

# Biomass Pyrolysis

A guide to UK capabilities



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## Foreword

Professor David MacKay  
Chief Scientific Advisor at the  
Department of Energy and  
Climate Change

Biomass is a limited resource, but a precious one with several important potential uses. With heroic effort, municipal, commercial, and industrial waste could provide 5 kWh per day per person of useful energy and UK wood, straw and woody crops another 22 kWh/d/p. This is not as big as **today's energy demand of 125**

kWh/d/p, but it is a significant potential energy source – so we had best not

squander biomass by burying it in the ground, or by inefficiently turning it into heat that disappears up a chimney, or by turning it into electricity if what we most badly want is jet fuel or feedstocks for essential chemicals or for industrial process. Furthermore, we certainly don't want to turn biomass into pollution.

That is why I am excited by the work on pyrolysis described in this guide. Pyrolysis has the potential to be robust to the physical and chemical variability of waste and crops. It has the potential to create a range of useful gases, oils and solids. It has the potential to be a component of electricity, transport fuel, industrial and agricultural systems with lower greenhouse gas emissions than today. Pyrolysis expands our options.

We should be aware of the potential of different options as we debate the kind of energy system that we want to build over the coming decades. Guides such as this help to build that awareness, and help guide research, innovation, and investment, as we work out our pathway to a secure, low-carbon energy system.



## Introduction

Tony Bridgwater  
Aston University Bioenergy Research Group,  
UK National Team Leader, IEA Bioenergy Task  
34 Pyrolysis

This Guide to UK Pyrolysis Activities summarises the range of research and commercial activities being undertaken in the UK as an aid to all involved in this expanding area including researchers, companies, policy makers, decision makers and stakeholders. The incentive for producing this guide is UK membership of the IEA Bioenergy Pyrolysis Task for three years from 2010 to 2012. 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 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](http://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.

Although not one of the largest Tasks, it has successfully carried out a programme of technical and economic evaluations including biorefinery applications and has had particular success in integrating the fast pyrolysis community through the mechanism of Round Robins. These are mechanisms that encourage laboratories to analyse, characterise and/or investigate particular properties of fast pyrolysis liquids (bio-oil) or 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]. The current Round Robin will investigate, evaluate and compare standard bio-oils for viscosity and stability in order to assess techniques at different laboratories and to compare the results. These benefit both the laboratories involved in providing benchmarks for analysis as well as the international community in determining 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](http://www.pyne.co.uk). This also contains updates on fast pyrolysis activities and technologies.

All entries are based on material supplied by each organisation and we would be pleased to hear about any additional activities and updates on what is reported here.

Tony Bridgwater ([a.v.bridgwater@aston.ac.uk](mailto:a.v.bridgwater@aston.ac.uk))  
Irene Watkinson ([i.i.watkinson@aston.ac.uk](mailto:i.i.watkinson@aston.ac.uk))

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## Advanced biofuels from waste

2G BioPOWER has the ultimate goal of producing advanced fully fungible biofuels from waste and has a vision of promoting such fuels through high profile motor sport and aviation. It is focusing on the use of pyrolysis and upgrading based on UOP and Envergent technologies (both part of Honeywell).

The company is currently developing projects to convert municipal, commercial & industrial waste into liquid fuels for heat, power and transportation. Projects will use waste wood, and biogenic feedstock from advanced waste separation, processed using **Envergent's RTP™ Pyrolysis technology** and then subsequently upgraded via hydroconversion from UOP. Initially the focus will be on the production of pyrolysis oil for combined heat and power applications to provide for a highly efficient use of the feedstock.

Full integration of the advanced waste separation and pyrolysis plant is also planned to optimise process operations using these feedstocks and to monitor and manage emissions. Further development will include the addition of a pilot plant demonstrating hydroconversion of pyrolysis oil to fungible hydrocarbons with a specific focus on middle distillates – for renewable diesel and aviation fuels.

2G BioPOWER has chosen to work with UOP and Envergent in order to gain access to the most advanced, and commercially established, conversion processes available. UOP is currently developing pyrolysis oil upgrading technology that will improve



Figure 1: 2G BioPOWER - Second generation energy for the future.

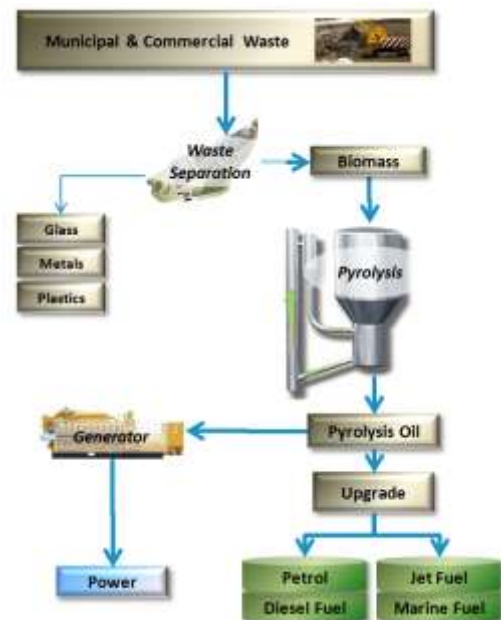


Figure 2: Reduce, reuse, recycle and recover.

stability of the products and remove highly reactive components that will allow more cost effective **downstream storage and processing**. RTP™ technology has been used commercially since 1989 and is currently used to process biomass and other feedstocks in eight North American units. The production of pyrolysis oil is envisioned taking place near areas of biomass and waste sources in order to transport a higher energy density product to the point of use or refinery.

Projects are currently under development in the South East and North East of England.

Contact  
Howard Jackson

2G BioPOWER Ltd, The Pent House, The Street, Smarden,  
Kent TN27 8QA

T: +44 (0)1233 770093 M: +44 (0)7860 232598  
E: [howard.jackson@2gbiopower.com](mailto:howard.jackson@2gbiopower.com)



# Institute of Biological Environmental and Rural Sciences (IBERS)

The Institute of Biological Environmental and Rural Sciences (IBERS) at Aberystwyth University has received funding from the Welsh Assembly Government to perform research into slow pyrolysis and the production and application of biochar.

Through the 'Biochar for business and the environment' (ABATE) project, IBERS has been performing trials using a novel on-site slow pyrolysis facility designed and built by the Cardiff based engineering company Sustainable Energy Ltd.



Figure 1: 500 kg batch slow pyrolysis reactor installed on site at IBERS, Aberystwyth.

The facility overcomes many of the limitations of traditional small-scale charcoal production methods by capturing and recycling the residual gases and heat produced to improve process efficiency, reduce emissions and maximise char yield. The facility also includes a condensation system for the collection of pyrolysis liquids and a heat exchange system to allow capture and utilisation of residual heat for space heating and drying.

