Air quality impacts of the use of Pyrolysis liquid fuels

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Executive summary

Defra commissioned a scoping study on whether any future use of pyrolysis oil as a fuel would have implications for air quality. Pyrolysis oil is produced from the thermal decomposition of material (biomass in this instance) in the absence of oxygen. Moderate processing temperatures and short vapour residence time are optimum for producing pyrolysis oil.

The conclusions of the study are :

- The diversity of feedstocks and manufacturing processes available to produce pyrolysis oils gives rise to wide variations of possible composition and properties in the products. This means that standardised products analogous to mineral fuel oil standard grades are very unlikely to be developed in the foreseeable future.
- Pyrolysis activities are regulated under the Environmental Permitting Regulations (England and Wales) Regulations 2010 (EPR).
- However, pyrolysis of wood which has not been chemically treated is not an activity under the Environmental Permitting Regulations (EPR). Also use of pyrolysis plant to produce charcoal is not a regulated activity under EPR.
- EPR does provide a mechanism for regulation of untreated wood pyrolysis plants if they are a directly associated activity to a regulated activity. Note that if the main activity is a combustion activity this would only be available for larger (>20 MWth) combustion plant.
- The Directive 2010/75/EU on Industrial Emissions (IED) extends the scope of regulated activities to include gasification or liquefaction of non-coal fuels (with a total rated thermal input of 20 MW or more). UK implementation of the IED will include measures to transpose the new IED activity to national regulations by January 2013.
- There are regulatory controls available through EPR for combustion of liquid fuels in boilers or furnaces ≥20MW thermal input. Lower thresholds apply for waste burning and for instances where the boiler or furnace is part of a large (≥50MW thermal input) combustion installation.
- There is limited data on emissions but these suggest that they should be of the same order as heavier fuel oils but higher than lighter oils.
- The published data indicate combustion systems for pyrolysis oil can be implemented on larger boilers, kilns and furnaces with appropriate modification to fuel storage, transfer and burner systems.
- There is insufficient evidence to indicate the type and extent of air quality emissions from use of pyrolysis oil but these will be dependent on the raw materials used and the pyrolysis process applied.
- Use of pyrolysis oil in installations regulated under the EPR allows control of impacts on the environment.

- For non-EPR activities, controls on emissions are limited but more evidence would be required before emission limits could be developed.
- The absence of product standards analogous to those for mineral fuel oils is likely to constrain small scale and domestic use.

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1 Introduction

Defra commissioned a scoping study of existing information to help determine whether any future use of pyrolysis oil as a fuel would have implications for air quality. Pyrolysis is thermal decomposition of material (biomass in this instance) in the absence of oxygen. Pyrolysis occurs in combustion and gasification processes where it is followed by oxidation of the pyrolysis products. Lower process temperature and longer vapour residence times favour the production of charcoal. High temperature and longer residence time increase the conversion to gas and, moderate temperature and short vapour residence time are optimum for producing pyrolysis oils[1].

The tasks carried out were:

1. To what extent pyrolysis, gasification and pyrolysis oil combustion are regulated activities under the Environmental Permitting Regulations and what emission controls would apply;
2. A review of published literature to determine the range of composition of liquid biofuels compared to fossil equivalents – focussing on nitrogen, sulphur, ash, moisture, chlorine, energy content – these will provide an indication of whether fuels are cleaner/dirtier than gas oil or heavy oil;
3. A review of published literature and an internet survey to assess potential technologies and feedstocks – virgin timber, waste wood, food or other wastes;
4. A review of published literature to determine available emission data focussing on boiler/heater technologies and use in engines. The review would focus on NO_x, SO_2, VOC, CO, PM emissions and (if available) PAH, dioxins and, metals, odour and compare against fossil fuel default factors.

The results of the study are summarised in the following sections.

[1] See IEA Bioenergy Task 34 – Pyrolysis : Principles of Pyrolysis here http://www.pyne.co.uk

2 Tasks

2.1 Task 1: Review of regulation of pyrolysis and pyrolysis oil combustion activities.

2.1.1 Pyrolysis activities

Pyrolysis activities are regulated under Part 2, Chapter 1 (Energy Activities), Section 1.2(j) of the Environmental Permitting Regulations (England and Wales) Regulations 2010 (EPR). Activities involving the 'pyrolysis, carbonisation, distillation, liquefaction, gasification and partial oxidation or other heat treatment' are defined as A(1) activities (regulated by the Environment Agency in England and Wales). Pyrolysis of waste may be regulated under activities in Part 2, Chapter 5 of EPR.

