Torftech Group

# BIOMASS GASIFICATION TECHNOLOGY PRESENTATION

May 2020

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# INTRODUCTION

## Torftech

- The Torftech Group is an IP, technology and engineering business.
- The Group owns rights to and continues to develop the TORBED®* family of industrial process technology which was originally invented by Chris Dodson, the Group's chairman.
- Invented in 1981 and first commercialized in 1985, the TORBED processors have a broad range of applications in contexts which require gas-to-solid contacting. They offer high precision processing within a compact footprint.
- The processors are marketed and sold by the Torftech companies under the TORBED brand name.
- They are supported by a rolling programme of patents and a strong IP culture.
- Multiple applications and markets.
- Strong operational track record.
- History of innovation and problem solving.


* TORBED is a registered trade mark of Mortimer Technology Holdings Limited

# INTRODUCTION

## Who We Are

**Torftech is a solutions-focused design engineering company.**

**Principally owned by its directors and staff.**

**We own the IP in the Torftech Technology.**

**The Torftech Technology is a materials processing platform based on the TORBED processor family.**

**Gas solid contacting devices which maximise efficiency and accuracy whilst minimising resource use.**

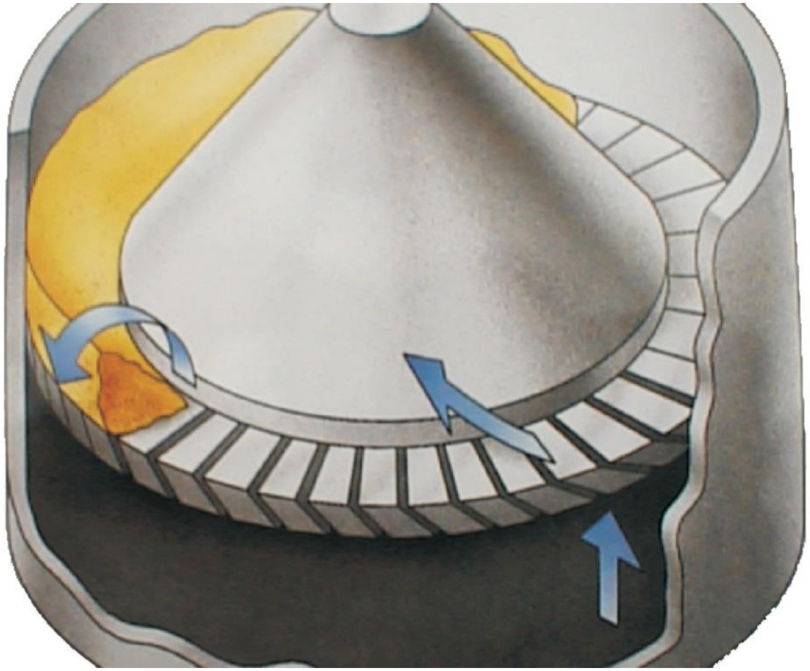
**Torftech has  successfully designed bespoke solutions using TORBED reactors for over 35 years.**

**The process control offered by the Torftech Technology permits the creation of value-added by-products.**

**These can add value to biomass-fuelled power generation.**

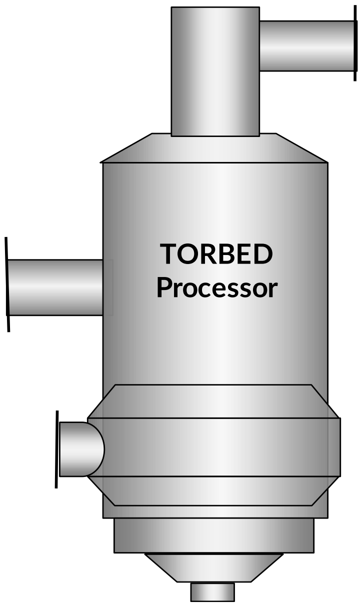
## TORBED Processors

- TORBED processors contain a toroidal fluidised bed that is created by introducing and then sustaining a steady feed of material into a specially-directed, fast-moving gas stream.
- The process gas stream lifts the material into a shallow compact bed imparting horizontal motion and subjecting the base layer of the bed to high impact gas velocities and thus higher heat and mass transfer rates.
- Material in the bed is vigorously mixed, ensuring consistent processing.
- The patented geometry and flow patterns of TORBED processors allow higher gas velocities without particle entrainment in the exhaust gas stream.
- This gives high slip velocities and thereby a high rate of reaction. This high reaction rate allows a low bed mass, giving excellent, real-time process control and accuracy.



*A TORBED Compact Bed Reactor ("CBR")*

## Key Features and Advantages




High material processing rate

Low bed mass

Low thermal inertia

Very rapid shut down

Fast start up

Enhanced safety and operational flexibility

Very accurate temperature control

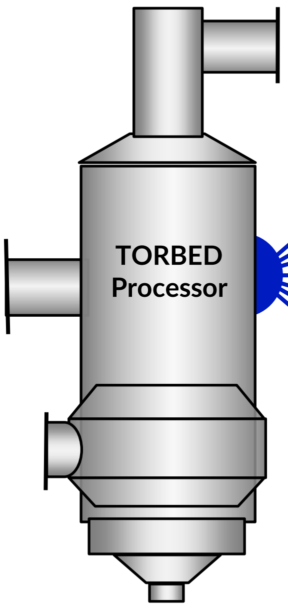
Allows for effective processing of challenging materials, eg:

- high carbon conversion in gasification of high alkali metal feedstock; and
- excellent carbon burnout of rice husk without crystalline ash formation.

At its heart, the technology is based on suspension of solids in a fast-moving gas stream within a cylinder-shaped chamber. The gas stream, which is directed at an angle imparting horizontal and vertical motion, lifts the solids into a toroidal fluidized bed and subjects the base layer of the bed to high impact gas velocities and thus high heat and mass transfer rates.

# INTRODUCTION

## Processes Using Our Equipment




**Food Manufacture**

*Pasteurising, cooking, blanching, drying, roasting, toasting, puffing, expansion, baking.*

**Activated Carbon and BioChar Production**

*Biomass and coal devolatilisation and activation, impregnation.*

**Biomass Processing and Power Generation**

*Drying, Torrefaction, Pyrolysis, Gasification, Combustion.*

**Sludge Processing and Disposal**

*Drying, gasification, combustion, carbon removal, pasteurisation, devolatilization.*

**Mineral Processing**

*Bloating, exfoliating, expanding, roasting, drying, calcining, thermal shattering, carbon removal.*

**Catalysts and Zeolytes**

*Drying, impregnation, regeneration, recovery, calcination.*

**Waste Processing and Disposal**

*Drying, gasification, combustion, carbon removal, scrubbing, pasteurisation, devolatilization.*