The slow pyrolysis facility is being trialled for farm-scale application and may process up to 600 kg per batch (on wood basis) from a diverse range of feedstocks, not just wood. The potential for value addition to underutilised resources and waste streams by converting material into biochar, bio-oil and heat is being investigated alongside research into product quality criteria and process optimisation to enhance both conversion efficiency and product quality. These slow pyrolysis trials are being performed in conjunction with other research taking place at IBERS looking into the environmental and agronomic benefits of biochar as a carbon sink and soil conditioner and to determine the effects of biochar addition on land/plant productivity.



Figure 2: 3D CAD of IBERS slow pyrolysis reactor as designed by Sustainable Energy Ltd.

Contact  
Dr Edward Hodgson

Institute of Biological Environmental and Rural Sciences (IBERS), Aberystwyth University, Gogerddan, Aberystwyth, Ceredigion, Wales, SY23 3EB  
T: +44 (0)1970 823126 E: ewh@aber.ac.uk

# Bioenergy Research Group

BERG is one of the best established academic bioenergy research groups in the world. We have been responsible for raising over £22 million from a variety of national and international organisations and our novel developments have led us to become one of **the world's leading university laboratories in thermal biomass processing**. Our interdisciplinary team of researchers come from a wide variety of backgrounds including chemical, mechanical and aerospace engineering, chemistry, physics, environmental studies and business studies.

The focus of our 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 2<sup>nd</sup> generation biofuels, and chemicals. There is complementary work on gasification, biomass pre-treatment, product upgrading, characterisation and analysis, chemicals production, system design, and technical and economic evaluation.

We have coordinated 15 European Framework projects and also lead the UK national centre of excellence in bioenergy and biofuels – SUPERGEN Bioenergy. The IEA Bioenergy Task on pyrolysis was created and led by us from 1992 until 2008. As a result of our steady stream of national and



Figure 1: 7 kg/h continuous fast pyrolysis unit.

international funding we have built up some of the most comprehensive university-based thermal processing facilities and capabilities in the world. These include extensive thermal processing facilities for fast pyrolysis, analysis, CFD and process modelling.

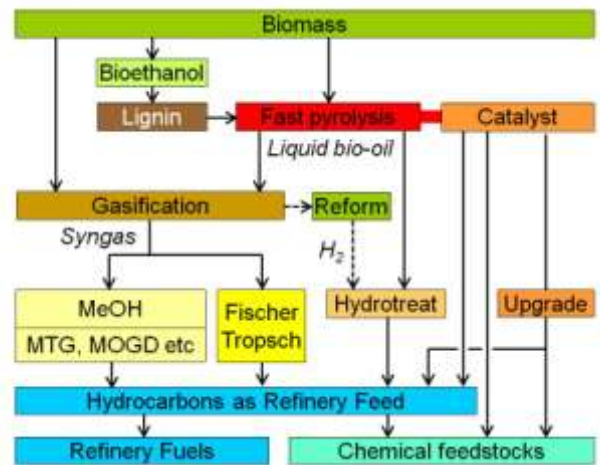


Figure 2: Process routes to hydrocarbon, biofuels and chemicals under evaluation.

Our key interests include:

- Biomass characterisation, preparation and pre-treatment;
- Fast pyrolysis of biomass and waste in continuous fluid bed and ablative reaction systems for bio-oil;
- Gasification of biomass in fixed and fluid beds;
- Analytical techniques for characterisation and evaluation of biomass;
- Characterisation and upgrading of bio-oil from fast pyrolysis;
- Development of applications for bio-oil for heat;
- Production of chemicals such as resin precursors for wood panels, slow release fertilisers and preservatives;
- Hydrocarbon transport fuel production by synthesis from syngas and upgrading of fast pyrolysis liquid;
- Biorefinery design, development and evaluation;
- Techno-economic analysis of bioenergy and biofuels production and biorefineries.

Contact  
Professor Tony Bridgwater

Bioenergy Research Group, School of Engineering and Applied Science, Aston University, Birmingham B4 7ET  
T: +44 (0)121 204 3381 E: a.v.bridgwater@aston.ac.uk



# European Bioenergy Research Institute

With the goal of accelerating the adoption and exploitation of biomass thermal conversion technologies, EBRI performs advanced research and knowledge transfer in all aspects of bioenergy. We act as a demonstrator of these technologies and provide industrial research collaborators with an opportunity to run process trials, evaluate feed materials, and study combinations of processes prior to investment.

Beside fast pyrolysis (embedding the work of BERG) and slow pyrolysis, intermediate pyrolysis is of major importance for the developments at EBRI. Our novel intermediate pyrolysis technology—with solid biomass residence times of about 10 minutes—is especially performing well, and is producing a valuable biochar as well as liquids suitable for engines or gasification.

EBRI is currently working to establish EBRI application centres (EBRIAC)—demonstrator sites for pyrolysis-based bioenergy technology, in India, Hungary, Germany and the UK. The Birmingham City Council has a strategy of reducing CO<sub>2</sub> emission by 60% by 2026 and has strongly recommended EBRI technology for meeting this objective.

We are due to complete the new EBRI building with a 400 KWel gasifier and 200 kg/h pyrolyser in spring 2012, providing new opportunities for research collaboration with industrial partners.

EBRI is also collaborating with Severn Trent Water to convert sewage sludge into heat and power; with



Figure 1: The new pyroformer technology for improved biochar and pyrolysis gas production – a 100 kg/h intermediate pyrolysis unit.

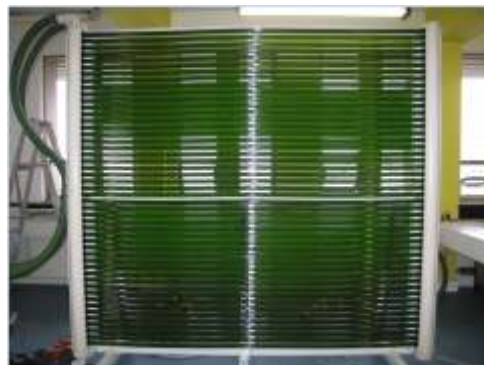


Figure 2: Photobioreactor for the production of algae. The recycling of fertiliser via biochar is one of the topics of investigation.

Johnson Matthey to develop catalyst-based tar reforming units; and with IIT Delhi, IIT Ropar and IISc Bangalore in the field of bioenergy solutions for rural areas.

Our key research interests are:

- Application of water-based pyrolysis fractions for anaerobic digestion;
- Closing of the fertiliser cycle for algae cultivation via pyrolysis of algae and extraction of biochar;
- Separation of hydrogen from reformed pyrolysis vapours and syngas from gasification of vapours;
- Direct application of pyrolysis bio-oil/biodiesel mixtures to engines (using rape and sewage sludge as feedstock);
- Micro kinetic studies for the evaluation of formal kinetic parameters of lignin degradation and tar formation;
- Catalytic conversion of bio-oil and pyrolysis gases.

Contact  
Professor Andreas Hornung

European Bioenergy Research Institute,  
School of Engineering and Applied Science,  
Aston University, Birmingham B4 7ET  
T: +44 (0)121 204 3391 E: a.hornung@aston.ac.uk



## Fast Pyrolysis Plant (FPP)

Biomass Engineering Ltd (BEL) started work on preliminary process and conceptual design of its fast pyrolysis plant (FPP) as far back as 2006. Subsequent equipment specifications, detailed design, manufacture and procurement followed and today the original concept is being turned into reality.

