Future Fuels Report

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Project ID: ECM_61934 Emission Factors for Domestic Solid Fuels

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Executive Summary

The following report is a summary of experimental results conducted at the University of Leeds with additional information collected during a literature review. Data collected at the University of Leeds relates to the following fuels of interest; *commercial coffee logs, biocoal* and *lignite*. The data are the product of experimental research undertaken on a 5.7 kW Waterford Stanley Oisin multifuel heating stove. Results have previously been reported in a series of publications which have been referenced throughout this summary. There is currently limited information available on these fuels with regards to emissions and combustion performance in small residential appliances. The aim of this work was to outline the results obtained during previous testing experiences for the purpose of guiding additional testing.

The primary findings of this report are outlined as follows;

Coffee logs are a newly emerged commercial fuel which has become a significant resource within the domestic heating market. Bio-bean is the most significant producer of spent coffee ground (SCG) briquettes within the UK fuel market. The fuel is an energy from waste product comprising recycled and compressed waste coffee grounds. Additionally, the manufacturer maintains that the SCG briquetted fuel burns 20% hotter than fuelwood with greenhouse gas emissions 130 % lower. Combustion testing was undertaken in parallel with willow fuelwood logs for comparative purposes; the experimental methodologies were maintained for both fuel types. The average burning rate was found to be higher during the combustion of the SCG coffee log briquettes during both the flaming (3.21 kg/hour) and smouldering (2.46 kg/hour) test phases. This is likely in response to the higher combustion temperatures observed during the combustion of the coffee log briquettes ($\bar{x}$ = 460 °C) when compared with fuelwood ($\bar{x}$ = 364 °C). The modified combustion efficiency (MCE) was applied as a proxy for the average combustion efficiency was found to be similar for both fuels. The average gaseous pollutant emission factor (EF) was found to be higher for CO_2, CO, CH_4, NOx and PM for coffee logs than for willow. High NOx emissions were observed due to the higher fuel nitrogen content associated with the coffee briquettes.

Lignite briquettes (brown coal) were tested alongside anthracite (hard coal) and bituminous coal (soft coal). The lignite briquettes presented the highest moisture content (13.4 %) resulting in the lowest heating value (LHV = 24.59 MJ/kg). Additionally, the lignite fuel maintained a volatile matter content which was significantly higher than the other fuels (50.6 %). The lignite briquettes burned at a faster rate than other coal-based fuels (0.99 kg/h) but slower than what is typically observed during fuelwood combustion. The CO emission observed during lignite combustion was higher than that which was observed during the combustion of smokeless anthracite but lower than what was observed during the combustion of bituminous coal. The NOx emission for each coal-based fuel were found to be similar. Lignite combustion resulted in a moderate PM emission (3 g/kg) which was higher than smokeless anthracite (0.5 g/kg) but lower than bituminous coal (4.16 g/kg).

Biocoal is a manufactured coal briquette comprising a biomass fraction with a supplemented coal or coal fraction. There is currently no clearly defined description of biocoal fuels with such products often including differing components and percentage compositions. Furthermore, the methods of material pre-treatment are also known to

vary during the manufacturing stage. A biocoal briquette comprising 50 % olive stone and 50 % coal-derived residues was tested alongside bituminous coal and seasoned hardwood. The rate of biocoal combustion was more similar to what was observed during the combustion of bituminous coal and slower than fuelwood combustion. The combustion temperature was found to be significantly lower than that of bituminous coal combustion and more similar to fuelwood combustion. The emission of CO was found to be high during biocoal combustion (141 g/kg) relative to fuelwood (117 g/kg) but lower than that of bituminous coal (158 g/kg). Furthermore, the NOx emission of biocoal was higher than fuelwood and more similar to bituminous coal due to variation in the fuel nitrogen content. There is considerable variability in EF calculated for PM between the different burn stages. The average PM emission factor over the whole combustion reaction was high for biocoal (3.0 g/kg) relative to fuelwood (2.09 g/kg) but was lower than bituminous coal (4.16 g/kg). The EC/TC value of soot derived from biocoal combustion was more similar to that of fuelwood.

It is recommended that additional testing of these fuels is required in order to fully ascertain the combustion properties in different domestic heating appliances and in order to fully understand the impact of these fuels in terms of pollutant emissions.

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Analysis of Potential Fuels

1.0 Spent Coffee Ground (SCG) Commercial Coffee Logs

Coffee products are identified as a potential source of biomass material for future fuels. Approximately 90% of the edible components of the coffee cherry are disregarded as agricultural waste with additional by-products including cascara/husk, parchment, mucilage, silverskin and spent coffee grounds (SCG) (Iriondo-DeHond et al., 2020). Significant quantities of SCG waste are generated globally. It is estimated that the number of coffee shops could reach 32,000 within the UK by 2025 (Allegra Strategies, 2017) with one in five people using such shops daily (Ferreira and Ferreira, 2018). The result of mass consumption is the generation of large quantities of spent coffee ground residues with as much as 500,000 tonnes of SCG waste generated within the UK annually (Bio-Bean, 2016). Currently, SCG produced in Europe is incinerated or disposed of via landfill (Mata et al., 2018; Ferreira and Ferreira, 2018). As a result, improved waste management is required to improve industry sustainability with fuel production outlined as a potential solution (McNutt and He, 2019; Iriondo-DeHond et al., 2020).

Bio-bean is the largest producer of SCG briquette fuel for use in residential stove appliances in the UK. Briquettes are said to burn 20% hotter than kiln-dried fuelwood logs and offers 130% savings on GHG emissions (Bio-Bean 2020). The dimensions of the briquettes are 105 mm x 72 mm (Bio-Bean, 2020). Bio-bean coffee logs are not authorised for use in Smoke Control Areas.

1.2 Direct Combustion of SCG Briquettes

SCG is commonly pelletized alone or applied as a mixture with other biomass materials including pine sawdust (Limousy et al., 2015; Iriondo-DeHond et al., 2020). These pellets/briquettes have been identified as an effective fuel resource given the high energy value (19.0-26.9 MJ/kg) following drying (Caetano et al., 2014). Initially SCG presents a higher moisture content (MC), often in excess of 50%, resulting in a lower heating value of just 8.4 MJ/kg (Kang et al., 2017). As a result, pre-treatment and drying is required during the formation of suitable fuel material. Derived pellets are also considered as a material suitable for direct combustion in small boiler systems (Limousy et al., 2015; Kang et al., 2017).

1.3 University of Leeds, Combustion Analysis

Combustion testing of bio-bean commercial coffee log briquettes was undertaken at the University of Leeds with results presented in Maxwell (2021).

1.3.1 Testing Method and Fuel Information

Combustion testing of Bio-Bean SCG briquettes was undertaken in a Waterford Stanley Oisin 5.7 kW multifuel heating stove with batches of approximately 1.5 ± 0.1 kg of fuel. Ignition was achieved using 0.11 ± 0.005 kg of Zip High Performance firelighter. The experimental procedure included a total of three test batches. The ignition batch was used for generating a nominal combustion condition within the stove and emission results were excluded from the analysis. The duration of each test batch varied with a reload point undertaken based upon the fuel mass (0.3 kg of the fuel batch remaining on the heated grate). An example of a briquetted SCG log applied within this testing is

shown in Figure 1. For comparative purposes a control fuel was tested under the same combustion conditions. The control fuel was willow fuelwood logs; the fuelwood was not debarked prior to testing. A summary of the fuel characterisation for both SCG briquettes and willow fuelwood logs is presented in **Table 1**.

Figure 1: An example of a Bio-Bean Coffee Log tested at the University of Leeds

Table 1: Summary of fuel characterisation

Fuel Composition	SCG Briquette	Willow Log
Moisture (wt.%$_{ar}$)	7.5	5.0
Volatile Matter (wt.%$_{db}$)	79	82
Fixed Carbon (wt.%$_{db}$)	17.9	16.3
Ash (wt.%$_{db}$)	3.01	1.68
Carbon (wt.%$_{daf}$)	53.0	49.0
Hydrogen (wt.%$_{daf}$)	7.1	6.8
Nitrogen (wt.%$_{daf}$)	1.89	0.54
Sulphur (wt.%$_{daf}$)	0.03	0.00
Oxygen (wt.%$_{daf}$)	37.9	43.8
Chlorine (wt.%$_{daf}$)	0.04	-
HHV* (MJ/kg$_{db}$)	21.1	19.28
SiO_2 (MJ/kg$_{db}$)	20.12	9.25
Fe_2O_3 (MJ/kg$_{db}$)	6.11	1.25
CaO (MJ/kg$_{db}$)	30.31	39.65
MgO (MJ/kg$_{db}$)	1.62	5.06
Na_2O (MJ/kg$_{db}$)	0.22	1.35
K_2O (MJ/kg$_{db}$)	23.26	22.11

* The calorific value is presented as the Higher Heating Value (HHV)

1.3.2 Combustion Conditions

The initial shape of the burning profile of the SCG briquettes differs to that of other briquetted fuels and fuelwood. Each briquette is coated in a thin wax-like film which