However, pyrolysis of wood which has not been chemically treated is excluded from direct A(1) regulation and is not subject to Local Authority (Part A(2) or Part B) control either. Also use of pyrolysis plant to produce charcoal is not a regulated activity under EPR.

EPR does provide a mechanism for regulatory control of untreated wood pyrolysis plants if they are integrated with an activity which is regulated under EPR (such as a combustion activity). The pyrolysis operation would need to meet the criteria of a directly associated activity but this allows the regulator to exercise control over emissions. Note that if the main activity is a combustion activity this would only be available for larger (>20 MWth) combustion plant. Given that most existing pyrolysis plants (see Task 3) process comparatively small quantities of feedstock, the size of combustion plant (unless the pyrolysis fuel is co-fired) is likely to be <20 MWth.

Note that EPR provides a mechanism for incorporating the regulatory requirements of Directive 96/61/EC on Integrated Pollution Prevention and Control (IPPC) and its successor, Directive 2010/75/EU on Industrial Emissions (IED)[2]. This is relevant because IPPC currently applies to coal gasification and liquefaction plants but the IED will apply to gasification or liquefaction of other fuels (with a total rated thermal input of 20 MW or more). UK implementation of the IED will include measures to transpose the requirements to the national instruments.

There are currently no pyrolysis plant producing liquid biofuel known to AEA operating in the UK. There are rendering plant (producing tallow by heat treatment of carcasses and animal by-products) and there are plant which use thermal and chemical treatments to modify tallow, vegetable oil and grain to produce biodiesel and bioethanol for transport fuels.

The current exclusion of untreated wood pyrolysis activities from direct EPR control is a little surprising given that many relevant pollutants listed under the IPPC Directive (and IED) are likely to be present in emissions from such plant. However, this may reflect the rarity of such

[2] The IED came into force in January 2011 and Member States have to transpose into national legislation by January 2013.

plant due to the emerging status of wood pyrolysis. The IED does partly address the issue for larger installations by incorporating liquefaction (at a 20 MW threshold).

There are regulatory controls available through EPR for combustion of liquid fuels and for pyrolysis of treated wood and wastes. These include permits, application of Best Available Techniques, emission limit values and monitoring. For A(1) and A(2) activities there is a requirement to assess impacts on air quality and other aspects of the environment.

However, at present, the control mechanisms for untreated wood pyrolysis in a stand-alone facility are more limited and comprise the planning approval process, Clean Air Act (for smoke) and Environmental Protection Act (nuisance for example smoke and odour).

2.1.2 Combustion activities

There are regulatory controls available through EPR for combustion of liquid fuels in boilers or furnaces ≥20MW thermal input. Lower thresholds apply for waste burning and for instances where the boiler or furnace is part of a large (≥50MW thermal input) combustion installation. Use of pyrolysis oils as fuel in other EPR activities (for example cement kilns) would also be an EPR activity. These controls include permits, application of Best Available Techniques, emission limit values and monitoring. For A(1) and A(2) activities there is a requirement to assess impacts on air quality and other aspects of the environment.

Combustion of pyrolysis oil in boilers or furnaces ≥20MW but less than 50 MW thermal input would be a Part B activity and the current guidance note[3] does not include provisions for pyrolysis oil (or other liquid biomass fuel). The proposed revision to the guidance note[4] for the activity does not include emission limit values for pyrolysis oil and does not explicitly cover liquid biomass fuels but does set emission limit values for biomass.

The Clean Air Act applies to boilers and furnaces which do not fall under EPR, this restricts emission of black smoke and particulate (grit and dust). In addition, for non-domestic appliances >366 kW output, Local Authority approval for chimney height is required.

2.2 Task 2: A review of published literature to determine the range of composition of liquid biofuels compared to fossil equivalents.