Initially, the plant is rated at 250 kg/hour feedstock input and is designed to convert sawdust from clean wood into pyrolysis oil. Future design amendments will accommodate a programme of trials on alternative potential fuels.

At the heart of the process is a purpose built reactor vessel that utilizes fluidized bed technology to convert the feedstock into pyrolysis gases before quenching them to form pyrolysis oil. Both char and recycle gas byproducts are used to heat the fluidized bed of the reactor.

Experimental analysis of the proposed initial feedstock has already been undertaken by Aston University on behalf of BEL using their 150g/h and 1kg/h pyrolysis rigs to establish conditions producing the highest organics yield. The results have been used to determine the optimum operating conditions for the FPP.

**The FPP will operate at BEL's purpose built facility in Newton-le-Willows** and is expected to be installed, commissioned and producing pyrolysis oil by the end of 2011/early 2012. A future programme of works will also include experimentation on the pyrolysis oils produced by various feedstocks in order to determine their potential for use as raw fuel, fuel additive and chemical agent.



Figure 1: Fast pyrolysis plant at Newton-le-Willows.

Contact  
Steve Scott

Biomass Engineering Ltd  
Junction Lane,  
Sankey Valley Industrial Estate,  
Newton-le-Willows, WA12 8DN  
T: +44 (0)1925 220338 E: s.scott@biomass.uk.com

# Cardiff Surfaces Materials & Catalysis Group

Our research group has extensive expertise developing new heterogeneous catalysts for the transformation of biomass into fuels and chemicals. We are particularly interested in understanding mechanisms of surface catalysed processes and our research focuses on applying *in situ* spectroscopies (e.g. EXAFS, DRIFTS and XRD) to follow the evolution of catalyst during operation. Using this improved understanding of the nature of the active site and deactivation processes, we aim to develop tailored catalytic materials. In particular, we are focusing on tuning pore architectures to improve in-pore mass transport of bulky reactants and products typically encountered during biomass transformation (Fig. 1).

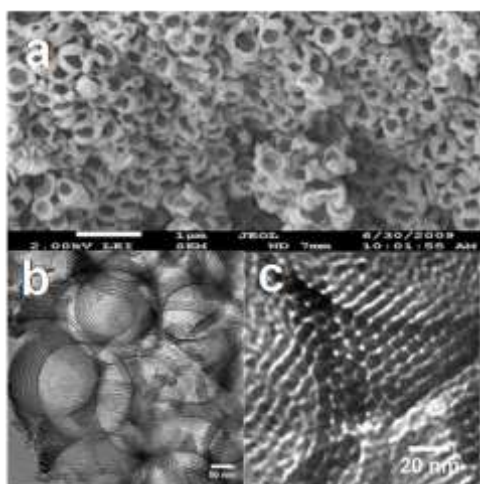


Figure 1: (a) SEM and (b, c) low and high magnification TEM images for hierarchical macro-mesoporous catalysts for biomass transformation to fuels & chemicals.

Current projects include the design of solid acid and base catalysts for biodiesel synthesis from algal and *Jatropha* oil feedstocks; the development of heterogeneous catalysts for the pre-treatment and upgrading of pyrolysis oil by hydrodeoxygenation; and the catalytic processing of lignocellulose feedstocks for fuels and chemicals manufacture.

## Research facilities

Our lab is well equipped with facilities for the synthesis, characterisation and testing of heterogeneous catalysts. The group has a reactor suite comprising several high temperature (~1200 °C)

continuous, plug-flow microreactors equipped with electronic mass flow controllers and syringe pumps for delivering accurate gas and vapour-phase reaction mixtures,

together with on-line GC/MS analysis suitable for activity screening, kinetic (isotope) studies, and precise steady state/lifetime analysis (Fig. 2); high pressure stirred autoclaves with *in situ* gas-dosing (10-300 bar and 120-300 °C) suitable for both materials processing and catalytic reactions; reactor systems for parallel catalyst screening and autosampler on-column GC and GC/MS capabilities for oil analysis.

We also have a wide spectrum of materials analysis facilities including a 1500 °C Thermogravimetric analyser with coupled gas-handling manifold and MS for temperature programmed desorption, reduction and oxidation; an imaging XPS spectrometer with heated stage to measure surface compositions during *in situ* catalyst processing; a porosimeter and chemisorption analyser for surface area and acid/base and metal site titrations; a DRIFT spectrometer equipped for *in situ* catalyst reaction studies; *in situ* XRD; Raman microscope; and an environmental SEM/EDAX.



Figure 2: Plug flow reactor equipped with online GC/MS.

Contact  
Dr Karen Wilson and/or Professor Adam F Lee

Cardiff Surfaces Materials & Catalysis Group,  
Cardiff Catalysis Institute, School of Chemistry,  
Cardiff University, Cardiff, CF10 3AT  
T: +44 (0)29 208 74000  
E: wilsonk5@cardiff.ac.uk E: leeaf@cardiff.ac.uk

## Biomass pyrolysis services

Conversion And Resource Evaluation Ltd. provides a wide range of services in biomass pyrolysis including:

- Detailed chemical engineering and process design of biomass pyrolysis systems, all unit operations from feedstock handling to end use for power, heat, chemicals and products;
- Organisation and evaluation of biomass and waste feedstock pyrolysis at laboratory, demonstration and commercial scale;
- 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 (heat, power, combined heat and power and chemicals/ 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.



Current activities in biomass pyrolysis:

- Design, build and commission a 50 kg/h slow pyrolysis reactor for char production with environmental compliance;
- Fast pyrolysis of biomass and wastes at 0.5, 1.5 and 250 kg/h for the production of liquids for subsequent upgrading to a blendate for liquid transport fuels; mass and energy balance modelling; techno-economic assessment of the production of the blendate from a 100,000 t/y input integrated biomass fast pyrolysis process;
- Optimisation of high temperature syngas cleaning for power generation;
- Refurbishment of a 5 kg/h fluid bed fast pyrolysis reactor system for the production of liquids for a UK university; component replacement and upgrading of control system;
- **Co-authoring of updated guide on 'Properties and fuel use of biomass derived fast pyrolysis liquids – a guide' with VTT ([www.vtt.fi/inf/pdf/publications/2010/P731.pdf](http://www.vtt.fi/inf/pdf/publications/2010/P731.pdf));**
- Pyrolysis of a high ash material for the recovery of metals from the char. Mass and energy balances and technology selection;
- Development of sensors for high temperature process monitoring; advice on gas contaminants during pyrolysis and gasification of biomass in a magnetic suspension balance and provision of advice on catalysts for gas cleaning and conditioning;
- UK technology review for biomass and wastes pyrolysis.