undergoes rapid combustion in the initial 5 min following ignition. This results in an initial peak in the burning rate as shown in **Figure 2**. Once the film has been combusted the briquette quickly disintegrates forming a soft powdered bed during the flaming phase. This powder-like bed appears to form an even distribution of both heat and mass on the stove grate. Following the ignition of the whole briquette, the burning rate profile of the SCG logs shows a general trend which is similar to that of other standard wood fuels, including the willow logs, whereby the rate of combustion increases quickly following ignition followed by a plateau stage after which the burning rate gradually declines during the smouldering (burnout) phase. The SCG briquettes maintain a prolonged flaming phase followed by a rapid shift to smouldering combustion. This differs from typical wood fuel combustion where the transition from flaming phase to smouldering phase is more gradual.
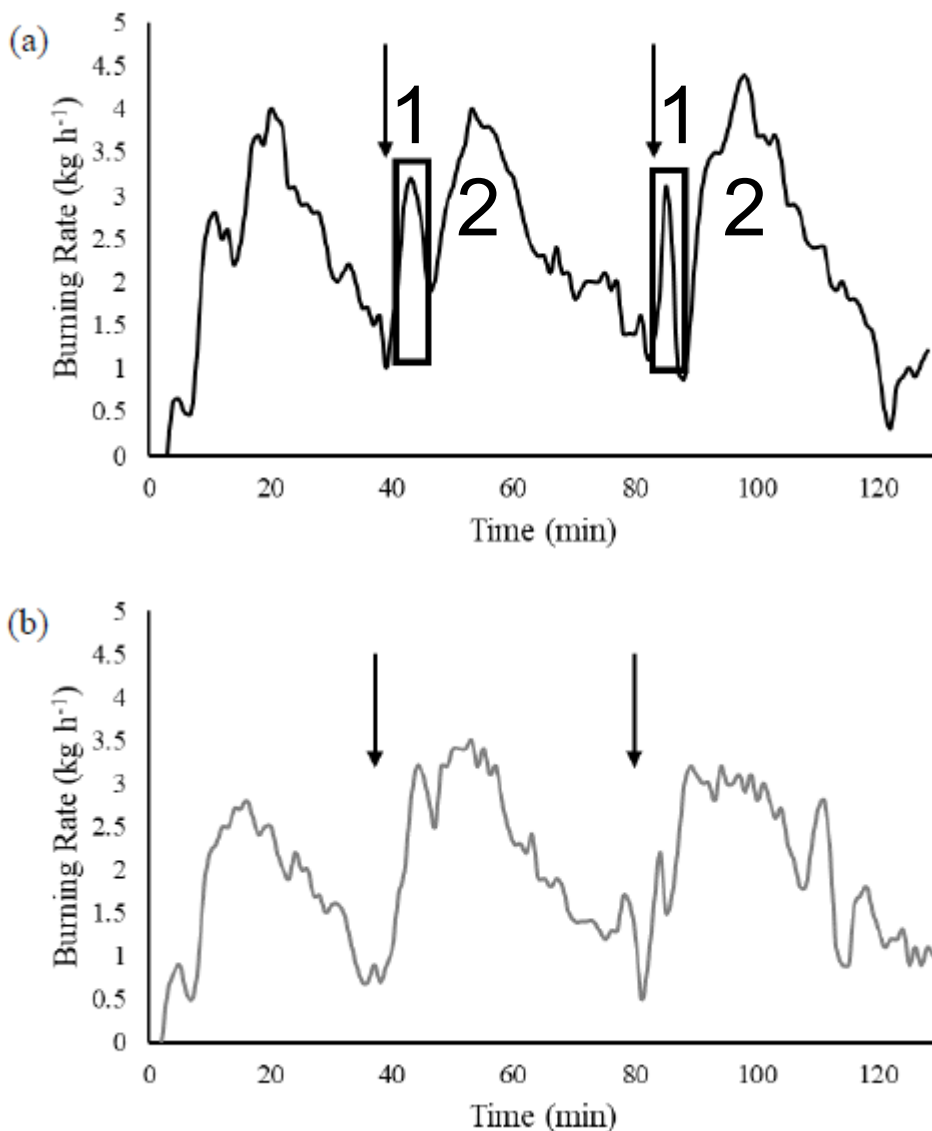

Figure 2: Burning rate profile of **[a] SCG briquette commercial coffee logs** and [b] willow fuelwood logs. ↓ identifies the point of fuel reloading. [1] identifies the point of wax-like film combustion and [2] identifies the generic biomass combustion profile in SCG briquettes.

Table 2 shows the average burning rates for SCG briquettes and fuelwood during flaming and smouldering combustion. The SCG briquettes present a higher rate of fuel conversion than the fuelwood. The average burning rate was 3.21 ± 0.08 kg/hour and 2.46 ± 0.18 kg/hour during the flaming phase and smouldering phase respectively. The average burning rate for SCG briquettes over the complete combustion cycle is therefore 2.83 kg/h. The rate of combustion is generally faster than that observed during the combustion of willow fuelwood under the same testing parameters. Fuelwood combusted at a rate of 2.98 ± 0.10 kg/hour during flaming combustion and 1.72 ± 0.05 kg/hour during smouldering combustion, with an average burning rate of fuelwood over the complete combustion cycle of 2.35 kg/hour. This equates to a combustion rate which is 7.43% higher during the flaming phase and 35.41% higher during the smouldering phase during the combustion of SCG briquettes.

Table 2: Fuel burning rate identified during the combustion of SCG briquettes and fuelwood logs

Combustion Phase		SCG Briquettes				Fuelwood Logs			
	Batch #	**1**	**2**	**Ave.**	**σ**	1	2	Ave.	σ
Flaming	Burning Rate (kg/hour)	3.15	3.26	3.21	0.08	3.05	2.91	2.98	0.10
Smouldering	Burning Rate (kg/hour)	2.58	2.33	2.46	0.18	1.75	1.68	1.72	0.05

The combustion temperature is higher when burning SCG briquettes compared to the logs as shown in **Table 3**. The average combustion temperature was 520 ± 14 °C and 400 ± 14 °C during the flaming phase and smouldering phase respectively. The average combustion temperature over the complete combustion cycle is therefore 460 °C. This is notably higher than the average temperature observed during the combustion of fuelwood which was 364 °C. The temperature at which the fuel is combusted is therefore 26% higher during SCG briquette testing.

Table 3: Combustion temperature identified during the combustion of SCG briquettes and fuelwood logs

Combustion Phase		SCG Briquettes				Fuelwood Logs			
	Batch #	**1**	**2**	**Ave.**	**σ**	1	2	Ave.	σ
Flaming	Ave. Temp (°C)	510	530	520	14	435	410	422.5	18
	Max. Temp. (°C)	590	600	595	7	470	480	475	7
Smouldering	Ave. Temp (°C)	410	390	400	14	310	300	305	7
	Max. Temp. (°C)	435	420	427.5	11	375	355	365	14

1.3.3 Gaseous Emissions

The emission of CO_2 and CO are directly comparable with the rate of fuel conversion. An increase in the burning rate generally corresponds with an increase in the rate of CO_2 formation and a reduction in CO. This is outlined by the difference in emission under flaming and smouldering conditions given in **Figure 3**. SCG briquettes produced an average emission concentration of 160,000 mg/m$^3_{db}$ and 7,300 mg/m$^3_{db}$ at STP for CO_2 and CO respectively. These emission values are higher than those observed during the combustion of willow logs, which produced an average emission concentration of 115,000 mg/m$^3_{db}$ and 4,600 mg/m$^3_{db}$ for CO_2 and CO respectively. Gaseous emission concentrations are provided at standard temperature and pressure.

The modified combustion efficiency, calculated as a function of the CO_2 and CO gaseous emission (CO_2/(CO_2+CO), was similar for both fuels. The MCE for SCG

briquettes was 95.6 while the MCE for fuelwood was 96.2. The emission concentration was higher during SCG testing; however the amount of CO relative to CO_2 was consistent with that identified during fuelwood combustion.
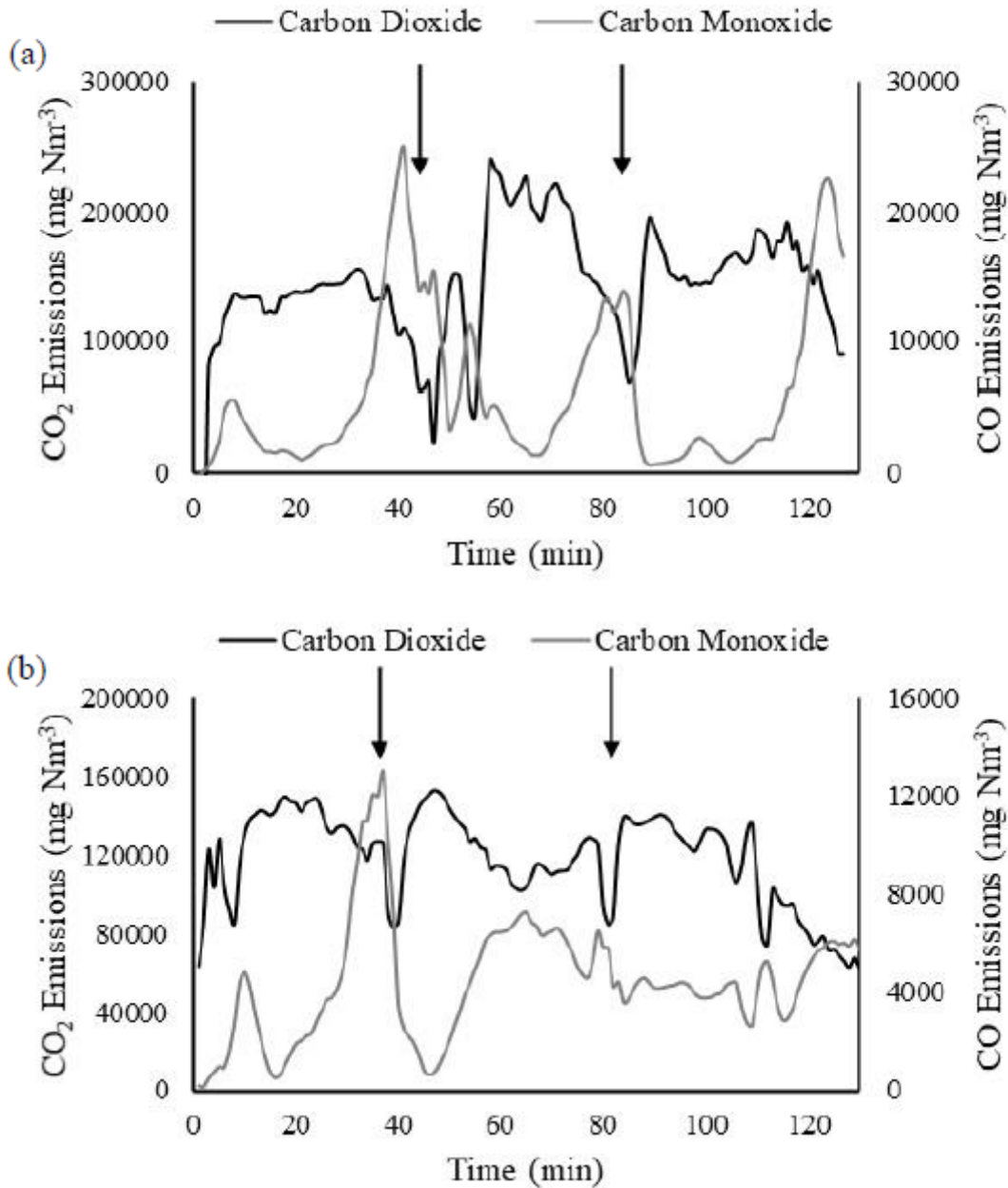

Figure 3: Emission profiles of CO_2 and CO during the combustion of [a] SCG briquettes and [b] willow fuelwood logs. ↓ identifies the point of fuel reloading.

A summary of the gaseous emission factor values for SCG briquettes are presented in **Table 4**. The emission factor values are generally higher than those observed during fuelwood combustion under the same conditions. The emission of CO_2 is 33% higher during the combustion of SCG briquettes when compared with willow fuelwood logs. Additionally, higher emissions are presented for both CO (66%) and CH_4 (63%).

Table 4: Gaseous emission factor values for SCG briquette commercial coffee logs. *Unit conversion calculated assuming a SCG HHV of 21.1 MJ/kg and fuelwood HHV of 19.3.

