2015

Biomass and Waste Pyrolysis
A Guide to UK Capabilities









Published by the Aston University European Bioenergy Research Institute (EBRI)

Pyrolysis

All types of pyrolysis are being researched and developed in the UK including fast, intermediate and slow pyrolysis, as well as torrefaction and production of biochar. Pyrolysis is thermal decomposition occurring in the absence of oxygen. Lower process temperatures and longer vapour residence times favour the production of charcoal. Higher temperatures and longer residence times increase biomass conversion to gas, and moderate temperatures and short vapour residence time are optimum for producing liquids. Three products – gas, liquid and solid – are always produced and the proportions can be controlled by the processing conditions. The map below shows the location of the pyrolysis activities reported in this guide.

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Foreword

Professor John Loughhead OBE FREng FTSE
Chief Scientific Advisor
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The UK has an ambitious legally binding goal of achieving an 80% reduction in greenhouse gas emissions by 2050. One of the key challenges in this target is to deliver a greatly decarbonised energy system. To achieve this affordably, while providing the security of supply that the country expects, it is very likely that bioenergy will play a contributory role along with other emerging technologies. To reap the greatest rewards from the inevitably large investment in decarbonisation, we have to work to minimise the cost of the energy system while creating a globally competitive UK technology supply industry which can maximise the economic return and is able to exploit export opportunities.

Innovation is key to reducing the cost of delivering bioenergy flexibly and has been one of the UK's strengths. Knowledge barriers both increase costs and delay uptake of new technologies. This Guide to the UK's Capabilities on Biomass and Waste Pyrolysis offers a way of breaking down these barriers and unleashing the potential of pyrolysis.

Pyrolysis can potentially handle physical and chemical variation in feedstocks from wastes and crops. It can be adapted to deliver high value chemicals as well as useful energy feedstocks such as gases, oils and solids without using fossil carbon. The Government has supported advanced conversion technologies including pyrolysis, through funding mechanisms including the Contracts for Difference regime and innovation funding to push forward their development to a greater level of technological readiness. There remain however substantial challenges to delivering cost-effective pyrolysis on the scale required so I particularly welcome this Guide as a key support to the sector in developing its contribution to a successful UK green economy.

Introduction

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IEA Bioenergy Task 34 Pyrolysis

This revised and updated Guide to UK Biomass and Waste Pyrolysis Activities summarises the range of research and commercial activities being undertaken in the UK. It is intended that this will help all involved in this expanding area, including researchers, companies, policy makers, decision makers and stakeholders, to be better informed of the UK's capabilities and expertise. The incentive for producing this guide is UK membership of the IEA Bioenergy Pyrolysis Task for three years from 2013 to 2015. IEA Bioenergy is well established as the leading international information exchange partnership in biomass, bioenergy and biofuels. It has existed for over 30 years and is based on a programme of Tasks centred on themes relating to biomass production and conversion. Full details can be found on the IEA Bioenergy website – www.ieabioenergy.com.

The current IEA Bioenergy Pyrolysis Task has evolved from the first IEA Bioenergy Task on fast pyrolysis initiated by Tony Bridgwater in 1994 [1] and then the European Commission sponsored networks ThermoNet [2,3] and ThermalNet [4] both of which included active participation by IEA Bioenergy in the pyrolysis area.

The Task has successfully carried out a programme of technical and economic evaluations and has had particular success in integrating the fast pyrolysis community through the mechanism of Round Robins. These encourage laboratories to analyse, characterise and/or investigate particular properties of fast pyrolysis liquids (bio-oil) or to evaluate fast pyrolysis as a technology for processing unusual materials. The results are shared and published where possible such as the evaluation of fast pyrolysis of lignin [5], and review of fast pyrolysis of biomass and product upgrading [6]. The current Round Robin is comparing fast pyrolysis processes in the member countries utilising standard feedstocks. Several characterisation and analysis methods are being used to assess processing methods at participating laboratories.

These benefit both the laboratories involved in providing benchmarks as well as the international community in developing standards and methods. Other activities in the Pyrolysis task include information exchange, technology updates and evaluations, and visits to laboratories or commercial plants. An electronic newsletter is published twice a year which is available from the website – www.pyne.co.uk. This also contains updates on fast pyrolysis activities and technologies.

In this guide, all entries are based on material supplied by each organisation. We would be pleased to hear about any additional activities and updates on what is reported here.

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References

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Tyre Pyrolysis

Keywords
Project development, Tyres, Carbon black, Incentives, Feasibility studies

2G BioPOWER is developing a UK pyrolysis project to convert used tyres into partially renewable oil, steel and carbon black, which will be re-used in rubber goods manufacture.

About 300k tonnes of used tyres in the UK are disposed of each year: at least two-thirds of which are burnt. The UK is driving hard towards the Circular Economy, which is consistent with moving waste reprocessing up the EU's Waste Hierarchy. Recovering carbon black and steel is a significant step in this direction and delivers materials and oil worth roughly £300 for each tonne of tyres.

Recycling these materials also reduces GHG emissions (one kilo of virgin carbon black requires approximately 1.5 litres of oil to produce).

Car tyres contain about 25% natural rubber. The resulting partially renewable oil can be upgraded to meet the UK's residual fuel oil Quality Protocol, but is already a flexible product for power and industrial heat applications, achieving higher conversion efficiency than the combustion of tyres alone.

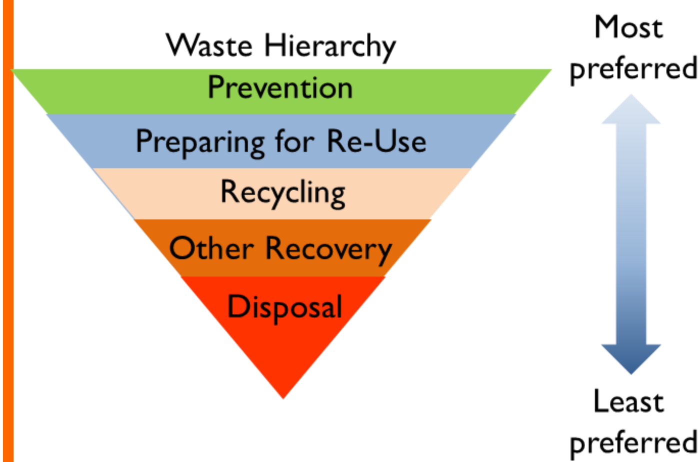

Figure 1: *EU waste hierarchy.*

www.2gbiopower.com

Figure 2: *Component manufactured with 100% 'recovered' carbon black (rCB).*

Producing 'recovered' carbon black ('rCB') makes the project less susceptible to variations in market factors than the production of oil alone and therefore provides a more stable long term disposal route for tyres. It is essential to secure market outlets to rubber manufacturers. A critical requirement, therefore, has been selecting a technology that achieves a consistently high quality rCB which performs as well in rubber compounds as virgin carbon black.

