Figure 2.5. During each test, the sample was drawn through only one of the filter holders at a time – a manually operated valve determines which filter holder is used.

Two absolute pressure transducers – one on either side of the filter holders – were used to monitor the pressure drop across the filter housings and thus provide an early warning of potential filter blockage. Should the pressure drop exceed ~ 0.3 bar, the sample flow was diverted to the second filter housing, so that PM sampling could continue uninterrupted even at very high PM loadings. PM emissions were then determined based on the mass change of all four filters. All filter mass measurements were performed using a Mettler College 150 precision mass balance.

Because persistently high PM loadings were observed with sod peat, it was decided to use both filter housings for all tests with this fuel. The sample flow was filtered through housing "A" for the first 30 minutes

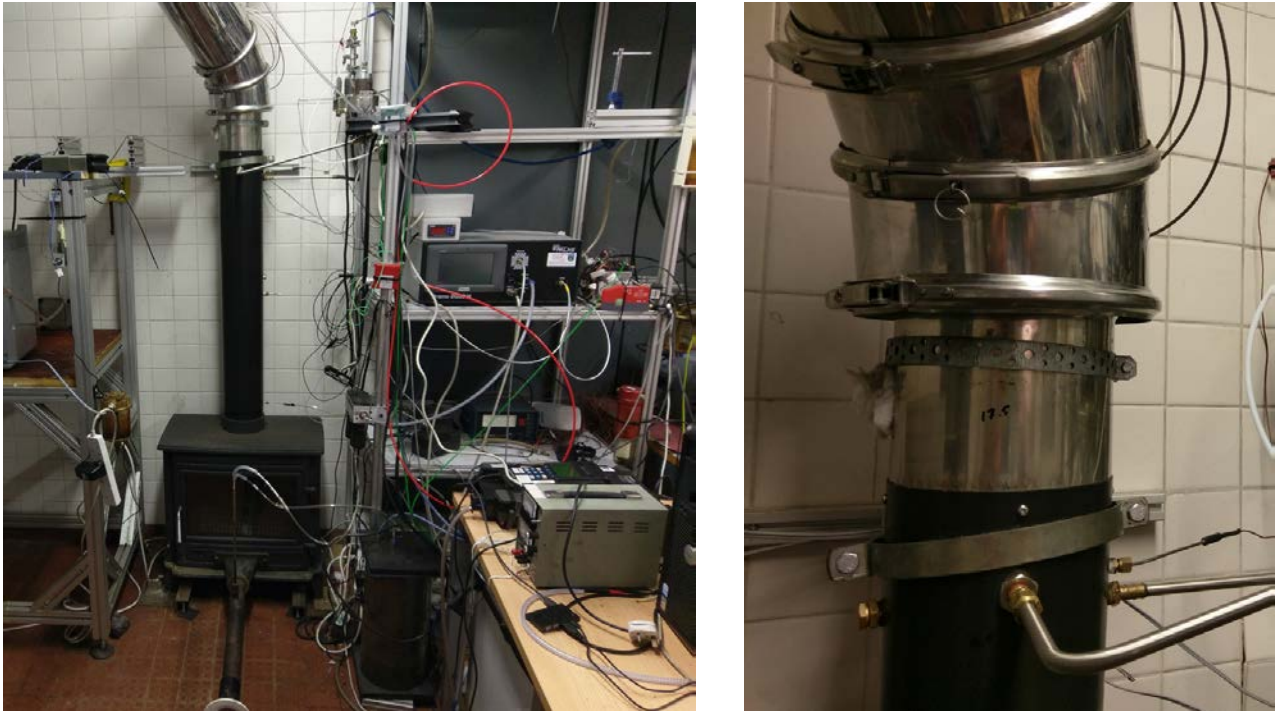


Figure 2.4. Overview of the stove test setup, showing the air inlet tube and stands for measurement equipment (left). A close-up view (right) of the connection between the exhaust flue and the laboratory extraction system (left). The sampling tubes for PM and gaseous emissions, and a thermocouple, are also visible in this image.

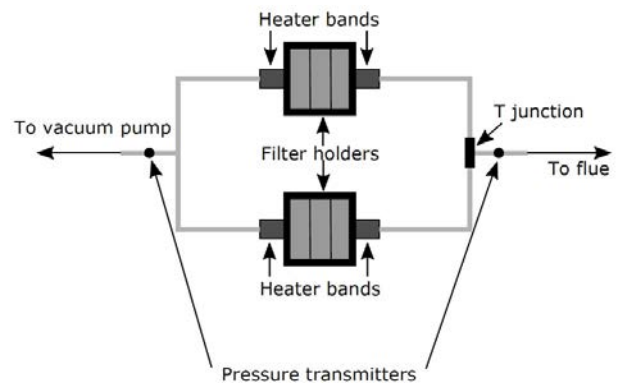


Figure 2.5. Photograph (left) and schematic (right) of the twin PM filter holder arrangement. The insulating blanket that encloses the filter housing during operation has been removed for clarity.

of each test and through filter housing “B” for the remaining 3.5 hours of the PM sampling.

As noted previously, each filter housing contains two filters in series: a relatively free-flowing pre-filter, followed by a high-efficiency filter. The filter holder is held in place using a clamp arrangement, with high-temperature O-rings maintaining the seal. There are also high-temperature O-rings within the filter holder, where it fits together, again to prevent leaks (Figure 2.6).

The details of the two filters are as follows:

1. pre-filter: Merck Millipore glass fibre filter without binder, APFD09050, pore size $2.7\ \mu\text{m}$;
2. high-efficiency filter: Pallflex borosilicate glass microfibre and woven glass cloth, Emfab TX40H120-WW, with a retention rate of 99.95%.

The first filter (i.e. the pre-filter) traps the majority of PM mass in the sample and prevents the high-efficiency filter from becoming blocked. The filter



Figure 2.6. The parallel filter housings, opened to reveal the internal configuration and clamping arrangement. The valve on the left determines which housing the sample will pass through.

holders were maintained at a temperature of 120°C, using copper heater bands and a temperature controller, to prevent condensation on the filters.

As PM accumulates on the filters, the filter pores become occluded; filter permeability is reduced and the pressure drop across the filter housing increases (as noted above). Without intervention, this would lead to a reduction in mass flow through the filters, making it difficult to determine the total mass of sample that was filtered during a test. A mass flow controller (MFC; Vögtlin Red-y Smart GSC-C9TA-BB12) was therefore used to maintain a constant sample flow rate throughout each test. The instantaneous flow rate is reported by the MFC five times per second and transferred to the data acquisition system. A very accurate estimate of the total flow sampled through the filters is therefore available at the end of the test.

To protect the delicate MFC and the vacuum pump, once the PM sample had been filtered it was cooled (by passing through a small fridge) to encourage condensation of water and VOCs. It was then drawn through a condensate trap and desiccant tube, before entering the MFC. The condensate collected in the trap was dark in colour and smelled pungently of organics (see Figure 2.7). No further analysis was performed on the condensate.

2.3.4 Gaseous emissions sampling equipment

The composition of the flue gas was measured using a Testo 350 XL gas analyser unit (Figure 2.8; details



Figure 2.7. A sample of the pungent condensate collected downstream of the PM sampling filters. Source: Comerford (2014).

in Appendix 2). A sample of the raw exhaust gas was drawn from a sampling port 95 cm above the top surface of the stove. The volume concentrations of O₂, CO₂, CO and NO_x were measured and logged at 10-second intervals. The manufacturers report an accuracy of ±6% for CO and NO_x measurements. The gas analyser unit is fitted with a non-dispersive infrared radiation (NDIR) absorption CO₂ sensor, with an uncertainty of ±2% as per the manufacturer.

To protect the Testo from the high PM loadings present in the sample stream, a single filter holder – identical to those used in the PM sampling stream – was inserted in the sampling line upstream of the Testo. This filter was also maintained at 120°C, although the line leading to the filter was about 100 cm in length and unheated so some condensation is likely to have occurred upstream of the filter housing. This has no consequences for the gas species measurements, however; the filter housing was heated only to prevent clogging of the filters by condensation within the housing and the sole purpose of the filters was to prevent PM reaching the gas analyser. Following the filters, the gas sample passed through a condensate trap and then into the Testo analyser.

The Testo draws flue gas using its own internal pump, with feedback control designed to maintain a flow rate of ≈1 l min⁻¹. A built-in Peltier cooling unit removes any remaining moisture from the gas sample (gas



Figure 2.8. The Testo 350 XL gas analyser used to determine gaseous emissions for all fuels.

concentrations are therefore reported on a “dry” basis), with the condensate collected in a small reservoir on the side of the unit. The reservoir is easily detached for emptying as required.

Communication between the Testo analyser and the host PC was via an RS232 connection and was controlled via Testo easyEmission software running on the PC. In addition to enabling real-time display of emission concentrations, the software allows all gaseous emission data to be exported to Excel for subsequent processing.

2.3.5 Ancillary measurements

In addition to the PM and gaseous emissions, the following ancillary measurements were recorded:

- the mass of fuel in the basket (Tedea Huntleigh 1042 load cell);
- the temperature at the top of the flue and at the bottom of the flue, the ambient temperature and the temperature of one of the filter holders (k-type thermocouples);
- the inlet air flow rate (pitot tube and Huba Control 694 pressure transducer);

- the pressure differential between the top of the flue (120 cm above the top surface of the stove) and the ambient pressure in the laboratory (Huba Control 694 pressure transducer);
- the absolute pressures on either side of the filter holders in the PM sampling line.

Acquisition, display and recording of these signals were controlled using a custom-developed LabVIEW interface. Each signal was sampled at 1 kHz for a period of 10 seconds, and the average value of each signal during that period was then recorded.

2.4 Test Procedure

2.4.1 Preparatory work

The computer that manages the data acquisition was switched on and the relevant software loaded. Ash from the previous day’s test, if present, was photographed; its weight was then recorded using the load cell and data acquisition system and it was moved into a bag by shaking the fuel basket. Any remaining mass was classified as unburned solids. If present, it was photographed, weighed as before and removed for disposal. The stove internals were then vacuumed and the stove glass cleaned.

Using tweezers, pre-conditioned filter papers were carefully transferred from the desiccant chamber to the filter housings. The heating system for the housing was switched on and the heating controller was set to 120°C.

The laboratory extractor fan was then switched on. Using the data acquisition system, the load cell was zeroed with the fuel basket and tray in position in the stove. The offset required to zero the load cell was noted, so that the corresponding correction could be applied to the recorded mass of ash and unburned solids.

The required quantities of test fuel, firelighters and, in the case of sod peat, kindling were weighed out. The fuel and firelighters were then arranged in the basket and the arrangement photographed (see Appendix 4 for a more detailed discussion of the fuel arrangement procedure).

Finally, the Testo gas analyser was switched to sampling mode.

2.4.2 Conducting the test – all fuels except sod peat

Once all preparations were complete, recording of data commenced. The firelighters were lit using a match and the stove door closed. The vacuum pump on the PM sampling line was switched on, the flow rate was confirmed as 3.5 g min^{-1} (controlled by the MFC) and the start time was noted. The ignition phase of the test was then photographed and the pressure drop across the stove was confirmed as 12 Pa – the butterfly valve in the exhaust duct was adjusted if necessary.

All test parameters (except PM filter mass) were recorded automatically at 10-second intervals through to the end of the test. As noted previously, the end of the test was defined as the point where the rate of mass loss from the fuel was asymptotically approaching zero, which typically corresponds to a mass loss rate of about 1 g min^{-1} . Photographs of the fire bed were taken during the ignition, flaming, smouldering and burnout phases of each test.

2.4.3 Conducting the test – sod peat

Once all preparations were complete, the firelighters and kindling of the ignition charge were ignited with a match and the stove door closed. Combustion of the kindling always progressed rapidly, with the flue gas temperature typically reaching 300°C within 8–12 minutes. At this point the ignition charge is sufficient to ensure combustion of sod peat. The stove door was opened, the pre-weighed test charge of sod peat was added to the fire using fire tongs and the door was closed. The vacuum pump on the PM sampling line was switched on, the flow rate was confirmed as 3.5 g min^{-1} (controlled by the MFC) and the start time was noted. This corresponds to the official start time of the test: all emissions and performance metrics are based on data gathered once the sod peat has been added to the fire.

The ignition phase of the test was then photographed and the pressure drop across the stove confirmed as 12 Pa – the butterfly valve in the exhaust duct was adjusted if necessary. The remainder of the test was performed as for all other fuels, except that two filter pairs were used (rather than one) to determine PM emissions for all tests with sod peat (see section 2.4.4).

2.4.4 Determination of PM mass

The PM mass was determined by measuring the change in weight of filter papers before and after a combustion test. To ensure consistency, filter papers were thermally treated prior to, and after, the test. The procedure was as follows:

- The filters were placed in an oven at 160°C for at least 1 hour, then transferred to a desiccant chamber at ambient temperature for at least 8 hours – typically overnight.
- Prior to commencing a test, the mass of each was determined using a precision, high-resolution (0.0001-g resolution) mass balance. Each filter was weighed five times and the individual values were recorded in a spreadsheet. The average of the recorded values was taken to be the initial filter mass.
- The filters were then transferred to a filter housing, which was sealed and then heated to 120°C prior to the start of a test.
- For all fuels other than sod peat, a sample of flue gas was usually drawn through only one of the filter holders. However, if the pressure drop across that filter housing became excessive – about 0.3 bar or more – sample flow was diverted through the second (parallel) filter pair.
- For tests with sod peat, both filter holders were used. Flue gas was sampled through filter pair “A” for the 30 minutes immediately following the addition of sod peat to the fire. After that time, the flow was diverted through filter pair “B” for a further 3.5 hours.
- With all fuels, PM sampling was stopped after 4 hours. This provided time (about 1 hour) for the filter housing to cool sufficiently for the filters to be safely removed. Compressed air was then used to blow any residual PM from the sampling line onto the filters.
- The filters were transferred to the oven at 160°C for 1 hour, before being placed in a desiccant chamber overnight.
- The following day, the mass of each filter was determined and recorded as before, and the average value recorded for each filter was taken to be the final filter mass.
- The difference between the initial and final mass of each filter was taken to be the mass of PM collected during that test.

- Each filter was then stored in a separate, clear plastic, ziplocked bag, with the date, filter type and fuel written clearly on the outside of the bag. A photograph was then taken of each bag, ensuring the bag label could be seen (see Figure 2.9 for an example).

Once the mass of PM collected on the filters has been determined, it is divided by the total mass flow through the filters during the PM sampling period – a measurement provided by the MFC – to determine the mass of PM collected per unit mass of flue gas filtered. The total mass of PM emitted during the sampling period is then determined as the product of PM mass per unit mass of flue gas and total mass of flue gas during the sampling period. The latter is equal to the sum of air mass and fuel mass consumed during the PM sampling period.

2.5 Arrangement of Fuel in the Stove

The goals, when arranging the fuel in the stove, were twofold: first, to enable the fuel to ignite and burn as cleanly and efficiently as possible; second, to provide consistency of initial conditions between tests. Some studies of biomass combustion have suggested that “top-down” ignition of the fuel minimises emissions

(Bäfver *et al.*, 2011; Nussbaumer, 2017), so this approach was used for all fuels in this study. A base layer of fuel was placed in the basket, firelighters were arranged in a consistent pattern on top and the remaining fuel was placed around and above the firelighters.

Consistency of stacking varied from fuel to fuel, depending on the size and shape of the fuel elements. Peat briquettes and smokeless coal were easiest to arrange, being of relatively uniform size and shape, although a fuel element might need to be broken in order to remain close to the 3.5-kg load target. Achieving consistency with wood logs, or bituminous coal, is considerably more difficult, but a satisfactory arrangement was achieved for each test.

Sod peat presented an exception to the general approach outlined above. On account of its very poor ignition characteristics, satisfactory combustion could not be achieved using firelighters and a fundamentally different approach was required. An “ignition charge” comprising 100 g of firelighters and 500 g of kiln-dried kindling was placed in the stove and lit. Once the flue gas temperature at the stove exit had stabilised at about 300°C, the stove door was opened and the sod peat added to the fire. Sampling of emissions commenced once the stove door was closed again.



Figure 2.9. A PM filter pair from a test of smokeless coal, following determination of PM mass. As noted above, the bulk of PM mass accumulates on the coarse pre-filter (right). The dark specks surrounding the central disc are residual deposits from the sampling line. Compressed air is used to blow these deposits onto the filter at the end of each test.

3 Data Analysis

Analysis of measured data is a critical feature of the work carried out during this project. This chapter presents an outline of the method used to calculate each of the principal metrics calculated for each fuel or test. Where necessary, a more detailed description of the calculation process is provided in Appendix 1. A comprehensive description is also embedded in the Excel workbooks and Python code used to process the measurements.

3.1 Calculation of Emission Factors

Emission factors constitute a primary output from this project. In general, an EF is defined as:

$$EF_i = \frac{\text{mass of pollutant}_i \text{ emitted}}{\text{energy consumed}} \quad (3.1)$$

It is usually expressed in units of g GJ⁻¹, or the numerically equivalent mg MJ⁻¹; the former is used throughout this report.

To calculate the EFs for a particular fuel, during a particular test, we need to know the total mass of pollutant emitted and the quantity of energy consumed. The first is determined by measuring the mass or concentration of pollutant in a sample of the flue gas and scaling appropriately to the full exhaust flow. Given the unsteady nature of the combustion process, and the presence of moisture in the raw fuel, estimating the mass of gaseous pollutant is not straightforward. It is derived from an estimate of the instantaneous combustion rate (outlined in section 3.2) as follows:

1. The total mass of gas i emitted during a test is obtained by integrating the value computed for each 10-second measurement interval, from the beginning ($t=0$) to the end of the test ($t=eot$).

$$m_i = \int_0^{eot} \dot{m}_i dt \quad (3.2)$$

2. The mass flow rate of gas i during each 10-second interval is derived from the instantaneous combustion rate.

$$\dot{m}_i = \dot{m}_{fuel} \times A \quad (3.3)$$

$$A = N_{dry} \times [i] \times \frac{M_i}{M_{fuel}} \quad (3.4)$$

In these equations, m_i = mass of gas i emitted during the test; \dot{m}_i = mass flow rate of gas i during some 10-second interval (g s⁻¹); \dot{m}_{fuel} = oxidation rate of fuel during this 10-second interval (g s⁻¹); $[i]$ = molar concentration of gas i in the dry exhaust in this 10-second interval (mol mol⁻¹); N_{dry} = moles of dry exhaust products produced per mole of fuel oxidised; M_i = molar mass of gas i (g mol⁻¹); and M_{fuel} = molar mass of fuel (g mol⁻¹).

The calculation of PM EFs, on the other hand, is straightforward: the total mass of PM collected on the filters is scaled up to match the total exhaust flow and divided by the energy consumed during the test:

$$EF_{PM} = \frac{m_{PM} \times \left(\frac{\dot{m}_{exhaust}}{\dot{m}_{filter}} \right)}{\text{energy consumed}} \quad (3.5)$$

In the above equation, m_{PM} = mass of particulate collected on the filters (g), $\dot{m}_{exhaust}$ = mass flow rate of exhaust gases from stove (g s⁻¹) and \dot{m}_{filter} = mass flow rate of exhaust gases through filters (g s⁻¹). Quantifying the amount of energy consumed is a simple task, but the energy being considered should be clearly defined. There are essentially the following three options:

1. The energy contained in the test fuel only (EF_{TFO} in this report). All measured emissions are attributed to the test fuel: emissions (and energy content) of firelighters are assumed to be negligibly small or the EF of the firelighters is assumed to be zero.
2. The total energy loaded in the stove (EF_{TEL} in this report). The measured emissions are attributed equally to the test fuel and to the firelighters based on their energy content. Essentially, the EF of the firelighters is assumed to be equal to the EF of the test fuel.
3. The energy delivered to the room (EF_{ETR} in this report). This interpretation accounts for the efficiency of the stove as well as the emission intensity of the fuel. The demand for heat is taken to be the ultimate source of the pollutant

emissions and therefore the determinant of how much fuel will be consumed.

The EFs are particularly useful when compiling national emission inventories, because they enable the (usually unknown) mass of a particular pollutant emitted to be estimated from the (usually known) quantity of fuel consumed. In that context, either EF_{TFO} or EF_{TEL} could be used. If consumption data for firelighters are available, then the use of EF_{TEL} is entirely defensible; if not, it will result in some underestimation of the true emissions from this source. Since the consumption of these fuels in Ireland almost always implies the use of firelighters, it is simpler to estimate national emissions based on EF_{TFO} and consumption of the test fuels only.

Notwithstanding the beguiling simplicity of the EFs as a weapon in the statistician's armoury, caution should be exercised in its application – particularly in the case of solid fuels. Depending on the pollutant concerned, the emission rate can vary by a factor of 10 or more across the various phases of the combustion process. An EF based on a single operating point (as is frequently the case) may not, therefore, provide a representative estimate of emissions from that source. Moreover, the emissions from a particular solid fuel will depend on the nature and installation of the appliance, on the skill of the operator and on the physical and chemical characteristics of the fuel elements being consumed. Not all “wood”, for instance, is of equal quality; the same caveat applies, to a smaller or greater extent, to all solid fuels of relevance to this study. Random variation in these factors is best accounted for by repeating each test sufficiently often that a statistical model of the true behaviour can be constructed.

The variability in each of these factors is reflected in the very broad range of EFs presented in the literature – the European Monitoring and Evaluation Programme (EMEP) guidebook, for instance, suggests a Tier 2 EF of 30–150 g GJ⁻¹ for NO_x, 400–1600 g GJ⁻¹ for the total suspended particulate and 1000–10,000 g GJ⁻¹ for CO for a wood-burning stove (EEA, 2016).

Obtaining a representative EF therefore requires the following three conditions to be fulfilled:

1. The fuel and appliance should be as close as possible to local practice.
2. Emissions should be determined over the full combustion cycle, with particular emphasis on the start-up.
3. Each test should be repeated until the confidence interval (CI) about the estimated EF is narrowed to an acceptable level.

It is also clear that the CI about the estimated EF is as important as the EF itself. A 95% CI is therefore computed for all EFs presented in this report.⁵ In addition to the mean EF and CI, the maximum, minimum and median of the values observed during the test programme are also presented, as shown in Figure 3.1.

3.2 Calculation of Stove Efficiency and Effectiveness

Stove efficiency is typically calculated using the loss method. The thermal energy in the fuel is known; thermal energy in the gas exiting the flue is assumed to be lost; the remainder is assumed to be delivered as useful heat to the room. Sometimes an adjustment is made for combustion efficiency and for unburnt fuel remaining in the grate. Using this approach:

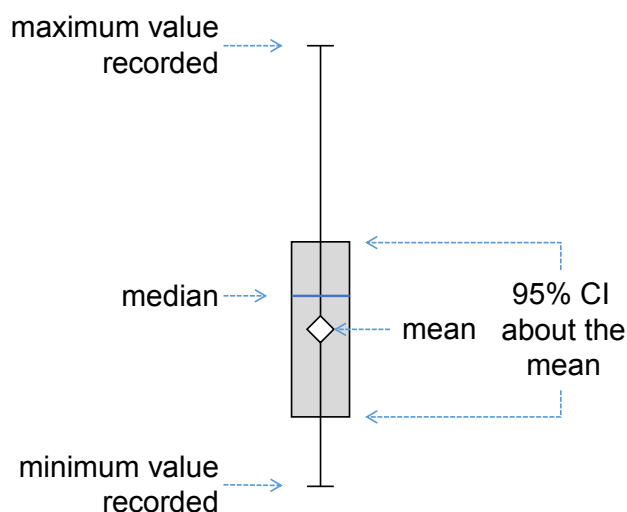


Figure 3.1. Representation of statistical properties of an estimated parameter, such as an EF, in this report.

⁵ The 95% CI is expected to bracket the true population EF in approximately 95% of cases.

$$\eta_{\text{stove}} = 1 - \frac{\text{losses}}{\text{LCV}} \quad (3.6)$$

where LCV denotes the lower calorific value of the fuel.

Although useful, this method overestimates the true efficiency, because it assumes that the full calorific energy of the fuel is released during combustion. However, as is evident from the presence of CO and other products of incomplete combustion in the flue gas, the full calorific energy of the fuel is not released, and so the denominator in equation 3.6 should be smaller than assumed here.