Contact  
Cordner Peacocke

Conversion And Resource Evaluation Ltd.  
83 Church Road, Holywood, Co. Down,  
Northern Ireland, BT18 9BY

T: +44 (0)2890 397811 E: [cpeacocke@care.demon.co.uk](mailto:cpeacocke@care.demon.co.uk)

# Centre for Energy and Resource Technology (CERT)

**Cranfield University's Centre for Energy and Resource Technology (CERT)** within the School of Applied Sciences has a growing range of activities in waste-to-energy, biomass utilisation and alternative fuels. CERT is active in the research and development of thermo-chemical processing techniques, including pyrolysis (Figure 1).

Among a wide range of energy-related facilities, the Centre operates a fixed bed reactor (up to 75 kWth) in both pyrolysis and gasification modes. This uses electrical trace heating to maintain the pyrolysis process temperature. The product gases are analyzed using infrared and thermal conductivity sensors with sampling of all other process streams and residues. This facility has been used to investigate slow and intermediate pyrolysis using different types of fuels, such as waste (MSW, commercial & industrial, etc.) and biomass (wood & agricultural residues), with respect to efficiency and contaminant issues (e.g. tar recovery). Along with this, CERT is active in developing feedstock pre-treatment methods to optimise process efficiency and operability, e.g. pelletizing feedstock blends to understand the impact of pellet characteristics (Figure 2).

CERT also has extensive facilities to assess the combustion performance of gaseous fuels, their clean-up and impact on combustion engine/gas turbine reliability. These facilities include use of a number of gas engines (up to 70 kWth each) and burner rigs (up

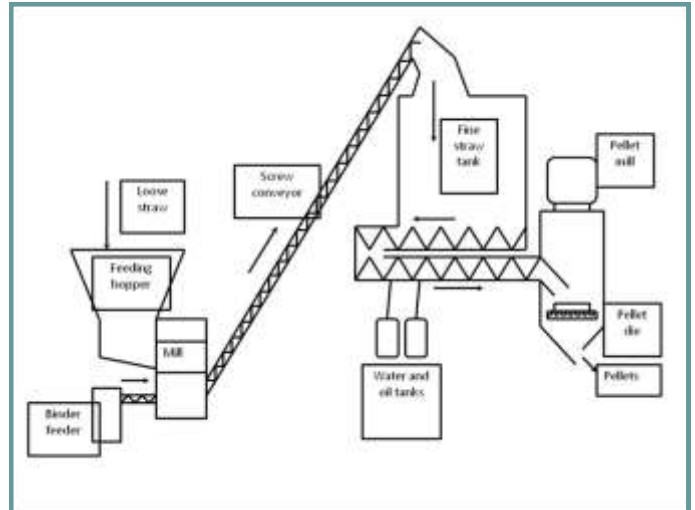


Figure 2: Schematic diagram of pelletiser facility at Cranfield.

to 1 MWth) configured for testing for power/heat generation or cogeneration. Gas cleaning/upgrading facilities include particle filtration (up to 800 °C), sorbent-based S and Cl removal, catalytic N reduction and sorbent/membrane-based CO<sub>2</sub> separation. The pyrolysis, gasification, pelletisation, gas cleaning and engine testing facilities serve as a test bed for continuing research and development of alternate fuels.

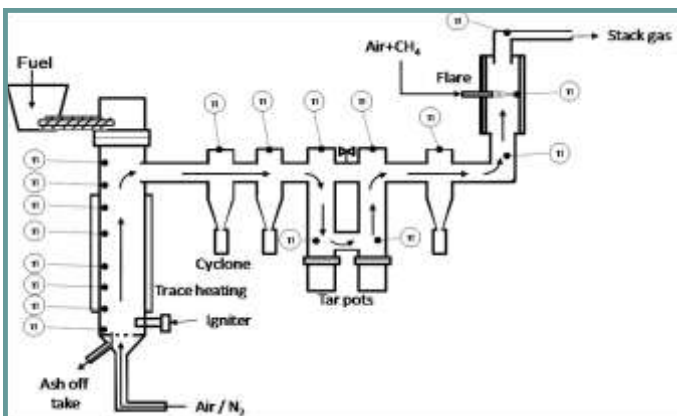


Figure 1: Schematic diagram of fixed bed pyrolyser.

Contact  
Professor John Oakey

Cranfield University, Cranfield, MK43 0AL  
T: +44 (0)1234 754253 E: j.e.oakey@cranfield.ac.uk





## Pure pyrolysis system

Environmental Power International Ltd (EPI) has developed and commercialised a unique pure pyrolysis system with application across a range of industries and sectors looking to better and more cost effectively manage their waste and maximise the generation of renewable energy.

The system comprises material feed process, core pyrolyser and gas clean up, and is modular, each module being a nominal 1 tonne per hour and capable of producing 1 MW electrical when the gas is burnt in an engine - 1 to 1.5 MW thermal is also available per MW electrical.



Figure 1: EPI's plant.

Due to its patented heating system, (using electricity as its parasitic source) material feed process and unique gas clean up, the EPI pyrolysis produces significant volumes of high calorific value gas, clean enough to be utilised directly in gas engines. The process is 35% electrically efficient (at terminals) and produces up to ten times more electricity than it consumes (subject to feedstock).

The technology is resilient and flexible and can be optimised to deal with most waste streams (allowing for appropriate pre-treatment), requiring materials with a 10/15% moisture content and run through a 30mm screen. The technology has a small physical footprint. Neither the core process nor the combustion of the synthetic gas falls under the Waste Incineration Directive.

EPI is currently working with the municipal, commercial, construction and arboricultural waste sectors, with commercial plants operating in London and Dorset. Further plants are under development both in the UK and abroad.

Contact

Mark Collins-Thomas

Environmental Power International Ltd  
Trowle Barn, Wingfield  
Trowbridge, Wiltshire, BA14 9LE

T: +44 (0)1225 765816 M: +44 (0)7970 65051  
E: [mark@epienergy.com](mailto:mark@epienergy.com)



## Biofuel development

Future Blends Ltd aims to develop low carbon, low-cost biofuels that can be integrated directly into the current fuel supply chain. The company was set up in 2010 to exploit the **outcome of the Carbon Trust's Pyrolysis Challenge** (<http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/pages/pyrolysis-challenge.aspx>) which was set up to develop a novel process to produce upgraded pyrolysis oils from waste biomass (such as municipal and wood waste) which can be blended with diesel at the point of distribution.



Analysis of the Future Blends process has shown that it potentially offers the lowest cost production route of any biofuel technology of between £0.30 and £0.48 per litre (lde). Further independent analysis has also shown that the carbon footprint of this new pyrolysis biofuel could achieve a carbon saving of 95% compared to conventional fossil fuels. This is significantly higher than some existing biofuels, which also do not currently factor in the impacts of land use change when calculating the carbon saving.

### Pyrolysis activities

The technical development is focused in two specific areas:

- Pyrolysis: High conversion yields of bio-oil from low-value biomass;
- Upgrading: Novel methods of upgrading bio-oil to transport-grade fuel are being developed. These are potentially more cost-effective than the hydrogenation routes conventionally used for upgrading pyrolysis oil.