The 'holy grail' is for rCB to be re-used in tyre manufacture, an industry which uses about 75% of all carbon black produced worldwide. 'rCB' is under constant review by tyre manufacturers as pyrolysis technologies mature. Whilst this will take time, 2GBioPOWER is actively marketing rCB to this sector.

A UK project is profitable without UK Government incentives. 2G BioPOWER has identified prospective sources of feedstock, offtakes, finance and sites.

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Slow Pyrolysis at IBERS

Keywords
Slow pyrolysis, Remediation, Torrefaction, Grasses, Bulk-production

Batch slow-pyrolysis production plant
Pilot-scale batch slow-pyrolysis unit designed by Sustainable Energy Ltd. and installed and operated by IBERS, Aberystwyth University. The plant optimises the production of solid char for a variety of end uses and operates flexibly over a full range of torrefaction/slow-pyrolysis temperatures and residence times. A fraction of the pyrolysis liquids produced are also condensed and collected as part of the process.

Plant description
Feedstock is heated in a 1.25m^3 mesh-bottomed stillage inside the reactor unit, held at net-positive pressure to inhibit ambient air ingress. It is heated via direct feed of hot gases from the combustor. Recirculated gas from exothermic reaction supplements the heating process. Additional resources include: Feedstock characterisation and analysis, customised tube furnace pyrolyser for smaller test batches, TG-GC-MS, TG-FTIR, and SEM. For wider capability please refer to the BEACON website.

Current projects
The facility is one component of the BEACON Biorefinery Centre of Excellence which seeks to build integrated 'Green Supply Chains' with a focus on developing new routes to functional, cost competitive products using biomass rather than fossil resources. Our intention is to understand and engage with businesses to cultivate and deliver 'Green Technology

Figure 1: *The pilot plant.*

Figure 2: *Loading of feedstock-filled stillage unit into unit for heating run.*

Solutions' to benefit industry across a range of sectors. To facilitate this we have a network of scientific expertise based at Aberystwyth, Bangor and Swansea Universities with capacity to provide solutions from bench to demonstration scale.

The plant is also currently producing bespoke chars for a DEFRA-funded Metal Mine Remediation Project, using char as a treatment medium, for contaminated mine waters. It is hoped to set out the case for the practical simplicity of batch slow-pyrolysis systems, and the economic advantage of utilisable low-temperature chars.

The plant is available for the bespoke production of char for research, and practical applications and we welcome collaborative project proposals.

http://beaconwales.org/en/facilities/aberystwyth-university/slow-pyrolysis-bio-char-production-plant

http://www.aber.ac.uk/en/iges/research-groups/enviro-geochem/mmr/

BEACON
From plants to products
O blanhigion i gynhyrchion

PRIFYSGOL ABERYSTWYTH UNIVERSITY

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Waste- or Biomass-to-Energy Pyrolysis

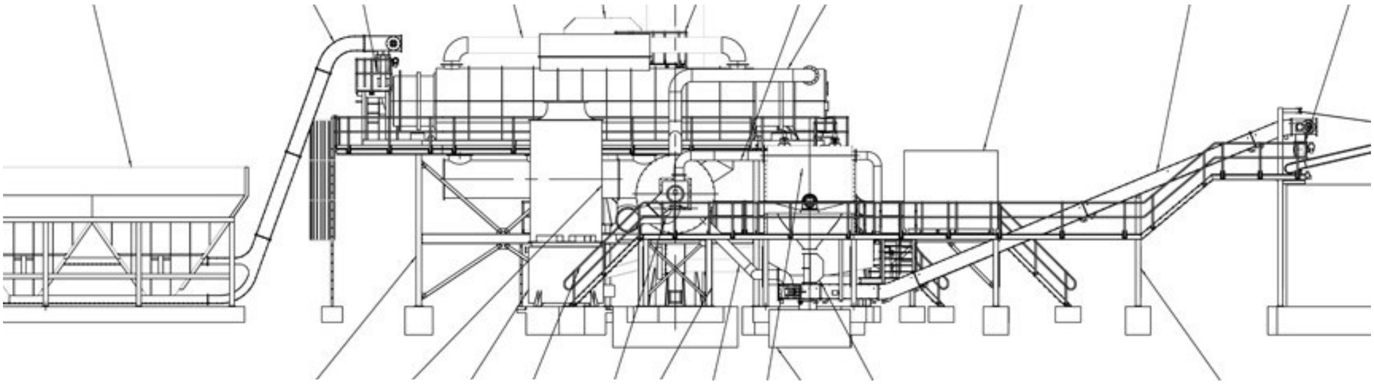

Figure 1: *Typical schematic of waste or biomass pyrolysis plant.*

Keywords
Pyrolysis, Low capex, High Calorific Value (CV) syngas, Engine, Turnkey

Anergy is a new emerging technology in waste or biomass to energy pyrolysis technology. It is focused on delivering turnkey 1-10MWe scale waste projects. It is based on the indirect fired kiln technology which has been developed by its sister company Ansac in Australia. Ansac has built and delivered over 200 indirect fired kilns globally focused on pyrolysis applications in the mining industry.

Figure 2: *Pyrolysis facility built in Western Australia by Ansac.*

www.greenanergy.com

Anergy was set up in 2008 to provide turnkey solutions based on the Ansac technology and has developed a very compact and low capex solution which is very good for small scale waste projects. Anergy has a philosophy that large scale plants in this segment are not sensible and that plants should be married up to the waste source.

Ansac and Anergy are currently working together to deliver a landmark wood waste to energy plant in Perth, Western Australia which will see the end of its commercialisation phase. This plant is expected to be operational in early 2016.

The Anergy process has the benefit of being highly efficient, flexible in terms of feedstocks, economical small scale and having best practice emission levels. The Ansac kiln technology at its heart allows very high temperature pyrolysis reducing the issue of tarring and making subsequent gas clean-up and treatment comparatively simple. Finally, the absence of any air usage in the process means that the final syngas stream that is produced is of a very high calorific value, making direct engine combustion reliable and efficient.