The availability of time-resolved combustion rate information, as discussed below, allows a more accurate estimate of stove efficiency to be obtained by enabling detailed tracking of energy flows at 10-second intervals. The calculation method used in this project is outlined in equation 3.7:

$$\eta_{\text{stove}} = \frac{E_{\text{released}} - E_{\text{flue}}}{E_{\text{consumed}}} = \left(\frac{E_{\text{oxidised}}}{E_{\text{consumed}}} \times \frac{E_{\text{released}}}{E_{\text{oxidised}}} \right) - \frac{E_{\text{flue}}}{E_{\text{consumed}}} \quad (3.7)$$

E_{consumed} = the calorific value of the mass of fuel consumed during the test. This is less than the total energy loaded, as some residual combustion continues after the official end of test time. E_{oxidised} = the calorific value of the mass of fuel oxidised during the test. This may be less than E_{consumed} as a result of the emission of “volatiles”. E_{released} = the actual energy released from the mass of fuel oxidised during the test. This is less than the calorific value because of incomplete combustion. E_{flue} = thermal energy lost in the gas exiting the flue during the test.

A stove effectiveness (η^*) can also be calculated, to account for any unburned solids found in the grate the following day, i.e. once the combustion is completely extinguished:

$$\eta_{\text{stove}}^* = \eta_{\text{stove}} \times \left(1 - \frac{E_{\text{unburned}}}{E_{\text{loaded}}} \right) \quad (3.8)$$

3.3 Determination of Time-resolved Combustion Rate

The emission intensity of solid fuels is intimately connected to the quality of the combustion process, which in turn is related to the rate of combustion. Knowledge of the time-resolved combustion rate therefore offers valuable insight into the factors that determine emission intensity.

Estimates of the combustion rate are usually based on a measurement of fuel consumption rate, i.e. the rate of decrease of fuel mass. Although this approach has some merits, such estimates cannot distinguish between combustion and moisture boil-off, and generally suffer from relatively poor resolution of mass loss rate.

The method adopted in this project relies instead on the measurement of the inlet air flow rate and on the measured concentration of exhaust gases. An outline of the method is as follows.

- The air:fuel ratio (AFR) of the combustion process – at each 10-second measurement interval – is inferred by combining the measured concentration of exhaust gas constituents with an assumed chemical composition of the fuel.⁶ (For a detailed description of this calculation, see section A1.2.)
- The air flow rate at each interval is obtained from a smoothed fit to measured data.
- The fuel combustion rate, and the mass flow rate of dry combustion products, can then be calculated knowing the AFR and the air mass flow rate.
- The mass flow rate of carbon is inferred from the mass flow rate of dry combustion products and measured concentrations of CO₂, CO and (if available) unburned hydrocarbons (UHCs).
- The rate of heat release is calculated from the mass flow rate of carbon, the assumed fuel composition and the enthalpy of formation of the combustion products.

A schematic outline of the logic flow used in the calculation is presented in Figure 3.2.

⁶ The overall chemical composition of the bulk fuel was determined from an ultimate analysis carried out by ESG. The assumption here is that the overall composition of the unburned fuel remains unchanged throughout the combustion process. In practice, lighter, hydrogen-rich elements of the fuel may be consumed preferentially during the early stages of combustion, so that the unburned fuel becomes increasingly carbon rich as the test proceeds. Since empirical data were not available to confirm, or quantify the significance of, this effect, a constant fuel composition has been assumed.

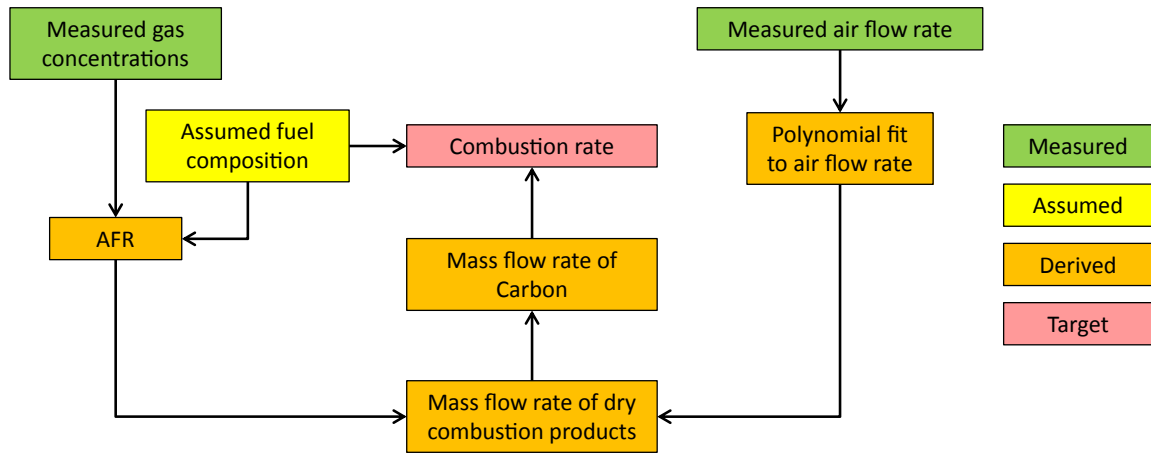


Figure 3.2. A schematic outline of the logic flow used to determine the time-resolved combustion rate.

This method has the advantage of providing an estimate of fuel combustion rate that is independent of the fuel mass measurement. It therefore offers the potential to distinguish between moisture boil-off and combustion. This distinction is discussed further in section 4.5.

3.4 Calculation of Time-resolved Emission Rate

Once the mass flow rate of dry combustion products is known at each 10-second interval, the time-resolved

flow emission rate of gaseous emissions is easily determined from the measured concentration of each gas in the exhaust products, as follows:

$$\dot{m}_i = \left(\dot{m}_{fuel} \right)_{gas\ analysis} \times \frac{m_i}{m_{fuel}} \quad (3.9)$$

The calculation of $\frac{m_i}{m_{fuel}}$ is detailed in Appendix 1.

As noted previously, time-resolved emission rate estimates are available for gaseous emissions only.

4 Results

Each combustion test yielded tens of thousands of raw data elements and hundreds of thousands of calculated results. Collapsing such substantial volumes of data into meaningful, easily comprehensible information represented a significant challenge. For the purposes of this report, the results are grouped in two broad categories:

1. High-level, statistical measures of performance associated with a particular fuel, such as EFs. These constitute the primary output of the project and are presented first.
2. Time-resolved parameters associated with a single test or group of tests. An example of these is the time-resolved emission rate.

4.1 Presentation of High-level, Statistical Data

High-level metrics – such as EFs – that incorporate statistical data from a number of tests are presented using box plots of the type shown in Figures 3.1 and 4.1. As an aide-memoire, the colour of a box reflects the fuel to which it refers: peat is brown, coals are black or grey, dry wood is green and wet wood is blue.

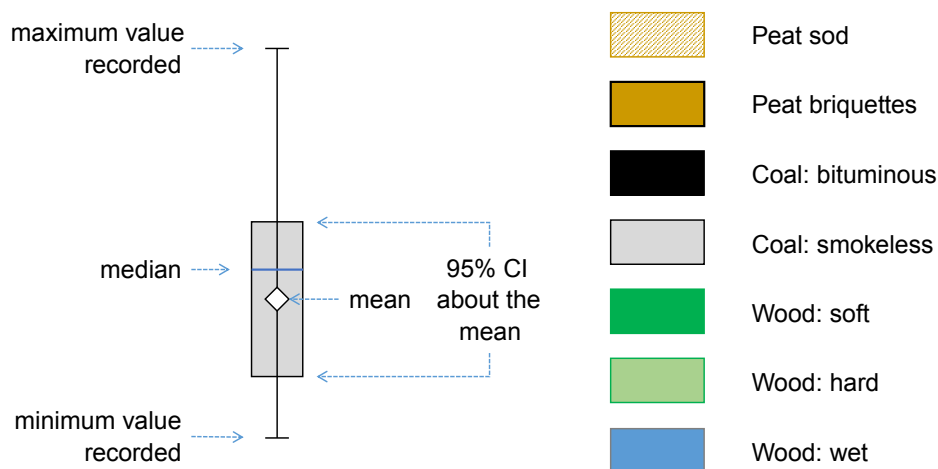


Figure 4.1. Each marker summarises the statistical properties of an estimated parameter, such as an EF. The colour of the shaded area denotes the fuel to which the estimate applies.

The same colour coding is used when presenting overall data from individual tests (e.g. Figure 4.4) and where time-resolved data are being compared for different fuels (e.g. see Figure 4.18).

Unfortunately, when time-resolved data are compared across tests of a single fuel, this system falls down, as colours are used to distinguish the individual tests from one another. Nonetheless, it is hoped that the colour coding system described previously will help to clarify rather than confuse.

4.2 Emission Factors of Primary Pollutants – NO_x

The NO_x EFs are presented in Figure 4.2 and Table 4.1. Table 4.1 also includes Tier 2-recommended values from the EMEP/European Environment Agency (EEA) *Air Pollutant Emission Inventory Guidebook 2016*, for reference (Trozzi, 2017). All values are presented in units of g of pollutant emitted per GJ of energy in the test fuel (LCV). Only the energy in the test fuel is considered; the energy content of the firelighters is ignored. These EFs therefore correspond to EF_{TFO}, as previously described in section 3.1.

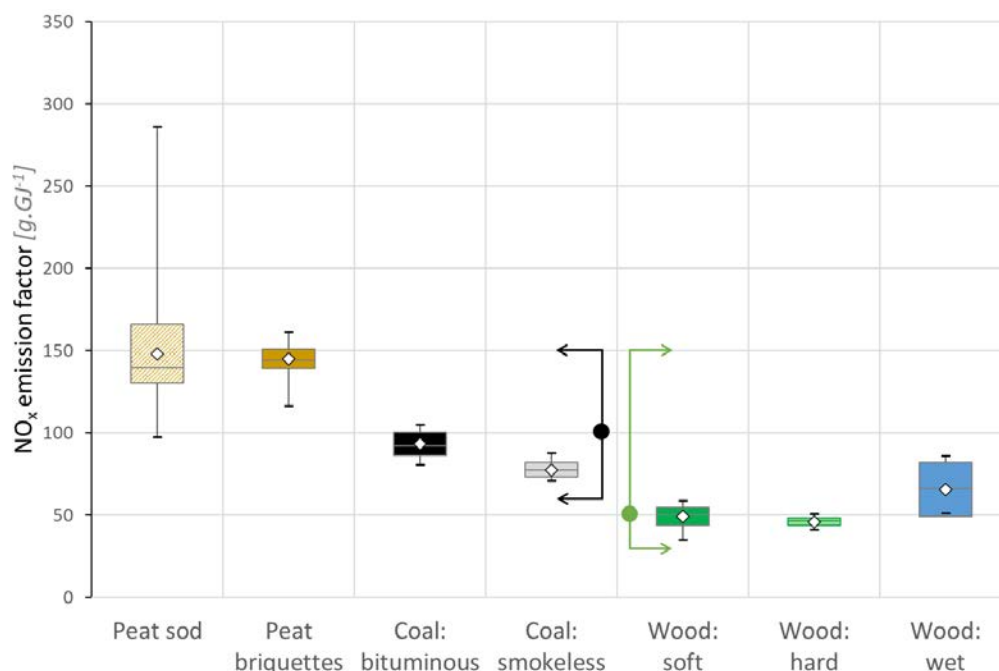


Figure 4.2. NO_x emission factors determined in this project for each of the fuels tested. Also shown are the range of Tier 2 values suggested for wood (green arrows, right) and for other solid fuels (black arrows, left) in the EMEP/EEA guidebook (Trozzi, 2017). The solid circles denote the EMEP/EEA-recommended value in each case.

Table 4.1. NO_x emission factors

	NO _x EFs (g GJ ⁻¹)						
	Peat sod	Peat briquettes	Coal: bituminous	Coal: smokeless	Wood: soft	Wood: hard	Wood: wet
Max.	286.2	161.4	105.0	87.7	58.9	50.7	86.1
Min.	97.4	116.3	80.7	70.9	34.8	41.1	51.5
NO _x EF	148	145	93	78	49	46	66
Median	140	144	92	77	50	47	66
NO _x 95% CI (±)	18 (12.1%)	6 (4.1%)	7 (7.7%)	4 (5.5%)	6 (11.3%)	2 (5.2%)	16 (25.0%)
EMEP	100 (60–150) ^a				50 (30–150) ^b		

Note: the shading indicates the parameter of interest. EFs are based on test fuel energy only.

^aTrozzi (2017), EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016, Table 3.14. The number in parentheses expresses that absolute value as a percentage of the mean emission factor.

^bTrozzi (2017), EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016, Table 3.40. The number in parentheses expresses that absolute value as a percentage of the mean emission factor.

A number of broad conclusions can be drawn from an examination of Figure 4.2 and Table 4.1.

- Three broad levels of NO_x emissions can be discerned:

(a) Peat-based fuels are highest, at ~150 g GJ⁻¹.

(b) Coal-like fuels are next, at ~80–90 g GJ⁻¹.

(c) Dry wood is lowest, at ~50 g GJ⁻¹.

This broad categorisation suggests that NO_x emissions from peat-based fuels appear to be ~50% higher than from coal-like fuels and three times higher than from dry wood.

2. The NO_x emissions from the “wet” wood tests are about 50% higher than from dry wood. However, given the limited number of tests with this fuel, and the caveats surrounding the representativeness of the wetting technique employed, these results should be treated with caution.
3. The 95% CIs are encouragingly narrow for most fuels; sod peat and wet wood are exceptions. It should be noted that the wide CI associated with the EF for wet wood is in large part a result of the limited number of tests carried out with this fuel; from a statistical perspective, this reduces confidence in the estimate of the mean.
4. The spread between the minimum and maximum values observed for the peat-based fuels – and especially for sod peat – is high; this is despite making every effort to replicate combustion conditions from test to test. It is probable, therefore, that the scatter observed in the laboratory tests reflects a high degree of variability inherent in the fuel and/or a high sensitivity to the details of the combustion process.
5. The NO_x EFs determined in this project for dry wood logs are very close to the corresponding guidance values in the EMEP/EEA guidebook (Trozzi, 2017). Those for the remaining fuels straddle the value suggested for “Solid fuel (not biomass)” and, with the exception of some tests using peat fuels, lie within the range of values suggested.

4.3 Emission Factors of Primary Pollutants – PM

The PM EFs obtained in this project are presented in Figure 4.3 and Table 4.2. As previously, Table 4.2 also includes Tier 2-recommended values from the EMEP/EEA *Air Pollutant Emission Inventory Guidebook 2016*, for reference (Trozzi, 2017). All values are presented in units of g GJ^{-1} (LCV, test fuel only – EF_{TFO}).

As before, a number of broad conclusions can be drawn from an examination of Figure 4.3 and Table 4.2:

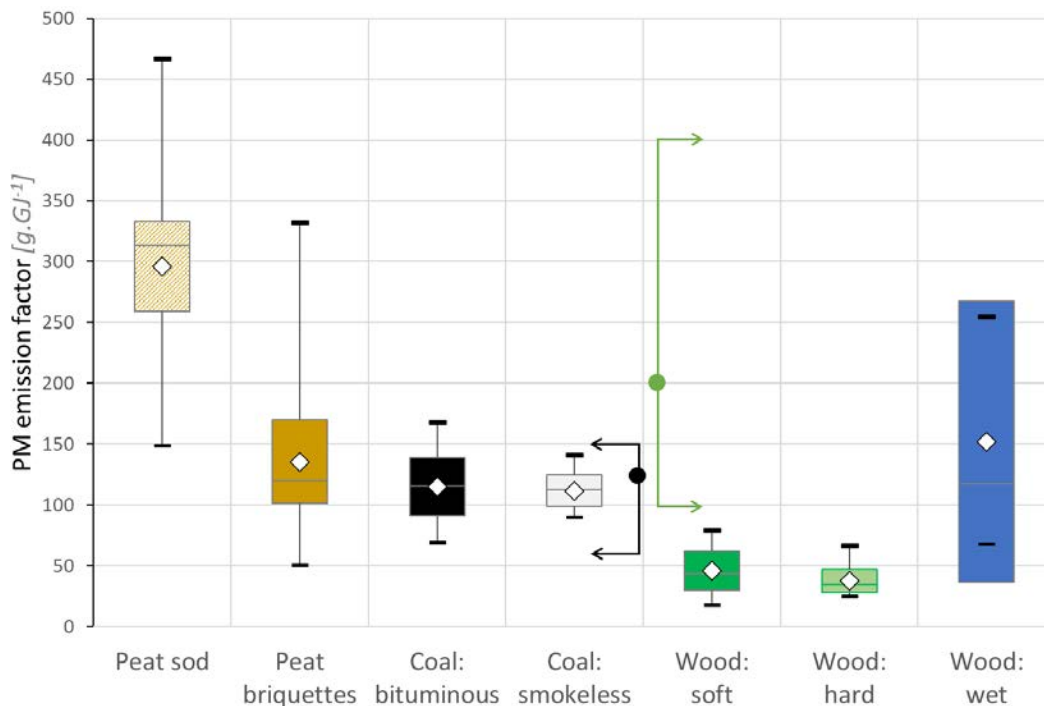


Figure 4.3. PM emission factors determined in this project for each of the fuels tested. Also shown are the range of Tier 2 values suggested for wood (green arrows, right) and for other solid fuels (black arrows, left) in the EMEP/EEA guidebook (Trozzi, 2017). The solid circles denote the EMEP/EEA-recommended value in each case.

Table 4.2. PM emission factors

	PM EFs (g GJ ⁻¹)						
	Peat sod	Peat briquettes	Coal: bituminous	Coal: smokeless	Wood: soft	Wood: hard	Wood: wet
Max.	467	333	168	141	79	67	255
Min.	149	51	69	90	18	25	68
PM EF	296	135	115	112	46	38	152
Median	313	120	115	113	44	35	118
PM 95% CI (±)	37 (12.5%)	34 (25.3%)	24 (20.9%)	13 (11.7%)	16 (35.3%)	9 (25.1%)	115 (76.1%)
EMEP (SP)	500 (240–600) ^a				760 (380–1520) ^b		200 (100–400) ^c

Note: EFs are based on test fuel energy only.

^aEMEP/EEA Air Pollutant Emission Inventory Guidebook 2016, Table 3.14. No value is given in this table for solid particle emissions, which constitute the bulk of the PM trapped on a hot filter. As noted in the guidebook and in the literature, PM mass from biomass combustion typically increases by a factor of 3–10 following dilution in air. Although equivalent data are not available for these fuels, applying a factor of 4 would suggest that an SP value of about 125 g GJ⁻¹ (60–150 g GJ⁻¹) for these fuels may be appropriate.

^bTrozzi (2017), EMEP/EEA air pollutant emission inventory guidebook 2016, Table 3.40: total aerosol formed after dilution.

^cTrozzi (2017), EMEP/EEA air pollutant emission inventory guidebook 2016, Table 3.40: solid particles only.

SP, solid particle.

- Three broad levels of PM emissions can be discerned:
 - Sod peat is highest, at ~300 g GJ⁻¹.
 - Peat briquettes, bituminous coal and “smokeless” coal are next; surprisingly, all produce similar levels of PM at ~125 g GJ⁻¹.
 - Dry wood is lowest, at ~50 g GJ⁻¹.
- Despite their classification as “smokeless” fuels, when tested over a full cycle (including ignition), both peat briquettes and smokeless nuggets exhibited a level of PM emissions similar to bituminous coal.
- The PM emissions from sod peat are six times higher than from dry wood and more than twice as high as from bituminous coal.
- The PM emissions from the “wet” wood tests are about three times higher than from dry wood. Notwithstanding the caveats mentioned previously, this is a very substantial effect.
- The 95% CIs are acceptably narrow for all fuels except wet wood, although they are significantly broader for PM than they are for NO_x.
- The test-to-test variation, or scatter, is much higher for the peat-based fuels and the wet wood than it is for the remaining fuels. As noted with respect to NO_x emissions, this probably reflects a high degree of variability between fuel elements.
- The PM EFs observed for peat briquettes, bituminous coal and smokeless nuggets are in line⁷ with the value suggested in the EMEP/EEA guidebook (Trozzi, 2017), whereas the PM EF observed for dry wood is substantially below, and for sod peat substantially above, the values suggested in the guidebook.

Figure 4.4 plots both EFs on a single chart. The colour associated with each data point reflects the fuel type, as before. An “ideal” fuel would be positioned in the bottom-left corner of the chart, exhibiting a low EF for both PM and NO_x; a fuel positioned near the top-right corner is highly undesirable.

⁷ EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016, Table 3.14. No value is given in this table for solid particle emissions – which constitute the bulk of the PM trapped on a hot filter. However, as noted in the guidebook and in the literature, PM mass from biomass combustion typically increases by a factor of 3–10 following dilution in air. Although equivalent data are not available for these fuels, applying a factor of 4 would suggest that an SP value of about 125 g GJ⁻¹ for these fuels may be appropriate, close to the measured values of 112–135 g GJ⁻¹.

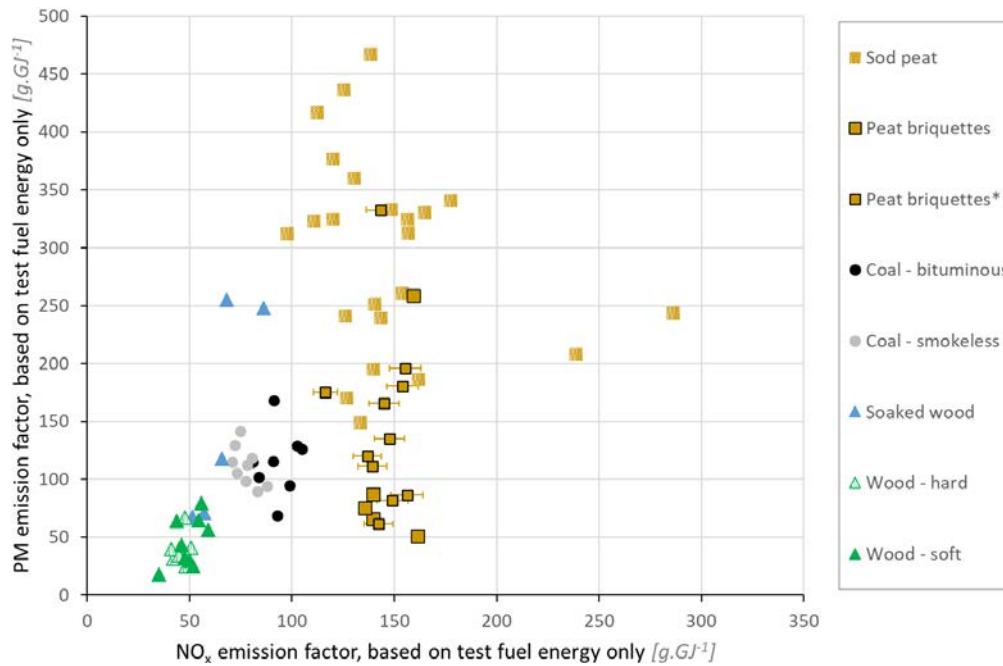


Figure 4.4. PM and NO_x emission factors observed in this project, by fuel type. Points labelled with an asterisk (i.e. peat briquette*) have a higher margin of error associated with the NO_x EF only.

Three broad groupings are easily discerned in Figure 4.4: (1) dry wood; (2) “wet” wood, bituminous coal and smokeless nuggets; and (3) peat-based fuels.

It is clear that dry wood generally outperforms the other fuels with respect to both NO_x and PM, but that emissions from “wet” wood are as high as – or higher than – those from bituminous coal. The quality – essentially the dryness – of the wood burned in a stove therefore exerts a very strong influence on the emissions generated.

The very high level of emissions, and enormous variation between tests, exhibited by sod peat is also evident. Although the reasons for such a large degree of scatter are unclear, the fact that significant scatter is also observed with peat briquettes suggests that it may reflect inherent heterogeneity in the chemical composition and/or physical characteristics of the peat itself.

In Figure 4.4, data points denoted “Peat briquettes*” have an error band associated with the NO_x EF. For those tests, a leak in the gaseous emissions sampling line was identified after the tests had been completed. It is possible to calculate a correction factor by referencing the CO₂ emissions to those of tests where no leak was present. This approach does introduce

additional uncertainty into the NO_x emission estimates, however (approximately 5%), and hence the error bands on these data points.

4.3.1 Contribution of firelighters to NO_x and PM emissions

Although emissions from firelighters were not a focus of this project, because they are used in all tests with each fuel, it is of interest to compare their emissions with those of the test fuels. Firelighters accounted for less than 3% of the mass loaded in each test and no more than 5% of the energy loaded; one might therefore assume that their contribution to total emissions would be small.