Contact  
Dr David Penfold

Future Blends Ltd.  
6th Floor, 5 New Street Square, London, EC4A 3BF  
T: +44 (0)20 78324745 E: david.penfold@carbontrust.co.uk

**Future  
Blends  
Ltd**

A Carbon Trust Enterprise

# Waste-to-energy gasification system

Hudol Ltd, a South Wales based company, has developed an efficient waste-to-energy gasification system that can treat a wide variety of materials ranging from biomass to oily sludge.

Hudol Ltd has developed an innovative robust and user-friendly gasification system which is able to efficiently process a range of materials and output a gas of high calorific value.

Initial funding for this project was provided by the Welsh European Funding Office. Private funding has since brought the concept to market.

## Background

Organic compounds will, if heated in a controlled manner, breakdown into lower molecular weight compounds, changing physical form as their molecular weight decreases. The Hudol technology allows unique control of these reactions such that a wide variety of materials can be treated. The treatment parameters can be altered to allow the composition of the gas that is produced to be optimised.

## Process

Materials are initially passed through two heated zones where the temperature is steadily raised to 500 °C. Material then flows directly into the gasification unit, where the temperature is raised to 900 °C. This is where the final product, syngas, is generated. The syngas is a mixture of methane, hydrogen and carbon monoxide. A small proportion of the syngas is utilised to run the equipment with excess gas available for numerous uses.

## Efficiency

**Hudol's system is unique in that the internal geometry** of the gasification chamber can be altered, which means that the retention time within the chamber can be adjusted, allowing a wide variety of materials to be treated, ranging from biomass to oily sludge and contaminated soil.

The process allows the gas composition to be modified and optimised. The gas composition from other systems is relatively fixed and often of low quality. The



Figure 1: Hudol's gasification system.

gas produced by the Hudol system, on the other hand, has a high calorific value of between 15 and 35 MJ/Kg.

The Hudol system is capable of swallowing 30,000 tonnes of biomass per year to create approximately 18 MW of gas every hour. This converts to around 4.5 MW per hour of electricity if a reciprocating gas engine is used.

Contact  
Dr Robert Prigmore

Hudol Ltd, 1 St Mary Street, Carmarthen,  
Carmarthenshire, SA31 1TN

T: +44 (0)1267 234231 E: robert.prigmore@hudol.co.uk





## Biochar Research Team

The Biochar Research Team at Swansea University (Colleges of Science and Engineering) is primarily concerned with how the **solid (“biochar”) product of biomass pyrolysis** can be used for carbon sequestration and as a soil improver. Our research interests include systems suited to developed and developing nations, as well as ones designed for coproduction of bioenergy with biochar. Team members utilise a tube-furnace reactor in which biomass samples can be pyrolysed under highly-controlled thermal and atmospheric conditions to emulate a variety of possible pyrolysis systems.

Subsequent physical and thermal analyses, and chemical characterisation of the char, are used to gain an understanding of how variations in biomass feedstock

and thermal-processing conditions affect the suitability of biochar as a soil amendment, its stability and key properties that determine how it will interact with the soil-plant system and with soil hydrology.

Some of the analytical methods used to date include <sup>13</sup>C nuclear magnetic resonance spectrometry (<sup>13</sup>C-NMR); thermo-gravimetric analysis (TGA); scanning electron

microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), X-ray fluorescence (XRF), atomic force microscopy (AFM), elemental analysis – isotope ratio mass spectrometry (EA-IRMS); and inductively-coupled plasma optical-emission spectrometry (ICP-OES).

Also, the Anila domestic-scale biomass-pyrolysis cooking stove (which has been proposed as a possible means to improve indoor air quality in developing countries while promoting the small-scale production of biochar) has been evaluated with regard to both health and safety considerations, and the quality of the biochar produced. Arrays of thermocouples have been used to monitor pyrolysis conditions within the stove. Their output has been related to the resulting biochar characteristics in order to assess the efficacy of pyrolysis of various feedstocks and its effects on their particle-size distributions and packing densities.

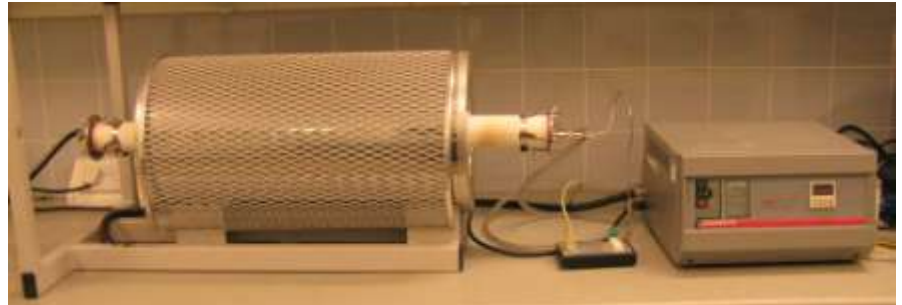


Figure 1: Tube furnace.



Figure 2: Anila in use.

Contact  
Professor Alayne Street-Perrott

Biochar Research Team, Swansea University,  
Singleton Park, Swansea, SA2 8PP

T: +44 (0)1792 205678 E: alayne@perrott3.freeserve.co.uk



Swansea University  
Prifysgol Abertawe



## Independent biorenewables advisor

NNFCC: A leading UK body supporting the private and public sectors with biorenewables expertise.

The NNFCC is a not-for-profit company, technical consultancy and trusted independent advisor **assisting delivery of the UK Government's** objectives for biorenewables, as well as providing impartial information to other Governmental departments, Non Governmental Organisations and commercial organisations. NNFCC provides advice and signposting services to sources of technology and funding plus technical consultancy services to industry and Government.

The NNFCC has a key focus on developing opportunities for biorenewables, including in chemicals, materials, fuels, heat and power. In the energy sector, NNFCC has strongly driven the opportunity to develop advanced processes and fuels such as Biomass to Liquids (BTL) and Anaerobic Digestion. Such specialist areas of knowledge are recognised in both Government and Industrial circles through invitations to serve on the committees of several bodies and associations and requests for studies.

Of the variety of advanced biofuels and bioenergy technologies of interest to the NNFCC, pyrolysis is of interest as it provides one of the few options to provide interruptible power from biomass; can produce power from wastes at higher efficiencies than conventional energy from waste technologies; can provide an alternative to mineral oils for heating and CHP, particularly where space is at a premium; and can potentially be used to produce biofuels. Pyrolysis features in much of our work for Government and Industry; two recent examples of this work are:

- Techno-Economic Assessment of Biomass 'Densification' Technologies. Biomass pelletisation, torrefaction and pyrolysis technologies were compared and opportunities **for these technologies in the UK's East Midlands** region were highlighted. Report available from: <http://www.nnfcc.co.uk/tools/techno-economic->



Figure 1: NNFCC bioliquids report.