The main sources of information for this part of the study were;

- Data extracted from the Phyllis database published by ECN in the Netherlands[5].
- The Internal Energy Agency (IEA) Bioenergy Agreement Task 34 website, also known as Pyne[6], and:

[3] Defra PG1/3 (95) Secretary of State's Guidance : Boilers and Furnaces, 20-50 MW net rated thermal input and Air Quality note AQ 23(04) amending Guidance PG3/1(95). Available here : http://www.defra.gov.uk/environment/quality/industrial/las-regulations/guidance/
[4] Defra Draft Process Guidance Note 1/03 (11) – Secretary of State's Consultation for Part B Process - Statutory Guidance for Boilers And Furnaces 20 – 50MW Thermal Input. Available here : http://archive.defra.gov.uk/environment/quality/pollution/ppc/consultations/pgn-1-03-11.pdf
[5] Phyllis, database for biomass and waste, http://www.ecn.nl/phyllis maintained by the Energy Research Centre of the Netherlands.
[6] www.pyne.co.uk

- Proprietary information published by the oil manufacturers, Dynamotive Energy Systems[7] and Ensyn[8].

A summary of ultimate analyses from the data reported in the Phyllis database is given in the table below with standard heating oil products as a comparison. Pyrolysis oil specifications[9] are included from ASTM D7544-10 and reported by the IEA Task 34. More complete data is given in Appendix 1. Fuel oil and gas oil characteristics are taken from the Digest of UK Energy Statistics (Carbon 'C' and heating values)[10], a report on use of Tallow in the EU[11] and, a report on pyrolysis oils by Sandia National Laboratories[12].

Table 1 Ultimate analyses of pyrolysis and other oils

Component	Units	Pyrolysis oils Mean value	Units	ASTM D7544	Fuel oil	Gas oil
Water content	wt% wet	18.8	wt%	≤30	0.02	<0.5
Volatiles	wt% daf	66.8				
Ash	wt% dry	0.1	wt%	≤0.25	<0.05	<0.08
HHV	kJ/kg daf	23723	kJ/kg	≥15000	43500	45600
LHV calc	kJ/kg daf	22699	kJ/kg		40800	42900
C	wt% daf	56.2	wt%		87.7	87.2
H	wt% daf	6.65	wt%		10.3	12.8
O	wt% daf	36.2	wt%		1.2	<0.1
N	wt% daf	0.57	wt%		0.48	<0.01
S	wt% daf	0.05	wt%	≤0.05	0.7 (≤1)	0.1 (≤0.1)
Cl	wt% daf	0.1	wt%			
Pyrolysis solids			wt%	≤2.5	na	na

daf – dry ash free

Bio-oil, frequently also referred to as bio crude, fast pyrolysis oil, flash pyrolysis oil, or pyrolysis liquid, bears little resemblance in its properties to hydrocarbon fuel. It is essentially a suspension of complex carbohydrates in water with comparatively high oxygen and water content and low carbon.

The concentrations of the minor components of ash, nitrogen, sulphur and halogens are dependent on the feedstock used to produce the oil. Thus oil from herbaceous plants and

[7] http://www.dynamotive.com/
[8] http://www.ensyn.com/
[9] ASTM D7544:2010 Standard Specifications for pyrolysis liquid biofuel, specification reported here http://pyne.co.uk/?_id=116
[10] Digest of UK Energy Statistics (2010) here : http://www.decc.gov.uk/assets/decc/Statistics/publications/dukes/314-dukes-2010-ann-a.pdf
[11] Assessment of the application of community legislation to the burning of rendered animal fat (Final report) by Ecolas NV for European Commission (DG Env) rep No 05/10572/AL Dec 2006.
[12] Combustion properties of biomass flash pyrolysis oils: Final Project report by Sandia National Laboratories for US Dept of Energy rep SAND99-8238 April 1999.

crop residues contain more ash and nitrogen than those derived from clean sawdust. This is shown in the Tables in Appendix 1.

The data from Phyllis also demonstrate a substantial variation in properties depending on the method of preparation, mostly related to the water content, although this may be an indicator for wider differences in the character of the organic fraction.

Ash components also reflect the origin as would be expected. Ash from wood derived oils is at very low concentrations and its chemical composition is rarely measured. There appears to be nothing that would give rise to undue concern in the measurements surveyed but the sample is small.

Pyrolysis processes always produce a mix of gas, char and oil. Proprietary processes separate the char from the oil with varying degrees of success which gives a further variable for product characterisation as the char contains most of the ash. The effective removal and/or combustion of pyrolysis solids in the liquid biofuel is an issue as it is a potential source of particulate emission.