ANERGY Ltd

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Pyrolysis at BERG and EBRI

The Bioenergy Research Group (BERG) is one of the best established academic bioenergy research groups in the world. Our novel developments have led us to become one of the world's leading university laboratories in thermal biomass processing. This history led to the creation of the European Bioenergy Research Institute (EBRI) at Aston University in 2013 with brand new state-of-the-art laboratories from an investment of nearly GBP20million (USD30 million).

The focus of BERG's research is fast pyrolysis which converts solid biomass into a valuable liquid energy carrier or fuel known as bio-oil that can be directly used for heat, power and chemicals; and can be readily upgraded into higher value 2nd generation biofuels and chemicals. There is complementary work on biomass pre-treatment, gasification, product upgrading, characterisation and analysis, chemicals production, system design, and technical and economic evaluation. The creation of EBRI, of which BERG is a key part, has broadened the range of activities into intermediate and slow pyrolysis, fluid bed and circulating fluid bed gasification, and most recently a major expansion into the synthesis and characterisation of catalysts especially focusing on biofuel and green chemical applications. We led the UK national centre of excellence in bioenergy and biofuels, SUPERGEN Bioenergy, which completed in 2011. The IEA Bioenergy Task 34 for Pyrolysis was created and led by Aston from 1992 until 2008. We have extensive R&D activities in several parts of the world including China and India.

Figure 1: *Mobile containerised Pyrofab based on Pyroformer™ technology developed by EBRI at Aston University.*

Figure 2: *Aston's 1kg h^{-1} continuous fast pyrolysis unit.*

As a result of its steady stream of national and international funding, EBRI has built up some of the most comprehensive university-based thermal processing facilities and capabilities in the world including extensive thermal processing facilities for pyrolysis, gasification, analysis, CFD and process modelling. Our key interests include:

- Biomass characterisation and pre-treatment;
- Fast pyrolysis of biomass and waste in continuous fluid bed systems for bio-oil;
- Gasification of biomass in fixed and fluid beds;
- Analytical techniques for characterisation and evaluation of biomass and bio-oils;
- Upgrading of bio-oil from fast pyrolysis by physical and catalytic processes;
- Development of applications for bio-oil;
- Development of catalysts for modifying bio-oil;
- Production of chemicals such as resin precursors for wood panels, fertilisers and preservatives;
- Biofuel production by upgrading of fast pyrolysis liquid and synthesis from syngas;
- Biorefinery design, development and evaluation;
- Techno-economic analysis of bioenergy and biofuels production and biorefineries.

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EBRI
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Biomass Pyrolysis Services

Conversion And Resource Evaluation has been providing a wide range of services in biomass pyrolysis since 1996 including:

- Detailed chemical engineering and process design of biomass pyrolysis systems, all unit operations from feedstock handling to end use for power, heat, CHP, chemicals and products;
- Organisation and evaluation of biomass and waste feedstock pyrolysis and gasification at laboratory, demonstration and commercial scale;
- Design and build of ATEX/DSEAR and IEC Ex compliant pyrolysis units for laboratory scale work;
- Technology surveys, reviews and feasibility studies on pyrolysis;
- Due diligence of pyrolysis technologies;
- Techno-economic modelling and evaluation of complete pyrolysis systems from feedstock reception to end use of products;
- Market evaluation of the opportunities for renewable products and technologies;
- Assistance with plant trouble-shooting, independent monitoring and evaluation, environmental legislation, process authorisation and compliance with emissions.

Figure 2: *5 kg/h fluid bed pyrolysis rig for Future Blends, UK.*

Current activities in biomass pyrolysis:

- Commissioning a 50 kg/h slow pyrolysis reactor for biochar production;
- High temperature syngas production from SRF/wood blends for power generation >10 MWe;
- Design and build of a 1-1½ kg/h fluidised bed fast pyrolysis rig for liquids production;
- High temperature pyrolysis of organic material for waste minimisation and syngas combustion for heat production. Test work and technology development < 100 kg/h;
- Design package for 5 kg/h fluidised bed fast pyrolysis rig for liquids production from waste biomass;
- Farm-scale pyrolysis and gasification for 250 kWe power production.

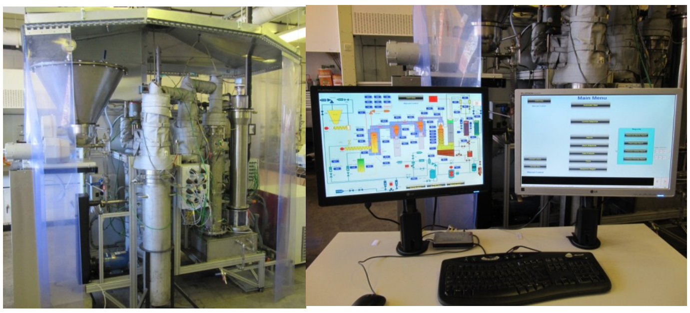

Figure 1: *(Left) Completed 5 kg/h (dry biomass input) rig overhaul, UK; (Right) New PLC system for pyrolysis rig.*

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CARE Conversion And Resource Evaluation Ltd.

End-of-life Plastic to Transport Fuel

Cynar PLC was founded in 2004 in order to help solve two of the world's most pressing environmental problems: the need for responsible end-of-life plastic waste management, and the need for secure localised supplies of alternative transport fuel. A decade on, after considerable technical fine-tuning, Cynar is a pioneer in commercialised pyrolysis technology that recycles end-of-life plastic waste into low sulphur diesel, kerosene and light oil (CynFuels™). With a full-scale pilot plant in Ireland, commercial plants in the UK and EU, and expansion plans in place for Latin America and Florida, Cynar is leading the way in the next generation of plastic-to-transport-fuel technology.

Cynar's patented process uses a combination of pyrolysis and distillation, with no catalyst and no combustion. Cynar technology involves heating non-recycled plastic (resin numbers 2, 4, 5 and 6) in the absence of oxygen to around 400 to 500°C. The resultant gas is then distilled to produce CynFuels™, consisting of approximately 70% diesel, 20% light oil and 10% kerosene. The syngas produced in the pyrolysis process is recycled to heat the pyrolysis pots. There is a 5% residual char that can be sold on, for example, to make briquettes for kiln firing. CynDiesel is a fungible drop-in fuel replacement and the other CynFuels™ can be blended or undergo further light processing to produce chemical and manufacturing feedstock. The Cynar process is continuous with a plant capacity of 20 tonnes per day, producing around 5.4 million litres of fuel annually from each plant.