As Figures 4.5 and 4.6 show, however, the EF of firelighters is surprisingly high; the NO_x EF is almost four times higher than for dry wood, while the PM EF is a shocking 10–15 times higher. These EFs were obtained by burning the firelighters in isolation and may not reflect their true EF when surrounded by combustible fuel. Nonetheless, it does appear that firelighters could potentially make a significant contribution to total PM emissions when burning solid fuels and might be considered worthy of further study.

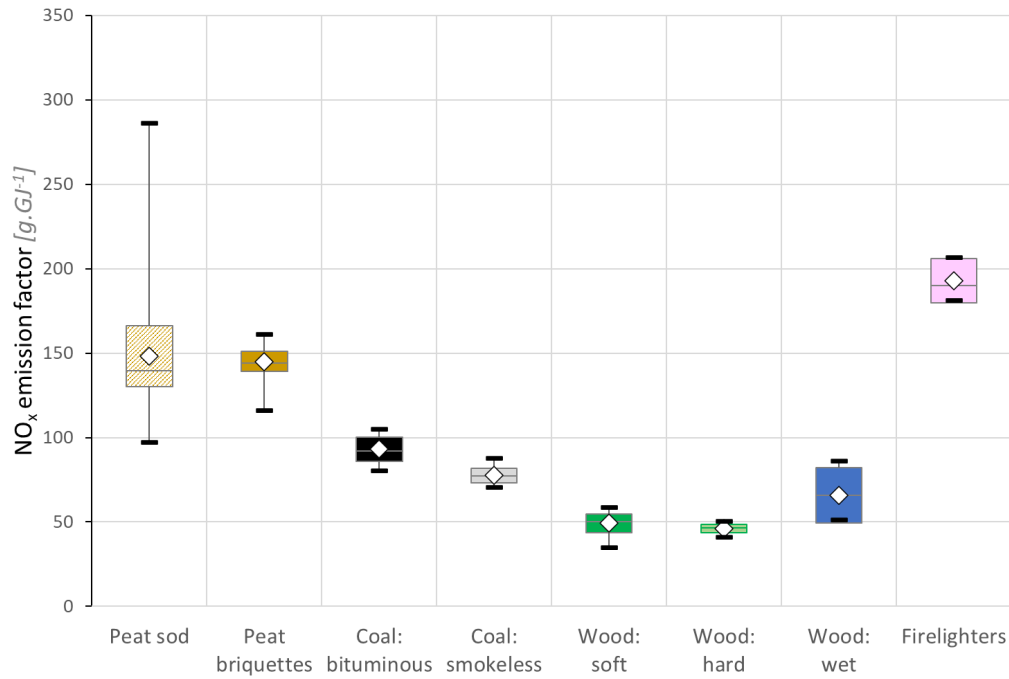


Figure 4.5. The NO_x emission factor of firelighters is higher than that of any fuel tested.

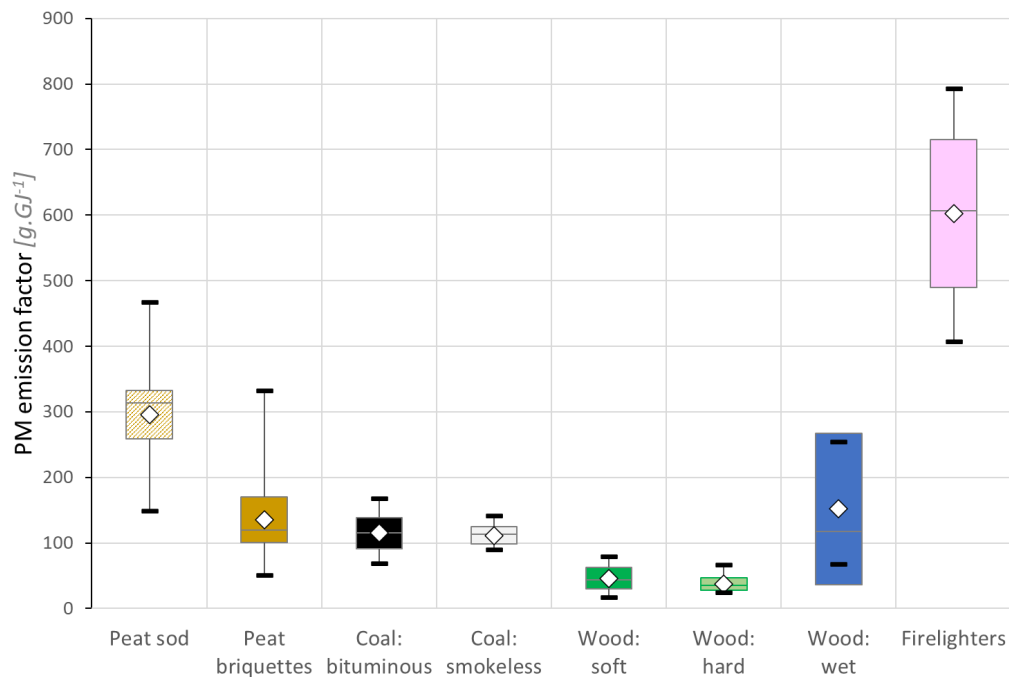


Figure 4.6. The PM emission factor of firelighters is twice as high as that of sod peat and 10 times higher than that of dry wood.

4.4 Secondary Emission Factors – CO and CO₂

In addition to NO_x, the Testo gas analyser recorded CO, CO₂ and O₂ concentrations in the exhaust gas at 10-second intervals. Although emissions of CO and

CO₂ were not expressly included in the deliverables for the project, it is of interest to examine them.

The CO EFs are presented in Figure 4.7. Absolute emission levels from all fuels are quite high, but they are in line with the EMEP/EEA guidebook values

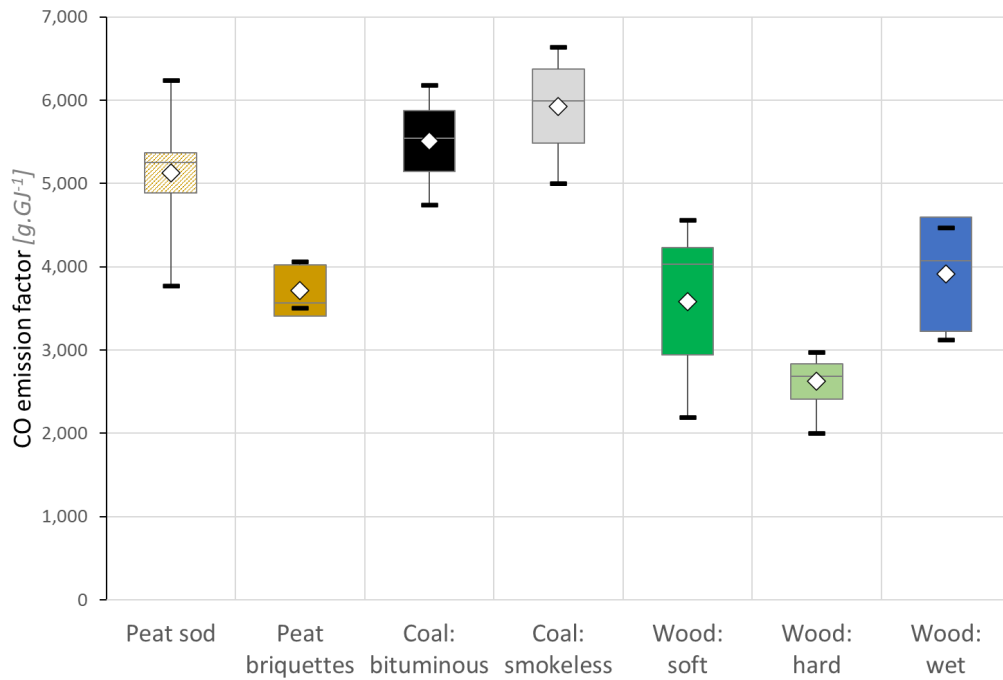


Figure 4.7. CO emission factors for all fuels tested.

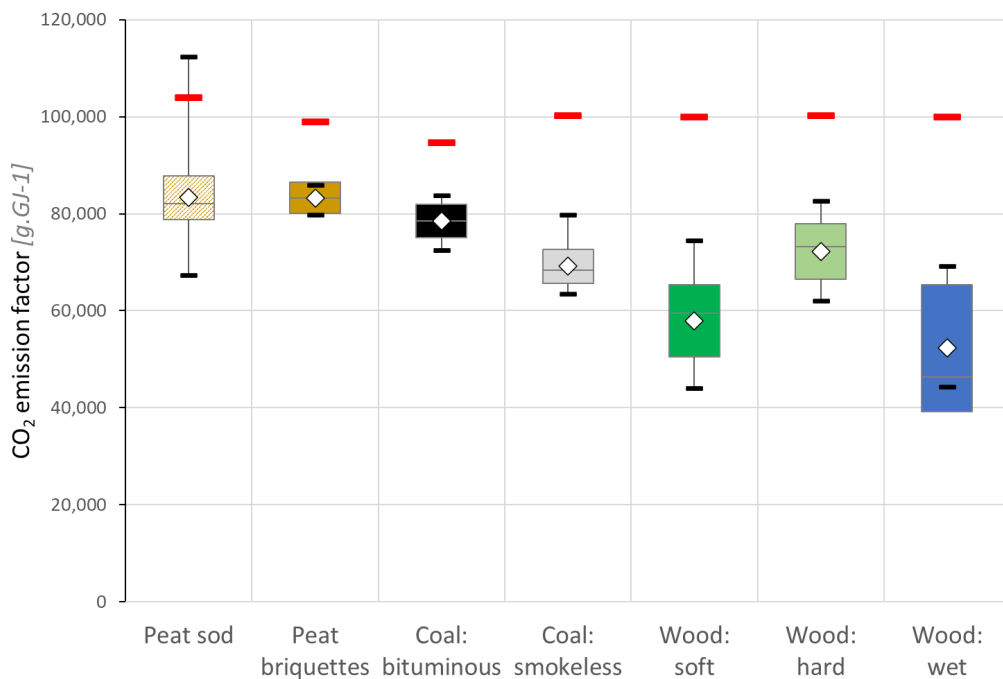


Figure 4.8. CO₂ emission factors for all fuels tested. The red horizontal bars denote the CO₂ EF associated with ideal combustion of each fuel, based on its chemical composition.

of 5000 g.GJ⁻¹ for solid fuels (not biomass) and 4000 g.GJ⁻¹ for biomass.

The CO₂ EFs are presented in Figure 4.8. In general, all fuels emit significantly less than the theoretical quantity of CO₂, shown as a red horizontal bar for

each fuel. This is to be expected, since all fuels emit some of their carbon as CO. The fact that, for some tests using sod peat, the CO₂ EF is higher than the maximum theoretical value might be interpreted as further evidence of the highly variable composition of this fuel.

4.5 Unexplained Emissions – “Volatiles”

As explained in Chapter 3 and in section A1.4, the unique analysis methodology developed during this project allows the fuel *combustion* rate to be distinguished from the fuel *consumption* rate. The cumulative difference between these two figures, over a complete combustion test, represents mass that has been lost from the fuel but has not oxidised. Some of this “lost” mass represents moisture that is bound to the fuel and evaporates during combustion. For all fuels, however, it was found that an additional quantity of “lost” mass could not be accounted for on this basis.

It appears probable that some volatile compounds may evaporate from the fuel during a test, but fail to oxidise before exiting the flue. Because the existing experimental rig lacked the equipment to confirm or reject this hypothesis, these emissions are referred to as “volatiles” throughout this report. However, the emissions appear to be real, as shown in Figure 4.9, and to vary consistently with fuel type.

It is well recognised in the literature that COCs are present in the exhaust from solid-fuel combustion systems. These COCs can lead to a substantial increase in the mass of PM emissions determined in a dilution tunnel, relative to those measured using a hot

filter method, as in this study. Combustion tests using wood and peat briquettes, during an earlier phase of the experimental programme, observed significant accumulations of COCs in a liquid trap associated with the PM sampling line, as shown in Figure 4.10.

Nonetheless, the absolute level of “volatile” emissions observed in this test programme is disconcertingly high – particularly for wood. For wood, at least some of the “volatile” emissions may be due to higher moisture content than reported in the samples sent for analysis, since the logs tend to equilibrate with the surrounding atmosphere. It is very unlikely that the majority of the observed effect is because of this, however.

4.6 Calculated Stove Efficiencies

As discussed in section 3.2, a value for both the stove efficiency and the stove effectiveness is calculated for each test; efficiency quantifies the fraction of the heat available from the fuel consumed during the test period that is transmitted to the room and effectiveness quantifies the fraction of heat available from the fuel loaded into the stove that is transmitted to the room.

As can be seen from Figure 4.11, stove efficiency ranges from about 35% (wet wood) to 60% (bituminous coal). The low efficiency values recorded for wood and smokeless coal are, in large part, a



Figure 4.9. “Volatiles” emission factors.

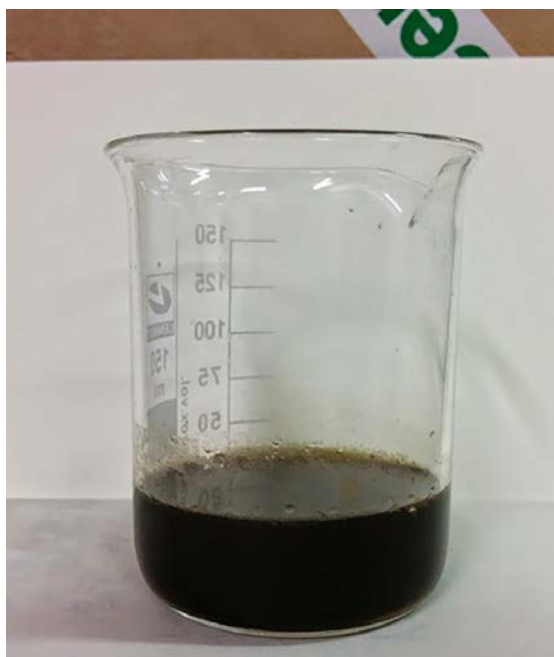


Figure 4.10. Liquid captured downstream of the PM filter in a PM sample train, following combustion tests using peat briquettes and wood. The PM sampling train employed for the tests differed in detail from that employed for tests presented in this report, but the same combustion configuration and test protocol were used. Source: Comerford (2014).



Figure 4.11. Stove efficiency, for each of the fuels tested.

consequence of the high “volatiles” EF associated with these fuels. Analysis of the combustion data suggests that a significant fraction of the combustible material in these fuels is not being oxidised prior to leaving the stove.

Figure 4.12 plots the corresponding values for stove effectiveness. For most fuels, efficiency and effectiveness exhibit very similar values; bituminous coal is the exception because of the presence of unburned solids in the ash. Thus, on the basis of

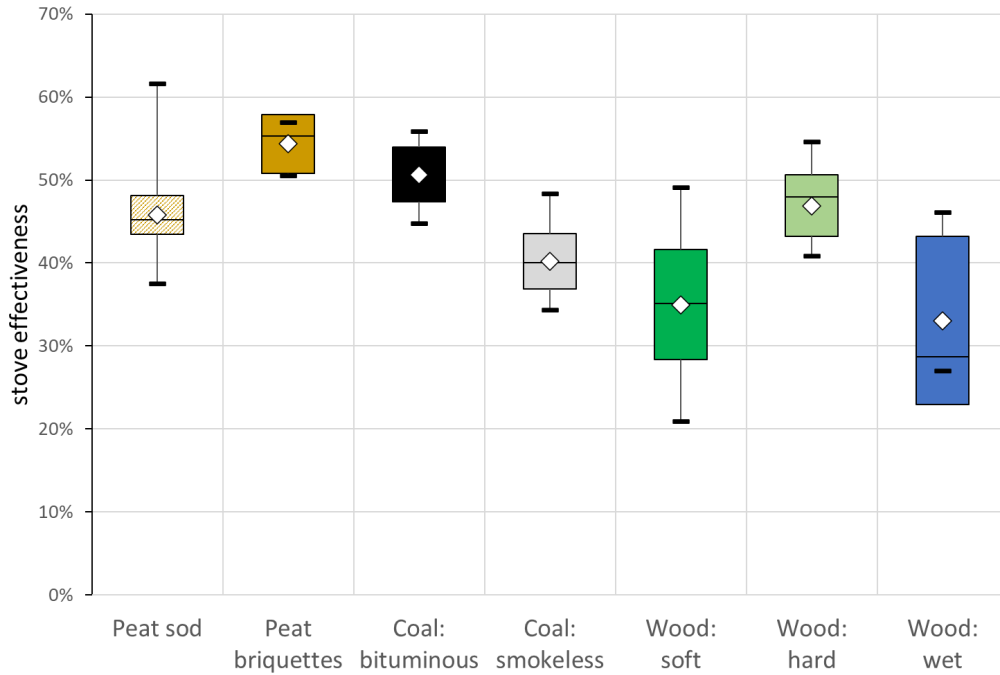


Figure 4.12. Stove effectiveness, for each of the fuels tested.

these calculations, peat briquettes transfer the largest fraction of the available heat to the room.

4.7 Emission Factors – Per Unit of Heat Delivered by the Stove

Emission factors are used mainly in the preparation of national emission inventories. In that context, it is useful to relate emissions to the quantity (or energy content) of fuel sold; all EFs presented thus far have been calculated on that basis. From a consumer's perspective, however, the fuel is consumed in order to deliver heat to a room and emissions are generated as a consequence of that desire. It is of interest, therefore, to compare the relative emissions associated with delivering a unit of room heating for each of the fuels tested. These EFs (EF_{ETR}) are calculated as follows:

$$EF_{ETR} = \eta_{stove}^* \times EF_{TFO} \quad (4.1)$$

where η_{stove}^* = stove effectiveness (see section 3.2); and EF_{TFO} = the EF based on the energy content of the test-fuel only.

The results of the calculations are presented in Figures 4.13–4.15. The principal impact of the calculation is to increase the EF for each fuel, since the stove effectiveness is less than 100%. However,

the impact is not the same for all fuels. Considering NO_x emissions first (Figure 4.13), peat sod is clearly the most NO_x -intensive fuel. The performance of smokeless coal, and of softwood, also deteriorates, making them equivalent to bituminous coal in NO_x intensity. The NO_x emissions of wet wood become equivalent to those of peat briquettes.

Figures 4.14 and 4.15 present similar data for PM emissions. Again, the performance of all fuels weakens when viewed from this perspective, but the ranking of peat briquettes improves relative to the other fuels, whereas the ranking of smokeless coal, softwood and wet wood deteriorates. Whether viewed as EF_{TFO} or EF_{ETR} , and whether considering NO_x or PM, kiln-dried hardwood remains the least emission-intensive of the fuels tested. However, concerns remain over the high level of apparent “volatile” emissions associated with all woody fuels (Figure 4.9).

4.8 Time-resolved Emission Rate of NO_x

Emission concentrations were recorded at 10-second intervals for all gaseous compounds. By combining these data with air flow rate and combustion rate information at the same interval, the time-resolved emission rate of each compound can be calculated.



Figure 4.13. NO_x EF_{ETR}, for each of the fuels tested. The relative position of sod peat, smokeless coal and softwood deteriorates when EFs are viewed from this perspective.

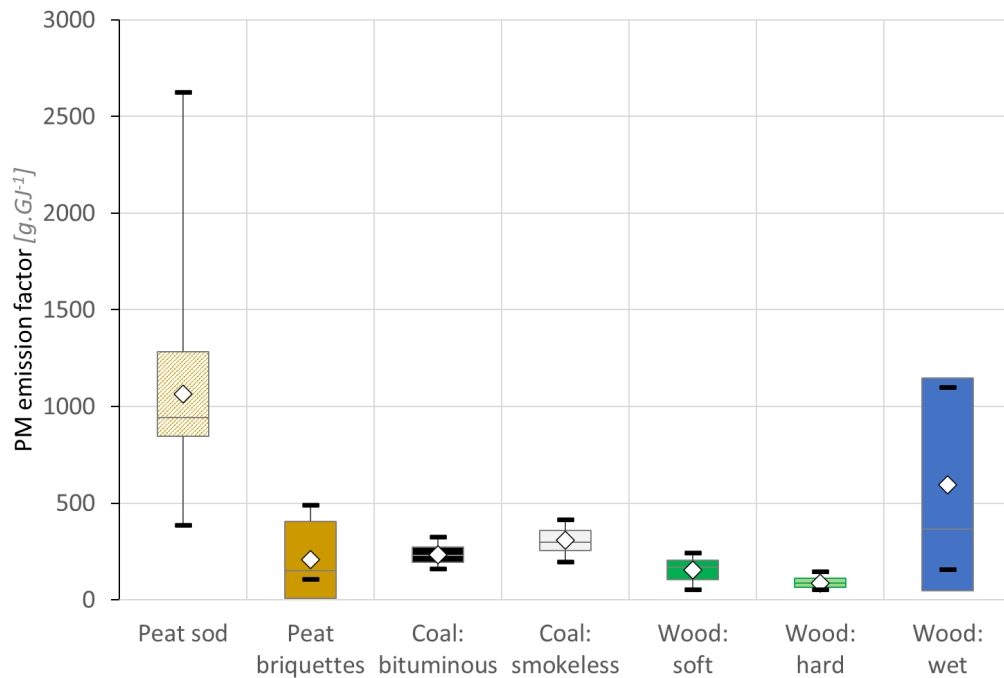


Figure 4.14. PM EF_{ETR}, for each of the fuels tested. The relative position of smokeless coal, and softwood deteriorates when EFs are viewed from this perspective.

Figure 4.16 presents the calculated NO_x emission rate for a selection of tests performed with kiln-dried hardwood (left) and peat briquettes (right). On account of the high combustion rate associated with kiln-dried wood, the NO_x emission rate peaks within

20–50 minutes and it declines almost to zero after 2 hours. Fairly significant variations in the emission pattern are evident between tests with this fuel.

Combustion proceeds at a lower rate with peat briquettes and NO_x emission therefore continues

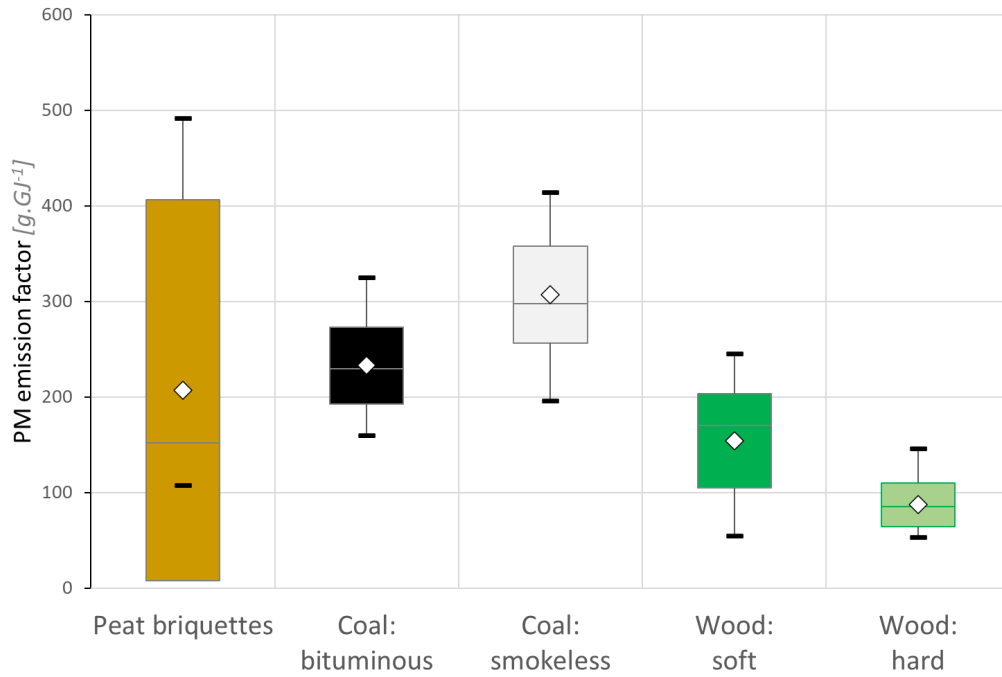


Figure 4.15. PM EF_{ETR} for the less PM-intensive fuels tested. The performance of smokeless coal is unimpressive viewed from this perspective.