Contaminated wood does not appear to be represented in Phyllis so it is not possible to comment on whether heavy metals would partition to the oil product.

The consequences of the composition are summarised by VTT on the IEA Task 34 Website.

- Liquid fuel with a heating value about 40% that of fuel oil/diesel.
- Does not mix with hydrocarbon fuels.
- Not as stable as fossil fuels, can separate into phases. Stability deteriorates with age.
- Density at 1.24 kg/litre is much higher than petroleum products, typically 0.85.
- The viscosity of the bio-oil as produced can vary from as low as 25 cSt to as high as 1000 cSt.

And most notably

- Quality needs definition for each application.

Although ASTM D7544 details physical and chemical requirements for pyrolysis liquid biofuels, these are intended for use in industrial burners designed to handle such fuels. It seems unlikely that a product standard for wider use (and in particular small scale use) could be introduced at present given the multiplicity of manufacturing methods and feedstocks combined with the undeveloped status of the technology in general.

2.3 Task 3: A review of published literature and an internet survey to assess potential technologies and feedstocks – virgin timber, waste wood, food or other wastes.

The main source of information for this task was the International Energy Agency (IEA) Task 34 website and reviews by the Finnish Technical Laboratory VTT[13] and Prof Bridgewater of Aston University [14].

Feedstocks to date have been limited to lignocellulosic biomass such as wood, herbaceous plants such as grasses, and crop residues such as straw and sugar cane bagasse. The majority of research and all of the commercial activity has concentrated on clean wood sawdust. The commercial possibilities of the other materials are recognised however. AEA is aware anecdotally of efforts in Germany to use pyrolysis to treat contaminated waste wood to obtain a "fuel product" with the contamination remaining the char and ash residue.

A table from the 2010 VTT review is reproduced below which shows the range of processes in operation or under development. A more exhaustive list is given in the recent review by Bridgewater.

What is clear is that there are many development strands but virtually no commercial production. It seems unlikely that such production could be started with in next two years in the UK. Should a facility be built in the UK or EU it would be regarded as a major advance and would come to Government's attention long before its products reach market

The only commercial production at present is by Ensyn and although fuel products are detailed in their publicity, is targeted almost exclusively towards food additives "liquid smoke".

[13] VTT PUBLICATIONS 731, Properties and fuel use of biomass derived fast pyrolysis liquids - A guide, Anja Oasmaa & Cordner Peacocke, 2010
[14] Article in press Bridgwater AV, Review of fast pyrolysis of biomass and product upgrading, Biomass and Bioenergy (2011), doi:10.1016/j.biombioe.2011.01.048

Table 3. Pyrolysis liquids production processes, 2010 (> 10 kg/h).

Host organisation	Country	Technology	kg/h	Applications	Status
ABRITech/ Advanced Biorefinery Inc., Forespect	Canada	Auger	70–700 2 000	Fuel	Operational Commissioning
Agri-Therm/ University of Western Ontario	Canada	Fluid bed	420	Fuel	Upgrade
Biomass Engineering Ltd.	UK	Fluid bed	250	Fuel and products	Construction
BTG	Netherlands	Rotating cone	200 5 000	Fuel and chemicals	Operational 5 t/h in design phase
BTG/Genting	Malaysia	Rotating cone	2 000	Fuel	Dormant
Dynamotive	Canada	Fluid bed	80 625	Fuel	Disassembled
Dynamotive	Canada	Fluid bed	4 200	Fuel	Operational
Dynamotive	Canada	Fluid bed	8 400	Fuel	Standby
KIT	Germany	Auger	1 000	Fuel	Operational
Metso	Finland	Fluid bed	300	Fuel	Operational
Pytec	Germany	Ablative	250	Fuel	Operational
Red Arrow/Ensyn several	USA	Circulating transported bed	125– 1 250	Fuel and chemical	Operational
University of Hamburg	Germany	Circulating transported bed	50	Waste disposal Fuel and chemicals	Operational
University of Science and Technology of China, Hefei	China	Fluid bed	120	Fuel	Operational
Virginia Tech	USA	Fluid bed	250	Fuel	Operational
VTT	Finland	Circulating transported bed	20	Fuel	Operational

2.4 Task 4 A review of published literature to determine available emission data focussing on boiler/heater technologies and use in engines.