Fuel	CO_2		CO		CH_4		NOx	
	kg/GJ_{dry}	g/kg_{dry}*	kg/GJ_{dry}	g/kg_{dry}*	kg/GJ_{dry}*	g/kg_{dry}	kg/GJ_{dry}	g/kg_{dry}*
SCG Briquettes	100	2110	5	105.5	0.26	5.5	0.19	4.0
Fuelwood	75	1446	3	57.8	0.16	3.1	0.08	1.5

The emission of NOx is higher than that observed during fuelwood combustion. NOx emission during SCG briquette testing was 0.19 kg/GJ_{dry}. In contrast the NOx emission observed during the combustion of willow fuelwood was 0.08 kg/GJ_{dry}. Higher NOx formation occurs because of the relatively high fuel nitrogen content (1.89 wt.%$_{daf.}$) associated with SCG products. Biomass combustion in heating stoves generally occurs at a relatively modest temperature, typically within the range of 800-1200°C, meaning that NOx formation via thermal mechanism is likely negligible (Skreiberg et al., 1997; Stubenberger et al., 2008; Mitchell et al., 2016). NOx formation through the conversion of nitrogen with the fuel is considered the most dominant route of formation during biomass combustion in this temperature range (Glarborg et al., 2003; Koppejan and Loo, 2008; Sommersacher et al., 2012; Bugge et al., 2020). The lower temperatures observed during the combustion of SCG briquettes (600 °C) suggests the formation of NOx by fuel nitrogen conversion only. The high fuel nitrogen content of spent coffee and SCG briquettes relative to other fuels is shown in **Figure 4**. This suggests that the nitrogen content in SCG briquettes is similar to that of bituminous coal or peat which are both significantly higher than that observed in fuelwood. It should be noted that wood, peat and coal have similar chemical structures with the -N in aromatic structures and the -N is released as CN radicals/HCN. Coffee waste without the caffeine has a similar -N content to straw (which have high fuel-N contents about 1.5 wt%) and in both cases is released as ammonia from the protein and carboxylic acid derivatives.
The combustion of fuels with a higher fuel-nitrogen content generally corresponds with an increase in NOx emission in contrast to fuels with a lower nitrogen content such as wood (Glarborg et al., 2003).
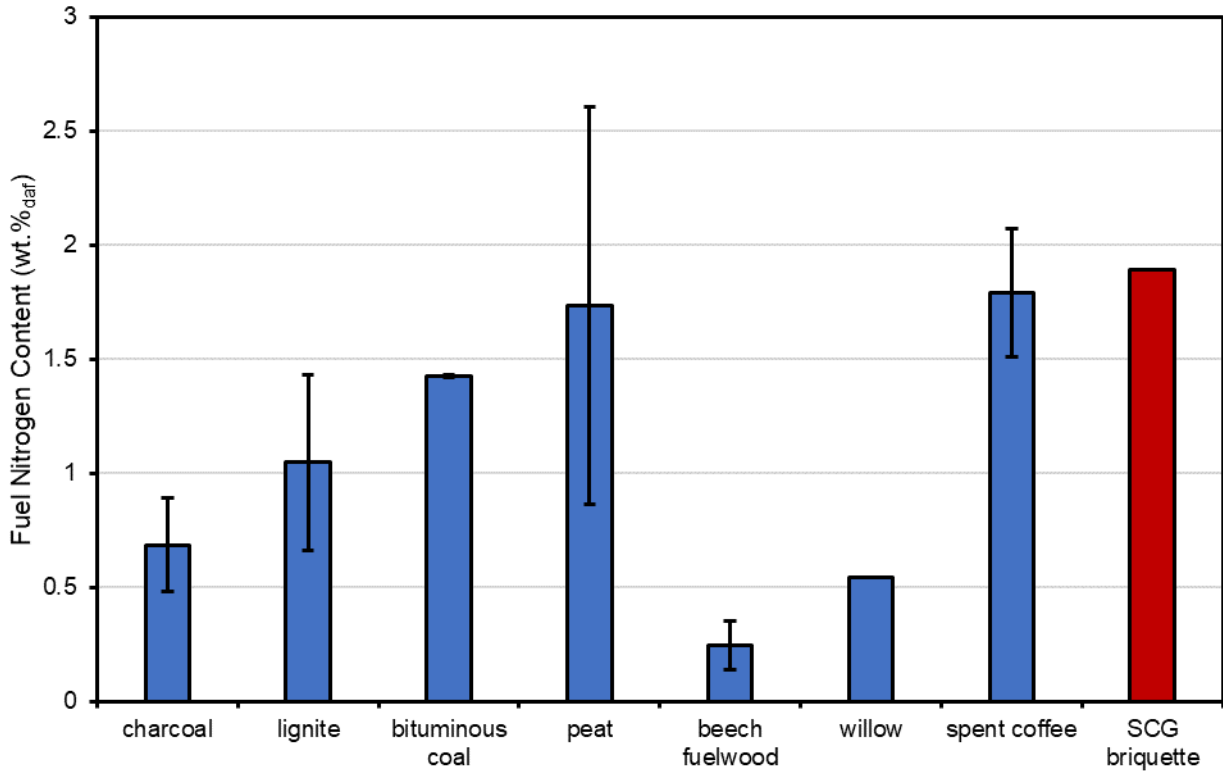
Figure 4: Variation in fuel nitrogen content for biomass, wood-based and coffee based fuels (Maxwell, 2021; Phyllis2, 2022)

1.3.4 Particulate Emissions

Table 5 shows the particulate emission factor values and soot characterisation results for SCG briquettes. The combustion of SCG briquettes results in a high level of formation of PM_t. Particulate sampling was undertaken throughout the duration of a complete single test batch. Emission factors are therefore representative of the average particulate emission observed during ignition, flaming combustion and the smouldering phase. The average emission during SCG briquette combustion was 0.34 kg/GJ$_{dry}$ which was notably higher than that observed during fuelwood combustion (0.20 kg/GJ$_{dry}$).

Particulate samples are noted to present physiochemical differences depending upon fuel type. PM_t samples collected during SCG briquette combustion are powder-like while material generated during the combustion of fuelwood has a more coalesced structure and is less powder-like.

EC/OC analysis of the <1μm particulate fraction was undertaken by SOCOTEC. Particulate matter collected during the combustion of SCG briquettes maintains a higher EC fraction and lower OC fraction than that derived from fuelwood combustion. It is therefore likely that woodsmoke maintains a larger organic tar-like fraction in contrast to smoke generated during the combustion of SCG briquettes. The higher EC/TC and lower OC value suggest more complete combustion when burning SCG briquettes. Furthermore, fuelwood combustion results in a larger fraction of fly-ash than SCG briquettes.

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Table 5: PM emission factor values for SCG briquette commercial coffee logs (Maxwell, 2021). *Unit conversion calculated assuming a SCG HHV of 21.1 MJ/kg and fuelwood HHV of 19.3.

Fuel	Emission Factor (kg/GJ dry)	Emission Factor (g/kg dry)*	Elemental Carbon (wt.%)	Organic Carbon (wt.%)	Ash (wt.%)	EC/TC
SCG Briquettes	**0.34**	**7.13**	**34.9**	**32.8**	**32.3**	**0.52**
Fuelwood	0.20	3.93	24.2	36.6	39.2	0.40

1.4 Additional literature results

There are few examples of SCG briquette testing in residential heating stoves within the literature. (Limousy et al., 2015) investigated the effect of SCG material in compressed logs for use in a cast-iron woodstove. Briquetted material comprised 20% SCG material and 80% pine sawdust. Tests were undertaken which include SCG/pine briquettes (100%), SCG/pine briquettes (50%) with a single beech log (50%) and beech fuelwood (100%). The findings of the investigation reveal elevated levels of pollutant emission when the amount of SCG-derived briquettes combusted in the stove are increased. Nevertheless, the emission concentration does not exceed the limitations outlined under "5-start Green Flame" guidance.

2.0 Lignite Briquettes

Lignite, or brown coal, is the lowest ranking coal and has a low heating value. The fuel is a fossil-derived material generated during the geological compression of peat. The fuel is commonly burned in the form of briquettes in locations of geological abundance i.e. Czech Republic, Hungary and Poland (Kerimary et al., 2017). Coal rank is defined by the extent of organic metamorphism during coalification and carbon content. An increase in coal maturity generally corresponds with an increase in coalification which has a subsequent effect on fuel utilisation potential (Lu et al., 2013). Lignite is the youngest coal making it the most peat-like and contains between 25 % and 35 % carbon with a higher moisture content leading to a low heating value. In contrast, anthracite has a carbon content between 86 % and 97 % making it the highest-ranking coal (EIA, 2021). Bituminous and sub-bituminous coal are intermediate in coal rank and have a carbon content between 35% and 85 % (AGI, n.d.) **Table 6** presents the variation in fuel characteristics for different types of coal.

Table 6: Fuel characteristics of different types of coal (Phyllis2, 2022).

Fuel	MC % (ar)	Volatile Matter % (daf)	Fixed Carbon % (daf)	Lower Heating Value MJ/kg (daf)
Anthracite (hard coal)	1.9	7.93	92.07	34.87
Bituminous (soft coal)	2.5	34.65	65.35	32.6
Lignite (brown coal)	**13.4**	**51.16**	**48.84**	**24.59**

2.1 University of Leeds, Combustion Analysis

Combustion testing of lignite briquettes was undertaken at the University of Leeds with results presented in (. Mitchell, 2017) and (Mitchell et al., 2016).

2.1.1 Data Limitation

The following investigation undertaken at the University of Leeds applied a modified testing approach whereby a single batch of test fuel was applied to the stove only. As a result, the combustion experiments undertaken in this study include cold-start data only with no subsequent reload or warm-start test information. This testing approach was maintained as a constant for all test fuels reviewed in this section.

2.1.2 Testing Method and Fuel Information

Combustion testing of lignite briquettes (RWE Union) was undertaken in a Waterford Stanley Oisin 5.7 kW multifuel heating stove. Each batch of fuel consisted of between 2-3 kg of material in accordance with the nominal heat output and efficiency described in BS EN 13240. The testing procedure included a single batch of test fuel only meaning that these results are representative of cold-start operation. Emission monitoring was undertaken during ignition, flaming combustion and smouldering phases. Ignition was achieved using Zip High Performance firelighter. An example of the briquetted lignite used is shown in **Figure 5**.
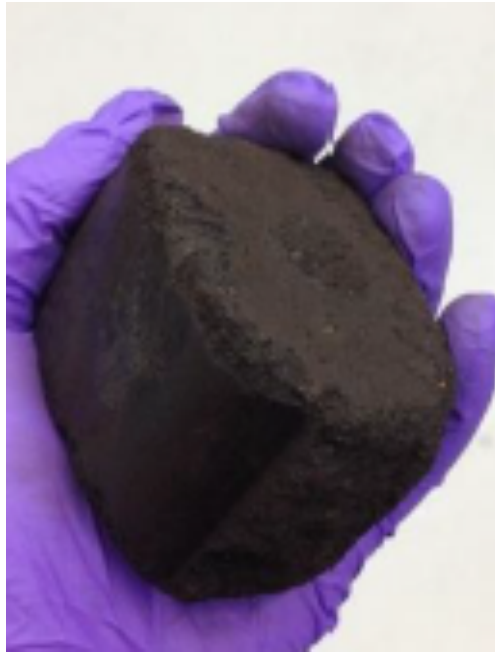
Figure 5: Example of lignite briquette [RWE Union, Germany]

For comparative purposes a number of other fuels have been included within this discussion. These fuels were tested under the same conditions with the results also reported in (E. Mitchell, 2017) and (Mitchell et al., 2016). These fuels included commercially available seasoned hardwood logs (MC of 8.4 %), air-dried hardwood logs (MC of 7.8 %), peat briquettes, bituminous coal (Poland), low smoke anthracite (Cosyglo, Arigna) and smokeless anthracite (Ecobrite, Arigna). A summary of the fuel characterisation for both lignite and additional test fuels is presented in **Table 7**.