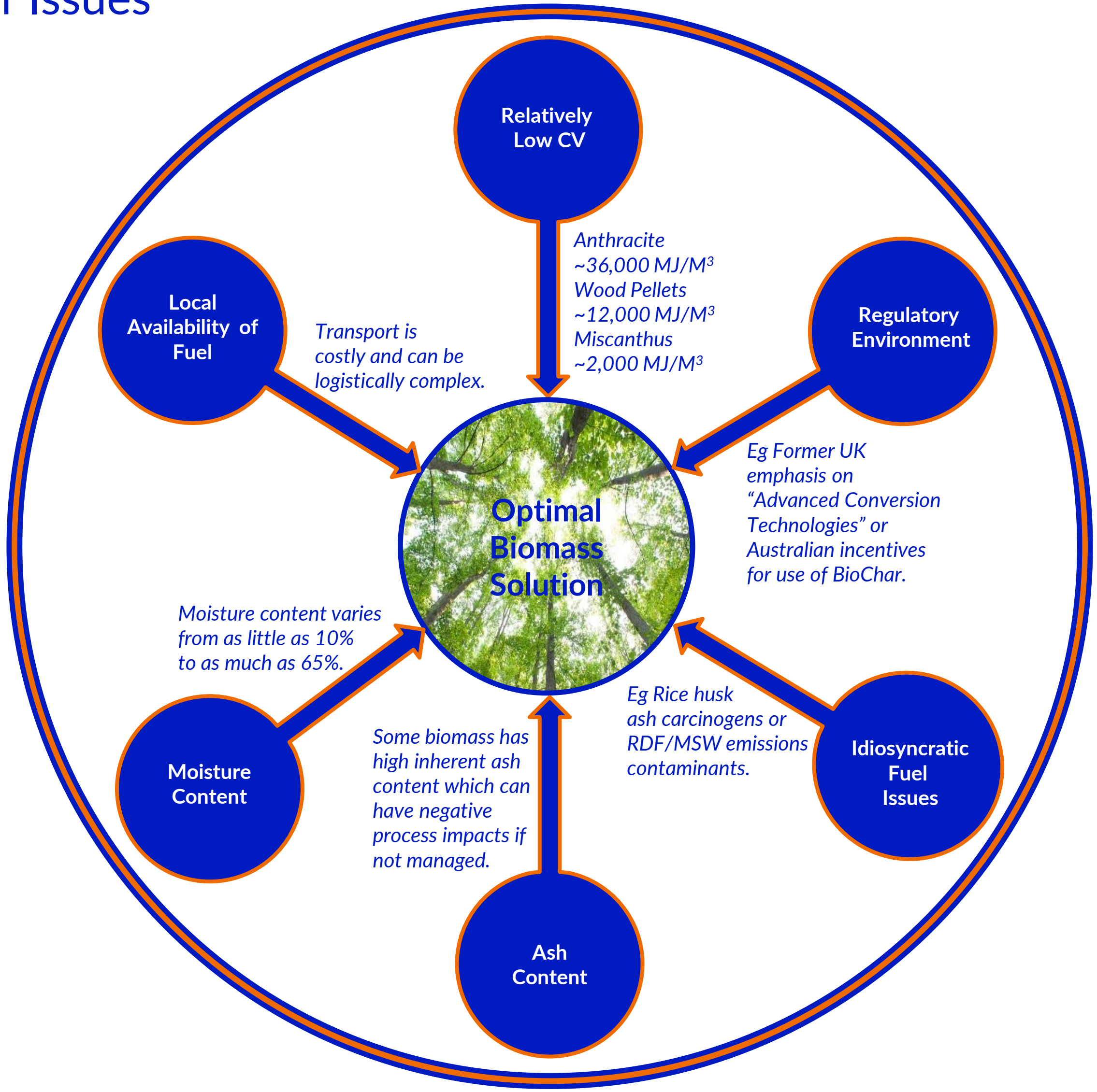
# Section II

# Biomass Power Generation

# Biomass Challenges: A Matrix of Issues

*Biomass and waste -based fuels for power generation present a range of systemic and idiosyncratic challenges which require a flexible technological approach.*

*TORBED Processors are adaptable and flexible and thereby ideally suited to address these challenges.*



Torftech Group

## TORBED Processor Applications

*Broad experience at commercial and/or pilot scale with a wide range of feedstocks.*


*Process*

**Drying** — Reduction of water content, typically to permit onward processing and improve downstream process efficiency.

**Torrefaction** — A roasting process reducing moisture and breaking down cellular structures, whilst preserving most volatiles. This increases energy density and brittleness, the latter permitting milling for ease of use in coal replacement.

Drying and Torrefaction: **Fuel improvement**

**Pyrolysis** — A higher temperature process that removes volatiles from the biomass, leaving a carbon char. Typically used where removal (and possibly recovery) of the volatiles is the objective.

**Gasification** — Essentially an oxygen-starved (and often lower temperature) partial combustion process that produces a syngas but does not achieve full carbon burnout, also producing a high quality char. Especially useful for managing biomass with high organic ash content.

**Combustion** — An oxygenated process that achieves full carbon burnout.

Gasification and Combustion: **Generation + Ash/Biochar**

**Comparisons of TORBED processors and other possible gasification equipment options are set out in Appendix III.**

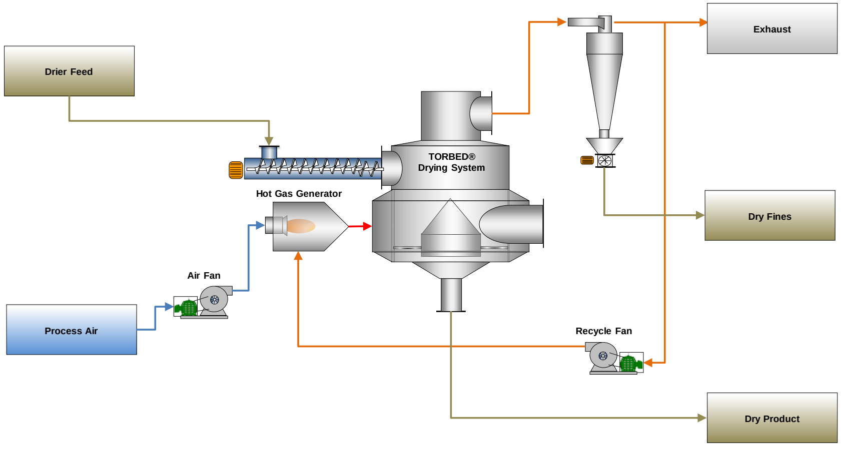
# Drying

- First large-scale TORBED dryer system was installed in 2004 and has run successfully ever since.
- Drying is typically a low temperature process.
- It can be a first stage in preparing biomass for transportation or for further processing.
- Potentially a highly efficient way of utilizing waste heat from another process.
- TORBED dryers have a much smaller footprint than conventional belt-based or rotary drum dryers.
- They also have the ability to **process fine particles** that can create dust control problems with other technologies.
- The plant shown opposite is used to dry waste paper sludge, which is then sold for use as animal bedding. A three stage TORBED dryer is in the foreground: the belt dryer it replaced remains in situ.
- The belt dryer, now decommissioned, used more energy, had higher operational costs and produced less output. The TORBED can be run remotely whilst the belt dryer required a team 24/7.