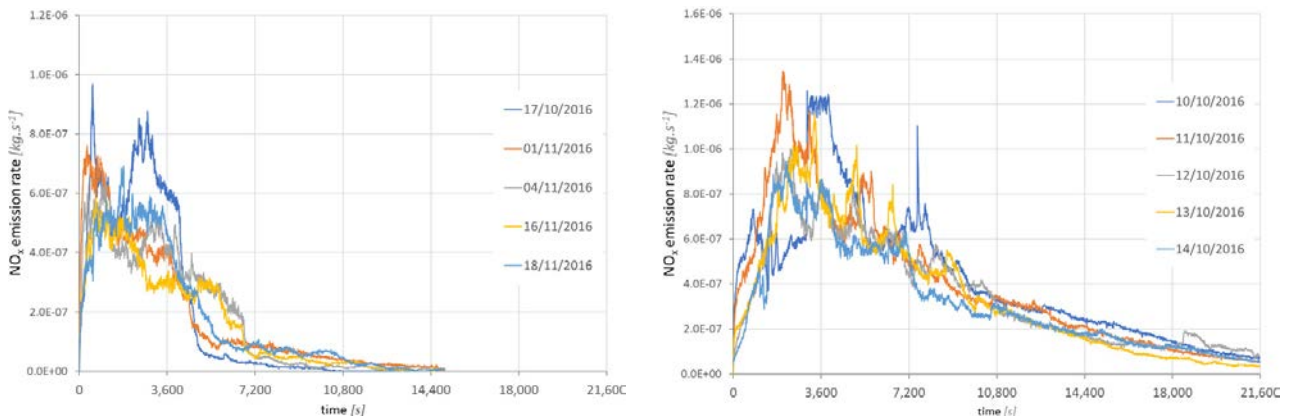


Figure 4.16. Time-resolved NO_x emission rates for five tests involving kiln-dried hardwood (left) and peat briquettes (right).

over a longer period. The peak emission rate is also about 50% higher than for kiln-dried wood, possibly a consequence of the higher nitrogen content of the peat-based fuel (see Figure A7.1). However, the pattern is slightly more consistent from test to test.

Figure 4.17 presents essentially the same data, but as a cumulative percentage of the total. The greater consistency of the NO_x emission rate for peat briquettes is evident from the tight spacing of the curves for this fuel (right), and the extended duration

over which the emission occurs is apparent in the shallower slope of the curves.

Bituminous coal, smokeless coal and, to a lesser extent, peat briquettes and wet wood exhibit a high emission ratio during the first 2 hours of the test, before settling down to a fairly steady – and quite similar – emission ratio of about 2 g kg⁻¹ (Figure 4.18). For hardwood, the emission ratio declines steadily over the first 2 hours, while for sod peat it remains relatively consistent over the first 4 hours and increases as the fuel burns out.

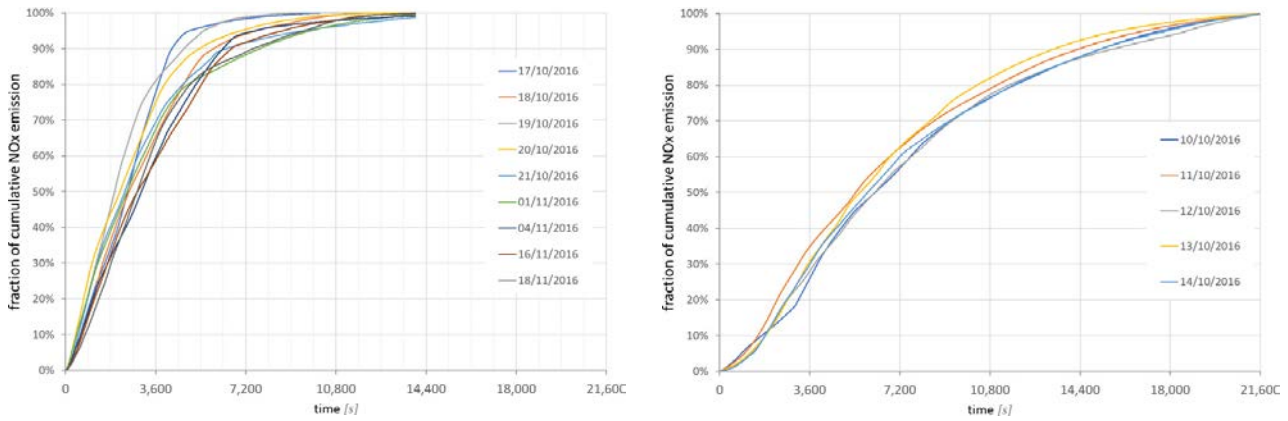


Figure 4.17. Cumulative fraction of NO_x emitted, as a function of time, for a series of tests involving kiln-dried wood (left) and peat briquettes (right).

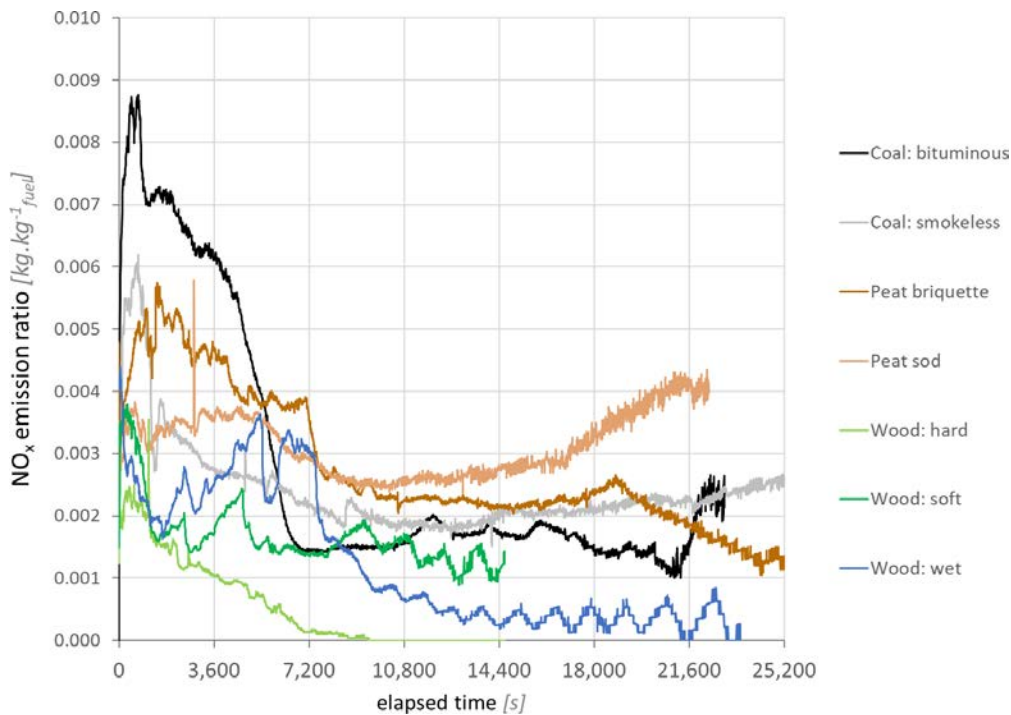


Figure 4.18. NO_x emission ratio (kg_{NO_x} emitted per kg_{fuel} consumed) for the seven fuels tested.

4.9 Time-resolved Emission Rate of PM

Time-resolved data of this quality are not, unfortunately, available for PM. However, for all tests involving sod peat, two separate PM filter sets were employed: set “A” for the first 30 minutes of the test and set “B” for the remaining 3.5 hours of PM sampling. Analysis of the filter sets shows that, on average, the PM deposition rate during the first 30 minutes of peat combustion is 10 times higher than during the following 3.5 hours.

A significant number of tests performed during the initial phase of the project used an optical probe to provide time-resolved estimates of PM concentration in the flue gas. All such data indicated that PM emission rates were high for a period of 30–60 minutes immediately following ignition and remained close to zero after that time.

These data indicate that inclusion of the ignition phase in any test protocol is essential for determining real-world PM EFs for solid-fuel appliances.

4.10 Time-resolved Emission of “Volatiles”

As previously discussed, the unique analysis methodology developed in this project allows the fuel *combustion* rate to be distinguished from the fuel *consumption* rate. The difference between these two figures represents fuel mass that has been consumed, but not oxidised, and is referred to throughout this report as “volatile” mass. Fuel-bound moisture is a known constituent of the “volatile” emissions, but is insufficient on its own to account for the total mass of such emissions inferred from the combustion rate analysis. It is therefore likely that the “volatiles” encompass both COCs and VOCs.

An example of the time-resolved emission rate of “volatiles”, for each of the fuels tested, is shown in Figure 4.19. Emissions from each fuel are characterised by a high rate of emission during the first 60 minutes or so of the combustion process, presumably associated with boil-off of bound water and volatile components. This early peak is followed by a gradual decline during the second hour or so, with emissions tending towards zero during the smouldering phase. The highest emission rates are observed for sod peat⁸ and for wood; the lowest rate is observed for bituminous coal.

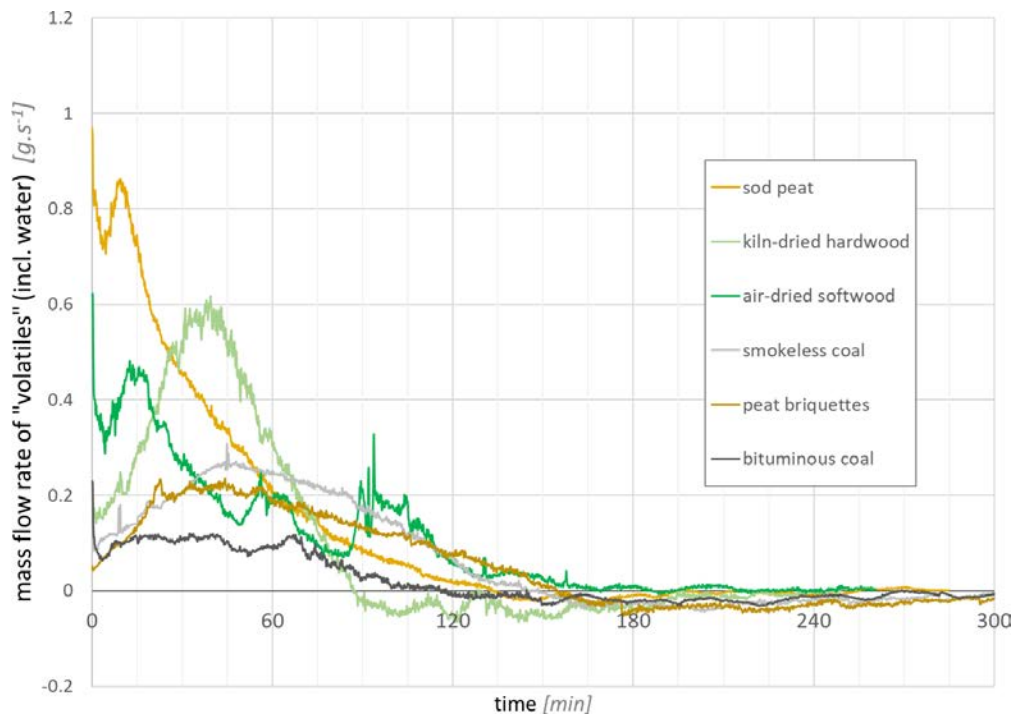


Figure 4.19. Emission rate of “volatiles”, as inferred from combustion rate analysis, for one test using each of the fuels tested. Note that the “volatiles” plotted here include bound water.

⁸ It should be noted that some of the “volatile” emissions attributed to sod peat are probably associated with the 500 g of kiln-dried hardwood used as an ignition charge for this fuel.

5 Discussion

The objective of this study was to obtain EFs for NO_x and PM associated with combustion of typical Irish fuels in a residential stove that are:

- representative of real-world, Irish conditions; and
- statistically robust.

That objective has been achieved and, in addition, unique analysis methods have been developed, new insights have been obtained into the factors governing emissions from this source, and gaps in the literature pertaining to emissions from peat-based fuels and smokeless coal have been addressed. Preliminary results from the project have been presented at two international conferences and a number of journal publications are currently in preparation.

However, although the narrow objective described previously has clearly been achieved, it is unclear whether or not the broader objective – of accurately quantifying pollutant emissions from residential combustion of solid fuels – has been met. The EFs presented in this report were obtained using a single appliance and it is unknown whether or not significant variations in EFs for some, or all, pollutants, when burning some or all of these test fuels, would be found using other stoves, or, indeed, open fires.

As noted by Wilton (2012), it is not clear if establishing an accurate EF for residential combustion of solid fuels is even an achievable goal, because so many variables interact in such complex ways to determine the ultimate level of emission. Consequently, the amount of testing required to establish robust EFs for all likely combinations of fuel, combustion system and operator behaviour would almost certainly be prohibitively expensive. Moreover, just specifying the appropriate test matrix would require a much more accurate picture of appliance use, and user behaviour, than is currently available.

Nonetheless, the results of this study clearly show that emissions – especially particulate emissions – from this source are very significant. Because those emissions are generated in incontrovertibly residential areas, they have the potential to impact appreciably on human health. That impact is likely to be most severe

where both population density and emission source density are high.

Hence, it is difficult to argue with the following statement, contained in a 2017 report issued by the International Energy Agency (IEA) Bioenergy Task 32 (Nussbaumer, 2017):

Applications [of residential biomass combustion] causing high emissions such as open fireplaces and old log wood appliances without combustion control should, however, be discouraged especially in urban areas.

5.1 Solid-fuel Emissions in Context

The intensity of the emissions associated with residential combustion of solid fuels is perhaps more easily appreciated by comparison with the current *bête noire* of the environmental movement: the diesel passenger car. Following revelations in September 2015 that Volkswagen had employed software in many of its cars that allowed it to cheat regulatory emissions tests, a number of studies have measured the emissions produced by diesel passenger cars during real-world operation. Collating data from the various studies, it has been found (e.g. Baldino *et al.*, 2017) that while some cars meet the current Euro 6 emissions standard in real-world operation, the majority do not; NO_x emissions in Baldino *et al.* (2017) were found to be, on average, four times higher than the legislative limit.

Diesel passenger cars are also associated, in the minds of many in the media and of many policymakers at least, with high levels of PM emissions. The perceived high level of PM emissions from these vehicles is the motivation behind the decision by the mayors of Paris, Madrid, Athens and Mexico City to ban diesel cars from their city centres by 2025 (Harvey, 2016).

Figure 5.1 overlays PM and NO_x EFs for both “compliant” and “typical” Euro 6 diesel passenger cars on the data for the solid fuels tested in this programme. It is evident that the NO_x EF for diesel passenger cars brackets the range of values

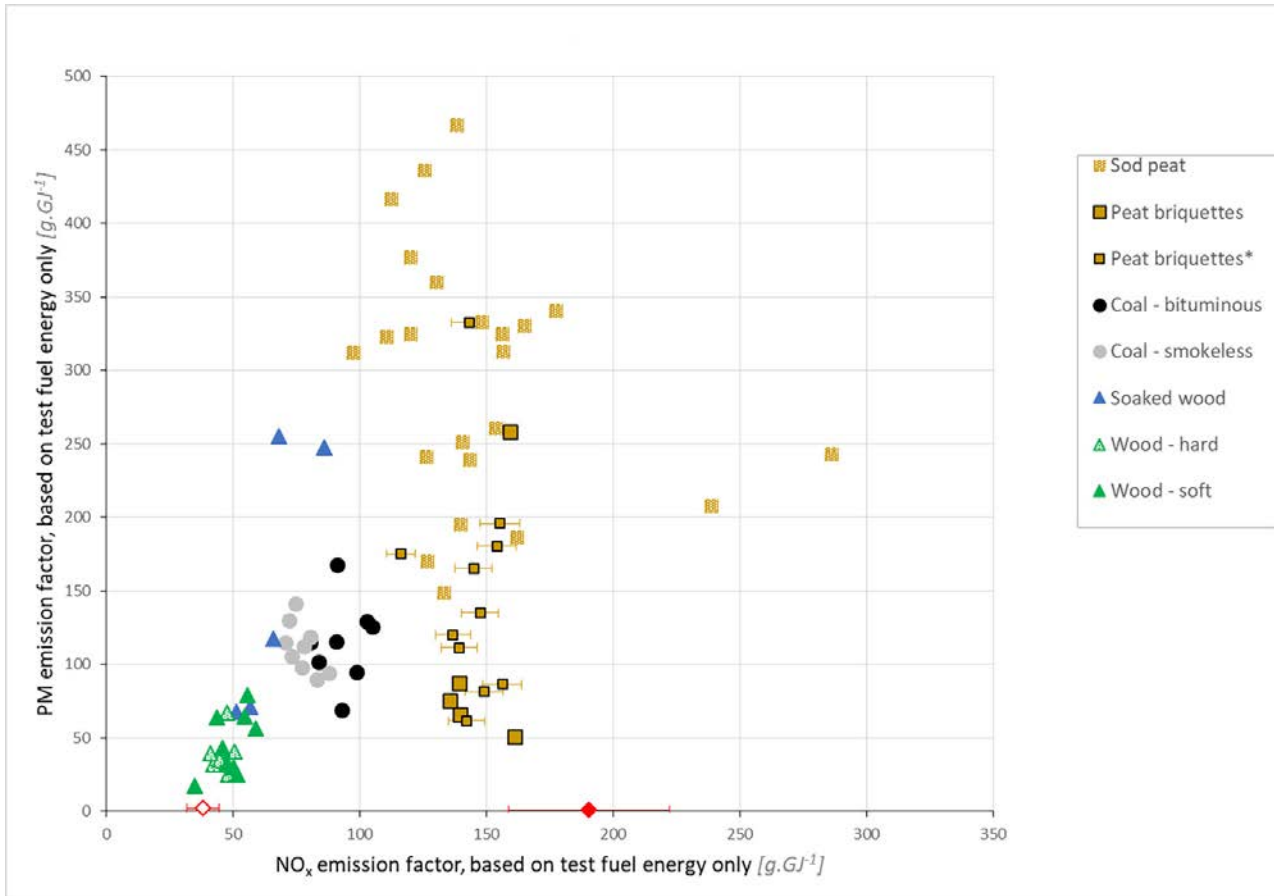


Figure 5.1. PM emission factor versus NO_x emission factor, for all tests reported. The red diamonds, near the bottom of the graph, show the equivalent emission factors for a typical (solid diamond) and a compliant (open diamond) Euro 6 diesel passenger car.

determined for combustion of solid fuels in a residential stove; stoves are about as bad as modern diesel cars with respect to NO_x emissions. The PM EFs tell a different story, however; the PM EF for residential combustion of solid fuels is one to two orders of magnitude higher than for diesel cars. To make matters worse, the PM EFs for the stove are based on “hot filter” measurements; those for the diesel cars are based on measurements of cooled and diluted exhaust and are therefore probably two to six times higher than would be obtained using a hot filter method.

Figure 5.2 offers an alternative perspective on the magnitude of this effect. The bars in Figure 5.2 denote the distance a typical Euro 6 diesel car would need to travel to emit a mass of PM equal to that emitted by burning 50 MJ of each fuel in a stove. This – 50 MJ – equates to the energy content of about six peat briquettes: a modest consumption for one evening of stove use, but equivalent to several thousands of

kilometres of emissions from a diesel car. It may be worth reiterating that the emissions from residential combustion of solid fuels occur in unavoidable proximity to residences, whereas a significant fraction of diesel car emissions are likely to occur at some remove from residences and pedestrians.

It is unsurprising, therefore, that source-attribution studies carried out in Paris (Crippa *et al.*, 2013), London (Xu *et al.*, 2016) and Florence, Barcelona and Milan (Amato *et al.*, 2016) all found that automotive exhaust makes a relatively minor contribution to fine PM in ambient air. In all cases except Barcelona, where penetration of residential solid-fuel combustion is very low, the contribution from biomass combustion exceeded that from traffic. It is worth remembering, in that context, that dry biomass produced the lowest PM EFs of all solid fuels evaluated in this project, although the high level of “volatile” emissions gives cause for concern.

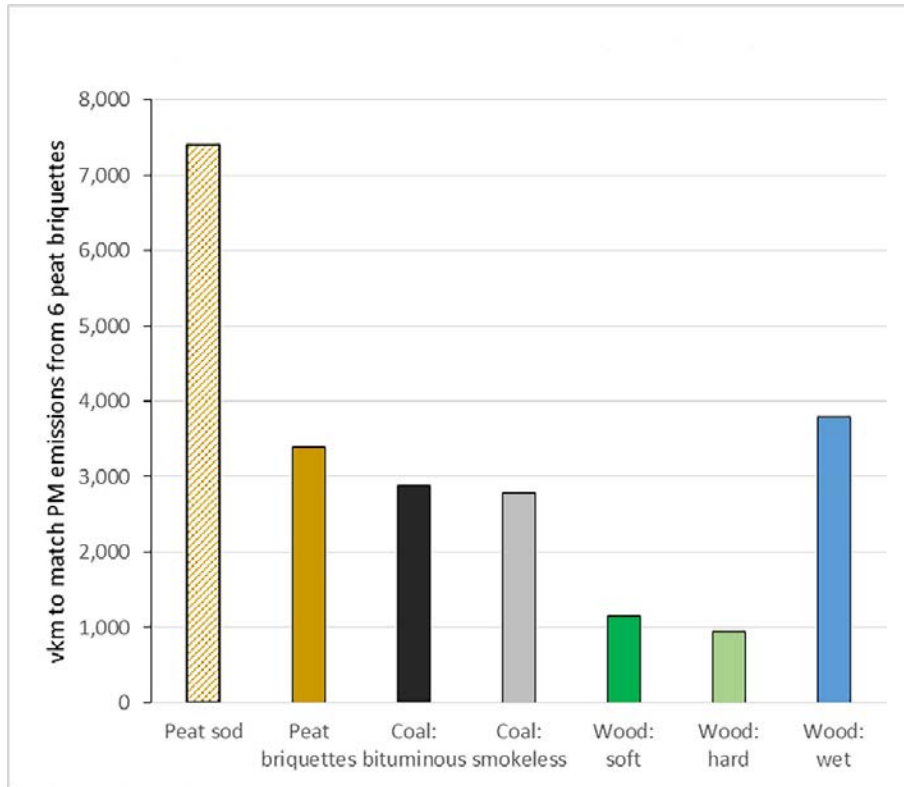


Figure 5.2. The distance a typical Euro 6 diesel passenger car would need to travel to emit the same mass of PM as one modest solid-fuel fire in a stove, for each of the fuels tested.

5.1.1 *Can emissions from solid-fuel stoves be controlled?*

Given the very high emission intensity of solid-fuel stoves, it is reasonable to ask whether or not legislative measures, such as performance standards, might be used to improve their performance. Although this approach might yield some benefits, those benefits are likely to be limited because the emissions that ultimately emerge from a residential stove are the integrated result of many factors, dominant among which are:

- quality of the appliance;
- quality of the installation (flue, etc.);
- quality of after-treatment systems;
- quality of the fuel;
- quality of the operator.

A significant shortfall in any one of these aspects of operation is sufficient to generate high levels of pollutant emissions. While legislative measures may help to improve appliance and installation quality, and could conceivably impact strongly on fuel quality,

legislation to control user behaviour is unenforceable in practice. In fact, user behaviour and fuel quality are linked, since the operator can choose to burn fuel of whatever quality they wish or which happens to be available and affordable. Proven and cost-effective after-treatment devices are not available for residential stoves, so that is not a viable option.

Although this study determined emissions from only a single stove, the discussion above highlights the fact that improved stove designs constitute a necessary – but not sufficient – precondition for reducing emissions from residential-scale solid-fuel combustion. As noted in Nussbaumer (2017):

Residential applications can also be justified if specific quality criteria for fuel and equipment are met. These include operating modern pellet boilers with high quality wood pellets and without too frequent start-ups or appropriately designing and operating log wood boilers, using seasoned dry wood logs, equipped with an electronic control and a heat storage tank.

For commercial- and industrial-scale appliances, on the other hand, regulation and enforcement of all five factors is both practical and cost-effective, because the de facto presence of automatic controls substantially reduces the potential for operator error.

The promotion of biomass-fuelled boilers of this scale is therefore entirely defensible. It is very difficult, however, to provide a rational basis for supporting the use of domestic-scale, solid-fuel combustion in urban areas.