Table 7: Summary of fuel characterisation

Fuel	MC %$_{ar}$	VM %$_{db}$	FC %$_{db}$	C %$_{daf}$	H %$_{daf}$	N %$_{daf}$	S %$_{daf}$
Seasoned hardwood logs	8.4	84.2	15.8	53.3	6.1	0.4	0.03
Air-dried hardwood logs	7.8	79.3	20.5	51.6	5.9	0.6	0.02
Peat briquettes	7.1	64.4	33.4	59.1	5	1.6	0.4
Bituminous coal	7.2	39.7	57.9	82.1	4.8	1.9	0.4
Low smoke anthracite	6.3	23.4	72.1	78	3.9	1.6	0.4
Smokeless anthracite	3.4	8.2	86.9	81.6	3.4	1.7	2
Lignite briquettes	**13.7**	**50.6**	**45.1**	**64.91**	**4.01**	**0.72**	**0.32**

Anthracite is the highest-ranking coal and presents a low volatile content and a high fixed carbon content. The anthracite coal applied in this study had a VM content between 23.4 % and 8.2 % with a FC content between 72.1 % and 86.9 %. Bituminous coal is an intermediate fuel with a VM content of 39.7 % and an FC content of 57.9 %. Lignite is the lowest-ranking coal with a VM content of 50.6 % and an FC content of 45.1 %. Additionally, the moisture content of the coal materials is noted to vary with anthracite presenting the lowest moisture content (6.3 % and 3.4 %), followed by bituminous coal (7.2 %) with lignite containing the highest moisture value (13.7 %). This is also affecting the calorific value of the fuel with anthracite maintaining the highest GCV and lignite containing the lowest. Figure 6 shows the differences in fuel properties and coal rank relative to biomass/peat fuels.
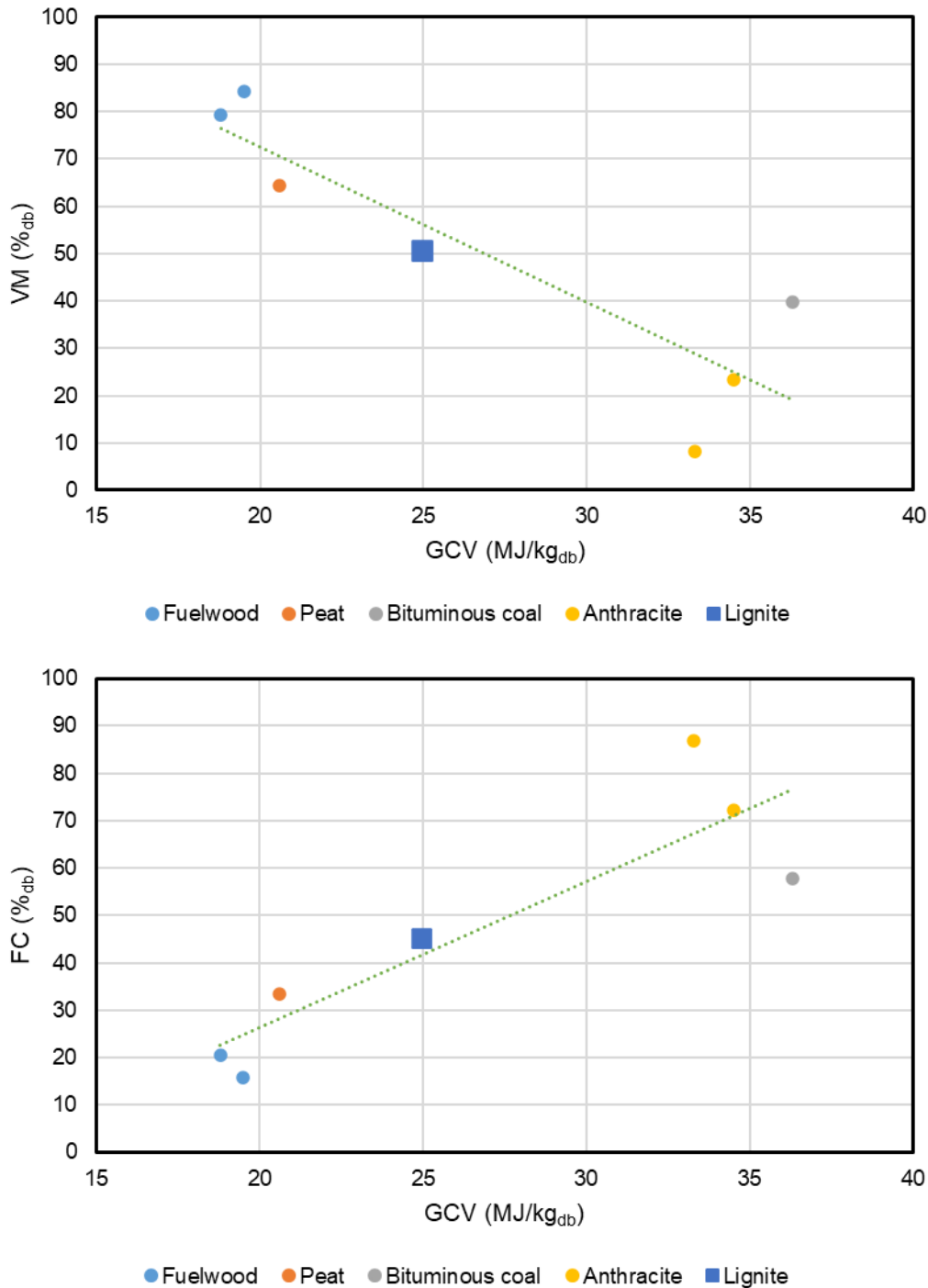
Figure 6: Differences in fuel properties of woody biomass/peat, lignite (low-ranking coal) and anthracite (high-ranking coal). Differences present variation in the Fixed Carbon (FC) and Volatile Matter (VM) relative to the Gross Calorific Value (GCV).

2.1.3 Combustion Conditions

The rate of fuel combustion is shown to vary by fuel type. During lignite combustion the average burning rate during the flaming phase was 1.52 kg/h. This is notably higher than the burning rates identified during bituminous coal (1.31 kg/hour) and anthracite (0.88 ± 0.16 kg/hour) but slower than that observed during fuelwood (2.48 ± 0.16 kg/hour) combustion. The rate of combustion during the flaming phase is similar to that

identified during the combustion of peat briquettes (1.61 kg/h). All coal fuels appear to maintain a similar burning rate during the smouldering phase with lignite burning at a rate of 0.45 kg/hr. Similarly, the burning rates of bituminous coal and anthracite were 0.43 kg/h and 0.48 ± 0.08 kg/h respectively. Due to the nature of biomass combustion all types of coal fuels burned at a higher rate during the smouldering phase than fuelwood logs. The average burning rate recorded over the complete combustion cycle was similar for lignite (0.81 kg/h) and bituminous coal (0.87 kg/h). These rates are slightly higher than that observed during the combustion of high-ranking coal (0.68 ± 0.04 kg/h). These rates are all considerably lower than that observed during the combustion of fuelwood and peat briquettes. A summary of the burning rates for each test fuel is shown in **Table 8**.

Table 8: Fuel burning rate for lignite briquettes and other common test fuels. The average burning rate is calculated as a function of the rates observed during the flaming phase and smouldering phase.

Fuel	Burning Rate (kg/h$_{db}$)		
	Flaming Phase	Smouldering Phase	Average*
Seasoned Hardwood	2.37	0.27	1.32
Air-Dried Hardwood	2.59	0.32	1.46
Peat Briquettes	1.61	0.36	0.99
Bituminous Coal	1.31	0.43	0.87
Low smoke anthracite	0.99	0.42	0.71
Smokeless anthracite	0.77	0.54	0.66
Lignite Briquette	**1.52**	**0.45**	**0.99**

* The average burning rate (kg/hour) is calculated as the average of the flaming and smouldering burning rates

2.1.4 Gaseous Emissions

The combustion of lignite resulted in a high level of CO formation. The average CO emission identified during the complete combustion cycle was 274 g/kg$_{db}$. The CO formation during flaming combustion was 92 g/kg$_{db}$ and was 380 g/kg$_{db}$ during the smouldering phase. The average CO formation was generally higher than that observed during the combustion of other coal fuels. CO formation during bituminous coal combustion was 158 g/kg$_{db}$ while formation during anthracite combustion was 157 g/kg$_{db}$ and 325 g/kg$_{db}$ ($\bar{x}$ = 241.0 ± 118.8 g/kg$_{db}$). The average CO emission during lignite combustion was 153 % higher than that observed during fuelwood combustion.
The NOx emission identified during the combustion of lignite was 6 g/kg$_{db}$. This value was similar to that observed during peat (6 g/kg$_{db}$), bituminous coal (6.3 g/kg$_{db}$) and anthracite (6.85 ± 0.49 g/kg$_{db}$) combustion. These values are significantly higher than that observed during fuelwood combustion (1.8 ± 0.99 g/kg$_{db}$). This is likely because of the lower fuel nitrogen content associated with biomass relative to coal products and peat briquettes. A summary of the gaseous pollutant emissions for each test fuel are shown in **Table 9**.

Table 9: Gaseous emission factor values for lignite briquettes and other common test fuels

Fuel	CO (g/kg$_{dry}$)	NOx (g/kg$_{dry}$)
Seasoned Hardwood	117	1.1
Air-Dried Hardwood	100	2.5
Peat Briquettes	101	6
Bituminous Coal	158	6.3
Low smoke anthracite	325	7.2
Smokeless anthracite	157	6.5
Lignite Briquette	**274**	**6**

2.1.5 Particulate Emissions

The combustion of lignite resulted in a moderate level of PM$_t$ formation. The average PM$_t$ emission observed during the flaming phase was 4.0 g/kg$_{db}$ while the average emission presented during the smouldering phase was 1.0 g/kg$_{db}$. The average PM$_t$ emission observed across the complete combustion cycle was 3.0 g/kg$_{db}$. These values are similar to those observed during the combustion of peat briquettes (2.48 g/kg$_{db}$) likely due to similarities in fuel properties and material structure. PM$_t$ emissions presented during bituminous coal (4.16 g/kg$_{db}$) combustion were higher than those shown during the combustion of lignite. This is unexpected given the lower VM of bituminous coal. This may be the result of the difference in VM composition. Bituminous coals produce VM rich in polyaromatics and with low oxygen contents, whereas lignite volatiles are simpler structures incorporating higher oxygen content. Thus, soot-forming routes are promoted during the combustion of VM from bituminous coals. Consequently, a period of notably heavy loading of PM was observed during the flaming phase of the bituminous coal under cold-start operation (7.48 g/kg$_{db}$), substantially higher than that observed during lignite combustion under the same condition (4.0 g/kg$_{db}$). A summary of the particulate pollutant emissions for each test fuel is shown in **Table 10**.