**Comparative footprints of a TORBED dryer and a set of belt dryers both designed to dry 14 tonnes of biomass per hour**

36m

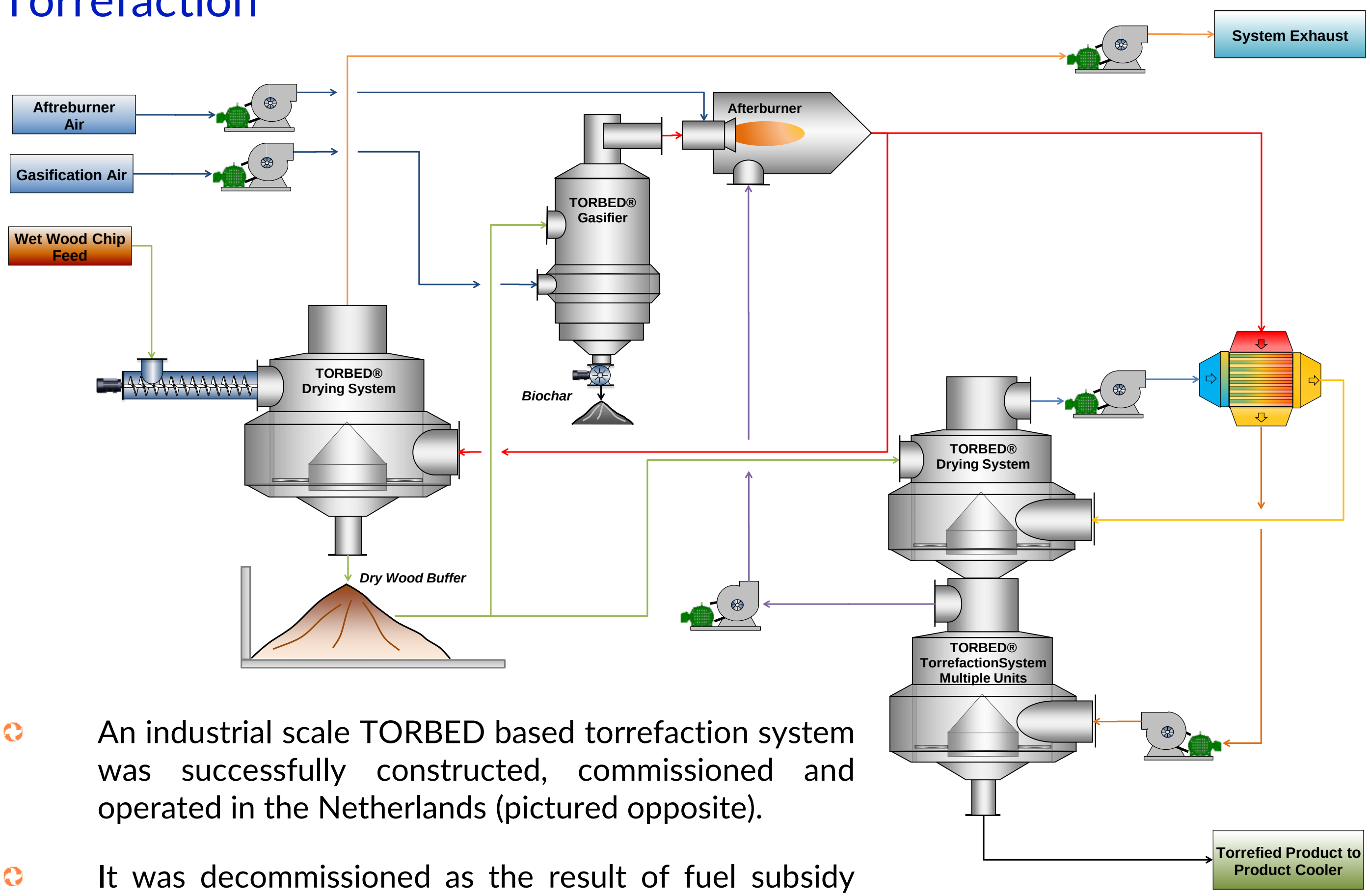
*Schematic of a TORBED drying plant*




*A TORBED-based drying plant in Holland*

# FUEL IMPROVEMENT

## Torrefaction

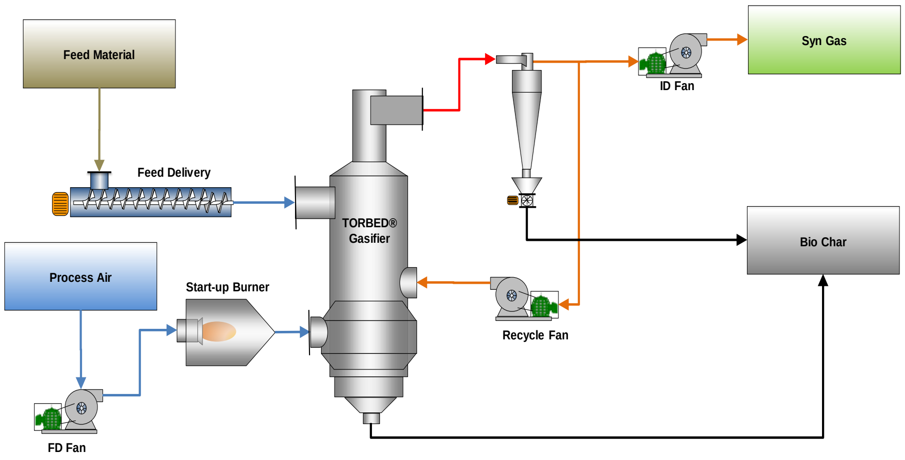



- An industrial scale TORBED based torrefaction system was successfully constructed, commissioned and operated in the Netherlands (pictured opposite).
- It was decommissioned as the result of fuel subsidy policy changes which rendered it uneconomic to run
- The process combines TORBED reactors in a number of different roles: low temperature drying, heat generation, high temperature drying, torrefaction and potentially cooling. The product is embrittled and suitable to replace coal in conventional power plants

## Gasification

- First TORBED gasifier was installed in 2005/6 in the Netherlands; it ran successfully for a number of years on miscellaneous general biomass.
- In a TORBEDgasifier, gasification is a high temperature, low oxygen process with multi-fuel capability and high operational flexibility.
- It involves conversion of solid fuel into a syngas which can be used as fuel for heat or electricity generation.
- Syngas has power house flexibility: it can be used to generate heat and electricity through either: gas engines; or a boiler and a steam turbine; or an ORC.
- The TORBED processors' ability to allow close temperature control facilitates management of ash fusion problems that are otherwise typical with biomass and waste combustion or gasification processes and avoids the need for regular shutdowns for ash removal.
- The process produces a carbon-containing char as a by-product, which, for example, can be used as a soil conditioner.

*Schematic of a TORBED gasification system*

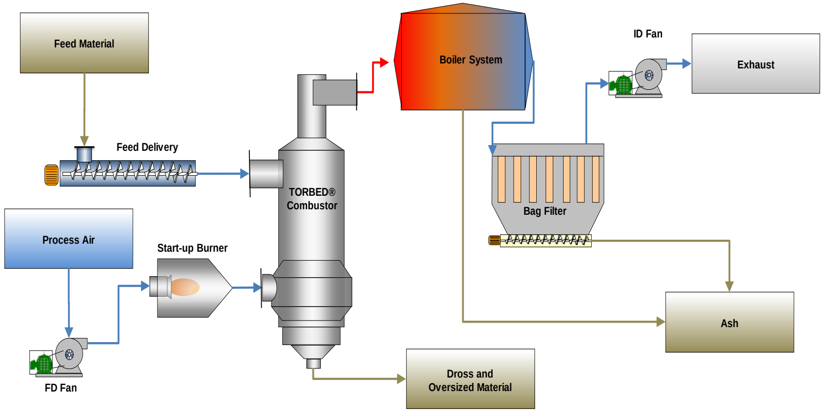



*A gas engine being delivered to a TORBED gasification plant*

## Combustion

- The first TORBED combustor was installed in 1989 and has run successfully since that date.
- In a combustion process, close to all carbon in the feedstock is consumed. (Carbon contents in final ash is typically <5% mass).
- Combustion is not suitable for all biomass-based fuels, as high temperatures may lead to ash slagging.
- It is particularly effective with low alkali metal ash biomass such as most woods or rice husk.
- It is also effective for applications where maximum carbon burnout is desirable, such as:
  - Production of rice husk ash for onward processing; and
  - Burnout of carbon from sewage sludge digestate to meet disposal regulations.
- TORBED combustors have been used to combust wood, rice husk, sewage sludge and paper sludge and to remove residual carbon or hydrocarbons from other materials.