[assessment-of-biomass-densification-technologies-nnfcc-08-015/at\\_download/file](http://www.nnfcc.co.uk/tools/evaluation-of-bioliquid-feedstocks-and-heat-electricity-and-chp-technologies-nnfcc-08-015/at_download/file)

- Bioliquids for Heat and Power Applications. In this project for DECC, NNFCC examined the technologies available for bioliquid (including pyrolysis oil) heat, power and CHP; bioliquid availabilities; and the potential for bioliquids to help meet 2020 renewable energy targets. Report available from: [http://www.nnfcc.co.uk/tools/evaluation-of-bioliquid-feedstocks-and-heat-electricity-and-chp-technologies-nnfcc-11-016/at\\_download/file](http://www.nnfcc.co.uk/tools/evaluation-of-bioliquid-feedstocks-and-heat-electricity-and-chp-technologies-nnfcc-11-016/at_download/file)

Contact  
Dr Geraint Evans

The NNFCC, Biocentre, York Science Park,  
Heslington, York YO10 5DG  
T: +44 (0)1904 435182 E: [g.evans@nnfcc.co.uk](mailto:g.evans@nnfcc.co.uk)

## UK 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

### 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 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 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



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



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

objective of this work is to develop 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.

These pyrolysis facilities are accompanied by state-of-the-art analytical instrumentation for online gas analysis (mass spectrometer) that allows us to obtain information on 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 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.

Contact  
Dr Ondřej Mašek

UK Biochar Research Centre, University of Edinburgh  
Crew Building, King's Buildings, Edinburgh, EH9 3JN  
T: +44 (0)131 650 5095 E: [ondrej.masek@ed.ac.uk](mailto:ondrej.masek@ed.ac.uk)

## Energy & Resources Research Institute

Biomass pyrolysis 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

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 0.5 m diameter oil-fired furnace with full exhaust gas analytical suite for pyrolysis oil combustion studies.

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.



Figure 1: Screw kiln pyrolysis-gasification reactor.

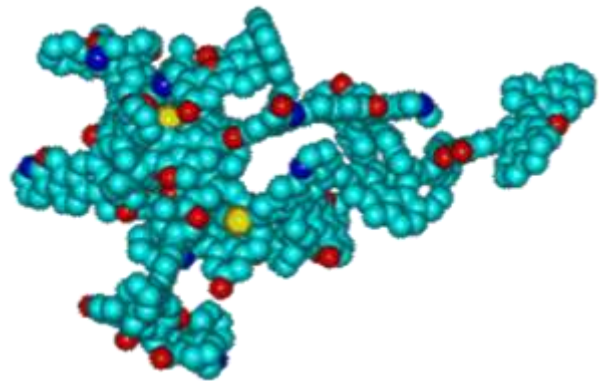


Figure 2: Understanding at a molecular level the changes a solid fuel particle undergoes during thermal processing.

Contact  
Professor Paul T Williams and/or Professor Jenny Jones

Energy & Resources Research Institute,  
The University of Leeds, Leeds, LS2 9JT  
T: +44 (0)113 243 1751  
E: p.t.williams@leeds.ac.uk E: j.m.jones@leeds.co.uk

[www.engineering.leeds.ac.uk/erri/](http://www.engineering.leeds.ac.uk/erri/)

# School of Chemical Engineering and Analytical Science

Our research activity involves thermodynamic, hydrodynamic and reaction kinetic studies of the pyrolysis process in which lignocellulosic resources are converted into organic liquid (bio-oil), light gas and char. While light gas can supply combined heat and power (CHP), char can be useful to improve soil nutritional quality. By optimising pyrolysis processes, it is possible to recover materials in a separate phase from bio-oils, relevant for processing household and municipal wastes.

We are also investigating whole system sustainability of bio-oil processing into methanol [1] or Fischer-Tropsch liquid synthesis upon gasification and gas clean up into syngas or hydrotreating and hydrocracking into biofuel [2] (Fig. 1). Our new invention relates to membrane reactor technology for bio-oil conversion into transportation fuels or chemicals, heat and captured CO<sub>2</sub>.

### In Dr Sadhukhan's visiting research and academic

activity with University of Surrey and Imperial College, highly integrated biomass gasification and solid oxide fuel cell (SOFC) CHP distributed systems were designed, wherein the exhaust gas as a source of steam and unreacted syngas from SOFC is integrated to the steam gasifier, utilising biomass volatilised gases and tars, which is separately carried out from the combustion of the remaining char of the biomass in the presence of depleted air from the SOFC [3-4] (Fig. 2). With Cardiff and Newcastle, we are developing heterogeneous catalysis and continuous process for high efficiency biodiesel synthesis and upgrading (EPSRC funded).

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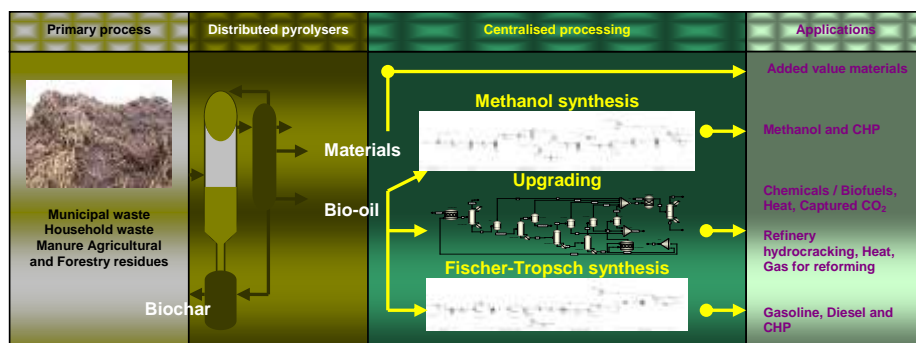


Figure 1: Whole system waste to polygeneration via distributed pyrolysis.

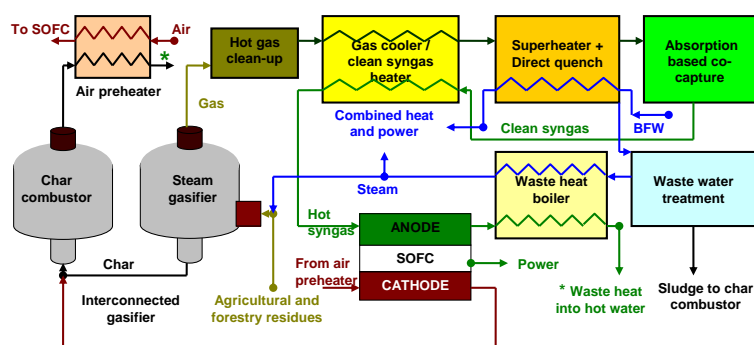


Figure 2: Integrated biomass gasification and SOFC CHP distributed system design.