Table 10: Emission factor values for lignite briquettes and other common test fuels

Fuel	VM %$_{db}$	PM$_t$ (g/kg$_{dry}$)
Seasoned Hardwood	84.2	2.09
Air-Dried Hardwood	79.3	1.5
Peat Briquette	64.4	2.48
Bituminous Coal	39.7	4.16
Low smoke anthracite	23.4	1.46
Smokeless anthracite	8.2	0.5
Lignite Briquette	**50.6**	**3**

The particulate emissions presented during the combustion of anthracite are lower than that observed during lignite testing. Anthracite presents a VM content notably lower than lignite resulting in lower PM formation. Similarly, PMt generated during the combustion of fuelwood is shown to be lower than those identified during lignite testing. The VM content of fuelwood is higher that found in lignite with variation in PMt concentration likely being affected by other mechanisms including chemical composition of the volatiles, combustion temperature, moisture content and physical fuel properties. Because of the difference in volatile matter composition, particularly the high internal O-content of biomass volatiles, there is a separate relationship between VM and PMt for each of the two types of fuels, fossil and biomass. A summary of the effect of VM on particulate pollutant emissions for each test fuel are shown in **Figure 7**.
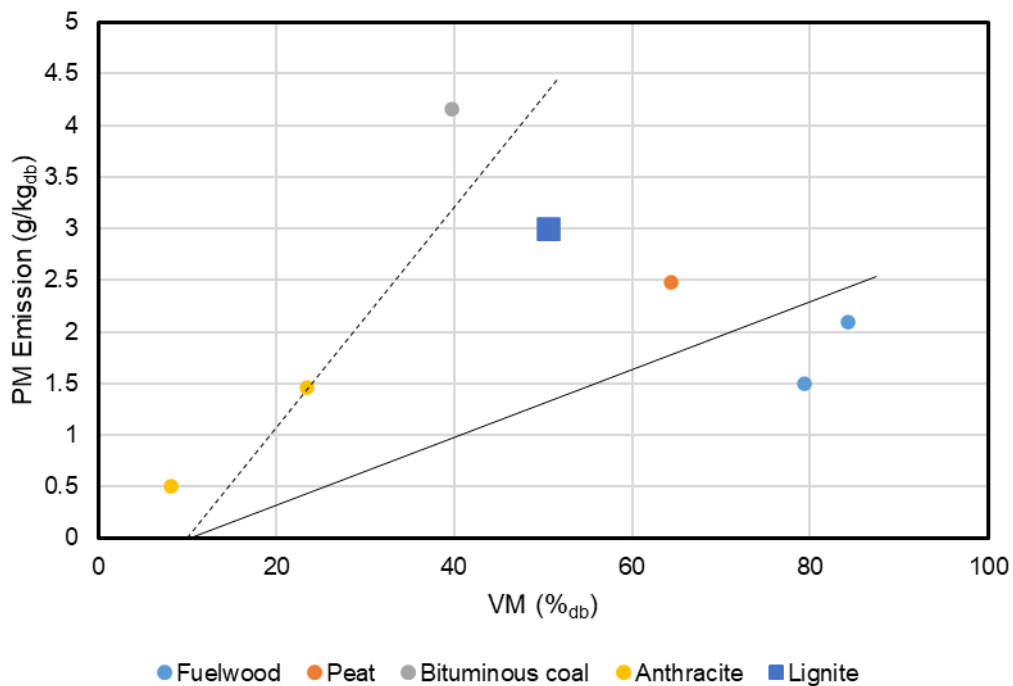

Figure 7: Effect of varying fuel volatile content on particulate formation during the combustion of woody biomass/peat, lignite (low-ranking coal) and anthracite (high-ranking coal). ···· presents the relationship between VM and PM for coal samples. — presents the relationship between VM and PM for biomass and peat samples.

2.2 Additional Literature Results

The physical and chemical properties of biomass derived fuels and fossil-based fuels are substantially different. Specific differences relate to the GCV, MC and VM (. Mitchell, 2017). As a result, combustion performance is commonly found to vary between these different types of fuels.

Regarding the comparison of lignite and fuelwood: Branc et al., (2011) identified generally higher particulate emissions during the combustion of lignite briquettes when compared to beech fuelwood. The combustion of fuelwood resulted in a PM emission of 42.6 g/GJ under standard operating conditions and 101 g/GJ following reloading. Alternatively, the combustion of lignite resulted in a PM emission of 135 g/GJ under standard operating conditions and 1,770 g/GJ following reloading. The performance of both lignite and beech fuelwood was noted to vary when firing in different combustion appliances. Notably higher emissions were observed following reloading which may be in response to the lower VM content which inhibits ease of ignition allowing for a prolonged smouldering phase (Martens et al., 2021). Martens et al., (2021) observed significantly higher emissions during the combustion of lignite in a Central European woodstove when compared to fuelwood firing under similar conditions. SO_2 emissions were shown to be 18.9 times higher during the combustion of lignite, in response to the higher fuel sulphur content. Furthermore, NH_3 emission was shown to be 3.4 times higher during the combustion of lignite. Other flue gas concentrations showed similar values for both fuelwood and lignite. The average CO emission during fuelwood was 1001 g/kg and was 1440 g/kg during lignite combustion. The average CH_4 emission during fuelwood was 28.3 g/kg and was 30.3 g/kg during lignite combustion. Similarly, (Fachinger et al., 2017) presents notably higher SO2 emissions (118 mg/MJ) during lignite combustion when compared with beech fuelwood (16.4 mg/MJ). Additionally, CO_2 formation was found to be lower during flaming combustion by a factor of 2.1 and burnout combustion by a factor of 1.2. Coincidently, CO emission was found to be higher during flaming combustion by a factor of 1.8 and burnout combustion by a factor of 2.8. This indicates inhibited combustion conditions during lignite firing suggested a reduction in combustion efficiency.

Regarding the comparison of lignite and bituminous coal; Bond et al., (2002) observed higher emissions during the combustion of bituminous coal. The average PM emission of bituminous coal was 12 ± 17 g/kg during bituminous coal firing and 4.6 ± 1.9 g/kg during lignite firing. These values are in line with the findings presented within the Leeds testing, (Mitchell, 2017) and (Mitchell et al., 2016), and, as discussed above are the result of differences in VM contents and compositions and MC values. Furthermore, issues associated with the combustion appliance and O_2 availability are suggested as another reason for higher emissions during bituminous coal testing.

3.0 Biocoal

Biocoal, also identified as synthetic coal or eCoal, is a briquetted fuel commonly comprising coal derivatives and processed residual biomass. The briquetted material may include anthracite fines, biomass components, petroleum coke and bituminous coal. These coal derivative products are added to the biomass fraction for the purpose of increasing the GCV of the fuel as well as encouraging a combustion material more similar in performance to manufactured solid fuel. As such, biocoal is here defined as any manufactured briquette comprising a biomass fraction with a supplemented coal or coke fraction.

The composition of biocoal products which are currently HETAS approved and are found on the list of DEFRA approved fuels include: 40-65% anthracite fines, 20-40% petroleum coke, 0-20% bituminous coal, 5-20% biomass, 0-10% biomass derived char and organic binder (not exceeding 20%). Alternatively, the composition may be 30-55% anthracite fines, 10-40% petroleum coke, 0-5% bituminous coal, 25-35% biomass and organic binder. Consequently, the products are generally found to contain up to 50% biomass i.e. up to 20% organic binder, commonly molasses, and 30% biomass – often crushed olive stone. Briquettes are formed via roll-pressing followed by heat treatment up to 300 °C and water quenching (CPL, n.d.; DEFRA, n.d.). The fuels are also presented as *Ready to Burn* certified manufactured solid fuels meaning that they have met sulphur content standard (not exceeding 2%) and smoke emission limits (less than 5 g per hour).

Note: there is currently no clear and defined description of biocoal fuels. This relates to both the fuel materials and the processes undertaken in their manufacture. Methods of biocoal production may include processes of biomass torrefaction, pyrolysis or hydrothermal carbonisation. Furthermore, biocoal material may include a variety of products, including coal and biomass, comprising different percentage weight fractions of the final briquetted fuel. In addition, biocoal may also be a briquetted material which comprises only pre-treated biomass (with binder or other compounds) which has no fossil-based components. Further definition is required in order to differentiate these products from other manufactured solid fuels. This will also aid in the standardisation of manufactured solid fuel production.

3.1 University of Leeds, Combustion Analysis

Combustion testing of 50:50 biomass and coal blend briquettes (CPL) was undertaken at the University of Leeds with results presented in (E. Mitchell, 2017) and (Mitchell et al., 2016). Additional fuels summarised in this section are reported in (Maxwell, 2021). A summary of the investigation into soot characteristics is taken from (Atiku et al., 2016) and (E. Mitchell, 2017).

3.1.1 Testing Method and Fuel Information

Combustion testing of biocoal briquettes (CPL) was undertaken in a Waterford Stanley Oisin 5.7 kW multifuel heating stove. Each batch of fuel consisted of between 2-3 kg of material in accordance with the nominal heat output and efficiency described in BS EN 13240. The testing procedure included a single batch of test fuel only meaning that these results are representative of cold-start operation. Emission monitoring was undertaken during ignition, flaming combustion and smouldering phases. Ignition was achieved using Zip High Performance firelighter. An example of the briquetted lignite applied within this testing is shown in **Figure 8**.

Figure 8: Example of biocoal 50:50 biomass and coal blend briquette [CPL]

The biocoal consists of a blended briquette comprising 50% biomass residue in the form of olive stone and 50% coal-derived residues. The fuel was supplied by CPL. The coal fraction comprises low sulphur petroleum coke, bituminous coal and anthracite. The approximate briquette diameter is 80 mm.

For comparative purposes a number of other fuels have been included within this report. These fuels were tested under the same conditions with the results also reported in (E. Mitchell, 2017) and (Mitchell et al., 2016). These fuels included bituminous Polish coal supplied in 100 mm lumps, commercially available seasoned hardwood logs (MC of 8.4 %) and olive stone briquettes (Arigna Fuels). A summary of the fuel characterisation for both biocoal and additional test fuels is presented in **Table 11**.

Table 11: Summary of fuel characterisation

Fuel	MC %$_{ar}$	VM %$_{db}$	FC %$_{db}$	C %$_{daf}$	H %$_{daf}$	N %$_{daf}$	S %$_{daf}$
Biocoal	**2.7**	**14.0**	**80.1**	**74.3**	**3.6**	**1.7**	**2.1**
Bituminous Coal	7.2	39.7	57.9	82.1	4.8	1.9	0.4
Seasoned Hardwood	8.4	84.2	15.8	53.3	6.1	0.4	0.03
Unprocessed Olive Stone (Phyllis2, 2022)	N/A	78.7	18.6	N/A	N/A	0.05	0.04
Olive Stone Briquette	14.8	82	17	56	5.2	0.50	0.13

The GCV of the biocoal fuel (27.6 MJ/kg) was found to be notably higher than that of the seasoned hardwood (19.5 MJ/kg) but also significantly lower than that of unprocessed bituminous coal (36.3 MJ/kg). Furthermore, the GCV of olive stone briquettes was 21.51 which was lower than that identified in the biocoal blend. This is predicted given that coal derivatives are applied to biomass feedstock as a method of increasing the calorific

value of the fuel for improved thermal performance. The GCV of unprocessed olive stone (the biomass fraction associated with the biocoal fuel) may be approximately 21.5 ± 0.1 MJ/kg (Phyllis2, 2022). As a result, the addition of the coal fraction has contributed in a significant increase in the GCV. The biocoal fuel was also found to maintain a very low VM and very high FC relative to the other test fuels and unprocessed olive stone. Additionally, the biocoal maintained a high fuel nitrogen more in line with what is generally observed for peat and other high sulphur fuels such as the bituminous coal detailed in Section 2.0.