*Schematic of a TORBED combustor/boiler system*




*A TORBED combustor-based power plant in Cambodia*

# Section III

# Biochar Production using the TORBED Gasification Process

# BIOCHAR PRODUCTION

## Key Competitive Advantage of the TORBED Gasifiers

Circular Economy

*Improvement in project revenues* ***unique*** *to TORBED processors*

**$$$**

**$40/MWh ++**


**Gasified in a TORBED processor gives a high grade carbon char**

- *Soil improvement*
- *Ground remediation*
- *Filtration*
- *BioFuel*
- *Activated Carbon*

# BIOCHAR PRODUCTION

## Char from General Biomass

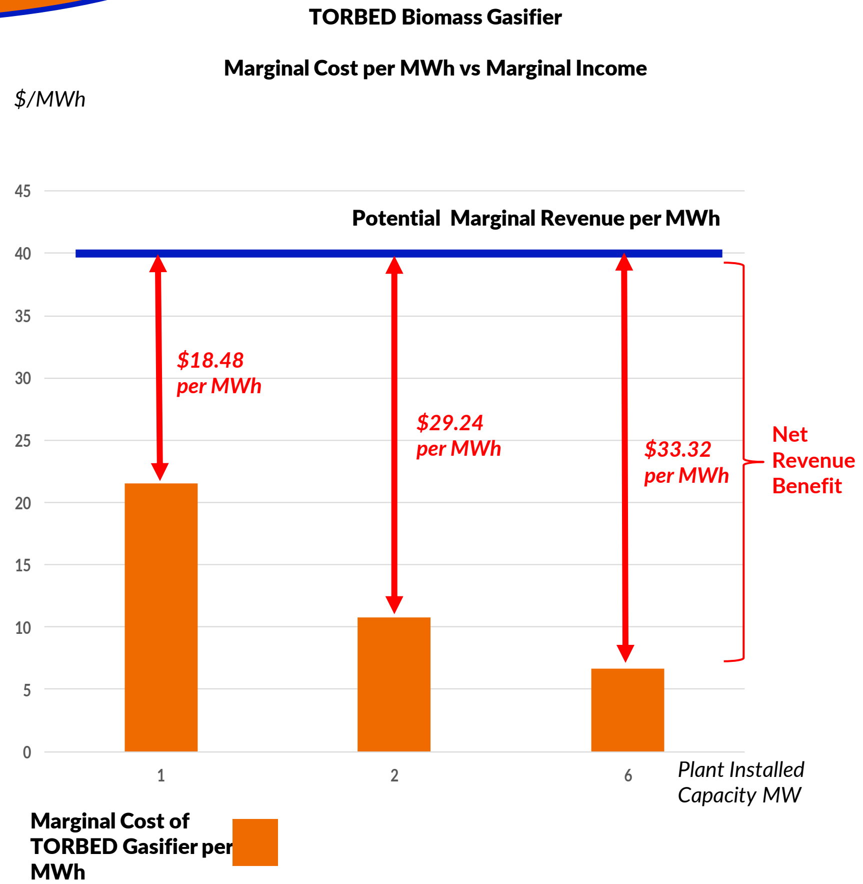
**UPSIDE GROSS REVENUE POTENTIAL OF $40++ PER MWh**

The TORBED gasifiers offer advantages over many competitors in terms of cost and scale

They offer further potential advantage with high ash content biomass such as straw, oil palm fruit bunches and bagasse

The gasification process produces ~160kg of carbon char per MWh from this type of biomass

Such carbon has a ready market as a soil remediator and a value of ~€250 per tonne and is capable of being processed to become activated.



# BIOCHAR PRODUCTION

Poster published by University of Leeds in June 2017 providing validation of the TORBED processor's ability to produce high quality char from both biomass and lignite.

## Biochars for the Adsorption of Environmental Pollutants

Christopher Holt, Samantha Sime, Aidan Westwood, Antonio Salituro, Rob Blissett.

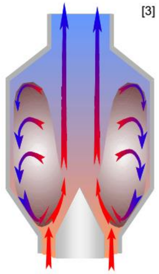
EPSRC
Pioneering research and skills

### Introduction

✓ 'Biochars': High carbon product produced from thermal decomposition of biomass with limited $O_2$ [1].

✓ Has many applications including: Additive to soil, adsorption of $CO_2$ and water treatment [2].

✓ Torftech TORBED reactors thought to produce highly porous biochars. They provided us with two biomass chars and three lignite chars to test [3].



[3]

Figure 1: TORBED reactor

### Methods

**Chars**
Gasification: Straw (690 ºC, Poland), Wood (750 ºC, Wales). Fast pyrolysis: Lignite chars(750 ºC, 830 ºC and 950 ºC).

- Surface area and porosity: Nitrogen desorption/adsorption isotherms.
- Surface oxygen functional groups: Thermal Analyser, Mass Spectrometer and a Fourier Transformed Infra-Red (STA-MS-FTIR).
- Measuring weight gain to assess $CO_2$ adsorption.

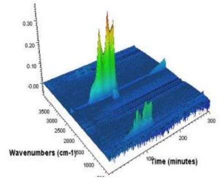
The char which demonstrated the highest surface area was then activated by chemical activation (KOH, 650 ºC, 1 hour 2:1 ratio) and physical activation ($CO_2$, 30 mins, 800 ºC), and the same analysis methods repeated.

### Results

✓ Wood has the lowest surface area and micropore volume. The straw char has a much higher surface area of 463.43 $m^2/g$.

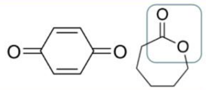
| Sample | Surface Area ($m^2/g$) | Micropore Volume (cc/g) |
|---|---|---|
| Straw Char | 463.43 | 1.84E-1 |
| Wood Char | 86.51 | 3.65E-2 |
| Lignite Char 750 ºC | 489.97 | 1.92E-1 |
| Lignite Char 830 ºC | 484.97 | 1.85E-1 |
| Lignite Char 950 ºC | 665.20 | 2.57E-1 |

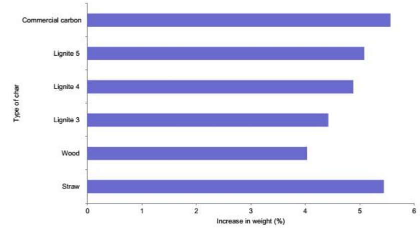
✓ From the STA-MS-FTIR, suggestions can be made as to the functional groups present on the surface of the char, depending on the temperature of CO and $CO_2$ evolution.