One of the challenges Cynar is currently approaching is the ability to use heavily contaminated farm, commercial and industrial plastics in its systems. These plastics are not typically recycled due to high biological and sediment contamination and often end up in landfill. Recently, Cynar's Irish branch received a grant from the Irish Environment Agency to trial farm plastic collection for potential use in Cynar systems and is currently running the project with the assistance of University College Dublin and the Irish Farmers Association. If successful, the project will demonstrate the suitability of contaminated farm plastics for diversion from landfill towards a valuable end-of-life use as fuel.

Figure 1: *Almeria Plant.*

Cynar also has a long-standing research relationship with Loughborough University's Department of Chemistry, where Cynar has been collaborating on a range of projects including research on feedstock yields, the ability to vary product types (diesel, lubricants, waxes) and the effects of contamination found in mixed plastic feedstock streams. The complications from multi -polymer "layered" feedstock is also being researched. In recognition of their work with Loughborough, Cynar were named finalists in Loughborough's 2015 Enterprise Awards in both the Economic Impact and International Impact categories.

Additionally, Cynar were 2014 finalists in the MRW National Recycling Awards and the European Business Awards for the Environment and are winners of the 2013 Midlands Ireland Best in Business Award and the 2013 London Sustainability Leaders Award.

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cynar® PLASTICS TO FUEL

Pure Pyrolysis Process

Environmental Power International Ltd., more widely known as EPi, has developed a unique, pure pyrolysis process suitable for a wide range of applications, across a broad range of sectors. This offers a number of unique advantages in terms of environmental impact and process flexibility. The EPi technology does not involve any combustion phases in the creation of an energy rich fuel gas, offering a highly efficient, flexible process, capable of optimisation to suit a wide variety of feedstocks.

The EPi technology delivers a low profile, small footprint, modular solution with the capability of offering a commercially viable solution for the treatment of biomass or the organic fraction of a wide range of waste materials. With zero airborne emissions from the core process, no odour and being extremely quiet in operation, the technology has received broad support from local communities and regulatory bodies alike. The only point of airborne emission comes at such time as the gas is passed to a gas engine to be converted into electrical energy.

***Figure 1:** EPi's full scale R&D facility at Mitcham (south London).*

The system comprises automated material feeding, a core pyrolysis processor with a fully integrated gas management system which produces a gas clean enough for direct use in a reciprocating gas engine. This gives the EPi process the capability of elevated electrical efficiency when compared against competing thermal technologies, with further opportunities for energy recovery from both heat and carbon char. A typical installation of six EPi modules has the capability of producing more than 7 MW hr electrical, 10-15 MW hr thermal and, dependent upon feedstock, a further range of commercial opportunities are available from use of the carbon char.

The technology is robust and extremely flexible and can be optimised to deal with a wide range of waste streams. As a result, 2015 sees EPi moving forward on a number of projects within the UK, providing solutions into industries as diverse as medical waste, municipal waste, commercial and industrial waste, forestry and sewage sludges. Further afield, EPi is engaged in commercial negotiations with government and environmental bodies in a number of countries, helping to deliver cutting edge solutions to a wide range of energy related, health and environmental challenges that exist in various parts of the world.

***Figure 2:** Part of EPi's gas management and conditioning plant.*

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Novel Processes for Upgraded Pyrolysis Oil

Future Blends Ltd. is developing low carbon, low cost biofuels and biochemicals technology solutions around a modified fast pyrolysis platform. The company was set up in 2010 under the auspices of the Carbon Trust's Pyrolysis Challenge, which aimed to create and develop novel processes to produce upgraded pyrolysis oils from waste biomass (such as waste wood and municipal wastes) that could be blended into existing fossil fuels or replace fossil fuels at point of use.

Future Blends operates out of purpose-built facilities in Milton Park near Oxford. The company has two operating pyrolysis rigs, a bench scale unit and a pilot plant, each utilising novel filtration techniques to produce a more stable and cleaner pyrolysis oil.
In addition it has a range of pyrolysis oil upgrading equipment which are being used to develop novel routes to advanced biochemicals, oil refinery blending components and advanced transportation fuels.

Techno-economic modelling has demonstrated the potential for producing cost-competitive pyrolysis oils for immediate application as a boiler fuel in specified markets, and for further upgrading to higher value transportation fuels and biochemical intermediates.

Future Blends is partnering with a range of academic and industrial organisations in UK and Asia to accelerate the development and deployment of its pyrolysis platform and upgrading processes.

Figure 2: *Bio-oil*

Figure 1: *5 kg/h fluid bed pyrolysis rig.*

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Future Blends Ltd
A Carbon Trust Enterprise

Pyrolysis and Upgrading of Waste and Biomass

Keywords
Pyrolysis, Non-thermal plasma, Upgrading, Pyrolysis liquid, Char, Gas-to-liquid

Pyrolysis and related research activities in the School of Chemical Engineering & Advanced Materials, Newcastle University focus on waste (municipal solid waste that cannot be reused or recycled, agricultural waste, etc.) and biomass. These consist of:

- Effect of feedstock and pyrolysis conditions on properties of products;
- Gas-to-liquid processes;
- Char production from slow pyrolysis for soil amelioration, carbon sequestration and water treatment;
- Non-thermal plasma assisted catalytic cracking of vegetable oil/waste oil;
- Non-thermal plasma assisted catalytic upgrading pyrolysis liquid;
- Interactions of highly energetic electrons and steam for steam reforming processes;
- Kinetic studies on pyrolysis and upgrading in the presence of plasma.

Alongside analytical equipment such as HPLC, GC/MS, BET surface analyser, etc., a range of facilities to support the pyrolysis research include: a small scale fixed bed pyrolyser that can hold a few litres of solid material, equipped with on-line GCs (Figure 1); a 30mm quartz tubular high temperature furnace that can be operated up to 1300-1400°C over a range of heating rates up to 100°C/min equipped with a weighing scale system and GC for weight loss measurements and gas compositions; a 100mm vertical quartz tube high temperature furnace (1300-1400°C) for gasification processes; a tubular reactor equipped with 2 ovens, 5 columns and 3 detectors GC for gas-to -liquid processes; a range of non-thermal plasma devices (Figure 2) for *in situ* upgrading and two-stage upgrading studies.