3. Sadhukhan J., Zhao Y., Leach M., Brandon N.P. and Shah N., 2010. Energy integration and analysis of solid oxide fuel cell based micro-CHP and other renewable systems using biomass waste derived syngas. *Industrial & Engineering Chemistry Research*, 49(22), 11506-11516.
4. Sadhukhan J., Zhao Y., Shah N. and Brandon N.P. 2010. Performance analysis of integrated biomass gasification fuel cell (BGFC) and biomass gasification combined cycle (BGCC) systems. *Chemical Engineering Science*, 65(6), 1942-1954.

Contact  
Dr Jhuma Sadhukhan

School of Chemical Engineering and Analytical Science,  
The University of Manchester, Manchester, M13 9PL  
T: +44 (0) 7971 291187  
E: jhumasadhukhan@gmail.com

MANCHESTER  
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of Manchester



# Biomass pyrolysis and related areas

Activities at the University of Nottingham on pyrolysis and related topics cover the following:

- Torrefaction – impact of feedstock and pyrolysis conditions on the composition and combustion characteristics;
- Fluidised bed gasification. Figure 1 shows a laboratory-scale, electrically heated, bubbling fluidized bed system which consists of a bubbling fluidized bed reactor, a single screw biomass feeding unit, a cyclone for primary particle removal, a cooler, a downstream gas cleaning unit, a combustor, air supply/preheating and data acquisition devices. Silica sand is used as the bed material with 2 ~ 3 kg/hr of SRC willow chips as the feedstock;
- Hydrothermal treatment at elevated temperatures and pressures both for liquid fuel production and for artificial maturation to produce coal and carbon-like materials;



Figure 1: Laboratory-scale, electrically heated, bubbling fluidized bed biomass gasification system for processing.

- Thermally mediated solvent extraction of biomass to produce liquid fuels and bitumen substitutes in high yield that are compatible with petroleum feedstocks, using both H-donor and non-H donor solvents. Hydrogen-donor solvents can give rise to selectivities of over 60% on a carbon basis to liquid products. Figure 2 shows the apparatus for investigating hydrothermal treatment and solvent mediated thermolysis showing a pressure vessel is immersed in a fluidized sandbath;
- In bed upgrading of fast pyrolysis oils with metals;
- Devolatilisation and subsequent char burn-out



Figure 2: Apparatus for investigating hydrothermal treatment and solvent mediated thermolysis showing a pressure vessel immersed in a fluidized sandbath.



Figure 3: Drop tube furnace for devolatilisation and char combustion studies on biomass.

under high heating rates using an entrained flow reactor to compare biomass combustion under normal air firing and oxyfuel conditions and how combustion is affected by degradation. The drop tube furnace used for biomass devolatilisation and combustion studies is shown in Figure 3.

The research is supported by EPSRC - fluidised bed gasification and the Engineering Doctorate Centre on Efficient Fossil Energy Technologies that includes a number of projects on biomass – and by industry, that includes a BP project on thermally mediated solvent extraction.

Contact  
Professor Colin Snape

University of Nottingham, Department of Chemical & Environmental Engineering, Faculty of Engineering,  
University Park, Nottingham, NG7 2RD  
T: +44 (0)115 951 4166 E: colin.snape@nottingham.ac.uk

# 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.

## 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 ( $\sim 10$  °C per minute) up to a controlled maximum ( $\sim 800$  °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 ( $\sim 25$ gms) 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.

## 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.



Figure 1: Pyrolysis products.

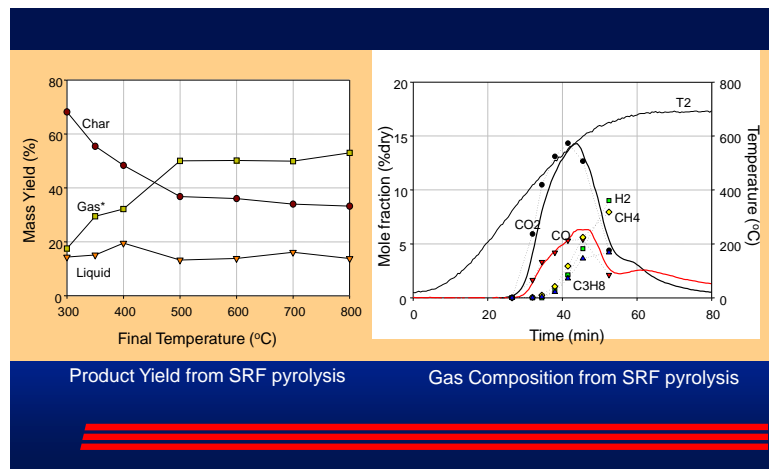


Figure 2: Product yield—storable char, oil and gas.

Contact  
Professor J Swithenbank and/or Professor Vida Sharifi

Department of Chemical and Biological Engineering,  
University of Sheffield, S1 3JD  
T: +44 (0)114 2227502 or +44 (0)114 2227518  
E: j.swithenbank@sheffield.ac.uk, v.n.sharifi@sheffield.ac.uk



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## Biomass thermo-chemical conversion

### Current activities

- Computational modelling of pyrolysis, gasification and combustion
- Kinetic study of biomass thermal decomposition
- Assessment of bioenergy and biofuel potentials

Dr Sai Gu is leading a research team at the University of Southampton in biomass thermo-chemical conversion. Their research covers computational modelling of pyrolysis, gasification and combustion, kinetic study of biomass thermal decomposition, assessment of feedstock and technology development in a global scale.

A close partnership has been formed between the Southampton group and the Bioenergy Research Group at Aston University. Dr Gu has been actively promoting advanced bioenergy technologies globally, currently being the PI of EPSRC Collaborative Research in Energy with South Africa, the lead academic of Leverhulme-Royal Society Africa Award 2009 with Ghana, the coordinator of FP7 ECOFUEL project with China.

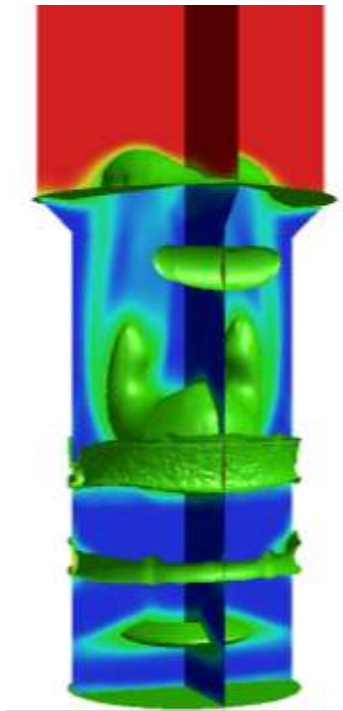


Figure 1: Bubbling fluidised bed.