✓ Straw and wood chars evolved CO at temperatures characteristic of lactone groups, and $CO_2$ at temperatures characteristic of quinone/semiquinone groups.

| CO Peak (K) | Possible Functional Group | $CO_2$ Peak (K) | Possible Functional Group |
|---|---|---|---|
| 1160 | Quinone/ Semiquinone | 879 | Lactone |
| | | 1109 | Uncertain |






✓ Straw char adsorbed the most $CO_2$.

✓ Lignite chars absorbed more the higher the production temperature.

✓ Straw show marginally less adsorption than the activated commercial carbon.

| | Yield (%) |
|---|---|
| $CO_2$ activation | 54.56 |
| KOH activation | 71.34 |

Yields from both activation methods.

✓KOH activated char contained a higher number of ultra-micropores (<7 Å).

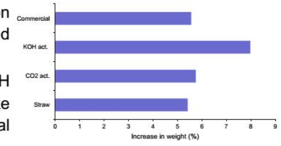
✓STA-MS-FTIR suggested the same functional groups as unactivated chars.

| Sample | Surface Area ($m^2/g$) | Micropore Volume (cc/g) |
|---|---|---|
| Straw char | 463.43 | 1.84E-1 |
| $CO_2$ act. char | 820.11 | 3.19E-1 |
| KOH act. char | 1177.04 | 4.56E-1 |

✓ $CO_2$ activation increased the uptake marginally.

✓KOH activation significantly increased uptake.

✓Both $CO_2$ and KOH activation increased uptake above the commercial carbon.




### Conclusion

✓Straw char demonstrated the highest surface area and micropore volume.
✓Chemically activated straw char had significantly improved surface area and $CO_2$ uptake.
✓Physical activation did not significantly improve the $CO_2$ uptake of the char.


References
[1] Gaunt, J.L. and Lehmann, J. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environmental Science & Technology. 2008, 42(11), pp.4152-4158.
[2] Lehmann, J. et al. Bio-char sequestration in terrestrial ecosystems–a review. Mitigation and adaptation strategies for global change. 2006, 11(2), pp.395-419.
[3] R. Blissett, 'Upgrading low rank coal for metallurgical pulverised coal injection applications', 2015 International Conference on Coal Science & Technology, 2015.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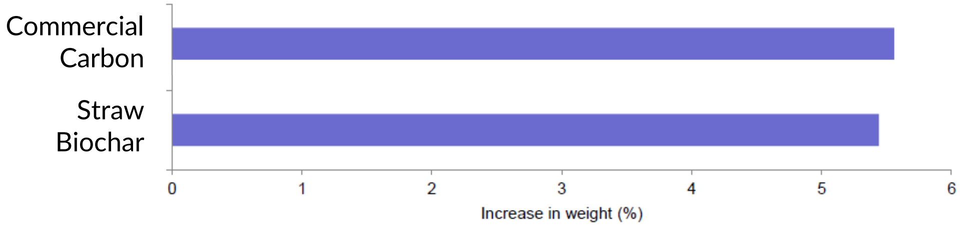
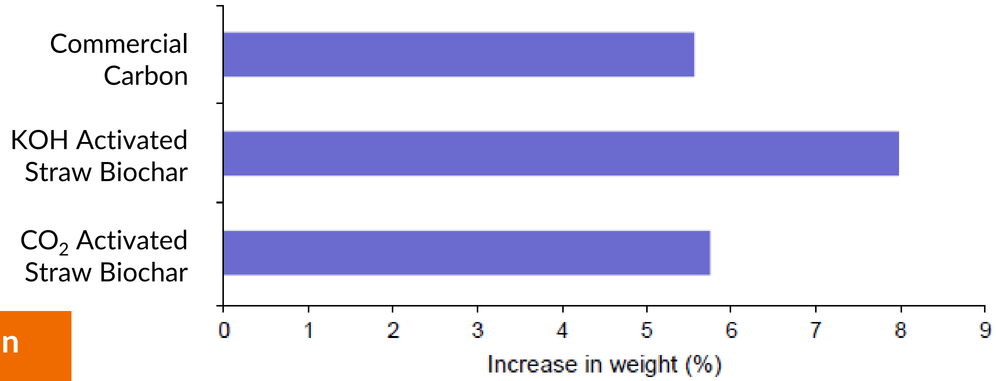
# BIOCHAR PRODUCTION

## From biomass to activated carbon

*Comparison of raw biochar $CO_2$ adsorption capabilities*




*Activation of straw char increases surface area and adsorption performance to over and above commercial activated carbons.*




**Extracts of Poster published by University of Leeds in June 2017 providing validation of the TORBED processor's ability to produce high quality char from both biomass and lignite.**