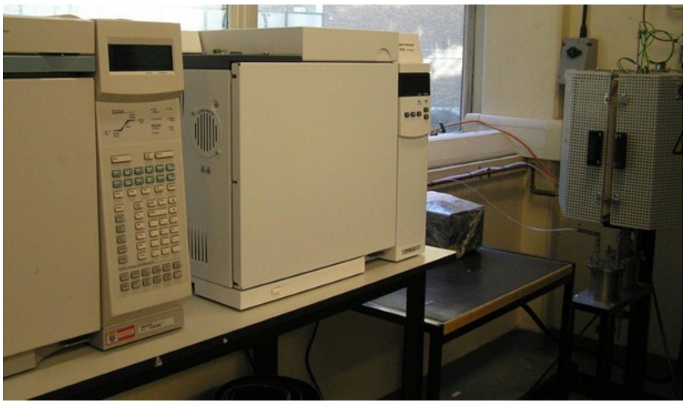

Figure 1: *Pyrolysis equipped with online GCs.*

Figure 2: *Pyrolysis equipped with non-thermal plasma system.*

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Biochar: Phosphorus Recovery: Renewable Heat

Keywords
Decentralised, Modular, P recovery, High-yield, Renewable-heat

PYREG (UK) is the UK base for PYREG GmbH. Our remit is to market and supply the latest versions of our reliable slow pyrolysis self-perpetuating thermal processes into the UK.

Process 1: Dry carbonisation - biomass to biochar
In the two-stage process, biomass is first heated up to 650°C in the PYREG® reactor; the biomass is carbonised to biochar; in the second stage the syngas produced in the reactor is completely burnt at approximately 1250°C in the combustion chamber. In the PYREG® process no substances of concern (SOC), e.g. condensates, tars are produced since the syngas does not cool down but is thermally oxidised.
Biomass specification:

- Dry substance content (DS) of at least 50%;
- Maximum size – 30mm;
- Pourable and free flowing;
- Minimum calorific value 10 MJ/kg.

Input: 2,000t p.a. Original substance (OS) with 50% DS
Output: approx. 300t p.a. biochar

A selection of PYREG® P500 characteristics:

- Decentralised use - container sized footprint;
- Automated process - low manpower input;
- Up to 150kW$_{th}$ can be used e.g. drying moist biomass or for heating;
- Low exhaust emissions, no harmful by-products;
- Solid high-quality biochar certifiable in conformity with the EBC & UK Biochar Quality Mandate (BQM).

Process 2: Staged combustion – recycling of municipal sewage sludge to recover phosphorus
Similar to Process 1, dried sewage sludge is carbonised and recycled to sewage sludge ash with no SOCs. In combination with the exhaust air treatment any heavy metal contamination e.g. mercury is eliminated.

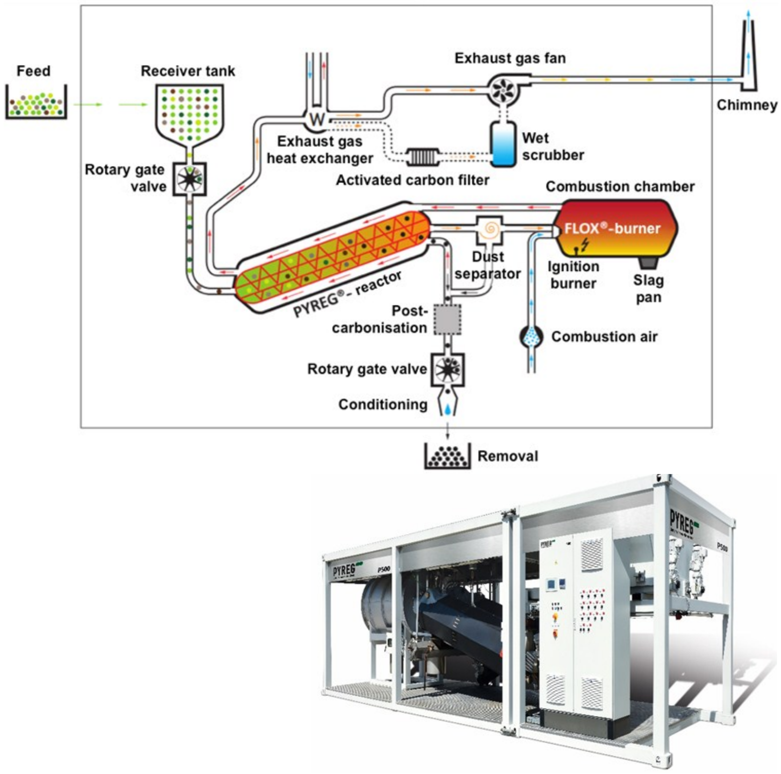

Figure 1: *PYREG®P500 module and its schematic diagram.*

Sludge specification:

- DS of at least 65%;
- Free flowing cake;
- Minimum calorific value 10 MJ/kg.

Input: 1,250t p.a. dried with 80% DS = 4,000t p.a. dewatered with 25% DS
Output: approx. 500t p.a. ash with up to 20% phosphorus having very high plant availability (end of pipe technology) fertiliser on account of the comparatively low reactor temperatures, plus spare renewable heat up to 250kW$_{th}$.

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PYREG

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Waste-to-Energy, Biomass Utilisation and Alternative Fuels

Keywords
Drying, Pyrolysis, Torrefaction, Gasification, Combustion

Key points

- Technology designer and supplier of state-of-the-art solid to gas reactors for drying, pyrolysis, torrefaction, gasification and combustion;
- Ability to process a wide range of feedstock including biomass, municipal wastes and industrial slurries;
- Areas of interest: feedstock upgrading and decentralised power generation.

Torftech Energy has a range of activities in waste-to-energy, biomass utilisation and alternative fuels. We are experts in gas solid processing technologies, with over 30 years of industrial experience. Our plants are based on the TORBED® reactor technology, a highly efficient gas solid contactor with excellent heat and mass transfer characteristics.

This technology and the company expertise have been used to tackle problems at a range of temperatures in a variety of fields including; mineral processing; catalyst regeneration; food processing; biomass gasification.

We have installed and commissioned multiple biomass gasifiers in the UK and Europe including a 6.3 MWe waste wood gasifier in Usk, Wales and a 5 MWth straw gasifier in Swindica, Poland. Further plants are under development both in the UK and abroad. Our current R&D activities are focused around improving the efficiency of the TORBED reactor and lowering its carbon footprint. Current research activities include:

- Oxy-gasification;
- Syngas upgrading for grid injection;
- Biofuel production;
- Torrefaction and pyrolysis;
- Upgrading of bio-products, e.g. char to biochar and activated carbon;
- Chemical engineering of thermal treatment reactions, reactor design and operation.

Facilities include a 500 kWth TORBED pilot plant capable of running in both pyrolysis and gasification modes. Feed trials have been conducted for a range of renewable and waste feedstocks including; waste wood chip, straw, sewage sludge and refuse derived fuel (RDF).