Obtaining information for this Task proved problematic with very little data reported. The most valuable sources are the 2010 **VTT** review and a **Sandia National Labs** (USA) report from 1999[15]. **Dynamotive** have published reports on boiler furnace and gas turbine (GT) performance [16]. **Biomass Technology Group** (BTG)[17] has also published data on a small

[15] SANDIA REPORT, SAND99-8238, Printed April 1999
[16] Dynamotive BioOil Information Booklet 2011. www.dynamotive.com

scale CHP engine and a 9 MW boiler burning pyrolysis oil. AEA is aware of work by Ensyn in Canada on boilers and GTs but this proved impossible to locate in the time for this study.

2.4.1 Sandia National Labs

The Report from the **Sandia National Labs** remains the most thorough examination of pyrolysis oil in the public domain. The main conclusions are:

2.4.1.1 Boilers

- Some preheating is desirable but it must be carried out in the burner supply pipe, not the fuel storage tank to avoid polymerisation.
- Steam and air atomisation is preferred over pressure to reduce issues with wear but pressure is acceptable. Carbon steel components corrode and stainless is preferred.
- The burner must be purged with a polar solvent such as ethanol before shut down to avoid blockage due to polymerisation and coking under the influence of furnace heat.
- Ignition is difficult and requires a preheated refractory section close to the burner or hydrocarbon support flame.
- Once ignited flame length is similar to oil.
- Heat release rates are similar to oil.
- NO_x emissions are lower than residual fuel oil but higher than lighter oils. However, some caution is advised as the fuel Nitrogen content is dependent on the feedstock. Herbaceous and crop residues have higher Nitrogen content. Thermal NO_x should be reduced due to the lower flame temperature from the high water content (compared to hydrocarbon fuel oils).
- CO and particulates are somewhat higher than oil. Again caution is advised as the emissions will be highly dependent on feedstock and the quality of atomisation.

2.4.1.2 Diesel Engines

The use of slow and medium speed diesel engines with pilot ignition has been investigated and found feasible but there remain significant development problems with wear, coking and combustion quality.

2.4.1.3 Gas turbines

Robust industrial gas turbines have been used with some success. Some tests report reduced NO_x emissions compared to oil, other report increased levels. Particulates and deposition seem to present problems.

2.4.1.4 Combustion science

Flame tunnel tests have shown that combustion usually proceeds as a series of droplet micro explosions in contrast to the mechanism of droplet evaporation of hydrocarbon oils. The processes of droplet formation and subsequent dispersion by micro explosion are fundamental to combustion performance. Both processes are strongly influenced by the production method, feedstock origin water and ethanol.

2.4.2 VTT study

VTT and Oilyon OY in Finland carried out work on boiler combustion and confirmed the above conclusions. In particular they emphasised the importance of water content and char content on the production of particulate emissions. High water content and high char content

[17] Information published at TCBiomass2011 and available here : http://www.btg-btl.com/index2.php

give high particulates. This is believed to be linked to atomisation behaviour as suggested by Sandia. This work is reported on the IEA Task 34 website[18].

The 2010 VTT review summarised current known activities, a table for power applications is reproduced below.

Table 12. Status of pyrolysis liquid-based power generation technologies.

	Gas turbine	Diesel engine	Co-firing (NG, coal)	Stirling
Development stage	2,500 kWe modified system ready for commercial demonstration No other modified GT plants available	Several engines tested: reliable system not yet developed Various activities ongoing	NG co-firing successfully tested	Short-term testing carried out in a very small unit
Major modifications, critical issues	Nozzles, materials, in-line cleaning system, feeding line	Injector and fuel pump material Emissions	Oil gun material, pump and feeding line	Pump and injector
R&D needs	Long-term commercial demonstration Modification of other GT turbomachines Demonstration of combined cycles	Development of: effective/reliable pumping and injections systems; good combustion to avoid deposits on the hot parts (cylinder, piston, injector); materials	Long-term commercial demonstration	Reliable small-scale Stirling engine to be developed and demonstrated long term with standard fuels before carrying out further tests on PO
Further developments	Application of pyrolysis liquids to MGT	Use of emulsions and blends for ignition, fuel handling and injection improvement	Further pyrolysis liquids cost reduction to make NG (first) and coal (second) co-firing economically possible	As above