*Comparison of activated char $CO_2$ adsorption capabilities*

# Section IV

# Biomass Gasification Case Studies

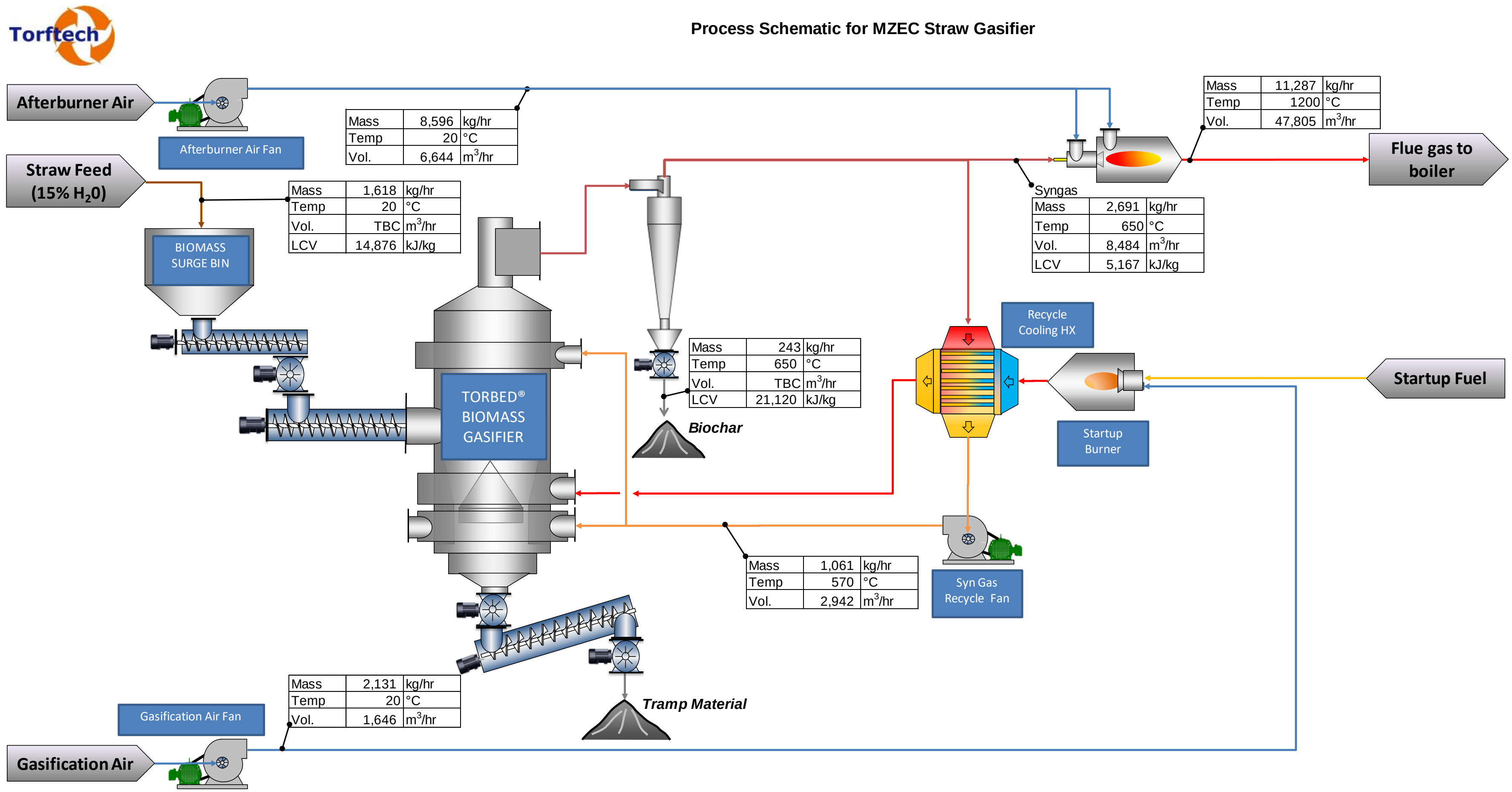
# T1000 STRAW GASIFIER

## Poland: MZEC Świdnica Biomass Heating Plant

- Modernisation of a coal-fired district heating station with a biomass gasifier and afterburner supplying heat from biomass.
- This combination of EBR and afterburner provides the foundation of the gasifier circuit for projects of this nature.
- Fuel
  - Straw
  - Wood
- 5$MW_{th}$ output
- Delivered/installed in 2013 and operating successfully.
- Producing char (pictured opposite) that is being sold commercially for soil and ground improvement applications.

# T1000 STRAW GASIFIER

## Poland: MZEC Świdnica Biomass Heating Plant Mass & Energy Balance



# T1000 STRAW GASIFIER

## Fuel, syngas and char analysis (2013)

| Straw Analysis | | Value |
|---|---|---|
| Moisture | % | 14.7 |
| Ash | % | 6.3 |
| NCV | kJ/kg | 14237 |
| Carbon | % | 39.3 |
| Hydrogen | % | 4.95 |
| Nitrogen | % | 0.83 |
| Sulphur | % | 0.27 |

| Gas Analysis | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| CO (%mol) | 16.47 | 20.06 | 19.61 |
| CO2 (%mol) | 13.18 | 11.48 | 11.39 |
| CH4 (%mol) | 4.41 | 4.77 | 4.62 |
| H2 (%mol) | 6.65 | 5.65 | 5.09 |
| C2H4 (%mol) | 1.15 | 1.24 | 1.2 |
| N2 (%mol) | 58.14 | 56.73 | 58 |
| Gas CV kJ/Nm3 | 5058 | 5590 | 5396 |

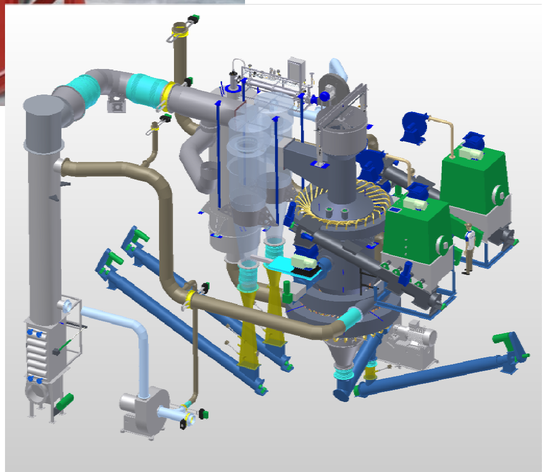
| Straw Char Analysis | | Value |
|---|---|---|
| Moisture | % | - |
| Ash | % | 33.4 |
| NCV | kJ/kg | 21335 |
| Carbon | % | 59.2 |
| Hydrogen | % | 1.19 |
| Nitrogen | % | 1.05 |
| Sulphur | % | 0.17 |

# T2000 Wood Chip Gasifier

## UK Biomass Gasification CHP Plant

- Located at Usk in South Wales.
- The Project consists of a 6.3MW wood-fired biomass power plant, based around a TORBED EBR gasifier and with power generated by a group of gas engines.
- Wood successfully gasified in April 2014 and power first generated in July 2014.
- Plant currently not operational owing to gas clean-up system (required for engines but not for steam turbines) by-product challenges unrelated to the TORBED gasifier. The plant is in the process of being redesigned, refinanced and recommissioned.
- 35% gross electrical energy from chemical energy. 25% overall plant gross efficiency.
- No stack: an important factor in planning deliberations.
- At full capacity, the plant would use approximately 45,000 tonnes of waste wood and waste wood fines per annum.