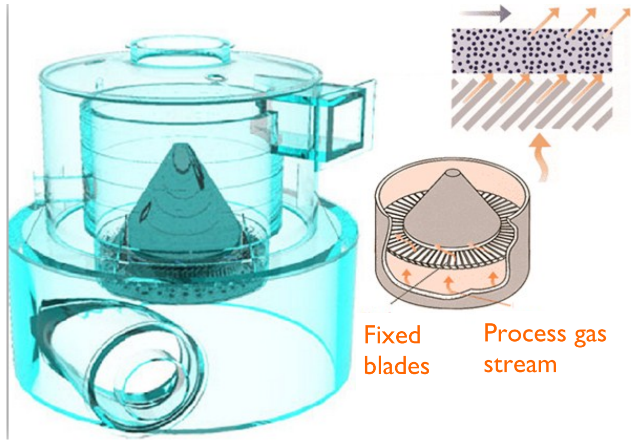

Figure 1: *The TORBED® Compact Bed Reactor (CBR). Gas is introduced underneath the blades of the CBR leading to high velocity gas jets that fluidise and fully mix the bed maximising gas-solid contact.*

Figure 2: *The 500 kWth TORBED® pilot test facility used to conduct thermal trials on a variety of sustainably sourced biomass and waste materials.*

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Catalytic Pyrolysis of Plastic Waste to Fuel

Keywords
Catalytic pyrolysis, plastic waste, techno-economical studies.

The Department of Chemical Engineering at University College London (UCL) is involved in the catalytic pyrolysis of plastic waste to fuel and has a bench scale fast catalytic pyrolysis rig (as shown in Figure 1).

Plastic waste is a cheap source of raw materials in times of accelerated depletion of natural resources to produce valuable products.

UCL is involved in studies of various catalyst systems and process conditions.

It is also currently involved in the techno-economical studies of co-processing of plastic waste.

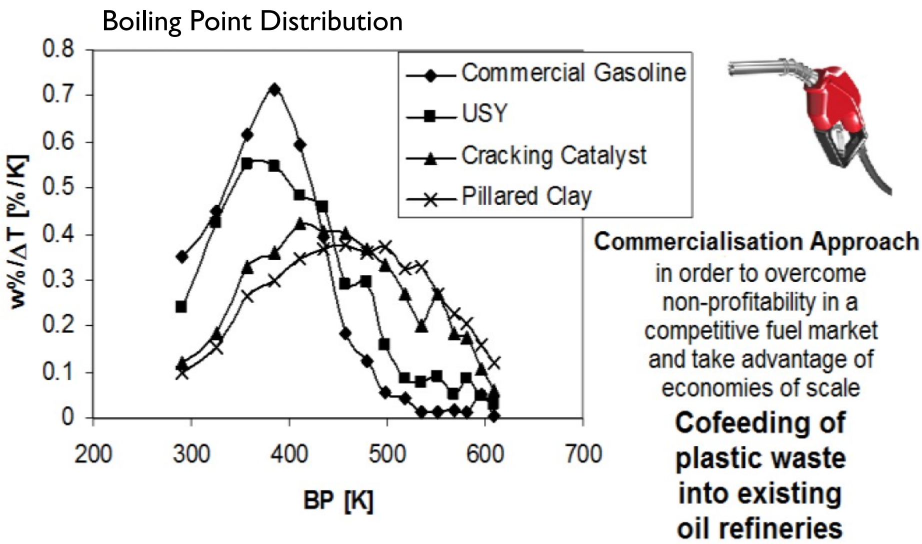

***Figure 2:** Boiling Point Distribution of liquid fuel from catalytic pyrolysis of polyethylene over various catalysts. Comparison with commercial gasoline (petrol).*

Catalytic Pyrolysis
The advantages of catalytic pyrolysis are as follows:
- Viable polymer recycling process;
- Liquid products in motor engine fuel range;
- Drastic lowering of process temperature;
- Low energy demands;
- Light hydrocarbon formation;
- Elimination of Fuel Upgrading Process Stage.

***Figure 1:** Bench scale experimental rig for catalytic pyrolysis.*

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Microwave Pyrolysis

Keywords
Microwave, Packaging laminates, Tyres, Vegetable oils, Automotive oils

For over 20 years, Professor Howard Chase's Biochemical and Environmental group has been researching the recovery of hydrocarbons and other chemicals from a variety of materials by pyrolysis. The technologies investigated utilise the microwave absorbing properties of particulate carbon to act as an agent to transfer the microwave-generated heat within the particles to materials that would not otherwise be efficient microwave receptors. In addition, the reductive environment generated by the hot carbon beneficially influences the chemistry occurring during the pyrolytic cracking of the hydrocarbons in the feedstock to smaller, fuel-like molecules.

Experimental work has been carried out at a variety of scales, involving both batch and continuous pyrolytic reactor set-ups. Research on the recovery of aluminium and hydrocarbon fuels from waste laminated packaging, originally sponsored by EPSRC, has resulted in the spin out of an award-winning company (Enval Limited, www.enval.com) which is now operating a microwave-heated treatment process at a commercial scale. In this process, the cracking of the long hydrocarbon chains that constitute the plastic layers of the packaging liberates the encased aluminium layer that remains in a non-oxidised metallic form as a consequence of the reducing environment. A short film describing the process and its potential can be found at http://www.cam.ac.uk/research/features/where-theres-muck-theres-aluminium-if-not-brass.

Figure 1: *Laboratory scale microwave heated pyrolysis apparatus.*

The process has also been successful in processing other hydrocarbon-containing materials such as used automotive and marine oils, waste and virgin vegetable oils and polyethylene, to generate hydrocarbon fuels. In all cases, sufficient hydrocarbon gas can be generated to generate the electricity needed to power the microwave generators and other auxiliaries in the process. Optimisation of pyrolysis conditions, and/or the addition of catalysts, can alter the average carbon number of hydrocarbon products so that they could be used for a variety of fuel purposes.

Figure 2: *Aluminium recovered from laminated beverage packaging.*

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Biochar Research Centre

Key points

- State-of-the-art laboratory and pilot-scale facilities for continuous pyrolysis;
- Ability to process wide range of feedstock including wastes;
- Areas of interest: biochar, pyrolysis, torrefaction, gas cleaning, pyrolysis liquids, co-generation, process integration.

Figure 2: *Continuous screw pyrolysis unit (5kg/h).*

Profile

The main objective of the centre is to study, assess and develop biochar as a means for climate change mitigation and adaptation (i.e. a valuable soil amendment and agricultural product). We identified early on the need for high quality (research grade) biochar in order to ensure meaningful and replicable results from biochar-soil-plant interaction studies. This was then the core idea around which pyrolysis capabilities at the UK Biochar Research Centre (UKBRC) have developed.