2.4.3 BTG emission trials

BTG of the Netherlands has undertaken trials with pyrolysis oil at a 9MWth industrial boiler and a single cylinder diesel engine generator (10 kW electrical output). At the boiler, the pyrolysis oil was used with a natural gas pilot flame providing about a quarter of the thermal input. NOx emissions were lower than for heavy fuel oil. The tests on the diesel engine included replacement of the fuel injection system and optimisation of the fuel an air supply system. A 12 hour continuous operation was achieved but required preheat of combustion air and in-house manufacture of stainless fuel supply components. Emissions of NOx were lower and CO higher than with conventional diesel fuel.

2.4.4 Other studies

In 2010 Metso in Finland burned 20 tons of bio oil in a district heating boiler Based on this experience bio-oil is considered by them to be technically suitable for replacing heavy fuel oil

[18] Available here www.pyne.co.uk

in district heating plants. Emissions (CO, NO_x, particulate) were close to heavy fuel oil. No significant odours to the neighborhood occurred.[19]

Dynamotive report the successful use of their oil in boilers, furnaces and kilns.

Such applications as are reported in the literature are generally for large industrial and district heating boilers, kilns and furnaces, essentially as a low carbon replacement for fuel oils. There is no expectation of pyrolysis oil being used in small commercial or domestic scale. This suggests that it would be possible to regulate on an individual installations basis.

The EU study on tallow use as a fuel indicates similar NO_x emission data as for fuel oil and, with the exception of PM (dust) emissions, tallow-fuelled boilers are generally able to meet emission limit values set by Directive 2000/76/EC on incineration of waste. However, although rendered animal fat (tallow) is produced by heat treatment, the process is not analogous to pyrolysis processes described for liquid biofuels. The tallow is separated from the heat-treated (cooked at low temperature) material by pressing, it has higher calorific value and lower moisture content than pyrolysis liquids, also tallow has similar properties to a heavy fuel oil and can be burned with comparatively minor modification to oil-fired boilers.

[19] Bio-oil production integrated to a fluidised bed boiler – experiences from pilot operation Featured Renewables August 17th, 2010 by IFandP Research

3 Conclusions relevant to air quality impacts

- The diversity of feedstocks and manufacturing processes available to produce pyrolysis oil give rise to wide variations of possible composition and properties of the products. This means that a coherent product standard analogous to mineral fuel oil standard grades is very unlikely.
- Pyrolysis activities are regulated under the Environmental Permitting Regulations (England and Wales) Regulations 2010 (EPR).
- However, pyrolysis of wood which has not been chemically treated is not an activity under the Environmental Permitting Regulations (EPR). Also use of pyrolysis plant to produce charcoal is not a regulated activity under EPR.
- EPR does provide a mechanism for regulation of untreated wood pyrolysis plants if they are a directly associated activity to a regulated activity. Note that if the main activity is a combustion activity this would only be available for larger (>20 MWth) combustion plant.
- The Directive 2010/75/EU on Industrial Emissions (IED) extends the scope of regulated activities to include gasification or liquefaction of non-coal fuels (with a total rated thermal input of 20 MW or more). UK implementation of the IED will include measures to transpose the new IED activity to national regulations.
- There are regulatory controls available through EPR for combustion of liquid fuels in boilers or furnaces ≥20MW thermal input. Lower thresholds apply for waste burning and for instances where the boiler or furnace is part of a large (≥50MW thermal input) combustion installation.
- There is limited data on emissions but these suggest that they should be of the same order as heavier fuel oils but higher than lighter oils.
- The published data indicate combustion systems for pyrolysis oil can be implemented on larger boilers, kilns and furnaces with appropriate modification to fuel storage, transfer and burner systems.
- There is insufficient evidence to indicate the type and extent of air quality emissions from use of pyrolysis oil but these will be dependent on the raw materials used and the pyrolysis process applied.
- Use of pyrolysis oil in installations regulated under the EPR allows control of impacts on the environment.
- For non-EPR activities, controls on emissions are limited but more evidence would be required before emission limits could be developed.
- The absence of product standards analogous to those for mineral fuel oils is likely to constrain small scale and domestic use.