*Usk Project and Processor*

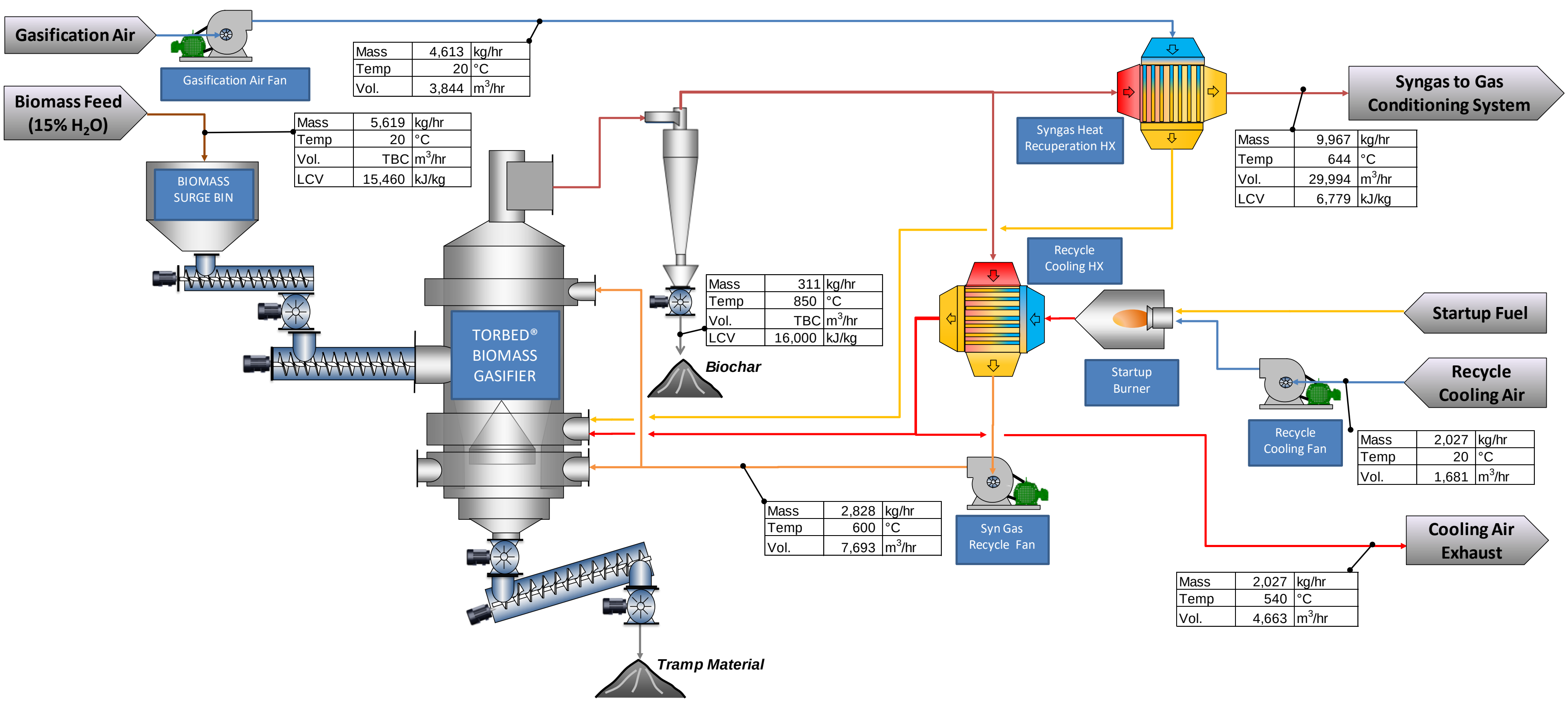


** Clean wood, relatively homogeneous (hard/soft wood), very few contaminants*

# T2000 Wood Chip Gasifier

## UK: Usk Biomass Gasifier CHP Mass & Energy Balance

**Process Schematic for Usk Waste Wood Chip Gasifier (Ash 3% wet basis)**



# T2000 Wood Chip Gasifier

## Fuel, syngas and char analysis (2015)

| Wood Chip Analysis** | | Value |
|---|---|---|
| Moisture | % | 12.7 |
| Ash | % | 0.6 |
| NCV | kJ/kg | NA |
| Carbon | % | 43.7 |
| Hydrogen | % | 5.3 |
| Nitrogen | % | 0.25 |
| Sulphur | % | 0.03 |

| Gas Analysis | Values |
|---|---|
| CO (%mol) | 19.8 |
| CO2 (%mol) | 15.2 |
| CH4 (%mol) | 5.4 |
| H2 (%mol) | 9.7 |
| C2H4 (%mol) | NA |
| N2 (%mol) | 49.1 |
| Gas CV kJ/Nm3 | 6400 |

| Wood Char Analysis | | Value |
|---|---|---|
| Moisture | % | - |
| Ash | % | 6.3 |
| NCV | kJ/kg | NA |
| Carbon | % | 88.5 |
| Hydrogen | % | 1.2 |
| Nitrogen | % | 0.5 |
| Sulphur | % | 0.1 |

* Due to limitations on the downstream process, the Usk gasifier was never run at full load. Analyses were obtained from 1/3 load operation. Carbon conversion in char is expected to improve at full load.

** This is an analysis of clean wood chip that was used during the commissioning period.

# Section V

# Team

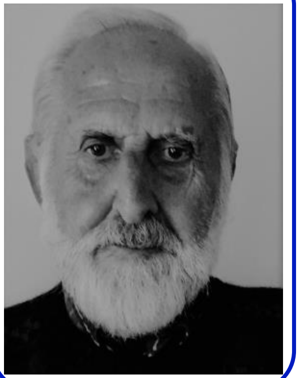
# Key Team Members

| Name<br>Function | | Biography |
|---|---|---|
| **Chris Dodson**<br><br>**Inventor and**<br><br>**Group Chairman** |  | Chris is a mechanical engineer with many years of industrial experience.<br><br>He worked for multinationals before establishing the Group some 30 years ago. He was the original inventor of the TORBED Reactor concepts and has continued to generate strong IP platforms to underpin the businesses. Chris has worked in Europe, North America, India and Australasia. His expertise is in R&D in the process industries providing practical solutions to process problems using gas/solid contacting. His revolutionary TORBED Reactor technologies have served the food, chemical, mineral, metallurgical, petroleum, power and environmental industries.<br><br>He is an experienced Director, having held Board positions in a range of companies and is: a Fellow of the Institute of Directors ("IoD") and a past member of its governing body; an Associate Fellow of the Institute of Chemical Engineers and a member of Catalyst[uk], a global network of business leaders who champion the UK as the world's best international business partner. |
| **Martin Groszek**<br><br>**MD Torftech Group**<br><br>**Chief Technology Officer** |  | Martin has extensive international experience working in capital goods, production, contract engineering and R&D environments for both corporates and SMEs.<br><br>After being awarded a BSc in Metallurgy, Martin travelled to South Africa where he took up a position with Anglo American and DeBeers. After five years of working in various coal, gold and diamond mines, where he was accountable for a major plant operation, Martin returned to the UK to take up a scholarship at Imperial College and obtained his MSc. He subsequently joined Davy McKee in a senior process engineering capacity before being asked to lead Davy's TORBED technology commercialisation team. In 1991 he joined Comalco (now RTZ) and moved to Melbourne Australia to take up a role commercialising new technology for Comalco's R&D division.<br><br>Returning to the UK in 1994, Martin joined Torftech as Operations Director, re-acquainting himself with the TORBED technology, and in 1997 was appointed Managing Director of Torftech Ltd. Martin is currently the Managing Director of the Torftech Group. |

# Key Team Members

| Name<br>Function | | Biography |
|---|---|---|
| **Andrew Bride**<br><br>**Finance Director** |  | Andrew joined Torftech in January 2014. He is responsible for the Group's financing, accounting budgetary, tax and risk functions.<br><br>With a background in infrastructure finance and an understanding of many of the sectors in which the Group works, he brings extensive experience of capital raising, contract structuring, commercial risk management and project development. Andrew has held positions at Morgan Grenfell, Deutsche Bank, EBRD, DEPFA Bank and Fieldstone, winning numerous industry awards for ground-breaking financings. His experience includes M&A, capital raising, securitization, project and export finance across a range of infrastructure sectors and geographies, principally in Asia and Eastern and Western Europe.<br><br>Andrew holds a MA in economics from Trinity College, Cambridge and is a Chartered Accountant. |
| **Daniel Groszek**<br><br>**Senior Process Engineer** |  | Daniel joined the Torftech group full time as a process engineer in July 2011, having first worked with the company in 2006.<br><br>He is responsible for the inception, development, delivery and commissioning of technical process solutions utilising the TORBED technology. This includes the design of research programs and innovation of TORBED systems for application across many industries. Daniel's responsibilities also extend to project development, in both technical and commercial capacities.<br><br>Since entering the company Daniel has worked commissioning four commercial plants as well as carrying out a series of test regimes in Torftech's pilot plants. He has also produced a range of technical and financial models along with functional specifications for the programming and operation of industrial facilities. In addition to this Daniel is part of the continuous effort to expand the portfolio of solutions that the Torftech group can offer.<br><br>Prior to joining Torftech Daniel completed a Physics degree at Imperial College London, graduating with first class honours. |