6 Conclusions and Recommendations

The main conclusions of this project can be summarised as follows:

1. Robust, full-cycle EFs have been established for the combustion of solid fuels in a residential stove.
2. The fuels tested encompass the main solid fuels that are consumed in the Irish residential sector.
3. All solid fuels tested, including fuels categorised as “smokeless” under Irish law, were found to generate very substantial levels of particulate emissions when tested over a complete combustion cycle that incorporates the ignition and smouldering phases.
4. Of the solid fuels tested, sod peat produces by far the highest level of both PM and NO_x emissions per unit energy loaded in the stove. It also produces by far the highest level of emissions per unit heat delivered to the space.
5. The lowest levels of both PM and NO_x were observed when burning kiln-dried hardwood logs. Wet logs, however, generated substantially higher emissions, broadly in line with peat-based fuels.
6. Some test-to-test variability of EFs was observed for all fuels tested; variability was greatest for peat-based fuels and for wet wood.
7. Inferred emission of “volatiles” from all fuels tested, but particularly from wood and sod peat, may be a cause for concern.
8. Firelighters contribute a disproportionately high fraction of PM emissions, relative to their energy content and mass.
9. However, the EFs presented in this report were obtained using a single appliance, and it is unknown whether or not significant variations in EFs for some or all pollutants, when burning some or all of these test fuels, would be found using other stoves or open fires.
10. It is not clear if establishing an accurate overall EF for residential combustion of solid fuels is an achievable goal, because the ultimate level of

emission is determined by complex interactions between many variables.

11. Nonetheless, the results of this study clearly show that emissions – especially particulate emissions – from this source are very significant.
12. Because those emissions are generated in residential areas, they have the potential to impact appreciably on human health. That impact is likely to be most severe where both population density and emission source density are high.

Based on those conclusions, the authors offer the following recommendations:

1. The combustion of solid fuels in manually operated, domestic-scale appliances should be discouraged in urban areas. Mandating the use of so-called smokeless fuels, while laudable in principle, is unlikely to mitigate particulate emissions by a significant amount. This is the primary recommendation from this study; the recommendations that follow should be considered as secondary.
2. Regulation of fuel quality for commercially traded wood fuels should be considered. The moisture content of wood fuels, in particular, has a significant bearing on both the emission intensity and the efficiency of the combustion process.
3. Imposition of PM emission standards for firelighters should be considered
4. Further investigation of the “volatile” emissions inferred in this project is recommended. If the apparent level of emissions is representative of the true value, it is likely that organic compounds constitute a significant fraction of those emissions. In that scenario, the potential health implications at local and regional scales are significant.
5. Stoves with electronic control of inlet air flow are preferred over those with purely manual controls.
6. Efforts should continue to elucidate the linkages between emission sources and local air quality.

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Abbreviations

AFR	Air:fuel ratio
CI	Confidence interval
COC	Condensable organic compound
EEA	European Environment Agency
EF	Emission factor
EF_{ETR}	EF based on energy delivered to the room
EF_{TEL}	EF based on total energy loaded
EF_{TFO}	EF based on test fuel only
EMEP	European Monitoring and Evaluation Programme
ESG	Environmental Scientifics Group
GJ	Gigajoule (10 ⁹ joules)
HFID	Heated flame-ionisation detector
LCV	Lower calorific value
LHV	Lower heating value
MFC	Mass flow controller
mg	Milligram (10 ⁻³ grams)
MJ	Megajoule (10 ⁶ joules)
NO_x	Oxides of nitrogen
PM	Particulate matter
PM_{2.5}	Particulate matter with a characteristic size of 2.5 µm or less
UHC	Unburned hydrocarbon
VOC	Volatile organic compound

Appendix 1 Calculation Methodologies

This appendix provides an outline of the calculation methodology employed in determining the main performance metrics for each combustion test.

A1.1 Calculation of Emission Factors

The EF for each of the gaseous pollutants is obtained by dividing the cumulative emissions of pollutant i by the appropriate energy value (i.e. energy loaded, energy of the test fuel or energy delivered to the room).

$$EF_i = \frac{m_i}{\text{energy consumed}} \quad (\text{A1.1})$$

The process is as follows:

1. For the gaseous EF, the cumulative emissions of component i are found by integrating the time-resolved emission rate over the duration of a test:

$$m_i = \int_0^{\text{eot}} \dot{m}_i dt \quad (\text{A1.2})$$

where eot denotes “end of test”.

2. The mass flow rate of gaseous component i is determined from the inferred mass consumption rate of fuel:

$$\dot{m}_i = (\dot{m}_{\text{fuel}})_{\text{gas analysis}} \times \frac{m_i}{m_{\text{fuel}}} \quad (\text{A1.3})$$

3. The mass consumption rate of fuel is determined from the measured air mass flow rate and the AFR calculated as shown in section A1.2.

$$(\dot{m}_{\text{fuel}})_{\text{gas analysis}} = \frac{\dot{m}_{\text{air}}}{\text{AFR}} \quad (\text{A1.4})$$

The mass of component i produced per unit mass of fuel consumed is obtained as follows:

$$\frac{m_i}{m_{\text{fuel}}} = \frac{N_i}{N_{\text{fuel}}} \times \frac{M_i}{M_{\text{fuel}}} \quad (\text{A1.5})$$

where M_i denotes the molar mass of component i and M_{fuel} denotes the molar mass of the fuel.

4. The number of moles of component i produced per mole of fuel consumed ($\frac{N_i}{N_{\text{fuel}}}$) is obtained by combining the measured concentration of

component i in the exhaust $[i]$ with the calculated moles of dry exhaust produced per mole of fuel consumed N_{dry} :

$$\frac{N_i}{N_{\text{fuel}}} = N_{\text{dry}} \times [i] \quad (\text{A1.6})$$

5. N_{dry} is obtained from a carbon balance between the fuel and the exhaust products:

$$N_{\text{dry}} = \frac{C_{\text{fuel}}}{[\text{CO}_2] + [\text{CO}] + [\text{UHC}]} \quad (\text{A1.7})$$

where C_{fuel} denotes the moles of carbon per mole of fuel. (For calculation purposes, the moles of each constituent in the fuel are normalised with respect to the carbon content; see the detailed calculation of AFR in the following section for more detail.)

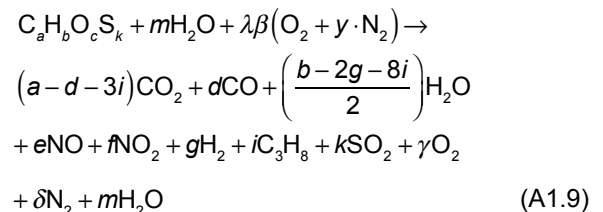
In the case of PM, time-resolved emission data are not available: the mass deposited on the filters is the integral of the mass deposition rate during the PM sampling period. The total PM emissions are calculated by scaling the observed mass to account for the total mass flow up the flue:

$$m_{\text{PM}} = m_{\text{filters}} \times \frac{m_{\text{flue}}}{m_{\text{sample}}} \quad (\text{A1.8})$$

where m_{PM} denotes the total mass of PM in the combustion products; m_{filters} denotes the mass of PM deposited on the sample filters; m_{flue} denotes the total mass of exhaust up the flue during the PM sampling period; and m_{sample} denotes the total mass of exhaust sampled (i.e. drawn through the PM filters) during the PM sampling period.

A1.2 Calculation of Instantaneous Air:Fuel Ratio

Start with the following combustion equation:



β in the above equation is the stoichiometric oxygen coefficient for the fuel:

$$\beta = \left(a + \frac{b}{4} - \frac{c}{2} + k \right) \quad (\text{A1.10})$$

It is assumed that:

1. The fraction of C, H, O, and S remaining in the ash, or embedded in the particulate emission from the combustion process, is negligibly small.
2. The moisture embedded in the fuel ($m\text{H}_2\text{O}$) is chemically inert, i.e. it takes no part in the reaction (although it will of course change phase). It is added as a separate term at the end of the equation, to distinguish it from water formed by combustion of the fuel.

All gas analysis is performed on a dry basis, so the measured concentration of the carbon-containing compounds can be written as:

$$\begin{aligned} [\text{CO}_2] &= \frac{N_{\text{CO}_2}}{N_{\text{dry}}} = \frac{(a-d-3i)}{N_{\text{dry}}}; \\ [\text{CO}] &= \frac{N_{\text{CO}}}{N_{\text{dry}}} = \frac{d}{N_{\text{dry}}}; \\ [\text{C}_3\text{H}_8] &= \frac{N_{\text{C}_3\text{H}_8}}{N_{\text{dry}}} = \frac{3i}{N_{\text{dry}}} \end{aligned} \quad (\text{A1.11})$$

Terms in square brackets (e.g. $[\text{CO}]$) denote the measured volumetric concentration (with a value between 0 and 1) of that component of the exhaust gas.

So:

$$[\text{CO}_2] + [\text{CO}] + [\text{C}_3\text{H}_8] = \frac{a}{N_{\text{dry}}} \quad (\text{A1.12})$$

Rearranging:

$$N_{\text{dry}} = \frac{a}{[\text{CO}_2] + [\text{CO}] + [\text{C}_3\text{H}_8]} \quad (\text{A1.13})$$

Since all the variables on the right-hand side of equation A1.13 are known, we can find N_{dry} .

Once we know N_{dry} , finding the coefficients d – γ is simple:

$$d = [\text{CO}]N_{\text{dry}}; e = [\text{NO}]N_{\text{dry}}; \text{ etc.} \quad (\text{A1.14})$$

The concentration of N_2 is not measured directly, but can be assumed to constitute the fraction of the flue gas that remains after all measured components have been subtracted. Hence, δ can be found:

$$\begin{aligned} [\text{N}_2] &= 1 - ([\text{CO}_2] + [\text{CO}] + [\text{NO}] + [\text{NO}_2] \\ &\quad + [\text{H}_2] + [\text{C}_3\text{H}_8] + [\text{SO}_2] + [\text{O}_2]) \end{aligned} \quad (\text{A1.15})$$

$$\delta = [\text{N}_2]N_{\text{dry}} \quad (\text{A1.16})$$

Performing an O_2 balance on the reaction equation gives:

$$\begin{aligned} \gamma &= \lambda\beta + \frac{c}{2} - (a-d-3i) - \frac{d}{2} \\ &\quad - \left(\frac{b-2g-8i}{4} \right) - \frac{e}{2} - f - k \end{aligned} \quad (\text{A1.17})$$

Rearranging:

$$\begin{aligned} \gamma &= \lambda\beta - \left[(a+f+k) - \left(\frac{c+d-2}{2} \right) \right. \\ &\quad \left. + \left(\frac{b-2g}{4} \right) + 5i \right] \end{aligned} \quad (\text{A1.18})^9$$

$$\therefore \gamma = \lambda\beta - \sigma \quad (\text{A1.19})$$

Since the (dry) oxygen concentration is measured:

$$\gamma = [\text{O}_2]N_{\text{dry}} = \lambda\beta - \sigma \quad (\text{A1.20})$$

Rearranging:

$$\lambda = \frac{[\text{O}_2]N_{\text{dry}} + \sigma}{\beta} \quad (\text{A1.21})$$

Since all terms on the right-hand side of equation A1.21 have already been found or directly measured, it is possible to solve for λ . This version of the equation has the following advantages:

1. The divisor is non-zero in all circumstances, since it depends on fuel composition only.
2. It incorporates terms for UHC and SO_2 that are absent from most alternative formulations.

9 The $5i$ is specific to the case where $\text{UHC} = \text{C}_3\text{H}_8$. For the general case where $\text{UHC} = \text{C}_n\text{H}_{2n+2}$, 5 becomes $((1.5 \times n) + 0.5)$.

A1.2.1 A note on moisture content

The λ calculated here is “blind” to the embedded moisture content of the fuel. The AFR for the process is obtained from:

$$AFR = \lambda \cdot AFR_{stoich} \quad (A1.22)$$

If the stoichiometric AFR (AFR_{stoich}) is calculated for the anhydrous fuel, then the AFR calculated using equation A1.22 will be higher than the true AFR.

Consider, for example, combustion of 1 kg of fuel with a moisture content of 10%. Only 0.9 kg of the fuel participates in the reaction described in equation A1.10 and so the AFR we calculate is based on the 0.9 kg of fuel oxidised, not on the total mass of fuel “consumed”. If the AFR obtained is, for example, 20:1, then the mass of air consumed is 18 kg (20×0.9), and not 20 kg, as might be expected if multiplying the measured fuel mass change by the calculated AFR. The “true” AFR, on the basis of mass of fuel consumed is, in this case, 18:1, and in the general case:

$$AFR_{true} = (1 - mc) AFR_{gas\ analysis} \quad (A1.23)$$

where mc denotes moisture content – the mass fraction of embedded moisture in the fuel.

This becomes significant when converting *measured emission concentrations* to *total mass emitted*, since the total mass of air consumed (and therefore of flue gas produced) is less than would be assumed based on the “raw” AFR calculated from gas analysis. The net effect is to reduce the total mass emitted by a factor $(1 - mc)$.

A1.3 Calculation of Combustion Efficiency

The combustion efficiency measures the fraction of the nominal energy content of a fuel (i.e. the LHV) that is actually released during a combustion process. It is calculated, at each 10-second interval, by comparing the enthalpy of the observed combustion products with the enthalpy of the ideal combustion process where all carbon forms CO_2 and all hydrogen forms H_2O :

$$\eta_{comb} = \frac{h_{f,fuel} - h_{f,products,ideal}}{h_{f,fuel} - h_{f,products,observed}} \quad (A1.24)$$

where h_f denotes the enthalpy of formation at reference conditions.

The h_f values for the ideal and observed combustion products are available in the literature. $h_{f,fuel}$ was estimated for each fuel as follows:

$$h_{f,fuel} = LHV_{fuel,DAF} + h_{f,products,ideal} \quad (A1.25)$$

The overall combustion efficiency for the test was obtained by integrating the mass-weighted combustion efficiency values calculated at each interval:

$$\eta_{comb,overall} = \int_0^{eot} (\dot{m}_{fuel})_{gas\ analysis} \times \eta_{comb} dt \quad (A1.26)$$

A1.4 Calculation of “Volatile” Emissions

An interesting feature of the analysis methodology developed for this project is the potential to distinguish between the fuel *consumption* rate, as measured using a load cell:

$$(\dot{m}_{fuel})_{consumed} = \int_0^{eot} (\dot{m}_{fuel})_{measured} dt \quad (A1.27)$$

and the fuel *combustion* rate (oxidation rate), as inferred from gas analysis and measured air flow rate:

$$(\dot{m}_{fuel})_{oxidised} = \int_0^{eot} (\dot{m}_{fuel})_{gas\ analysis} dt \quad (A1.28)$$

Because these two parameters are calculated independently of one another, it should be possible, in principle, to infer the rate of moisture loss as the difference between these two terms. However, it was found that the difference between these two terms, when summed over the full test duration, frequently exceeded – by a substantial amount – the mass of moisture bound to the fuel. Since no obvious source for this discrepancy could be found, the missing mass has been attributed to the emission of volatile compounds from individual fuel elements during the boil-off phase. Since direct evidence for the existence of these volatile emissions could not be found without access to a sophisticated HFID analyser, they are referred to as “volatiles” throughout this report, signifying the uncertainty that remains concerning their nature and origin.

Since neither the “volatiles” nor the evaporation of bound moisture could be directly measured with the existing experimental setup, the time-resolved “volatile” emissions include both. However, knowing the mass of bound moisture initially contained in the fuel charge loaded in the stove, it is possible to infer

the total mass of non-moisture volatile emissions associated with a given test:

$$m_{\text{volatiles}} = (m_{\text{fuel}})_{\text{consumed}} - (m_{\text{fuel}})_{\text{oxidised}} - m_{\text{bound moisture}} \quad (\text{A1.29})$$

As shown in Figure 4.10, significant quantities of oily condensate have been found in the exhaust gases

from similar tests reported in Comerford (2014), so the emission of volatile compounds during the tests reported here is extremely plausible. The magnitude of those emissions – particularly for wood and peat – are surprisingly high, however, and cast some doubt on their veracity.

Appendix 2 Equipment Specifications

Summary technical specifications for key experimental equipment are presented in this appendix.

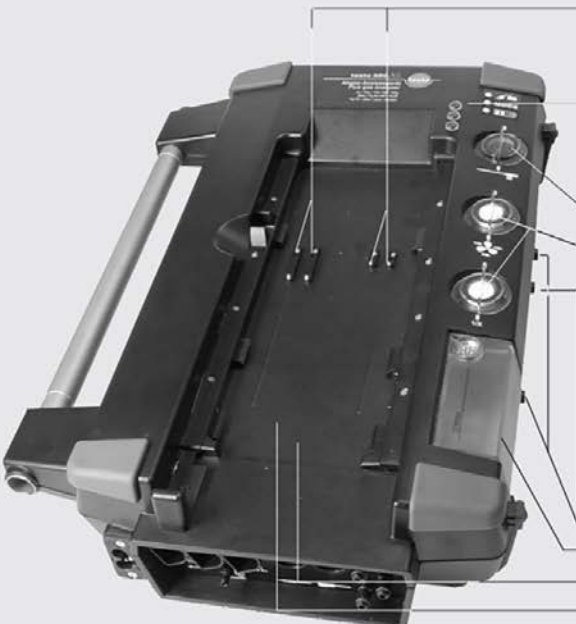
A2.1 Testo 350 XL Gas Analyser

Selected data from the operating manual for the Testo 350 XL gas analyser are presented here. Further details are available at www.testo350.com.

1. Description of the system components

1.3 Analyser box 350 M/XL

1.3.1 General description



Status LEDs

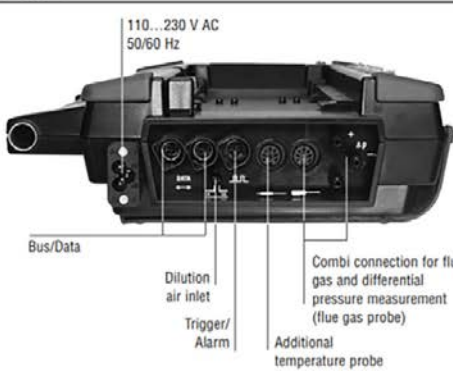
Status display of LEDs in the flue gas analyser box

LED1 (Power):	
Mains operation	Green/Permanent
Battery operation (batt. full)	Green/Flashing
Battery operation (batt. empty)	Red/Flashing
Battery recharging, Off mode	Off

LED2 (Status):	
Measuring	Green/Permanent
Fresh air/Zeroing	Green/Flashing
Defect	Red/Flashing

LED3 (Battery recharging):	
Battery recharging (fast charge)	Green, flashing
Batt. full, compensation charge	Green, permanent

Connections



The analyser box contains the gas sensors, the measured gas and purging pumps, Peltier gas preparation, gas paths, all filters, electronic evaluating and storage, the mains adapter and NiMH battery (service time approx. 2 - 3 hours of continuous operation, reduction with CO₂ IR module).

Differences between testo 350M and testo 350 XL:

Description	testo 350 M	testo 350 XL
Max. gas sensors	4	6
Basic version equipped with	O ₂ ; CO	O ₂ ; CO; NO; NO ₂
Capable of extension with	NO; NOlow; NO ₂ ; SO ₂ ; COlow; CO ₂ (IR)	SO ₂ ; H ₂ S; HC; NOlow; COlow; CO ₂ (IR)
Fresh air valve	Option	Standard
Trigger input	—	Option

8. Technical data

8.1 Logger

Technical data, testo 454 logger

Probe type	Vane	Thermal	Testo humid. sensor, capacitive	Pressure	
Meas. range	0... +60 m/s	0... +20 m/s	0... +100 %RH	+10... +30,000 hPa	
Accuracy ±1 digit	See "Probes data" for system accuracy	±0.01 m/s (0... +1.99 m/s) ±0.02 m/s (+2... +4.99 m/s) ±0.04 m/s (+5... +20 m/s)	See probe data	Probe 0638 1345 Probe 0638 1445 Probe 0638 1545 Probe 0638 1645 ±0.1 % of f.v. Probe 0638 1740 Probe 0638 1840 ±0.2 % of f.v.	
Resolution	0.01 m/s (for Ø 60/100 mm), 0.1 m/s (for remaining probes)	0.01 m/s (0... +20 m/s)	0.1 %RH (0... +100 %RH)	0.001 hPa (probe 0638 1345) 0.001 hPa (probe 0638 1445) 0.01 hPa (probe 0638 1545) 1 hPa (probe 0638 1645) 0.01 bar (probe 0638 1740) 0.01 bar (probe 0638 1840)	
Probe type	Pt100	Type K (NiCr-Ni)	Type S (Pt10Rh-Pt)	Type J (Fe-CuNi)	Type T (Cu-CuNi)
Meas. range	-200... +800 °C	-200... +1,370 °C	0... +1,760 °C	-200... +1,000 °C	-40... +350 °C
Accuracy ±1 Digit	±0.1 °C (-49.9... +99.9 °C) ±0.4 °C (-99.9... -50 °C) ±0.4 °C (+100... +199.9 °C) ±1 °C (-200... -100 °C) ±1 °C (+200... +800 °C)	±0.4 °C (-100... +200 °C) ±1 °C (-200... -100.1 °C) ±1 °C (+200.1... +1,370 °C)	±1 °C (0... +1,760 °C)	±0.4 °C (-150... +150 °C) ±1 °C (-200... -150.1 °C) ±1 °C (+150.1... +199.9 °C)	±0.4 °C (-40... +200 °C) ±1 °C (+200.1... +350 °C)
Resolution	0.01 °C (-99.9... +300 °C) 0.1 °C (-200... -100 °C) 0.1 °C (+301... +800 °C)	0.1 °C (-200... +1,370 °C)	1 °C (0... +1,760 °C)	0.1 °C (-200... +1,000 °C)	0.1 °C (-40... +350 °C)
Probe type	NTC	CO probe	CO2 probe	CO2 probe	
Meas. range	-40... +150 °C	0... +500 ppm CO	0... +1 Vol. % CO2	0... +10,000 ppm CO2	
Accuracy ±1 Digit	±0.2 °C (-10... +50 °C) ±0.4 °C (+51... +150 °C) ±4 °C (-40... -11 °C)	±5 % of mv. (0... +500 ppm CO)	See probe data	See probe data	
Resolution	0.1 °C (-40... +150 °C)				
Probe type	Mechanical	Current/voltage measurement	Current/voltage measurement	Control unit, integ. press. sensor	Control unit, integ. press. sensor
Meas. range	+20... +20,000 rpm	0... +20 mA	0... +10 V	-200... +200 hPa	-40... +40 hPa
Accuracy ±1 Digit	(+20... +20,000 rpm)	±0.04 mA (0... +20 mA)	±0.01 V (0... +10 V)	±1 % of mv. (-50... -200 hPa) ±1 % of mv. (+50... +200 hPa) ±0.5 hPa (-49.9... +49.9 hPa)	±1 % of mv. (-3... -40 hPa) ±1 % of mv. (+3... +40 hPa) ±0.03 hPa (-2.99... +2.99 hPa)
Resolution	1 rpm (+20... +20,000 rpm)	0.01 mA (0... +20 mA)	0.01 V (0... +10 V)	0.1 hPa (-200... +200 hPa)	0.01 hPa (-40... +40 hPa)
	testo 454, Control Unit	Logger, measures and saves readings	Analog output box (mA out)	Powerbox	
Oper. temp.	-5... +45 °C	-10... +50 °C	-10... +50 °C	0... +40 °C	
Storage temp.	-20... +50 °C	-25... +60 °C	-25... +60 °C	-20... +50 °C	
Battery type	4 AA batteries	Alkali manganese			
Battery life	8 h *1	24 h *2		35 h	
Memory	250,000	250,000			
Weight	850 g	450 g	305 g	700 g	
Dimensions	252 x 115 x 58 mm	200 x 89 x 37 mm	200 x 89 x 37 mm	200 x 89 x 37 mm	
Warranty	2 years	3 years	3 years	3 years	