3.1.2 Combustion Conditions

The burning rate of biocoal resembles that of coal rather than biomass. Following ignition, an initial peak is observed during the combustion of both the fuelwood and olive stone briquettes which is not observed in coal-like products. The increased volatile composition of biomass fuels and residues, in comparison to coal products, leads to generally more extensive devolatilisation and lower ignition temperatures (Mando, 2013). This is subsequently followed by a high rate of conversion during the flaming phase followed by a sudden reduction following the onset of the burnout phase. Alternatively, during the combustion of both the biocoal and bituminous coal the burning rate gradually increases to a plateau during the flaming phase followed by a graduated reduction in the burning rate throughout the smouldering phase. This trend is outlined in **Figure 9**. The combustion temperature follows a similar trend whereby clear differentiation between the flaming phase and the burnout phase is apparent when fuelwood and olive stone briquettes are applied to the stove. Alternatively, the combustion temperature undergoes an initial increase to the point of plateau combustion during the flaming phase followed by a gradual reduction in temperature throughout the burnout phase. As a result, it appears that the biocoal material burns in a manner more similar to coal than biomass.

Table 12 presents a summary of the combustion conditions identified during the testing of biocoal and other test fuels. The average burning rate during the flaming phase is notably lower during the combustion of biocoal and bituminous coal when compared to fuelwood. In contrast, the average burning rate during the smouldering phase is notably higher during the combustion of both biocoal and bituminous coal. The average burning rate presented across the complete combustion cycle is generally slower for biocoal, and similar to bituminous coal, rather than fuelwood. This reduced burning rate is likely due to the lower fraction of volatiles and higher fraction of fixed carbon within the fuel composition (Fachinger et al., 2017).

Table 12: Summary of burning conditions identified during the complete combustion reaction under cold-start operation.

Fuel	Burning Rate (kg/hour)			Ave. Flue Gas Temperature (°C)
	Flaming Phase	Smouldering Phase	Ave*	
Biocoal	**1.05**	**0.58**	**0.82**	**247**
Bituminous Coal	1.31	0.43	0.87	310
Seasoned Hardwood	2.37	0.27	1.32	241
Olive Stone Briquette	N/A	N/A	0.78	193

* The average burning rate (kg/hour) is calculated as the average of the flaming and smouldering burning rates
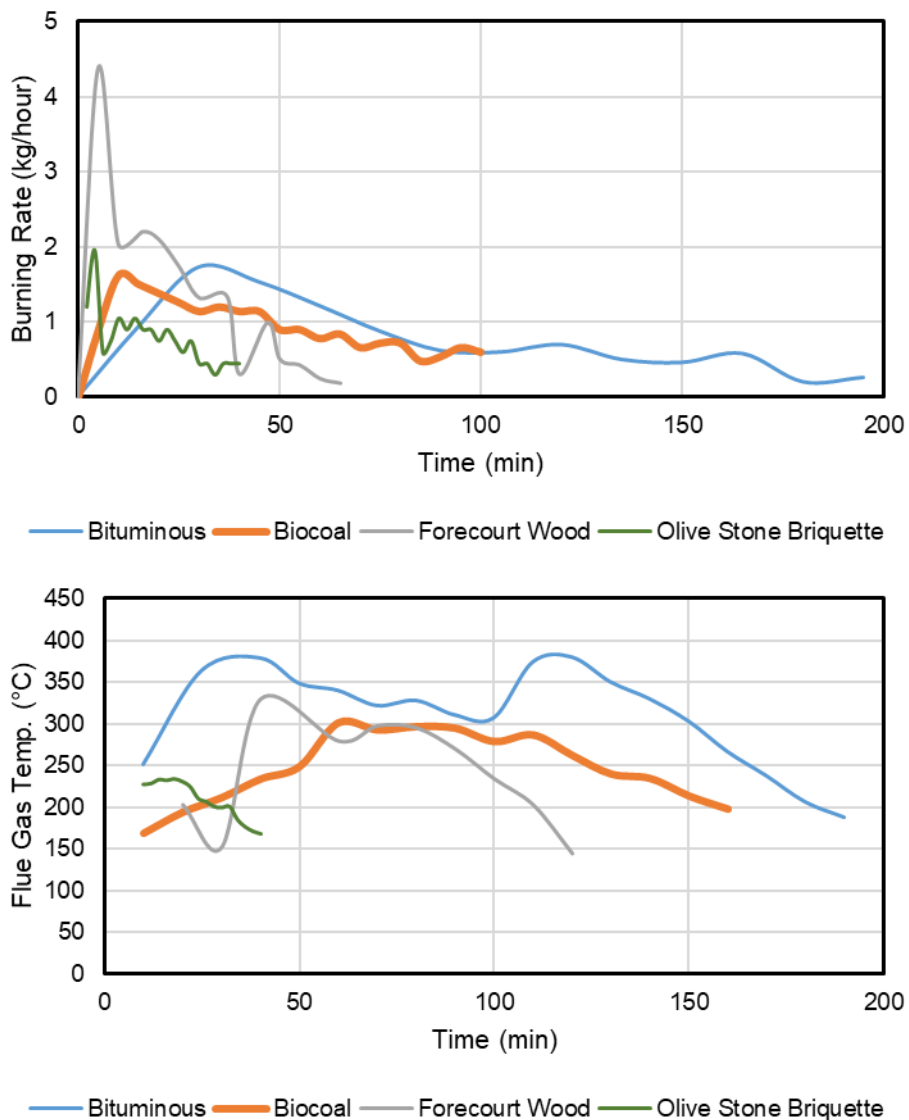
Figure 9: Variation in burning rate and temperature identified during the combustion of bituminous coal, biocoal, forecourt fuelwood and olive stone briquettes.

3.1.3 Gaseous Emissions

Figure 10 shows the emission gaseous profiles for biocoal, bituminous coal and fuelwood presented in ppm and corrected to 11% O_2. Regarding CO (top), the emission profiles for each of the three fuels are similar whereby the extent of the emission during ignition is moderate, this is then followed by a period of minimal ignition during the flaming phase, this phase is then followed by a period of high ignition as the reaction moves into a smouldering-type reaction. As discussed, the burning rates for each of the fuels differs which influences the total duration of the experiment. The fuelwood presents the highest burning rate (1.32 kg/hour) followed by bituminous coal (0.87 kg/hour) with biocoal presenting the slowest rate of conversion (0.82). As a result, the duration of each test differs subject to the rate of conversion. Interesting, regardless of the burning rate each of the fuels appears to progress to the period of high CO formation at the same point (approximately 60 min ~). The CO profile of fuelwood is

similar to that identified during previous studies (Duarte et al., 2014) whereby the emission rate is high during ignition, followed by a period of low formation during the smouldering phase followed by a subsequent period of high formation during the smouldering combustion. Similarly, the CO emission profile of the bituminous coal is similar to that identified in (Trubetskaya et al., 2021) whereby the emission concentration is low or moderate during ignition and the flaming phase followed by a gradual increase in concentration during smouldering combustion. The smouldering period is generally longer in coal combustion than in biomass combustion. The CO profile for biocoal is shown to be between the fuelwood and coal fuels. High emissions are presented during ignition which is like fuelwood. Additionally, high emissions are shown for a prolonged period during smouldering which is more like coal. This is likely in response to the variable composition of the biocoal briquettes. The NOx emission profiles for biocoal and bituminous coal are similar while the emission of fuelwood differs. NOx formation for biocoal and bituminous coal is high during ignition with a subsequently reduced concentration observed during flaming combustion. The concentration is then increased throughout the smouldering phase. Alternatively, the NOx emission for fuelwood reduces during the burnout phase in response to a lower rate of fuel nitrogen conversion.
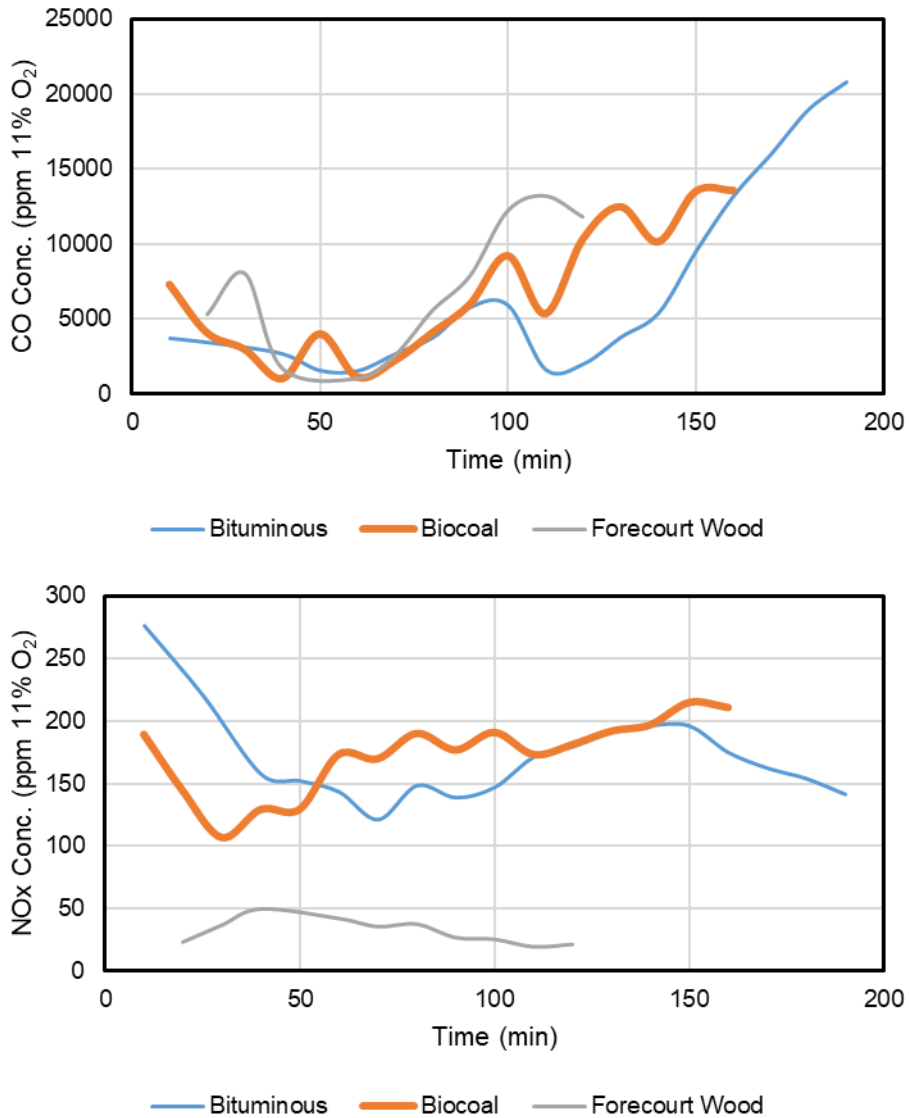
Figure 104: CO and NOx emission concentrations identified during the combustion of bituminous coal, biocoal, forecourt fuelwood and olive stone briquettes.