Appendices

Appendix 1: Pyrolysis Oil Composition data extracted from PHYLLIS Database

Appendix 1 - Pyrolysis Oil Composition data extracted from PHYLLIS Database

Ultimate - All Pyrolysis oils

Component	Units	Mean value	Min value	Max value	Std dev in %	Number of refs
Water content	wt% wet	18.8	0	35	45	21
Volatiles	wt% daf	66.8	61.6	71.8	5	6
Ash	wt% dry	0.1	0	0.3	140	21
HHV	kJ/kg daf	23723	14200	30496	13	24
LHV calc	kJ/kg daf	22699	20640	28811	10	23
C	wt% daf	56.2	41	69.9	11	25
H	wt% daf	6.65	5	7.8	9	25
O	wt% daf	36.2	20	49.5	17	25
N	wt% daf	0.57	0.04	3.11	129	25
S	wt% daf	0.05	0.01	0.16	99	17
Cl	wt% daf	0.1	0.1	0.1	0	3
F	wt% daf	-	-	-	-	0
Br	wt% daf	-	-	-	-	0

Ultimate - Wood only pyrolysis oils

Component	Units	Mean value	Min value	Max value	Std dev in %	Number of refs
Water content	wt% wet	18.7	0	29.7	35	14
Volatiles	wt% daf	67.9	64.5	71.8	4	5
Ash	wt% dry	0.1	0	0.8	267	15
HHV	kJ/kg daf	24014	22166	33965	12	15
LHV calc	kJ/kg daf	22586	20726	32074	13	15
C	wt% daf	58.2	52.4	72.9	8	15
H	wt% daf	6.54	5	8.67	11	15
O	wt% daf	34.8	18.7	39.7	15	15
N	wt% daf	0.17	0.04	0.31	49	15
S	wt% daf	0.03	0.01	0.05	44	8
Cl	wt% daf	-	-	-	-	0
F	wt% daf	-	-	-	-	0
Br	wt% daf	-	-	-	-	0

Ultimate - Herbaceous and crop residue

Component	Units	Mean value	Min value	Max value	Std dev in %	Number of refs
Water content	wt% wet	26	0	63	84	8
Volatiles	wt% daf	61.6	61.6	61.6	0	1
Ash	wt% dry	0.1	0	0.3	100	4
HHV	kJ/kg daf	26052	22100	30496	12	7
LHV calc	kJ/kg daf	24535	20640	28811	13	7
C	wt% daf	49.7	16.3	69.9	32	11
H	wt% daf	6.57	5.5	7.72	11	11
O	wt% daf	42.2	20	78	41	11
N	wt% daf	1.21	0.12	3.11	74	11
S	wt% daf	0.1	0.01	0.33	100	9
Cl	wt% daf	0.1	0.1	0.1	0	3
F	wt% daf	-	-	-	-	0
Br	wt% daf	-	-	-	-	0

Ash analysis all pyrolysis oils

Component	Units	Mean value	Min value	Max value	Std dev in %	Number of refs
Al	mg/kg dry	6.3	0.3	28	141	9
As	mg/kg dry	0.2	0.2	0.2	0	1
B	mg/kg dry	0.1	0.1	0.1	0	1
Ba	mg/kg dry	0.6	0.6	0.6	0	1
Ca	mg/kg dry	15.9	1	50	96	12
Cd	mg/kg dry	0.2	0.2	0.2	0	1
Co	mg/kg dry	0.1	0.1	0.1	34	2
Cr	mg/kg dry	0.4	0.2	0.6	63	2
Cu	mg/kg dry	1.6	0.9	2.3	62	2
Fe	mg/kg dry	137.7	15	230	71	4
Hg	mg/kg dry	-	-	-	-	0
K	mg/kg dry	10.7	1	35	108	12
Mg	mg/kg dry	5.7	0.7	17	94	11
Mn	mg/kg dry	0.5	0	2	141	7
Mo	mg/kg dry	-	-	-	-	0
Na	mg/kg dry	3.9	0.9	21.5	171	9
Ni	mg/kg dry	2.2	0.2	6.6	132	4
P	mg/kg dry	7.8	1	14	85	4
Pb	mg/kg dry	2.8	0.6	4.9	110	2
Sb	mg/kg dry	4	0.3	7.7	131	2
Se	mg/kg dry	0.2	0.1	0.2	47	2
Si	mg/kg dry	21.4	5.3	30	65	3
Sn	mg/kg dry	0.2	0.2	0.2	0	1
Sr	mg/kg dry	0.1	0.1	0.1	0	1
Te	mg/kg dry	-	-	-	-	0
Ti	mg/kg dry	0.3	0.2	0.7	65	6
V	mg/kg dry	0.3	0	1	171	8
Zn	mg/kg dry	27.6	1.7	43.7	71	4