*1 Battery life in continuous operation with 1 T/C probe

*2 Battery life in continuous operation with a logger/4 T/C probes

8. Technical data

8.2 Analyser box

Technical data for testo 350 M, testo 350 XL analysis box

Probe type	O2 measurement	CO (H2 compensated)	COlow meas. (H2 compensated)	CO2	NO meas. (option for testo 350 M)	NOlow measurement	NO2 measuring module (option for testo 350 M)	SO2 measurement	CO2 measurement (IR)
Meas. range	0... +25 Vol.% O2	0... +10000 ppm CO	0... +500 ppm CO	0... CO2max Vol.% CO2	0... +3000 ppm NO	0... +300 ppm NO	0... +500 ppm NO2	0... +5000 ppm SO2	0... 50Vol.% CO2
Accuracy ± 1 digit	±0.8% of f.v. (0... +25 Vol.% O2)	±5% of mv (+100... +2000 ppm CO) ±10% of mv (+2001... +10000 ppm CO) ±10 ppm CO (0... +99 ppm CO)	±5% of mv (+40... +500 ppm CO) ±2 ppm CO (0... +39.9 ppm CO)	Calculated from O2	±5% of mv (+100... +1999.9 ppm NO) ±10% of mv (+2000... +3000 ppm NO) ±5 ppm NO (0... +99 ppm NO)	±5% of mv (+40... +300 ppm NO) ±2 ppm NO (0... +39.9 ppm NO)	±5% of mv (+100... +500 ppm NO2) ±5 ppm NO2 (0... +99.9 ppm NO2)	±5% of mv (+100... +2000 ppm SO2) ±10% of mv (+2001... +5000 ppm SO2) ±5 ppm SO2 (0... +99 ppm SO2)	±0.3Vol% + 1% v. Max. (0... 25 Vol.% CO2) ±0.5Vol% + 1.5% v. Max. (>25... 50 Vol.% CO2)
Resolution	0.1 Vol.% O2 (0... +25 Vol.% O2)	1 ppm CO (0... +10000 ppm CO)	0.1 ppm CO (0... +500 ppm CO)	0.01 Vol.% CO2	1 ppm NO (0... +3000 ppm NO)	0.1 ppm NO (0... +300 ppm NO)	0.1 ppm NO2 (0... +500 ppm NO2)	1 ppm SO2 (0... +5000 ppm SO2)	0.01 Vol.% CO2 (0... 25 Vol.%) 0.1 Vol.% CO2 (>25 Vol.%)
Reaction time	20 s	40 s	40 s	20 s	30 s	30 s	40 s	30 s	< 10sec
Reaction type	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO

Probe type	Efficiency	Flue gas loss	Differential pressure 1	Differential pressure 2	Velocity	Temperature measurement		
Meas. range	0... +120 %	-20... +99.9 % qA	-200... +200 hPa	-40... +40 hPa	0... +40 m/s	-40... +1200 °C		
Accuracy ± 1 digit			±1.5% of mv (-50... -200 hPa) ±1.5% of mv (+50... +200 hPa) ±0.5 hPa (-49.9... +49.9 hPa)	±1.5% of mv (-40... -3 hPa) ±1.5% of mv (+3... +40 hPa) ±0.03 hPa (-2.99... +2.99 hPa)		±0.5% of mv (+100... +1200 °C) ±0.5 °C (-40... +99.9 °C)		
Resolution	0.1 % (0... +120 %)	0.1 % qA (-20... +99.9 % qA)	0.1 hPa (-200... +200 hPa)	0.01 hPa (-40... +40 hPa)	0.1 m/s (0... +40 m/s)	0.1 °C (-40... +1200 °C)		
Reaction time								
Reaction type								

Dimensions 395x275x95 mm
Weight 3200 g
Storage temp. -20... +50 °C
Oper. temp. -5... +45 °C
Material/Housing ABS

Additional technical data:
Memory: 250 000 readings
Power supply: Via integrated mains unit (90 V to 260 V, 47 to 63 Hz)
or exchangeable rechargeable batteries
Electrical power required:
0.5 A (110 V AC), 0.3 A (230 V AC)
Dew point calculation: 0 to 99°C td
Maximum positive pressure: 50 hPa (500 mm water column)
Maximum negative pressure: 200 hPa (2000 mm water column)
Pump flow: 0.8 m/s with flow monitoring
Max. dust load: 20 g/m³ dust in flue gas
Max. humidity load: +70°C
Dew point temperature at inlet

Measuring range extension (dilution) for CO:
dilution factors 0, 2, 5, 10, 20, 40
Dilution gas: Fresh air or N2
Accuracy: Reading plus max. 2%
Event trigger socket testo 350XL:
Voltage: 5 to 12 Volt
(ascending or descending edge)
Impulse width >1 s
Load: 5 V/max. 5 mA, 12 V/max. 40 mA

Warranty:
Analysers: 2 years (excluding working parts e.g. measuring cells)
CO/NO/NO2/SO2/H2S/HC/CO2 measuring cell: 1 year
O2 measuring cell: 1.5 years

Additional technical data only for testo 350 XL analysis box

Fühlertyp	H2S measurement
Meas. range	0... +300 ppm
Accuracy ± 1 Digit	±5% of mv (+40... +300 ppm) ±2 ppm (0... +39.9 ppm)
Resolution	0.1 ppm (0... +300 ppm)
Reaction time	35 sec
Reaction type	ISO

Additional technical data:
Event trigger socket: 5 bis 12 V (ascending or descending edge)

Technical data, HC module

Parameter	Methane	Propane	Butane
Meas. range ¹	100 to 40,000 ppm	100 to 21,000 ppm	100 to 18,000 ppm
Accuracy	< 400 ppm (100...4000 ppm) < 10 % of mv. (>4000 ppm)	< 400 ppm (100...4000 ppm) < 10 % of mv. (>4000 ppm)	< 400 ppm (100...4000 ppm) < 10 % of mv. (>4000 ppm)
Resolution	10 ppm	10 ppm	10 ppm
Min. O2 requirement in flue gas	2% + (2 x mv. methane)	2% + (5 x mv. propane)	2% + (6.5 x mv. butane)
Reaction time ISO	< 40 sec.	< 40 sec.	< 40 sec.
Response factor ²	1	1.5	2

¹ Lower explosion limit (LEL) must be upheld.

² The HC module is factory adjusted to methane.
The user can adjust the module to another gas.

A2.2 Vögtlin Red-y Smart GSC-C9TA-BB12 Mass Flow Controller

Selected data from the operating manual for the

Vögtlin Red-y Smart GSC-C9TA-BB12 MFC are presented here. Further details are available at www.voegtlin.com.

red-y smart series

2. Technical data

2.10 General device specifications

Accuracy

<i>Standard</i>	±1.0% of full scale
<i>Hi-Performance</i>	±0.3% of full scale, ±0.5% of reading
<i>GSM < 200 l/min Air</i>	
<i>GSC < 150 l/min Air</i>	

Dynamics

<i>Standard</i>	1:50 (signal suppression less than 0.85% of full scale)
<i>Hi-Performance</i>	1:100 (signal suppression less than 0.8% of full scale)
Response time:	50 ms
Reproducibility:	±0,2% of full scale
Long-term stability:	< 1% of reading / year
Temperature coefficient:	< 0.025% FS measuring range type / °C
Pressure coefficient:	< 0.2% / bar of reading (typical N2)
Control stability:	±0,2% of full scale
Working pressure range:	0.2 - 11 bar a (GSC with valve type 4.5 and 8 max 8bar s)
Test pressure:	16 bar a
Storage conditions:	-20 to 80°C (-4 to 176 F), 0-95% RH, non-considering
Temperature range:	0 – 50 °C (32 bis 122 F), 0-95%, RH, non-considering
	<i>Do not expose device to direct sun light.</i>
Leakage rate	
Externally:	1 x 10 ⁻⁶ mbar·l/s He
Control valve:	1 x 10 ⁻⁶ mbar·l/s He
Warm-up time:	< 1 sec. for full accuracy

2.11 Mechanical specifications

Materials

<i>Code A model (aluminum):</i>	Anodized aluminum, stainless steel 1.4305
<i>Code S model (stainless steel):</i>	Stainless steel 1.4305
Sensor area:	Silicon, glass, epoxy
Seal material:	FKM, optional EPDM or FFKM
Mechanical connection (types A, B, C):	G1/4" female thread at both ends, optional with fittings (see appendix 'Accessories')
Mechanical connection (type D):	G1/2" female thread at both ends, optional with fittings (see appendix 'Accessories')
Electrical power supply:	9-pin D-Sub plug connector (male) (connections for supply, analog setpoint-actual values and ModBus RTU digital communication)

Huba Controls type 694 differential pressure transducer

Technical overview

Pressure range	
Relative and differential	-0.5 ... 0.5 mbar / 0 ... 1 – 50 mbar

Operating conditions

Medium		Air and neutral gases	
Temperature	Medium / ambient	0 ... +70 °C	
	Storage	-10 ... +70 °C	
	No condensation		
Tolerable overload on one side	Application at over pressure range	P1 = 100 mbar	P2 = 4 mbar
	Application at under pressure range	P1 = -4 mbar	P2 = -100 mbar
Rupture pressure	ambient temperature	2 x overload	
	70 °C	1.5 x overload	

Materials in contact with medium

Sensor	Ceramic Al ₂ O ₃ (96%)
Diaphragm	Silicone
Housing	Polycarbonat PC

Electrical overview

	Output	Power supply	Load	Current consumption ¹⁾
2 wire	4 ... 20 mA	11.0 ... 33 VDC	< $\frac{\text{supply voltage} - 11 \text{ V}}{100 \pm 1}$ (Ohm)	< 20 mA
	0 ... 10 V	13.5 ... 33 VDC / 24 VAC ±15%	> 10 kOhm	< 10 mA
3 wire	0 ... 20 mA	13.5 ... 33 VDC / 24 VAC ±15%	< 400 Ohm	< 30 mA
	4 ... 20 mA	13.5 ... 33 VDC / 24 VAC ±15%	< 400 Ohm	< 30 mA
Polarity reversal protection Short circuit proof and protected against polarity reversal. Each connection is protected against crossover up to max. supply voltage.				

Dynamic response

Response time	< 10 ms
Load cycle	< 10 Hz

Protection standard

Without cover	IP 00
With cover	IP 54
	IP 65

Display

LCD display	3 digit
-------------	---------

Setting range

Zero point	±10% fs
Full scale	40 ... 100% fs

Electrical connection

Screw terminals for wire and stranded conductors up to 1.5 mm ²	
Cable gland with built-in strain relief PG11	

Pressure connection

Connection pipe	Ø 6.2 mm
-----------------	----------

Mounting instructions

Installation arrangement	Factory adjustment:	Vertical, with pressure connections downwards ²⁾
		Horizontal with cover downwards ³⁾
		Horizontal with cover upwards ⁴⁾
Mounting	Mounting bracket (integrated in case)	

Tests / Admissions

ETL	
Electromagnetic compatibility	CE conformity acc. EN 61326-2-3

Weight

Without display	~ 90 g
With display	~ 100 g

Packaging

Single packaging in cardboard	
-------------------------------	--

Accuracy

Parameter	Unit	±0.5 mbar	0 ... 1 mbar	0 ... 3 mbar	0 ... 5 mbar	0 ... 10 - 50 mbar
Tolerance zero point	max. % fs	±1.0	±1.0	±0.7	±0.7	±0.7
Tolerance zero full scale	max. % fs	±1.0	±1.0	±0.7	±0.7	±0.7
Resolution	% fs	0.2	0.2	0.1	0.1	0.1
Total of linearity, hysteresis and repeatability	max. % fs	±3.0	±2.0	±1.0	±1.0	±0.6
Long term stability acc. to DIN EN 60770	% fs	±1.0	±1.0	±1.0	±1.0	±1.0
TC zero point ⁴⁾	typ. % fs/10K	±0.2	±0.2	±0.2	±0.1	±0.1
TC zero point ⁴⁾	max. % fs/10K	±1.0	±1.0	±0.5	±0.4	±0.4
TC sensitivity ⁴⁾	typ. % fs/10K	±0.3	±0.3	±0.2	±0.1	±0.1
TC sensitivity ⁴⁾	max. % fs/10K	±0.6	±0.6	±0.5	±0.5	±0.2

- no additional root-extracted errors

Test conditions: 25 °C, 45% rF, Power supply 24 VDC
TC z.p. / TC z.p. 0 ... 70 °C

¹⁾ At nominal pressure

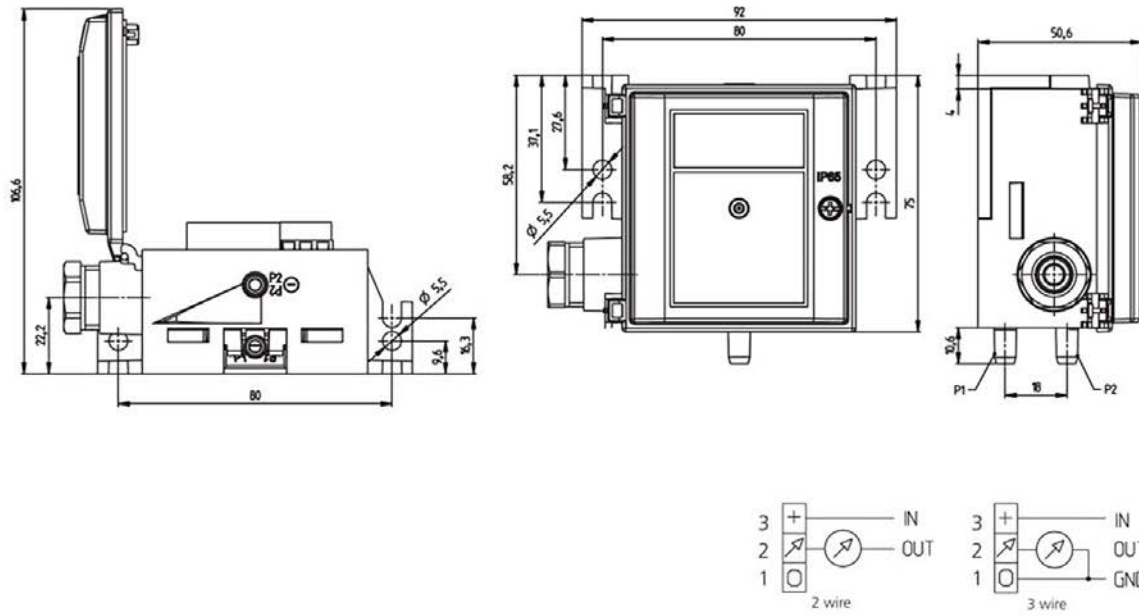
⁴⁾ Signal approximately ~13 Pa lower than actual pressure

²⁾ At ± types forcible

³⁾ TC = Temperature coefficient

³⁾ Signal approximately ~13 Pa higher than actual pressure

Dimensions in mm / Electrical connections



A2.3 Teda Huntleigh Model 1042 Load Cell

VPGTransducers

Celtron • Revere • Sensortronics • Teda-Huntleigh

Model 1042
Teda-Huntleigh

Low Profile Aluminum Load Cell

FEATURES

- Capacities 1–200 kg
- Aluminum construction
- Single-point 400 x 400 mm platform
- OIML R60 and NTEP approved
- IP66 protection
- Available with metric and UNC threads
- **Optional**
 - ATEX, FM, and IECEx approvals available
 - High stiffness version available for dynamic weighing applications



APPLICATIONS

- Bench scales
- Counting scales
- Grocery scales

DESCRIPTION

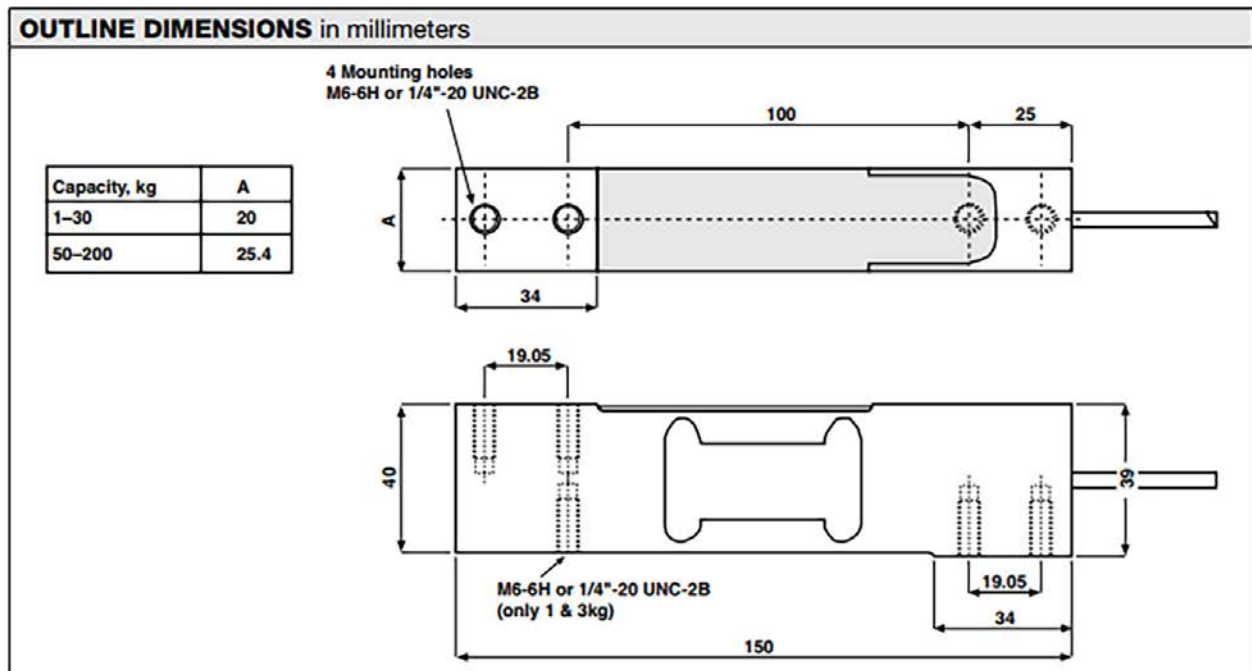
Model 1042 is a low profile single-point load cell designed for direct mounting in weighing platforms.

Its small physical size, combined with high accuracy and low cost, makes this load cell ideally suited for retail, bench and counting scales.

Capacities of 5 kg and above are supplied as standard in anodized aluminum. This high accuracy load cell is approved to NTEP and other stringent approval standards, including OIML R60.

A humidity resistant protective coating assures long-term stability over the entire compensated temperature range.

The two additional sense wires feed back the voltage reaching the load cell. Complete compensation of changes in lead resistance due to temperature change and/or cable extension, is achieved by feeding this voltage into the appropriate electronics.



Model 1042

Tedea-Huntleigh

VPGTransducers

Celltron • Revere • Sensortronics • Tedea-Huntleigh

Low Profile Aluminum Load Cell

SPECIFICATIONS					
PARAMETER	VALUE				UNIT
Rated capacity—R.C. (E_{max})	1 ⁽¹⁾ , 3, 5, 7, 10, 15, 20, 30, 50, 75, 100, 150 ⁽¹⁾ , 200 ⁽¹⁾				kg
NTEP/OIML accuracy class	NTEP	Non-Approved	C3 ⁽²⁾	C6 ⁽²⁾	
Maximum no. of intervals (n)	5000 single	1000	3000	6000 ⁽⁴⁾	
$Y = E_{max}/V_{min}$	10000	1400	6000	10000	Maximum available 20000
Rated output—R.O.	2.0				mV/V
Rated output tolerance	0.2				±mV/V
Zero balance	0.2				±mV/V
Zero return, 30 min.	0.0100	0.0500	0.0170	0.0083	±% of applied load
Total error (per OIML R60)	0.0200	0.0300	0.0200	0.0100	±% of rated output
Temperature effect on zero	0.0014	0.0100	0.0023	0.0014	±% of rated output/°C
Temperature effect on output	0.0010	0.0030	0.0010	0.00058	±% of applied load/°C
Eccentric loading error	0.0042	0.0074	0.0049	0.0024	±% of rated load/cm
Temp. range, compensated	-10 to +40				°C
Temp. range, safe	-30 to +70				°C
Maximum safe central overload	150				% of R.C.
Ultimate central overload	300				% of R.C.
Excitation, recommended	10				VDC or VAC RMS
Excitation, maximum	15				VDC or VAC RMS
Input impedance	415±20				Ω
Output impedance	350±3				Ω
Insulation resistance	>2000				MΩ
Cable length	1 ⁽³⁾				m
Cable type	6 wire, PVC, single floating screen				Standard
Construction	Plated (anodize) aluminum				
Environmental protection	IP66				
Platform size (max)	400 x 400				mm
Recommended torque	Up to 30 kg: 7.0 35 kg and above: 10.0				N*m

⁽¹⁾ 1 kg and 200 kg not approved by OIML; 150 and 200 kg are not approved by NTEP.

⁽²⁾ 50% utilization.

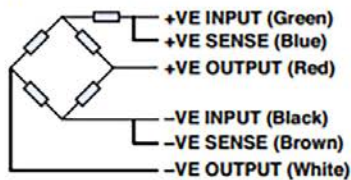
⁽³⁾ 60% utilization.

⁽⁴⁾ 6000 divisions from 20 kg to 100 kg.

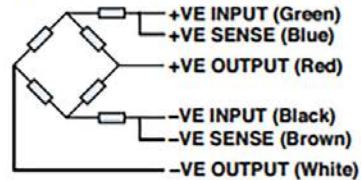
⁽⁵⁾ Options: 4-wire cable; different cable lengths; side cable entry.

All specifications subject to change without notice.

WIRING SCHEMATIC DIAGRAM
(Unbalanced bridge configuration)



WIRING SCHEMATIC DIAGRAM
(Balanced bridge configuration)



A2.4 PM Filter Specifications

A2.4.1 Merck Millipore APFD09050 (coarse filter)

Overview

Description	
Catalogue Number	APFD09050
Description	Glass Fiber Filter without binder

Product Information	
Filter Code	APFD
Filter Color	White
Maximum Operating Temperature	500 °C
Filter Type	Depth filter

Applications	
Application	This 90 mm hydrophilic Glass Fiber filter with a 2.7 µm pore sizes recommended prefilter for 0.9 to 8µm filters, especially for proteinaceous & heavily contaminated liquids. Can be sterilized by EO, gamma & autoclave.

Biological Information	
Wettability	Hydrophilic

Physicochemical Information	
Pore Size	2.7 µm
Gravimetric Extractables	300%
Porosity %	90%
Water Flow Rate	• 2.7 mL/min x cm ²

Dimensions	
Filter Surface	Plain
Thickness	470 µm
Filter Diameter (ø)	90 mm

Materials Information	
Chemistry	• Glass Fiber

Packaging Information	
Material Size	50 pack, APFD, 90 mm

A2.4.2 Pallflex Emfab TX40H120-WW (fine filter)

The 90-mm diameter version of this filter was used for all tests.

TECHNICAL INFORMATION

Description	Pall Emfab Filters
	TX40H120-WW
Filter Media	Borosilicate microfibers reinforced with woven glass cloth and bonded with PTFE
Diameters Available	46.2mm, 47mm, 70mm, 90mm
Typical Thickness	148µm (7 mils)
Typical Filter Weight	5.0 mg/cm ²
Typical Water Flow	
Rated at 5 PSIG (0.35 Bar)	32 mL/min/cm ²
Typical Air Flow Rate	
Rated at 10 PSIG (0.7 Bar)	68 L/in/cm ²
Maximum Operating Temperature-Air	260°C (500°F)
Typical Aerosol Retention (DOP)	99.90%

Appendix 3 Test Fuel Properties

Table A3.1 summarises the property values used for each fuel when calculating EFs and other data throughout this test programme. The values are equal

to, or derived from, proximate and ultimate analyses carried out by ESG on behalf of the project.

Table A3.1. Thermal, physical and chemical properties of test fuels employed for all calculations

Fuel properties	Briquettes	Wood	Bituminous	Smokeless	Sod	Firelighters	Bituminous	Smokeless	Softwood	Hardwood	Peat_briq	Peat_sod
Heating values (dry, ash free), MJkg ⁻¹												
LHV	21.716	18.401	33.176	33.096	20.918	34.088	32.753	25.151	19.562	18.601	21.638	20.899
HHV	23.163	20.177	34.430	34.110	22.512	36.530	33.963	26.756	21.220	20.033	23.003	22.997
hfg_H2O_fuel	0.976	1.266	1.014	0.803	0.932	2.442	0.961	0.871	1.155	1.175	0.869	0.364
Ultimate analysis												
Mass fraction (%)												
massf_C	59.04	50.23	84.14	85.81	57.26	74.50	84.17	68.81	53.31	50.84	58.06	59.69
massf_H	4.83	6.27	5.00	3.97	4.61	12.05	4.75	4.31	5.72	5.82	4.30	1.80
massf_O	34.38	43.27	8.25	6.32	36.76	8.10	8.88	25.73	40.65	43.12	35.67	37.06
massf_S	0.31	0.02	0.47	2.06	0.25	0.20	0.47	0.33	0.02	0.02	0.32	0.24
massf_N	1.37	0.20	1.66	1.79	1.04	4.82	1.52	0.78	0.29	0.20	1.57	1.18
Mol fraction												
mol_perC_C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
mol_perC_H	0.97	1.49	0.71	0.55	0.96	1.93	0.67	0.75	1.28	1.36	0.88	0.36
mol_perC_O	0.44	0.65	0.07	0.06	0.48	0.08	0.08	0.28	0.57	0.64	0.46	0.47
mol_perC_S	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mol_perC_N	0.02	0.00	0.02	0.02	0.02	0.06	0.02	0.01	0.00	0.00	0.02	0.02
Molar mass												
molwt_perC_fuel	20.313	23.890	14.193	13.980	20.942	16.056	14.228	17.434	22.509	23.605	20.653	20.100
Fuel identifier												
Fuel code	1	2	3	4	5	6	7	8	9	10	11	12

Table A3.1. Continued

Fuel properties	Briquettes	Wood	Bituminous	Smokeless	Sod	Firelighters	Bituminous	Smokeless	Softwood	Hardwood	Peat_briq	Peat_sod
							2017	2017	2017	2017	2017	2017
Other fuel properties												
SEAI CO ₂ EF (g GJ ⁻¹)	98,900		94,600		104,000						98,900	
Max theor. CO ₂ EF (g GJ ⁻¹)	99,748	100,091	93,443	95,099	100,442	80,390	94,417	100,347	99,927	100,208	98,456	104,746
ESG mc (%)	13.0	14.3	4.8	3.9	19.0		4.6	17.3	14.3	6.2	13.1	40.2
ESG ash (%)	6.4	0.4	3.1	4.0	1.8	1.7	3.4	3.2	0.8	0.5	11.3	1.5
ESG volatiles (%)	66.9	86.1	36.3	21.3	68.1	94.3	34.6	52.3	80.6	85.4	67.9	67.2
ESG chlorine (%)	0.07	0.01	0.48	0.04	0.08	0.33	0.21	0.04	0.01	0.00	0.08	0.03
hf_ideal_products (MJ kg ⁻¹)	-25.17	-23.99	-33.75	-32.92	-24.33	-39.01	-33.37	-27.74	-24.34	-23.65	-4.22	-21.74
hf_fuel (MJ kg ⁻¹)	-3.46	-5.59	-0.57	0.18	-3.41	-4.92	-0.61	-2.59	-4.78	-5.05	-2.58	-0.84

EF, emission factor; HHV, higher heating value; mc, moisture content.