The NOx emission factors are shown to vary with fuel nitrogen content. The high fuel nitrogen content of bituminous coal (1.9 %) and biocoal (1.7 %) results in high NOx formation. The low fuel nitrogen content of fuelwood (0.4 %) results in a comparatively low NOx emission. The NOx emission for biocoal is similar to that of bituminous coal. The fuel nitrogen content of the biogenic fraction (unprocessed olive stone) is low (Phyllis2, 2022) and has shown to be low in similar fuels (Maxwell, 2021). This suggests that the majority of the NOx emission is associated with the coal-product fraction. CO formation is principally controlled by combustion temperature and residence time. Improved combustion conditions generally correspond with a reduction in CO formation (Vakkilainen, 2017). CO is shown to be highest for bituminous coal (158 g/kg) and biocoal (141 g/kg) and low during the combustion of fuelwood (117 g/kg). The level of CO emitted is dependent upon combustion temperature above the grate. A summary of the CO and NOx emission factors is presented in **Table 13**.

Table 13: Gaseous emission factor values for biocoal and other common test fuels

Fuel	CO (g/kg$_{dry}$)	NOx (g/kg$_{dry}$)
Bituminous Coal	158	6.3
Biocoal	**141**	**6.1**
Forecourt Wood	117	1.1

3.1.4 Particulate Emissions

PM formation is shown to vary between biocoal and fuelwood, as shown in **Figure 11**. The emission concentration is shown to be high during the ignition of biocoal with values similar to those identified during the combustion of bituminous coal. This is in contrast to fuelwood where the level of emission during ignition is low. The amount of PM generated following ignition is reduced during the flaming and smouldering phases during the combustion of the biocoal and bituminous coal. The lowest formation occurs during the final burnout phases. Alternatively, the amount of PM formation increases during the flaming phase of fuelwood combustion followed by low emission during burnout.
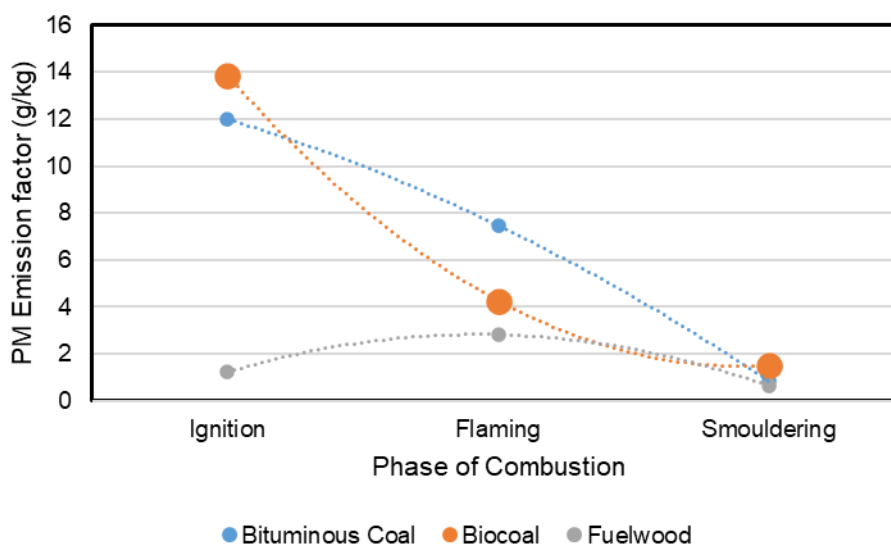

Figure 115: Variation in particulate emission under different stages of combustion.

Relative to fuelwood and bituminous coal, the combustion of biocoal resulted in a moderate level of PM$_t$ formation. The average PMt generated during start-up was very high resulting in an emission factor of 13.9 g/kg$_{db}$. The average PM$_t$ emission observed during the flaming phase was 4.27 g/kg$_{db}$ while the average emission presented during the smouldering phase was 1.51 g/kg$_{db}$. The average PM$_t$ emission observed across the complete combustion cycle was 3.04 g/kg$_{db}$. The emission of soot generated during the combustion of biocoal was most similar to that identified during the combustion of bituminous coal. The average emission of PMt during bituminous coal combustion was 12.0 g/kg$_{db}$, 7.48 g/kg$_{db}$, and 0.84 g/kg$_{db}$. Therefore, higher soot emission was observed during the ignition and smouldering phases of biocoal combustion while higher formation was observed during the flaming phase of bituminous coal combustion. The average PM$_t$ emission across the whole combustion reaction was highest during bituminous coal combustion (4.16 g/kg$_{db}$) followed by biocoal (3.04 g/kg$_{db}$) with relatively

low emissions observed during the combustion of fuelwood (2.09 g/kg$_{db}$). A summary of the PMt emissions for the test fuels is presented in **Table 14**.

Table 14: Particulate emission factor values for biocoal and other common test fuels

Fuel	PM Emission Factor (g/kg)				EC/TC
	Ignition	Flaming	Smouldering	Whole Batch Cycle	
Bituminous Coal	12	7.48	0.84	4.16	0.62
Biocoal	**13.88**	**4.27**	**1.51**	**3.04**	**0.25**
Forecourt Wood	1.22	2.82	0.64	2.09	0.3

Notable variation in the composition of soot samples collected during the combustion of biocoal and other test fuels is presented in **Figure 12** Biocoal presents the lowest OC content (14.3 mg/MJ) with bituminous coal providing a similar content of 17.7 mg/MJ. These values are significantly lower than that observed during the combustion of fuelwood (27.1 mg/MJ). The emission of EC is very low during the combustion of biocoal (6.2 mg/MJ) relative to fuelwood (18.5 mg/MJ). The EC content of soot derived from bituminous coal combustion was the highest with an emission factor of 98.6 mg/MJ.
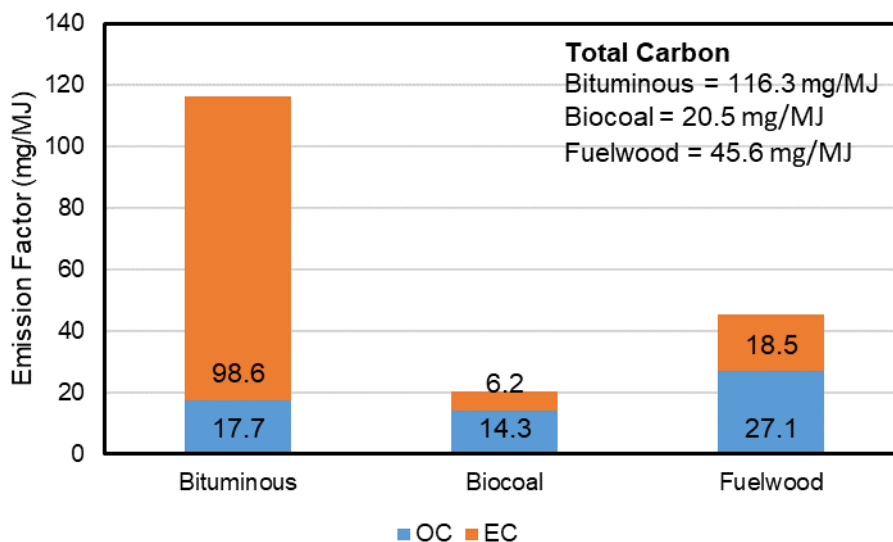

Figure 126: OC and EC emission factors for biocoal, bituminous coal and fuelwood. Emission factors are presented in mg/MJ.

The correlation between EC and OC fractionation of soot is a function of the fuel VM content (Li et al., 2016). The VM content of the fuels was as follows; bituminous coal was 39.7 %, fuelwood was 84.2 % and biocoal was 14.0 %. Additional fuels have been added into **Figure 9** which provides a correlation between the fuel VM content and the EC/TC ratio. These additional fuels include air-dried hardwood, low smoke solid fuel and smokeless solid fuel. An increase in the relative content of OC results in a decrease in the EC/TC ratio. Alternatively, an increase in the relative content of EC results in an increase in the EC/TC ratio (Price-Allison et al., 2019). This process is highlighted in **Figure 12**. The EC/TC value for biocoal is low, EC/TC = 0.25, and is subject to the low VM content of the fuel. The EC content of the soot was high EC = 6.2 mg/MJ) while the OC content was relatively low (OC + 14.3 mg/MJ). This is generally conducive to patterns of high combustion efficiency. As such, the soot fractional composition is more

similar to that observed during the combustion of smokeless fuel where the EC/TC is 0.23 and the VM content is 8.2 %. A higher VM content is shown for low-smoke coal (VM = 23.4 %) resulting in a higher EC/TC ratio of 0.38. Bituminous coal maintains a higher VM content (VM = 39.7 %) which corresponds to a high EC/TC ratio of 0.62. This correlation appears to differ slightly during the combustion of fuelwood whereby a very high fuel VM content (VM = 81.8 ± 3.5 %) corresponds to only a moderate EC/TC ratio of 0.4 ± 0.1.
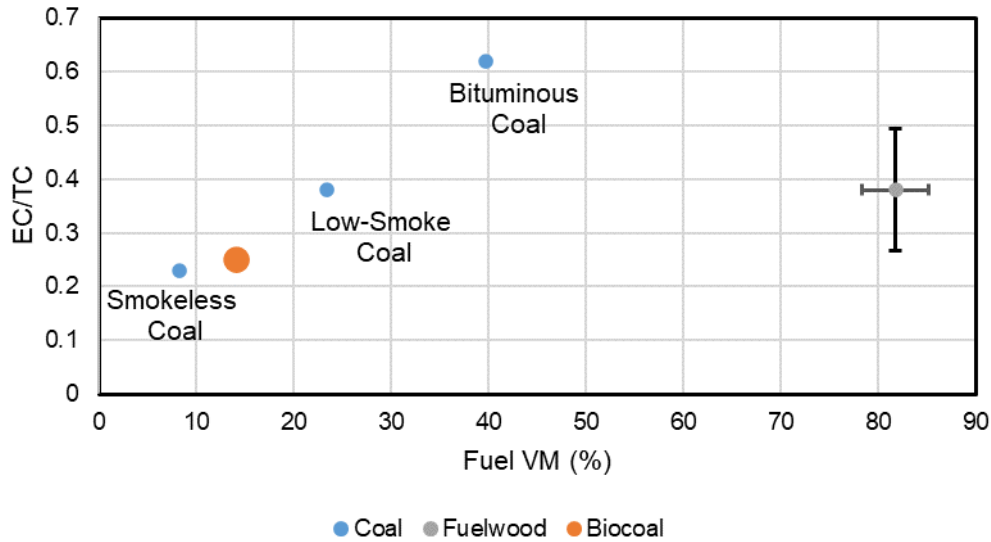

Figure 137: Effect of fuel volatile matter content on EC/TC ratio is biocoal, fuelwood and other coal products.