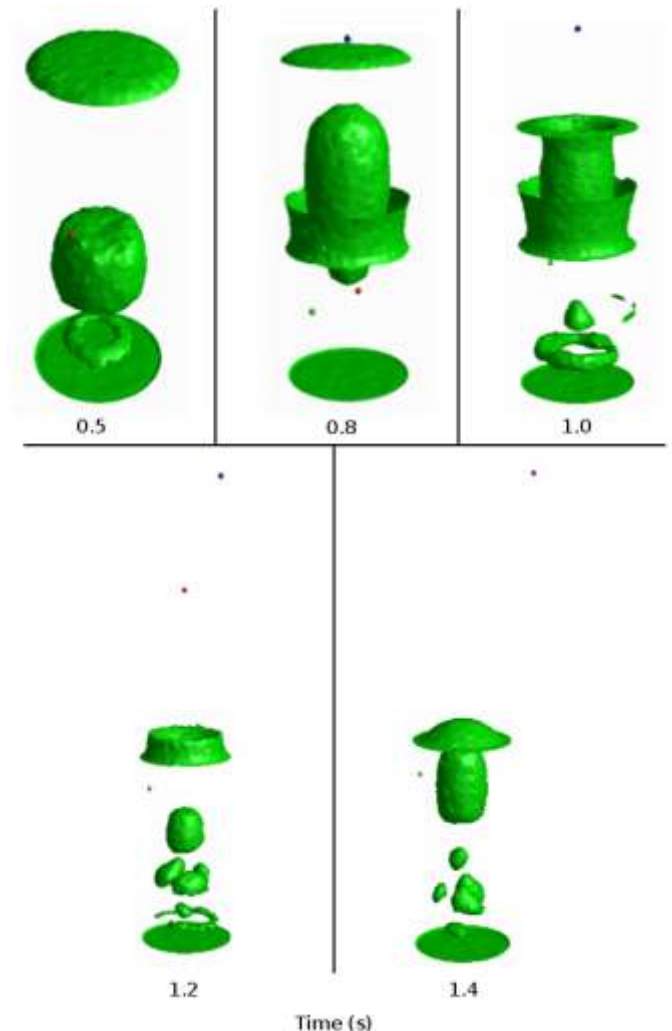


Figure 2: Bubble particle interactions.

Contact  
Dr Sai Gu

School of Engineering Sciences, University of Southampton,  
Highfield, Southampton SO17 1BJ  
T: +44 (0)23 8059 4760 E: s.gu@soton.ac.uk



## Biomass thermal treatment

Pyrolysis research at the University of Warwick makes use of a 100mm diameter, 4m high circulating fluidised bed (CFB), and a 200mm diameter, 1m high bubbling fluidised bed (BFB); each capable of operation in combustion, gasification or pyrolysis mode. The advantages of fluidised beds are excellent gas-solid contact, and high mass and heat transport for optimum conversion efficiency. These units have the capability to treat a wide range of biomass and post-consumer waste types at temperatures up to 900 °C and mass rates of 5 to 25 kg/hr. This allows the assessment of different biomass reactions and their respective reaction kinetics, the energy or chemicals production capability, the processing problems, the required optimum CFB or BFB operating conditions, and the exhaust gas emissions associated with the thermal treatments. The results of such experimental work are used to design the appropriate reactor. The group has experience of willow, spruce/pine, sewage sludge, and crushed waste plastics.



Figure 1: Circulating Fluidised Bed (CFB) rig.



Figure 2: Professor Jan Baeyens with a sample of waste to be treated.

We work closely with crop science researchers in the School of Life Sciences, enabling us to take an integrated approach to bio-processing, from the field to the product.

### Warwick's strengths include:

- chemical engineering of thermal treatment reactions, reactor design and operation;
- crop science and sustainable agriculture;
- life cycle assessment (LCA) applied to bio-products;
- upgrading of bio-products, e.g. char to bio-char, bio-lime or activated carbon, separation of organics in the condensable liquid fraction, further processing of the syngas, etc.

We collaborate with the University of Birmingham Centre for Positron Imaging for the measurement of solids motion in reactors and with the University of Leuven in Belgium for chemical aspects of biomass treatment. We also work with the University of Birmingham on the production of hydrogen from bio-waste as part of the AWM Science City and SCRATCH initiatives.

Contact  
Professor Jonathan Seville

University of Warwick, Coventry CV4 7AL  
T: +44 (0)24 7652 3523 E: j.p.k.seville@warwick.ac.uk

# Microwave thermo-chemical 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 the use of microwaves to selectively activate components of biomass leading to a much more controlled decomposition process than can normally be achieved. The outcome is a range of valuable products including pyrolysis liquids and bio-chars and chemicals from sustainable sources of carbon including waste materials.

Microwave irradiation is rapid and volumetric with the whole material heated simultaneously thus allowing the processing of poor thermal conducting materials such as wood. Microwave heating can be controlled instantly and the power applied can be accurately regulated. This allows safe and precise control, even when applying very rapid heating rates. Furthermore, microwave pyrolysis occurs at lower temperatures whilst generating materials with higher calorific values (See Fig. 1).

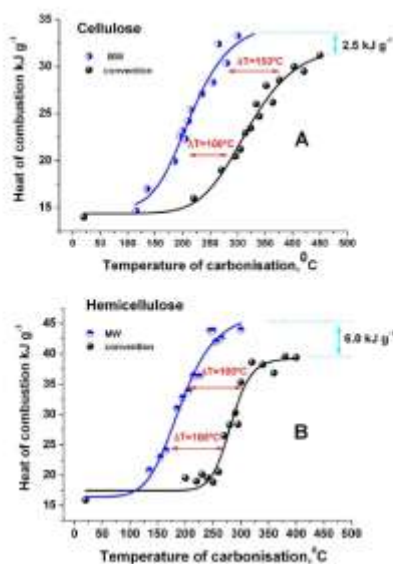


Figure 1: Heat of capacity versus temperature of carbonisation for biomass components from microwave and conventional pyrolysis.

The team at the Green Chemistry Centre have proven this technology at scales from grams to tens of kilograms (See Fig. 2).

In 2011, we will expand our facility into the Biorenewables Development Centre, a multi-functional space containing semi-scale



Figure 2: Output from larger scale microwave mediated pyrolysis of biomass.



equipment for microwave pyrolysis, supercritical CO<sub>2</sub> extraction, ammonia fibre expansion and fermentation alongside all the necessary pre-treatment 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.

Contact  
Professor James H. Clark  
Dr Mark J. Gronnow (General Enquiries)

Green Chemistry Centre of Excellence, Department of  
Chemistry, University of York, York, YO10 5DD  
T: + 44 (0)1904 322559  
E: james.clark@york.ac.uk E: mark.gronnow@york.ac.uk

[www.york.ac.uk/  
greenchemistry](http://www.york.ac.uk/greenchemistry)

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## Editorial team

If you would like to contribute to the next edition of this guide contact the Editors, Tony Bridgwater and/or Irene Watkinson at:  
Bioenergy Research Group, Aston University,  
Birmingham B4 7ET, UK.

Tony Bridgwater  
T: +44 (0)121 204 3381  
E: [a.v.bridgwater@aston.ac.uk](mailto:a.v.bridgwater@aston.ac.uk)

Irene Watkinson  
T: +44 (0)121 204 3430  
E: [i.i.watkinson@aston.ac.uk](mailto:i.i.watkinson@aston.ac.uk)

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