A3.1 ESG Analyses

A3.1.1 Bituminous coal



Analysis Report

Report Number: 17/FEB/COA/706662
 Supplier: University College Dublin
 Belfield
 Dublin 4
 Ireland

Site: U.C.D
 Grade: 40978
 Our Ref: Coal
 Customer Ref: POLISH COAL

Laboratory References

Date Sampled: 28 February 2017
 Date Received: 28 February 2017
 Test Date: 28 February 2017 to 9 March 2017
 Date Reported: 9 March 2017

Sample Number: 706662
 6m Bottle: 20023
 72m Bottle: 9564
 Bio Bottle: -

Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	3.0	-	-
Ash	CA3	%	3.4	3.5	3.6	-
Total Moisture	SP1 & CA1	%	4.6	-	-	-
Volatile Matter	CA6	%	31.8	32.3	33.3	34.6
Sulphur	CA31	%	0.43	0.44	0.45	0.47
Chlorine	CA36	%	0.19	0.19	0.20	0.21
Gross Calorific Value	CA11	kJ/kg	31246	31770	32753	33963
Net Calorific Value	*	kJ/kg	30133	-	-	-
Carbon	CA9	%	77.44	78.74	81.17	84.17
Hydrogen	CA9	%	4.37	4.44	4.58	4.75
Nitrogen	CA9	%	1.40	1.42	1.47	1.52

--END OF REPORT--

**Analysis Report****Page 1 of 1**

Report Number: 14/MAY/COA/9905a

Client **University College Dublin**
 School of Mechanical & Materials Engineering
 Belfield
 Dublin 4
 Ireland

Sample Reference: **Polish Coal**

Date Sampled:

Date Received: 12 May 2014

Test Date: 14 to 27 May 2014

Date Reported: 27 May 2014

			Results Basis	
Method Reference		Units	As Received *	Dry Ash Free *
SP1 & CA1	Total Moisture	%	4.8	-
CA 3	Ash	%	3.1	-
CA 6	Volatile Matter	%	33.4	36.3
CA31	Total Sulphur	%	0.43	-
CA34 / CA35	Chlorine	%	0.25	-
CA9	Carbon	%	77.49	-
CA9	Hydrogen	%	4.60	-
CA9	Nitrogen	%	1.53	-
CA11	Gross Calorific Value	kJ/kg	31707	34430
*	Net Calorific Value	kJ/kg	30552	-

* Calculated using UKAS accredited results

A3.1.2 Smokeless coal



Analysis Report

Report Number: 17/FEB/COA/706661
 Supplier: University College Dublin
 Belfield
 Dublin 4
 Ireland

Site: U.C.D
 Grade: 40978
 Our Ref: Coal
 Customer Ref: SMOKELESS COAL

Laboratory References

Date Sampled: 28 February 2017
 Date Received: 28 February 2017
 Test Date: 28 February 2017 to 9 March 2017
 Date Reported: 9 March 2017

Sample Number: 706661
 6m Bottle: 19021
 72m Bottle: 5901
 Bio Bottle: -

Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	9.8	-	-
Ash	CA3	%	3.2	3.5	3.9	-
Total Moisture	SP1 & CA1	%	17.3	-	-	-
Volatile Matter	CA6	%	41.6	45.4	50.3	52.3
Sulphur	CA31	%	0.26	0.28	0.31	0.33
Chlorine	CA36	%	0.03	0.03	0.04	0.04
Gross Calorific Value	CA11	kJ/kg	21271	23200	25721	26756
Net Calorific Value	*	kJ/kg	19995	-	-	-
Carbon	CA9	%	54.70	59.66	66.14	68.81
Hydrogen	CA9	%	3.43	3.74	4.15	4.31
Nitrogen	CA9	%	0.62	0.68	0.75	0.78

--END OF REPORT--



Analysis Report

Page 1 of 1

Report Number: 14/MAY/COA/9905b

Client **University College Dublin**
School of Mechanical & Materials Engineering
Belfield
Dublin 4
Ireland

Sample Reference: **Smokeless Coal Ovoids**

Date Sampled:

Date Received: 12 May 2014

Test Date: 14 to 27 May 2014

Date Reported: 27 May 2014

Method Reference		Units	Results Basis	
			As Received *	Dry Ash Free *
SP1 & CA1	Total Moisture	%	3.9	-
CA 3	Ash	%	4.0	-
CA 6	Volatile Matter	%	19.6	21.3
CA31	Total Sulphur	%	1.90	-
CA34 / CA35	Chlorine	%	0.04	-
CA9	Carbon	%	79.03	-
CA9	Hydrogen	%	3.66	-
CA9	Nitrogen	%	1.65	-
CA11	Gross Calorific Value	kJ/kg	31416	34110
*	Net Calorific Value	kJ/kg	30482	-

* Calculated using UKAS accredited results

A3.1.3 Peat briquettes



Analysis Report

Report Number: 17/FEB/COA/707140
 Supplier: University College Dublin
 Belfield
 Dublin 4
 Ireland

Site: U.C.D
 Grade: 40986
 Our Ref: PEAT
 Customer Ref: PEAT BRIQUETTES

Laboratory References

Date Sampled: 28 February 2017
 Date Received: 28 February 2017
 Test Date: 28 February 2017 to 16 March 2017
 Date Reported: 16 March 2017

Sample Number: 707140
 6m Bottle:
 72m Bottle: 16424
 Bio Bottle: 707140



Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	10.7	-	-
Ash	CA3	%	11.3	11.6	13.0	-
Total Moisture	SP19 & CA2	%	13.1	-	-	-
Volatile Matter	CA6	%	51.3	52.7	59.0	67.9
Sulphur	CA31	%	0.24	0.25	0.28	0.32
Chlorine	**	%	0.06	0.06	0.07	0.08
Gross Calorific Value	CA11	kJ/kg	17390	17870	20012	23003
Net Calorific Value	*	kJ/kg	16358	-	-	-
Carbon	CA9	%	43.89	45.10	50.51	58.06
Hydrogen	CA9	%	3.25	3.34	3.74	4.30
Nitrogen	CA9	%	1.19	1.22	1.37	1.57

--END OF REPORT--



Analysis Report

Page 1 of 1

Report Number: 14/MAY/COA/9907a

Client: **University College Dublin**
School of Mechanical & Materials Engineering
Belfield
Dublin 4
Ireland

Sample Reference **Peat Briquettes**

Date Sampled:

Date Received: 12 May 2014

Test Date: 14 to 30 May 2014

Date Reported: 30 May 2014

Method Reference		Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
SP20	Total Moisture	%	13.0	-	-	-
CA2	Analysis Moisture	%	-	9.2	-	-
CA 3	Ash	%	6.4	6.7	7.4	-
CA 6	Volatile Matter	%	53.9	56.3	62.0	66.9
CA31	Total Sulphur	%	0.25	0.26	0.29	0.31
**	Chlorine	%	0.06	0.06	0.07	0.07
CA9	Carbon	%	47.57	49.65	54.68	59.04
CA9	Hydrogen	%	3.89	4.06	4.47	4.83
CA9	Nitrogen	%	1.10	1.15	1.27	1.37
CA11	Gross Calorific Value	kJ/kg	18665	19480	21454	23163
*	Net Calorific Value	kJ/kg	17499	-	-	-

Report Authorised By
Jonathan Clay
Head of Client Services
(Energy Services Reporting)
For and on behalf of Environmental Scientifics Group Ltd

* denotes calculated values using UKAS accredited results

** Non accredited method for this matrix

*** sub contracted test

A3.1.4 Sod peat

**Analysis Report**

Report Number: 17/FEB/COA/707141

Supplier: University College Dublin
Belfield
Dublin 4
Ireland

Site: U.C.D

Grade: 40986

Our Ref: PEAT

Customer Ref: SOD PEAT

Laboratory References

Date Sampled: 28 February 2017

Sample Number: 707141

Date Received: 28 February 2017

6m Bottle:

Test Date: 28 February 2017 to 16 March 2017

72m Bottle: 16425

Date Reported: 16 March 2017

Bio Bottle: 707141

Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	26.0	-	-
Ash	CA3	%	1.5	1.9	2.5	-
Total Moisture	SP19 & CA2	%	40.2	-	-	-
Volatile Matter	CA6	%	39.2	48.5	65.6	67.2
Sulphur	CA31	%	0.14	0.17	0.23	0.24
Chlorine	**	%	0.02	0.03	0.03	0.03
Gross Calorific Value	CA11	kJ/kg	13407	16590	22420	22997
Net Calorific Value	*	kJ/kg	12184	-	-	-
Carbon	CA9	%	34.80	43.06	58.19	59.69
Hydrogen	CA9	%	1.05	1.30	1.76	1.80
Nitrogen	CA9	%	0.69	0.85	1.15	1.18

--END OF REPORT--



Analysis Report

Page 1 of 1

Report Number: 14/MAY/COA/9907b

Client: **University College Dublin**
School of Mechanical & Materials Engineering
Belfield
Dublin 4
Ireland

Sample Reference: **Sod Peat**

Date Sampled:

Date Received: 12 May 2014

Test Date: 14 to 30 May 2014

Date Reported: 30 May 2014

Method Reference		Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
SP20	Total Moisture	%	19.0	-	-	-
CA2	Analysis Moisture	%	-	11.6	-	-
CA 3	Ash	%	1.8	2.0	2.3	-
CA 6	Volatile Matter	%	53.9	58.8	66.5	68.1
CA31	Total Sulphur	%	0.20	0.22	0.25	0.25
**	Chlorine	%	0.06	0.07	0.08	0.08
CA9	Carbon	%	45.33	49.47	55.96	57.26
CA9	Hydrogen	%	3.65	3.98	4.50	4.61
CA9	Nitrogen	%	0.82	0.90	1.02	1.04
CA11	Gross Calorific Value	kJ/kg	17822	19450	22002	22512
*	Net Calorific Value	kJ/kg	16560	-	-	-

Report Authorised By
Jonathan Clay
Head of Client Services
(Energy Services Reporting)
For and on behalf of Environmental Scientifics Group Ltd

* denotes calculated values using UKAS accredited results
** Non accredited method for this matrix
*** sub contracted test

A3.1.5 Kiln-dried hardwood



Analysis Report

Report Number: 17/FEB/COA/707143
 Supplier: University College Dublin
 Belfield
 Dublin 4
 Ireland

Site: U.C.D
 Grade: 40985
 Our Ref: BIO
 Customer Ref: WOOD SAMPLE 2

Laboratory References

Date Sampled: 28 February 2017
 Date Received: 28 February 2017
 Test Date: 28 February 2017 to 10 March 2017
 Date Reported: 16 March 2017

Sample Number: 707143
 6m Bottle:
 72m Bottle:
 Bio Bottle: 707143

Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	5.0	-	-
Ash	CA3	%	0.5	0.5	0.5	-
Total Moisture	SP19 & CA2	%	6.2	-	-	-
Volatile Matter	CA6	%	79.7	80.7	85.0	85.4
Sulphur	CA31	%	0.02	0.02	0.02	0.02
Chlorine	CA36	%	< 0.01	< 0.01	< 0.01	< 0.01
Gross Calorific Value	CA11	kJ/kg	18691	18930	19926	20033
Net Calorific Value	*	kJ/kg	17355	-	-	-
Carbon	CA9	%	47.43	48.04	50.57	50.84
Hydrogen	CA9	%	5.43	5.50	5.79	5.82
Nitrogen	CA9	%	0.19	0.19	0.20	0.20

--END OF REPORT--

A3.1.6 Air-dried softwood

**Analysis Report**

Report Number: 17/FEB/COA/707142
 Supplier: University College Dublin
 Belfield
 Dublin 4
 Ireland

Site: U.C.D
 Grade: 40985
 Our Ref: BIO
 Customer Ref: WOOD SAMPLE 1

Laboratory References

Date Sampled: 28 February 2017
 Date Received: 28 February 2017
 Test Date: 28 February 2017 to 10 March 2017
 Date Reported: 16 March 2017

Sample Number: 707142
 6m Bottle:
 72m Bottle:
 Bio Bottle: 707142

Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	7.1	-	-
Ash	CA3	%	0.8	0.9	0.9	-
Total Moisture	SP19 & CA2	%	14.3	-	-	-
Volatile Matter	CA6	%	68.4	74.1	79.8	80.6
Sulphur	CA31	%	0.02	0.02	0.02	0.02
Chlorine	CA36	%	0.01	0.01	0.01	0.01
Gross Calorific Value	CA11	kJ/kg	18016	19530	21022	21220
Net Calorific Value	*	kJ/kg	16608	-	-	-
Carbon	CA9	%	45.26	49.06	52.81	53.31
Hydrogen	CA9	%	4.86	5.27	5.67	5.72
Nitrogen	CA9	%	0.25	0.27	0.29	0.29

--END OF REPORT--



Analysis Report

Page 1 of 1

Report Number: 14/MAY/COA/9906

Client: **University College Dublin**
School of Mechanical & Materials Engineering
Belfield
Dublin 4
Ireland

Sample Reference **Wood Logs**

Date Sampled:

Date Received: 12 May 2014

Test Date: 14 to 28 May 2014

Date Reported: 28 May 2014

Method Reference		Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
SP20	Total Moisture	%	14.3	-	-	-
CA2	Analysis Moisture	%	-	3.4	-	-
CA 3	Ash	%	0.4	0.5	0.5	-
CA 6	Volatile Matter	%	73.4	82.7	85.6	86.1
CA31	Total Sulphur	%	0.02	0.02	0.02	0.02
**	Chlorine	%	0.01	0.01	0.01	0.01
CA9	Carbon	%	42.82	48.27	49.97	50.23
CA9	Hydrogen	%	5.35	6.03	6.24	6.27
CA9	Nitrogen	%	0.17	0.19	0.20	0.20
CA11	Gross Calorific Value	kJ/kg	17202	19390	20072	20177
*	Net Calorific Value	kJ/kg	15688	-	-	-

Report Authorised By
Jonathan Clay
Head of Client Services
(Energy Services Reporting)
For and on behalf of Environmental Scientifics Group Ltd

A3.1.7 Firelighters

**Analysis Report**

Report Number: 17/FEB/COA/707144
 Supplier: University College Dublin
 Belfield
 Dublin 4
 Ireland

Site: U.C.D
 Grade: 40984
 Our Ref: SRF
 Customer Ref: FIRELIGHTERS

Laboratory References

Date Sampled: 28 February 2017
 Date Received: 28 February 2017
 Test Date: 28 February 2017 to 15 March 2017
 Date Reported: 16 March 2017

Sample Number: 707144
 6m Bottle:
 72m Bottle:
 Bio Bottle: 707144

Test	Method Reference	Units	Results Basis			
			As Received *	As Analysed	Dry *	Dry Ash Free *
Analysis Moisture	CA2	%	-	< 0.1	-	-
Ash	CA3	%	-	1.7	1.7	-
Volatile Matter	CA6	%	-	94.3	94.3	95.9
Sulphur	CA31	%	-	0.15	0.15	0.20
Chlorine	CA36	%	-	0.32	0.32	0.33
Gross Calorific Value	CA11	kJ/kg	-	36530	-	-
Carbon	CA9	%	-	73.23	-	-
Hydrogen	CA9	%	-	11.85	11.85	12.05
Nitrogen	CA9	%	-	4.74	4.74	4.82

--END OF REPORT--

Appendix 4 Arrangement of Fuel in the Stove, Prior to Ignition

The goals, when arranging the fuel in the stove, were twofold: first, to enable the fuel to ignite and burn as cleanly and efficiently as possible; second, to provide consistency of initial conditions between tests. Some studies of biomass combustion have suggested that “top-down” ignition of the fuel minimises emissions (Bäfver *et al.*, 2011; Nussbaumer, 2017), so this approach was used for all fuels in this study. A base layer of fuel was placed in the basket, firelighters were arranged in a consistent pattern on top and the remaining fuel was placed around and above the firelighters.

Consistency of stacking varied from fuel to fuel, depending on the size and shape of the fuel elements. Peat briquettes and smokeless coal were easiest to arrange, being of relatively uniform size and shape,

although a fuel element might need to be broken in order to remain close to the 3.5-kg load target. Achieving consistency with wood logs, or bituminous coal, is considerably more difficult, but a satisfactory arrangement was achieved for each test.

A4.1 Peat Briquettes (Figure A4.1)

Peat briquettes are the easiest of these fuels to arrange consistently. For all tests, two briquettes were placed face-down on the floor of the basket; three briquettes were positioned, on their side, on top of these two; firelighters were placed in the two channels formed by these three briquettes; and finally two more briquettes were placed, flat, across the top, forming a “roof” over the firelighters.

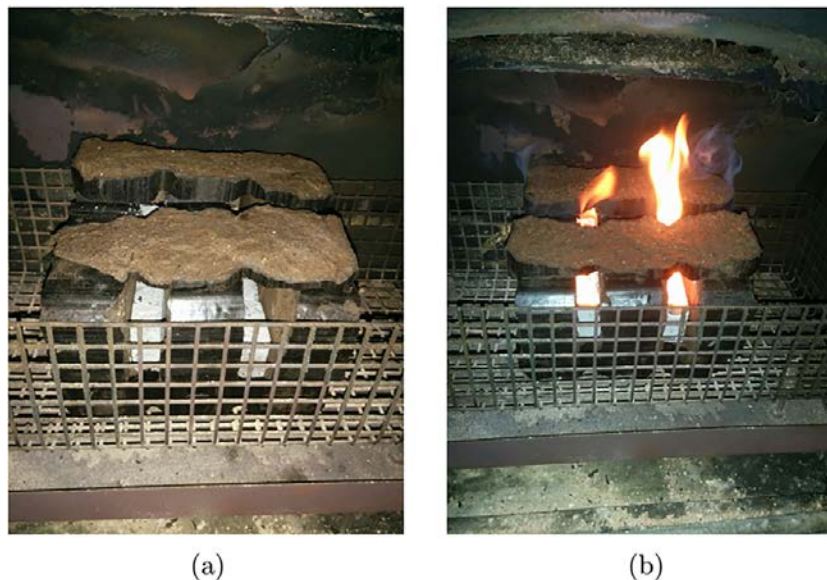


Figure A4.1. Arrangement of briquettes and firelighters in the stove (a) prior to and (b) immediately after ignition. The top two briquettes were trimmed to achieve the target load of 3.5 kg of test fuel.

A4.2 Bituminous Coal (Figure A4.2)

Bituminous coal pieces are non-uniform in size and shape and therefore can be difficult to arrange consistently. A layer of coal was placed on the basket, with firelighters sitting on this layer. Additional coal was then stacked around and on top of the firelighters, until the required 3.5 kg had been added.



(a)



(b)

Figure A4.2. Arrangement of bituminous coal in the stove (a) prior to and (b) immediately after ignition. The stability of the fuel stack varied from test to test.



(a)



(b)

Figure A4.3. Arrangement of smokeless coal pieces and firelighters in the stove (a) prior to and (b) immediately after ignition.

A4.4 Kiln-dried Hardwood (Figure A4.4)

The hardwood logs are typically fairly uniform in shape. However, because the mass density of dry wood is lower than that of the other fuels, 3.5kg of logs consumes significantly more space in the stove, making them difficult at times to stack. Some trial and error is required to find the best way to fit the logs for any given burn.



(a)



(b)

Figure A4.4. Arrangement of kiln-dried logs and firelighters in the stove (a) prior to and (b) immediately after ignition



(a)



(b)

Figure A4.5. Arrangement of air-dried softwood logs and firelighters in the stove (a) prior to and (b) immediately after ignition

A4.6 Sod Peat (Figure A4.6)

Sod peat presented an exception to the general approach outlined above. Because of its very poor ignition characteristics, satisfactory combustion could not be achieved using firelighters and a fundamentally different approach was required. An “ignition charge” comprising 100 g of firelighters and 500 g of kiln-dried

kindling was placed in the stove and lit. Once the flue gas temperature at the stove exit had stabilised at about 300°C (which usually occurred within 8–12 minutes of ignition), the stove door was opened and the sod peat added to the fire. In general, larger sod is placed directly onto the fire bed, with smaller pieces placed on top of these. Sampling of emissions commenced once the stove door was closed again.



(a)



(b)

Figure A4.6. (a) Arrangement of kindling and firelighters in the stove. (b) The sod peat was added to the kindling once a hot, stable fire bed had been formed.

Appendix 5 Combustion Image Samples

These images provide snapshots of a single combustion experiment for each fuel tested. They provide an overview of the progression of a typical experiment with each fuel.

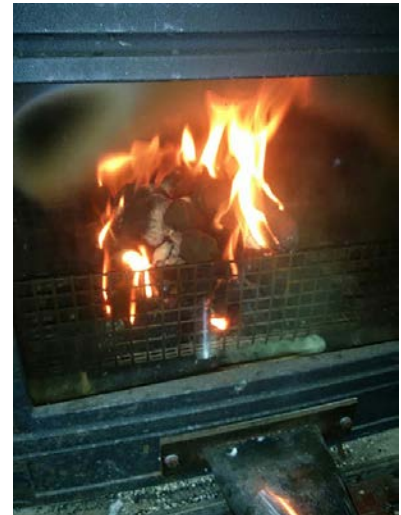
A5.1 Bituminous Coal – 29 September 2016



(a)



(b)



(c)



(d)



(e)



(f)

Figure A5.1. (a) Fuel arrangement ($t=0$); (b) $t+15$ minutes; (c) $t+1$ hour; (d) $t+2$ hours; (e) $t+4$ hours; (f) $t+7$ hours.