3.2 Additional Literature Results

The term biocoal is often used in reference to several manufactured solid fuel materials. In relation to the current work, the term biocoal refers to a briquetted solid fuel comprising a combination of milled biomass and powdered mineral fuel. Biomass generally presents a low energy density and high volatile content resulting in high emissions. The co-combustion, or blending, of waste biomass and coal fines allows for the development of a higher grade fuel as well as providing for alternative waste streams (Christoforou and Fokaides, 2016). Furthermore, the addition of a biomass fraction may lead to reductions in the fuel sulphur content relative to that of the parent coal material (Blesa et al., 2003).

The blending of milled biomass with coal has been shown to produce briquetted fuels maintaining a higher calorific value than unprocessed biomass. Previous work by (Onuegbu et al., 2011) identified an increase in the CV of blended briquettes when the relative fraction of bituminous coal was increased. Nevertheless, there are very few studies which have addressed the potential use of biomass and coal blend briquettes in small-scale residential heating appliances.

4.0 Summary of tested fuels (University of Leeds)

| Fuel | Combustion Conditions | | MCE | CO₂ (g/kg) | CO (g/kg) | CH₄ (g/kg) | NOx (g/kg) | PMₜ (g/kg) | EC/TC |
	Burning Rate (kg/hour)	Temp (°C)							
Coffee Logs	**3.21**	**460**	**95.6**	**2110**	**105.5**	**5.5**	**4.0**	**7.13**	**0.52**
Beech Fuelwood	2.98	364	96.2	1446	57.8	3.1	1.5	3.93	0.40
Seasoned Hardwood	1.32	241	-	-	117	-	1.1	2.09	0.3
Air-Dried Hardwood	1.46	317	-		100	-	2.5	1.5	0.46
Peat Briquettes	0.99	228	-	-	101	-	6	2.48	0.28
Bituminous Coal	0.87	310	-	-	158	-	6.3	4.16	0.62
Low smoke anthracite	0.71	285	-	-	325	-	7.2	1.46	0.38
Smokeless anthracite	0.66	246	-	-	157	-	6.5	0.5	0.23
Lignite Briquettes	**0.99**		**-**	**-**	**274**	**-**	**6**	**3**	**-**
Biocoal	**0.82**	**247**	**-**	**-**	**141**	**-**	**6.1**	**3.04**	**0.25**

5.0 References

AGI n.d. What are the different types of coal. Available from: https://www.americangeosciences.org/critical-issues/faq/what-are-the-different-types-of-coal.

Atiku, F.A., Mitchell, E.J.S., Lea-Langton, A.R., Jones, J.M., Williams, A. and Bartle, K.D. 2016. The Impact of Fuel Properties on the Composition of Soot Produced by the Combustion of Residential Solid Fuels in a Domestic Stove. *Fuel Processing Technology*. **151**, pp.117–125.

Bio-Bean 2020. About coffee logs. Available from: https://www.bio-bean.com/coffee-logs/.

Bio-Bean 2016. Bio-Bean, About us.

Blesa, M.J., Miranda, J.L., Izquierdo, M.T. and Moliner, R. 2003. Curing temperature effect on mechanical strength of smokeless fuel briquettes prepared with molasses. *Fuel*. **82**(8), pp.943–947.

Bond, T.C., Covert, D.S., Kramlich, J.C., Larson, T.V. and Charlson, R.J. 2002. Primary particle emissions from residential coal burning: Optical properties and size distributions. *Journal of Geophysical Research*. **107**(D21), p.8347.

Branc, M., Horak, J. and Ochodek, T. 2011. Fine particle emissions from combustion of wood and lignite in small furnaces. *Environmental Protection Engineering*. **37**(2), pp.123–132.

Bugge, M., Skreiberg, Ø., Haugen, N.E.L. and Carlsson, P. 2020. Predicting NOx emissions from wood stoves using detailed chemistry and computational fluid dynamics. *Energy Procedia*. **75**(1876), pp.1740–1745.

Caetano, N.S., Silva, V.F.M., Melo, A.C., Martins, A.A. and Mata, T.M. 2014. Spent coffee grounds for biodiesel production and other applications. *Clean Technologies and Environmental Policy*. **16**, pp.1423–1430.

Christoforou, E. and Fokaides, P.A. 2016. A review of olive mill solid wastes to energy utilization techniques. *Waste Management*. **49**, pp.346–363.

CPL n.d. Low CO2 smokeless coal for open fires and multi-fuel stoves. *Renewable smokeless fuel*. [Online]. Available from: https://cplindustries.co.uk/how-do-we-make-ecoal/.

DEFRA n.d. Authorised fuels in all countries. *Authorised/certified fuels*. [Online]. Available from: https://smokecontrol.defra.gov.uk/fuel-details.php?id=1.

Duarte, M., Vicente, E., Calvo, A., Nunes, T., Tarelho, L. and Alves, C. 2014. Gaseous and particulate emissions from the combustion of wood in a Portuguese stove *In*: *SPEIC14 - Towards Sustainable Combustion*.

EIA 2021. Coal explained. *Basics*. [Online]. Available from: https://www.eia.gov/energyexplained/coal/.

Fachinger, F., Drewnick, F., Gieré, R. and Borrmann, S. 2017. How the user can influence particulate emissions from residential wood and pellet stoves: Emission factors for different fuels and burning conditions. *Atmospheric Environment*. **158**, pp.216–226.

Ferreira, J. and Ferreira, C. 2018. From bean to cup and beyond: Exploring ethical consumption and coffee shops. *Journal of Consumer Ethics*. **2**(2), pp.34–47.

Glarborg, P., Jensen, A.D. and Johnsson, J.E. 2003. Fuel nitrogen conversion in solid fuel fired systems. *Progress in Energy and Combustion Science*. **29**(2), pp.89–113.

Iriondo-DeHond, A., Iriondo-DeHond, M. and del Castillo, M.D. 2020. Applications of compounds from coffee processing by-products. *Biomolecules*. **10**(9), p.1219.

Kang, S.B., Oh, H.Y., Kim, J.J. and Choi, K.S. 2017. Characteristics of spent coffee ground as a fuel and combustion test in a small boiler (6.5 kW). *Renewable Energy*. **113**, pp.1208–1214.

Kerimary, A., Rojas-Solorzano, L., Torkmahalleh, M.A., Hopke, P.K. and Ó Gallachoir, B.P. 2017. Coal use for residential heating: Patterns, health implications and lessons learned. *Energy for Sustainable Development*. **40**, pp.19–30.

Koppejan, J. and Loo, S. van 2008. *The Handbook of Biomass Combustion and Co-firing*. London: Routledge.

Li, Q., Jiang, J., Zhang, Q., Zhou, W., Cai, S., Duan, L., Ge, S. and Hao, J. 2016. Influences of coal size, volatile matter content, and additive on primary particulate matter emissions from household stove combustion. *Fuel*. **182**, pp.780–787.

Limousy, L., Jeguirim, M., Labbe, S., Balay, F. and Fossard, E. 2015. Performance and emissions characteristics of compressed spent coffee ground/wood chip logs in a residential stove. *Energy for Sustainable Development*. **28**, pp.52–59.

Lu, L., Devasahayam, S. and Sahajwalla, V. 2013. Evaluation of coal for metallurgical applications *In*: D. Osborne, ed. *The Coal Handbook: Towards Cleaner Production*. Woodhead Publishing, pp.352–386.

Mando, M. 2013. Biomass Combustion and Co-Firing *In*: L. Rosendahl, ed. *Biomass Combustion Science, Technology and Engineering*. Oxford: Woodhead Publishing.

Martens, P., Czech, H., Tissari, J., Ihalainen, M., Suhonen, H., Sklorz, M., Jokiniemi, J., Sippula, O. and Zimmermann, R. 2021. Emissions of gaseous and volatile organic compounds from residential heating: A comparison of brown coal briquettes and logwood combustion. *Energy and Fuels*. **35**(17), pp.14010–14022.

Mata, T.M., Martins, A.A. and Caetano, N.S. 2018. Bio-refinery approach for spent coffee grounds valorization. *Bioresource Technology*. **247**, pp.1077–1084.

Maxwell, D.P. 2021. *Combustion of alternative and low-grade biomass fuels on small-scale systems: Potential and potimisation through pre-treatment*. University of Leeds.

McNutt, J. and He, W. 2019. Spent coffee grounds: A review on current utilisation. *Journal of Industrial and Engineering Chemistry*. **71**, pp.78–88.

Mitchell, E.J.S. 2017. *Emission from residential solid fuel combustion and implications for air quality and climate change*. University of Leeds.

Mitchell, E.J.S., Lea-Langton, A.R., Jones, J.M., Williams, A., Layden, P. and Johnson, R. 2016. The impact of fuel properties on the emissions from the combustion of biomass and other solid fuels in a fixed bed domestic stove. *Fuel Processing Technology*. **142**, pp.115–123.

Onuegbu, T.U., Ekpunobi, U.E., Ogbu, I.M., Ekeoma, M.O. and Obumselu, F.O. 2011. Comparative studies of ignition time and water boiling test of coal and biomass briquettes blend. *International Journal of Recent Research and Applied Studies*. **7**(2), pp.153–159.

Phyllis2 2022. Phyllis2 Database. Available from: https://phyllis.nl/.

Price-Allison, A., Lea-Langton, A.R., Mitchell, Edward J. S.Gudka, B., Jones, J.M., Mason, P.E. and Williams, A. 2019. Emissions Performance of High Moisture Wood Fuels Burned in a Residential Stove. *Fuel*. **239**, pp.1038–1045.

Skreiberg, Ø., Hustad, J. and Karlsvik, E. 1997. Empirical NOx-Modelling and Experimental Results from Wood Stove Combustion *In*: *Developments in Thermochemical Biomass Conversion*. Dordrecht: Springer, pp.1462–1476.

Sommersacher, P., Brunner, T. and Obernberger, I. 2012. Fuel indexes: A novel method for the evaluation of relevant combustion properties of new biomass fuels *In*: *Energy and Fuels*. American Chemical Society, pp.380–390.

Strategies, A. 2017. *Project Cafe 2017*. London.

Stubenberger, G., Scharler, R., Zahirovic, S. and Obernberger, I. 2008. Experimental investigation of nitrogen species release from different solid biomass fuels as a basis for release models. *Fuel*. **87**, pp.793–806.

Trubetskaya, A., Lin, C., Ovadnevaite, J., Ceburnis, D., O'Dowd, C., Leahy, J.J., Monaghan, R.F.D., Johnson, R., Layden, P. and Smith, W. 2021. Study of Emissions from Domestic Solid-Fuel Stove Combustion in Ireland. *Energy and Fuels*. **35**, p.4978.

Vakkilainen, E.K. 2017. *Steam Generation from Biomass*. Oxford: Butterworth-Heinemann.