Due to the focus on biochar production we selected slow pyrolysis as the technology of choice, and our state-of-the-art facilities range from bench-scale batch units to a pilot-scale continuous pyrolysis unit. These facilities allow us to study pyrolysis under a wide range of settings, such as peak temperatures (250-850°C) and residence times (from a few seconds to several hours), and all this under well controlled (reproducible) conditions. As a result we are able to produce "specified biochar" i.e. biochar produced under carefully defined and controlled conditions. The objective of this work is to develop an understanding of how feedstock and production conditions influence not only the physical/chemical properties of biochar but also its functional properties as a carbon sink and/or soil conditioner. One of the outputs has been the development of a set of standard biochar materials for research and development purposes (http://www.biochar.ac.uk/standard_materials.php).

Figure 1: *Pilot-scale pyrolysis unit (50kg/h).*

These pyrolysis facilities are equipped with advanced monitoring and control systems, and are accompanied by state-of-the-art analytical instrumentation for online gas analysis (mass spectrometer) that allows us to obtain information on the composition of gases at different stages of the pyrolysis process as well as information on the energy content in the gas stream. This together with data on composition and energy content in the liquid stream (collected separately) then serves as an input to LCA and modelling of biochar pyrolysis systems.

Beside the focus on solid products from pyrolysis, we are interested in the liquid and gaseous co-products since their use is necessary to maximise the overall system benefits.

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Biomass and Waste Pyrolysis and Modelling

The University of Leeds hosts the £4.2m EPSRC Centre for Doctoral Training in Bioenergy (awarded 2014). Within the centre, biomass thermal treatment research includes: fundamental studies of the impact of inorganics and metals in thermal conversion of biomass; optimisation of fuel quality and yield of energy crops; alternative biomass resources including marine biomass and waste; biomass pre-treatment to improve fuel properties for various conversion processes, in particular: torrefaction; soot characterisation and understanding the mechanism of PAH and soot formation; the nitrogen cycle in biomass production and the influence on nitrogen chemistry in thermal conversion; co-firing coal and biomass; novel steam reforming for the production of hydrogen from pyrolysis and vegetable oil; and hydrogen from biomass and wastes by pyrolysis-gasification.

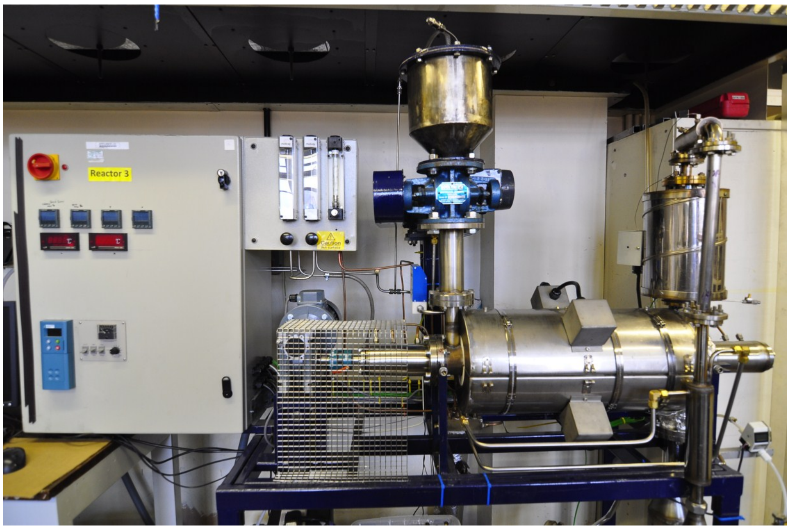

Figure 1: *Screw kiln pyrolysis-gasification reactor.*

Experimental work is complemented by theoretical studies using thermodynamic, kinetic, or molecular modelling software. A range of bench scale and mini-pilot scale reactors for pyrolysis investigations of waste/ biomass process parameters, including; continuous screw kiln pyrolysis-gasification reactor enabling first stage pyrolysis at 500°C and second stage steam catalytic gasification at 800°C. Fully instrumented with lab-view; 3m long x 0.5m diameter oil-fired furnace with full exhaust gas analytical suite for pyrolysis oil combustion studies.

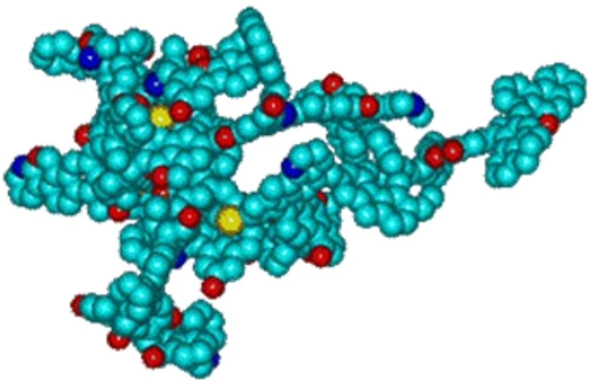

Figure 2: *Understanding at a molecular level the changes a solid fuel particle undergoes during thermal processing.*

A wide range of advanced analytical equipment for fuel and product characterisation including; pyrolysis-gas chromatography-mass spectrometry of biomass; gas chromatography-atomic emission spectrometry; thermogravimetric analysis-mass spectrometry; inductively coupled plasma-mass spectrometry; thermogravimetric analysis-fourier transform infra-red spectrometry; size exclusion chromatography; and a full suite of fuel testing equipment.

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Biomass Pyrolysis and Related Areas

Our pyrolysis activities are related to gasification studies and modelling of industrial combustion, pyrolysis and gasification processes. The pyrolysis part of these processes is essentially a slow process. The fuels considered are pure biomass or segregated municipal wastes.