Ash analysis wood derived pyrolysis oils

Component	Units	Mean value	Min value	Max value	Std dev in %	Number of refs
Al	mg/kg dry	1.1	0.3	2	57	5
As	mg/kg dry	-	-	-	-	0
B	mg/kg dry	-	-	-	-	0
Ba	mg/kg dry	-	-	-	-	0
Ca	mg/kg dry	12.1	1	50	138	8
Cd	mg/kg dry	-	-	-	-	0
Co	mg/kg dry	-	-	-	-	0
Cr	mg/kg dry	-	-	-	-	0
Cu	mg/kg dry	-	-	-	-	0
Fe	mg/kg dry	-	-	-	-	0
Hg	mg/kg dry	-	-	-	-	0
K	mg/kg dry	9.4	1	29	109	8
Mg	mg/kg dry	4.1	0.7	12	93	7
Mn	mg/kg dry	0.1	0	0.2	63	5
Mo	mg/kg dry	-	-	-	-	0
Na	mg/kg dry	2	0.9	4	63	5
Ni	mg/kg dry	-	-	-	-	0
P	mg/kg dry	-	-	-	-	0
Pb	mg/kg dry	-	-	-	-	0
Sb	mg/kg dry	-	-	-	-	0
Se	mg/kg dry	-	-	-	-	0
Si	mg/kg dry	-	-	-	-	0
Sn	mg/kg dry	-	-	-	-	0
Sr	mg/kg dry	-	-	-	-	0
Te	mg/kg dry	-	-	-	-	0
Ti	mg/kg dry	0.3	0.2	0.7	77	4
V	mg/kg dry	0	0	0	0	4
Zn	mg/kg dry	-	-	-	-	0

Ash analysis herbaceous and crop residue derived pyrolysis oils						
Component	**Units**	**Mean value**	**Min value**	**Max value**	**Std dev in %**	**Number of refs**
Al	mg/kg dry	10.1	10.1	10.1	0	1
As	mg/kg dry	-	-	-	-	0
B	mg/kg dry	-	-	-	-	0
Ba	mg/kg dry	-	-	-	-	0
Ca	mg/kg dry	33.8	33.8	33.8	0	1
Cd	mg/kg dry	-	-	-	-	0
Co	mg/kg dry	0.1	0.1	0.1	0	1
Cr	mg/kg dry	0.6	0.6	0.6	0	1
Cu	mg/kg dry	2.3	2.3	2.3	0	1
Fe	mg/kg dry	105.8	105.8	105.8	0	1
Hg	mg/kg dry	-	-	-	-	0
K	mg/kg dry	5.3	5.3	5.3	0	1
Mg	mg/kg dry	2.2	2.2	2.2	0	1
Mn	mg/kg dry	1.1	1.1	1.1	0	1
Mo	mg/kg dry	-	-	-	-	0
Na	mg/kg dry	21.5	21.5	21.5	0	1
Ni	mg/kg dry	1.1	1.1	1.1	0	1
P	mg/kg dry	3.3	3.3	3.3	0	1
Pb	mg/kg dry	4.9	4.9	4.9	0	1
Sb	mg/kg dry	7.7	7.7	7.7	0	1
Se	mg/kg dry	0.2	0.2	0.2	0	1
Si	mg/kg dry	-	-	-	-	0
Sn	mg/kg dry	-	-	-	-	0
Sr	mg/kg dry	-	-	-	-	0
Te	mg/kg dry	-	-	-	-	0
Ti	mg/kg dry	0.2	0.2	0.2	0	1
V	mg/kg dry	0	0	0	0	1
Zn	mg/kg dry	43.7	43.7	43.7	0	1

PHYLLIS is a database containing composition data for biomass and waste and is maintained by the Energy Research Centre of the Netherlands (ECN) and available here http://www.ecn.nl/phyllis/.

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