A5.2 Peat Briquettes – 12 May 2016

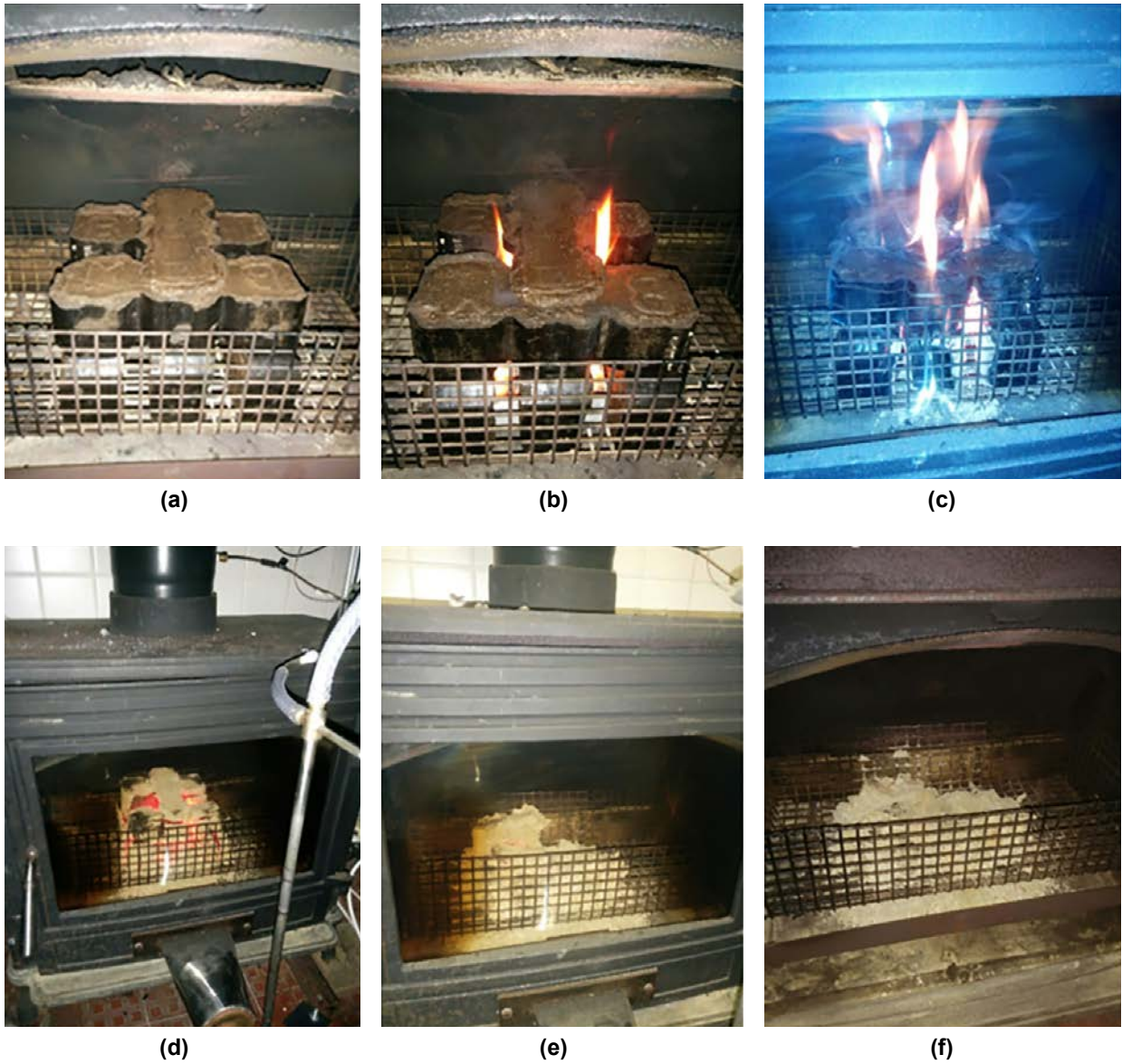


Figure A5.2. (a) Fuel arrangement ($t=0$); (b) $t+15$ minutes; (c) $t+70$ minutes; (d) $t+2.5$ hours; (e) $t+4.5$ hours; (f) $t+1$ day.

**A5.3 Smokeless Coal –
15 September 2016**



(a)



(b)



(c)



(d)



(e)



(f)

Figure A5.3. (a) Fuel arrangement ($t=0$); (b) $t+1$ minute; (c) $t+2$ hours; (d) $t+2.4$ hours; (e) $t+4$ hours; (f) $t+1$ day.

**A5.4 Kiln-dried Hardwood –
17 October 2016**



(a)



(b)



(c)



(d)



(e)



(f)

Figure A5.4. (a) Fuel arrangement ($t=0$); (b) $t+3$ minutes; (c) $t+50$ minutes; (d) $t+1.8$ hours; (e) $t+2.5$ hours; (f) $t+8$ hours.

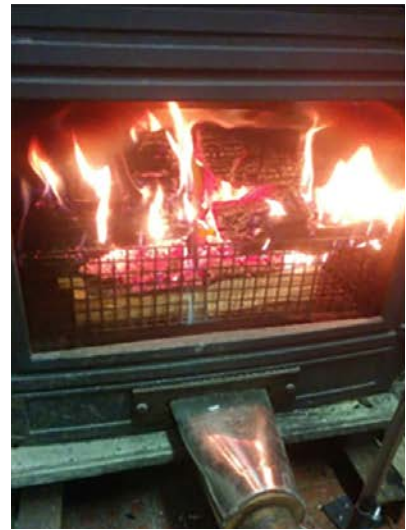
**A5.5 Air-dried Softwood –
28 October 2016**



(a)



(b)



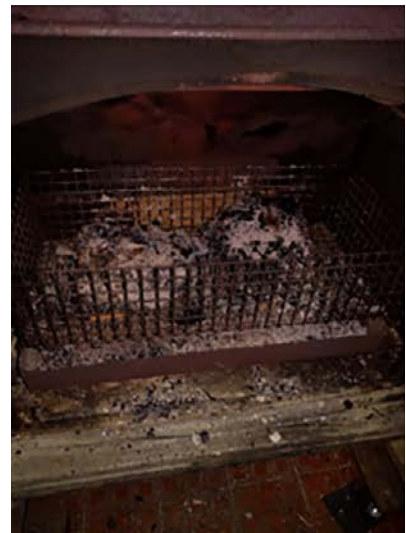
(c)



(d)



(e)



(f)

Figure A5.5. (a) Fuel arrangement ($t=0$); (b) $t+3$ minutes; (c) $t+40$ minutes; (d) $t+1.6$ hours; (e) $t+2.2$ hours; (f) $t+3$ days.

A5.6 Sod Peat – 20 February 2017



(a)



(b)



(c)



(d)



(e)



(f)

Figure A5.6. (a) Fuel arrangement ($t=0$); (b) $t+8$ minutes; (c) $t+25$ minutes; (d) $t+50$ minutes; (e) $t+1.5$ hours; (f) $t+1$ day.

Appendix 6 Comparison of Mass Collected on the PM Sampling Filter and on the Filter in the Gas Sampling Line

The filters used to determine the PM EF for each test are connected to the sampling port in the flue via a short, horizontal metal tube that is maintained at high temperature throughout the test. The likelihood of condensation within that tube is therefore low. Moreover, the contents of the tube are blown onto a filter paper at the end of each test, so that any mass deposited in the tube is recovered prior to weighing the filters.

In contrast, the purpose of the filter in the gas sampling line is simply to prevent PM reaching the gas analyser. Although the filter housing is heated (to prevent condensation on the filters themselves, which can cause blockage), the gas is transported to the filter via a plastic tube about 120 cm in length, which incorporates an elevation increase of about 90 cm

– with the explicit intention of discouraging the flow of liquid droplets as far as the filter housing. The sample flow rate through the gas line is about one-third of that in the PM sampling line and is less accurately controlled.

Nonetheless, one would expect some correlation between the mass of PM collected on the PM sampling line and that collected on the gas line. As shown below, the results are encouraging but with some intriguing discrepancies.

Figure A6.1 plots the crude PM EF, obtained using the filters on the gas sampling line, against the true EF for all fuels tested. A reasonably good correlation is observed, albeit with substantial scatter for sod peat and bituminous coal in particular. Figure A6.2 presents the same information for each fuel in isolation.

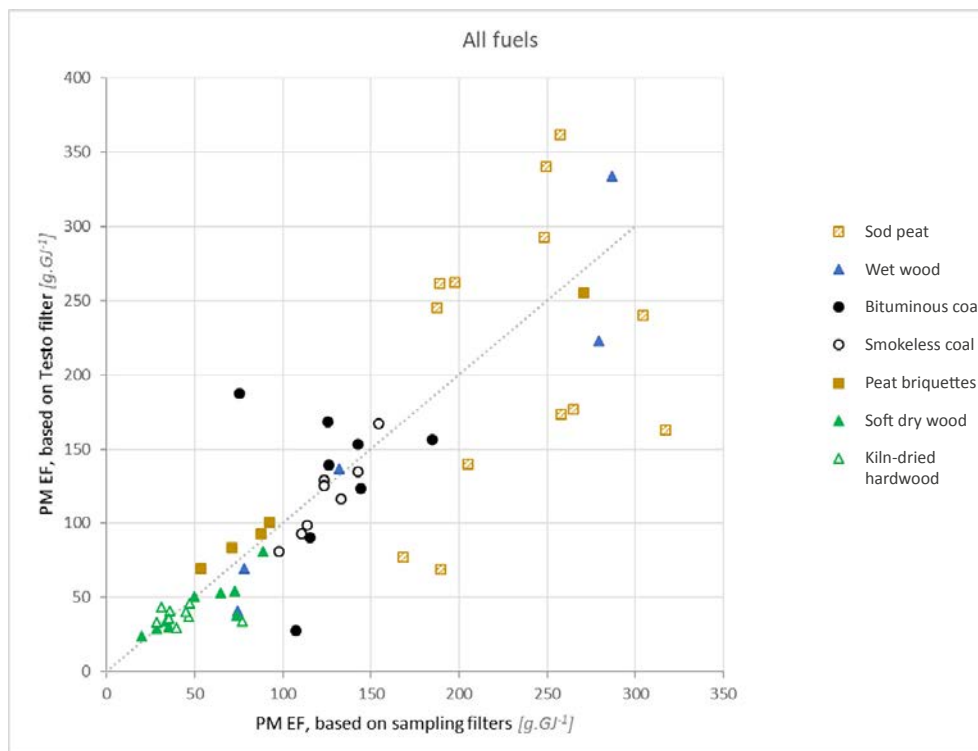


Figure A6.1. Comparison between the true PM emission factor and the emission factor estimated from the filter on the gas sampling line (Testo filter), for all fuels. The dashed line represents the locus of equal values.

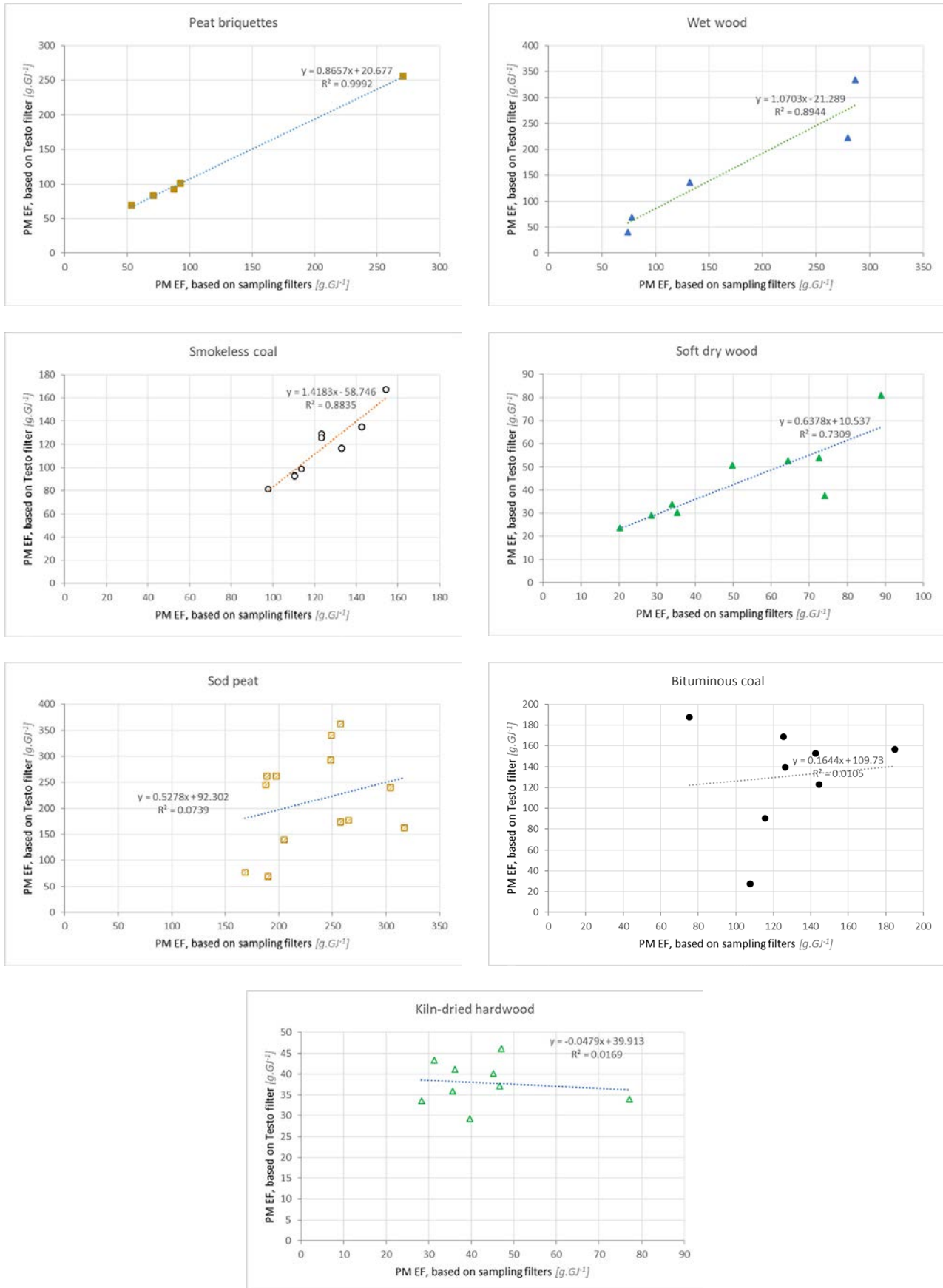


Figure A6.2. Comparison between the true PM emission factor and the emission factor estimated from the filter on the gas sampling line (Testo filter), for each fuel individually. Strong variations can be seen in the strength – and for kiln-dried hardwood, even the direction – of the correlation.

Appendix 7 Influence of Fuel Chemistry on PM and NO_x Emissions

Because combustion in solid-fuel stoves occurs at relatively modest temperatures (<1000°C), and dissociation of the molecular nitrogen in air becomes significant only at temperatures above this value, combustion theory predicts that most of the NO_x formed is derived from fuel-bound nitrogen. Figure A7.1 plots, for the fuels tested and for firelighters, the NO_x EF as a function of the fuel nitrogen content – with the latter expressed in terms of grams of nitrogen per gigajoule of energy in each fuel.

It is clear from Figure A7.1 that a strong correlation exists between the observed NO_x EF and the nitrogen content of the fuel: the R^2 value of 0.924 is high. The slope of the best-fit line represents the mass of NO_x emitted per unit mass of fuel consumed, i.e. $g_{NO_x}/g_{N \text{ in fuel}}$.

As noted throughout this report, PM formation mechanisms are complex and sensitive to many variables. Nonetheless, the PM captured using the hot-filter measurement technique employed in this project will be dominated by solid, carbonaceous

particles. One might therefore reasonably expect that the carbon content of the fuel would influence the mass of PM produced. A slightly more sophisticated analysis of the combustion process would infer that the ratio of carbon atoms to hydrogen atoms – the C:H ratio – would offer a more reliable indicator of probable PM emission intensity.

Figure A7.2 plots the PM EF, as a function of C:H ratio, for each of the fuels tested and for firelighters. It is clear that the PM emission intensity of the firelighters is an order of magnitude higher than that of the test fuels. However, if the firelighters are therefore excluded from the regression analysis, a very good correlation is found between the mean ($\pm 95\%$ CI) PM EF and the C:H ratio of the fuel, with an R^2 value of 0.946. It should be noted, however, that the C:H ratio is a weak predictor of the probable PM emissions from an individual combustion test, as illustrated in Figure A7.3. The same figure also underlines, once again, the very substantial test-to-test variability of PM emissions associated with peat-based fuels and with sod peat in particular.

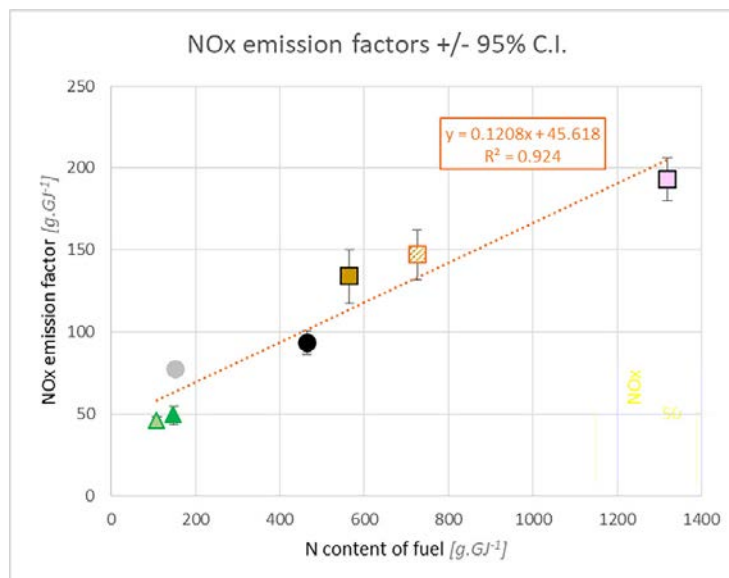


Figure A7.1. Mean NO_x emission factors (with 95% CIs shown as vertical bars) for the individual fuels as a function of fuel nitrogen content. Individual fuels are identified as follows: light-green triangle – kiln-dried hardwood; solid green triangle – air-dried softwood; grey circle – smokeless coal nuggets; solid black circle – bituminous coal; solid brown square – peat briquettes; hatched brown square – sod peat; pink square – firelighters.

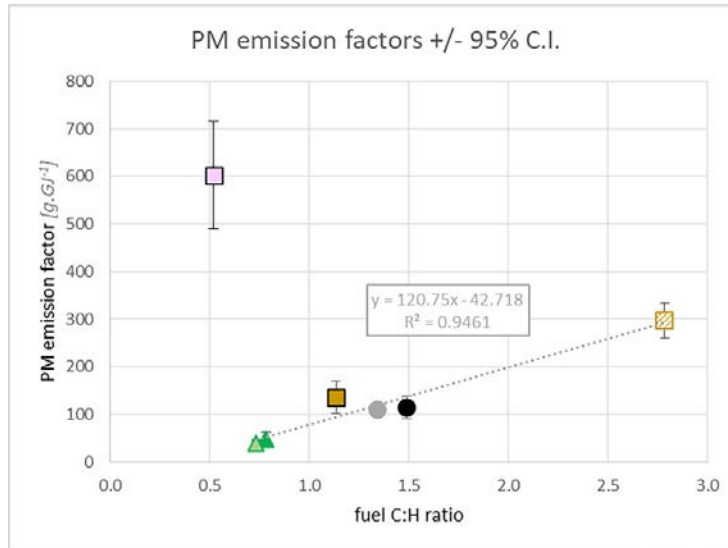


Figure A7.2. Mean PM emission factors (with 95% CIs shown as horizontal bars) for the individual fuels as a function of molar C:H ratio. Individual fuels are identified as follows: light-green triangle – kiln-dried hardwood; solid green triangle – air-dried softwood; grey circle – smokeless coal nuggets; solid black circle – bituminous coal; solid brown square – peat briquettes; hatched brown square – sod peat; pink square – firelighters.

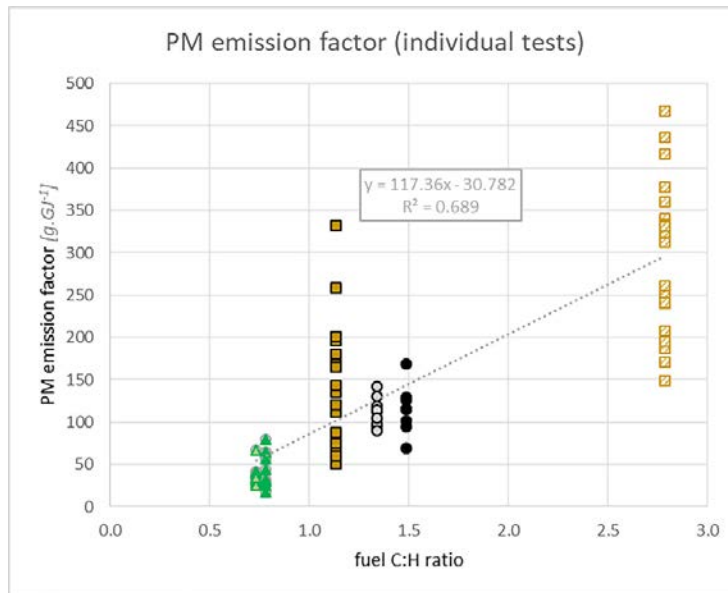


Figure A7.3. PM emission factors, as a function of C:H ratio, for individual combustion tests. Individual fuels are identified as follows: light-green triangle – kiln-dried hardwood; solid green triangle – air-dried softwood; grey circle – smokeless coal nuggets; solid black circle – bituminous coal; solid brown square – peat briquettes; hatched brown square – sod peat.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Gníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: Déanaimid córais éifeachtacha rialaithe agus comhlionta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.

Eolas: Soláthraimid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírthe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.

Tacaíocht: Bimid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola (*m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola*);
- gníomhaíochtaí tionsclaíocha ar scála mór (*m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta*);
- an diantalmhaíocht (*m.sh. muca, éanlaith*);
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe (*OGM*);
- foinsí radaíochta ianúcháin (*m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha*);
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídionn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uisce idirchriosacha agus cósta na hÉireann, agus screamhuisc; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil (*m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí*).

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaitheint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn (*m.sh. mórfhleananna forbartha*).

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d’earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol (*m.sh. Timpeall an Tí, léarscáileanna radóin*).
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chos agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d’Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair inní agus le comhairle a chur ar an mBord.

Emission Factors from Domestic-scale Solid-fuel Appliances (EFDOSOF)



Authors: W.J. Smith and C. Quinn

The Emission Factors from Domestic-scale Solid-fuel Appliances (EFDOSOF) study set out to establish representative, real-world emission factors (EFs) for the range of solid fuels used for residential combustion in Ireland. The improved EFs developed during this study will inform and improve Ireland's response to the UNECE Convention on Long-range Transboundary Air Pollution and to the EU National Emission Ceilings Directive. The EF data can also be used to refine spatially resolved estimates of emission intensity from these sources and to inform policy at local and national levels.

Identifying Pressures

In Ireland, particulate matter with a characteristic size of 2.5 microns or less (PM_{2.5}) is the primary cause of premature death linked to air pollution; the 2019 air quality report from the European Environment Agency attributes over 90% of such deaths to this cause. Although the introduction of a smoky coal ban has significantly improved air quality and mortality rates in a number of Irish towns and cities, combustion of solid fuels in the residential sector remains the largest single contributor of these emissions and also contributes significantly to emissions of gaseous pollutants such as nitrogen oxides, carbon monoxide and sulfur oxides. Establishing representative EFs for the combustion of solid fuels is required to ensure robust national reporting of air pollutant emissions and to inform policies to reduce air pollution.

The EFs presented in this report were obtained using a domestic stove designed to current standards; EFs for open fires are likely to be higher and those for stoves designed to Ecodesign Directive standards are likely to be lower than those presented here. Particulate emissions were determined by passing a sample of raw flue gas through a heated (120°C) filter. PM data obtained using this "hot filter" technique are generally lower than those obtained using a dilution tunnel, particularly for fuels (such as wood and peat) containing a high proportion of volatiles. This report highlights that significant variations occur from test to test, and emissions from the ignition and start-up phases contribute significantly to total emissions. This makes the determination of representative EFs challenging, a challenge that was overcome by completing several hundred such tests to provide statistically robust EFs.

Informing Policy

These results are unique in several respects: they represent emissions over the complete combustion cycle, from ignition through to extinction; they cover sod peat, peat briquettes, bituminous and smokeless coals, hardwood, softwood and firelighters; and they are statistically robust. The results reveal that emissions of PM_{2.5} were high, relative to other sources, for all fuels tested (10–100 times higher than for a modern diesel passenger car). PM_{2.5} emissions from sod peat were highest of all fuels tested. Firelighters, although accounting for only 3% of fuel mass, were found to contribute 15–40% of PM_{2.5} emissions for a typical test. These findings provide a firm basis on which to build policies to improve urban air quality and to reduce negative impacts of emissions of PM_{2.5} on human health.

Developing Solutions

This report concludes that the combustion of solid fuels in manually operated stoves and other domestic-scale appliances results in high levels of emissions of PM_{2.5}. The adverse impact on local air quality will be greatest in urban areas and where the use of such appliances is concentrated. The combustion of sod peat in urban areas is especially undesirable.

The study highlighted that the moisture content of wood fuels has a significant bearing on both the emission intensity and the efficiency of the combustion process. This report recommends considering the regulation of fuel quality for commercially traded wood fuels.

Finally, this study has identified firelighters as a potentially significant, and previously unrecognised, source of particulate emissions. The report recommends that development and imposition of particulate matter emission standards for firelighters may be advisable.