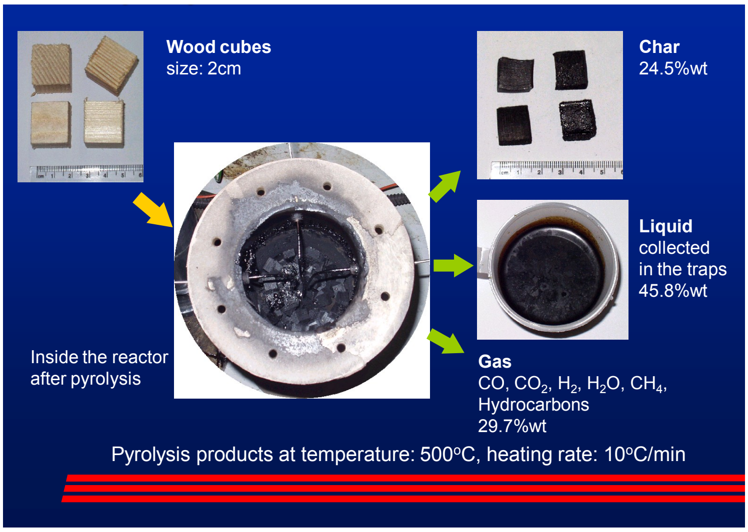

Figure 1: *Pyrolysis products.*

Slow pyrolysis facility

This consists of two chambers that each can hold a few litres of solid material. Electronic controllers are set to heat the material at a uniform rate (~10°C per minute) up to a controlled maximum (~800°C) maintained for a defined period. A stream of nitrogen flushes the gases and vapours through the second chamber into the analysers. The optional second chamber can contain inert or active (catalytic) material, again at programmed temperatures.

Pyrolysis tube apparatus

This apparatus is essentially a vertical 50mm quartz tubular high temperature furnace that can be operated up to 1400°C. The sample (~25gms) is usually placed in a mesh container for weight change measurements and again the emitted gases/ vapours are analysed. In order to investigate gasification of the material, steam and oxygen can be passed through in addition to inert gases.

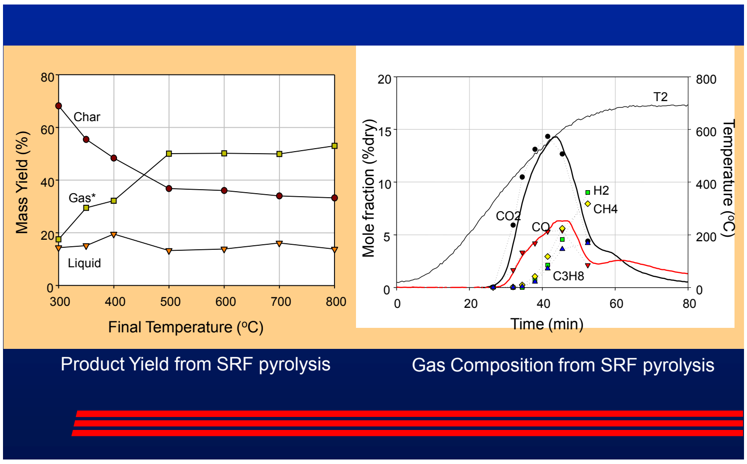

Figure 2: *Product yield - storable char, oil and gas.*

Rotating kiln

This rotating reaction chamber is usually operated in batch mode where time duration from introduction of material (250g) represents distance along an industrial rotating kiln. The reactions are usually carried through to completion and the ash analysed to provide key process information. A typical batch would consist of feed material.

Shaft kiln

This is a well insulated cylindrical chamber of 200mm diameter and over 1m long that is mounted vertically with load cells for continuous weight measurement. The main purpose of this apparatus is to provide both coefficients for our FLIC numerical code and validation of our modelling results.

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Microwave Thermochemical Conversion

The Green Chemistry Centre of Excellence promotes the application of green and sustainable technologies particularly those that can be used to deliver products that meet consumer and legislation requirements. We have proven that microwave irradiation is an efficient method of biomass activation. Microwave irradiation is rapid and volumetric with the whole material heated simultaneously thus allowing the processing of poor thermal conducting materials such as lignocellulosic biomass. Microwave heating can be controlled instantly and the power applied can be precisely regulated. The use of microwaves in pyrolysis leads to a controlled thermochemical decomposition process with more selective activation of biomass components than can normally be achieved. The outcome is a range of valuable products including pyrolysis liquids, biochars and chemicals or hydrolysis sugars from sustainable sources of carbon including waste materials. Microwave pyrolysis occurs at lower temperatures (<200°C) whilst generating char materials with higher calorific values and high quality pyrolysis oils. The microwave application in biomass hydrolysis yields to 30% glucose with no detectable inhibitors without the addition of extra acid or base.

The team has proven this technology at scales from grams to tens of kilograms. In 2011, the Biorenewables Development Centre opened an open access facility for demonstration of semi-scale equipment for microwave pyrolysis, supercritical CO2 extraction and fermentation alongside all the necessary pre-treatment and downstream processing apparatus. This facility enables us to:

- Conduct world leading research on the controlled microwave decomposition of biomass;
- Optimize process conditions for the preparation of liquid fuel (intermediate), solid fuel and chemical products;
- Develop and improve design of associated microwave processing equipment;
- Prove processes in continuous mode and in production of multi kilogram quantities of products;
- Produce products and intermediates for testing and further work with industry and in collaboration with external organisations;
- Link clean chemical technologies to gain maximum value from biomass waste.

We welcome enquiries from companies and other organisations wishing to use this equipment.

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Figure 1: *Outputs from larger scale microwave pyrolysis system.*

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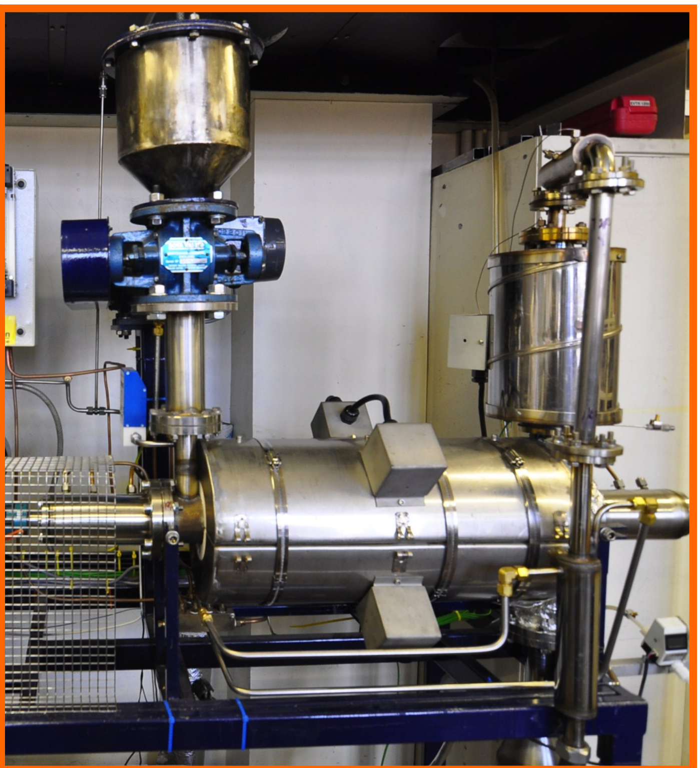

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