# KEY TEAM MEMBERS

| Name<br>Function | | Biography |
|---|---|---|
| **Jin Feng Goh**<br><br>**Senior Process Engineer** |  | Jin joined the Torftech group in 2007 as a project engineer assisting the commissioning of TORBED plants. He is now principally responsible for process simulations and overall plant design.<br><br>Throughout the 12 years of service, Jin has designed and commissioned the full range of commercial biomass processing plants, including dryers, gasifiers and combustors. This has given him wide experience in the biomass industry with a particular focus on both the solids handling and processing challenges presented by this material.<br><br>The experienced gained at commercial plants is enriched with more processing experience at Torftech's pilot plant. Here, Jin has carried out multiple tests on client supplied materials to determine the best processing conditions. The conditions are then taken back into his process models for further optimisation of the commercial plant.<br><br>Jin holds an MSc. in Renewable Energy from the University of Reading and is a mechanical engineering graduate from Univesiti Teknologi Malaysia. He speaks English, Mandarin Chinese, Malay and Italian. |
| **Bob Laughlin**<br><br>**Director Process Development** |  | Bob has been involved with the Torftech Group for 22 years and is Director of Process Development.<br><br>Bob's work focuses on developing Process Flow Diagrams for new potential applications for the TORBED reactor technology. This involves developing imaginative approaches to meet a clients need by establishing a practical process approach that minimizes capital cost and energy consumption. Bob is also involved in running pilot scale tests of new applications in a pilot plant in Mississauga Ontario.<br><br>Bob has both a B.Sc and Ph.D. in Chemical Engineering from University College London, and is a licensed Professional Engineer in the province of Ontario |

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# Appendix I

# References

## Past Performance

*From*

*To*

- First commercial sale in 1985.
- More than 180 units sold, of which key concentrations have been:
  - 46 for biomass/waste processing,
  - 81 to the food processing industry, and
  - 22 for vermiculite manufacture and processing

  with the balance being used in highly-customized, one-off applications or for research.
- Ranging in size from 50mm to 6m.
- TORBED processors have a design life in excess of 25 years.
  - The oldest currently operational TORBED reactor was installed in 1989 and has been in continuous operation, subject to routine maintenance, since that time.
- In excess of 5,000,000 fleet operating hours

***No TORBED, properly used, has ever been the subject of mechanical or structural failure within its design life.***

- Correctly operated and maintained, based on the data available to Torftech, they have historically attained availability figures of 90-95% depending on the application and the detailed design of the individual TORBED processor.

## Proven Technology with Multiple Applications and Global Clients

*The TORBED technology has a rich industrial heritage with an extensive and successful track record across a range of challenging applications.*

### Food

Kellogg's, Kraft, Unilever, Kettle, Dalgety, Nestlé, Sanitarium, PepsiCo, Lorenz, DuPont, Arnott's, Cadbury, Limagrain, Martin Carwardine & Co, Daesang

### Sludges

Eliquo Stulz, meral, sappi, TNO innovation for life

### Catalysts

Sasol, Rhodia, Porocel, Shell, molecular

### Biomass/Power

Yanmar, ADB, Swedish Energy Agency, Cedrus Technologie, for Nature Solutions, Krex spółka z o.o., Angkor Bio Cogen, Biomasa Partner, AgriProtein

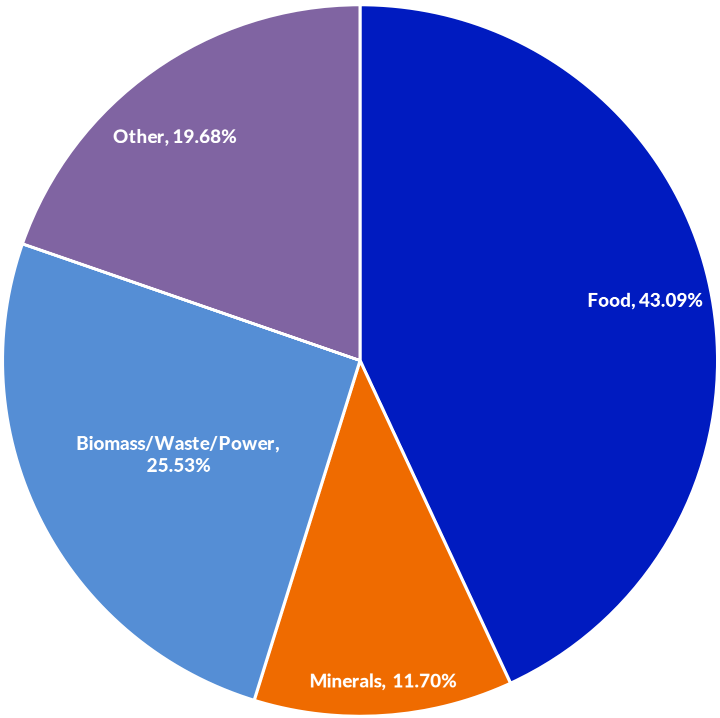
### Minerals

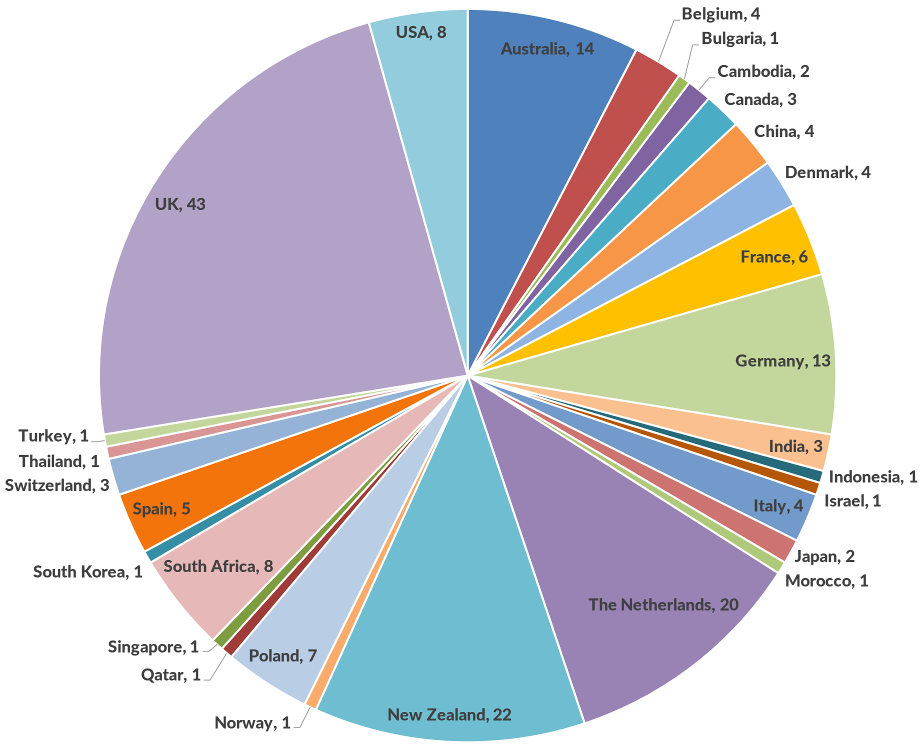
Saint-Gobain, Imerys, British Gypsum, Fisons, Sumitomo Corporation, Promat, Isola, Impextraco, Titanium Industries, Barrick, Mackeen holding

### Wastes

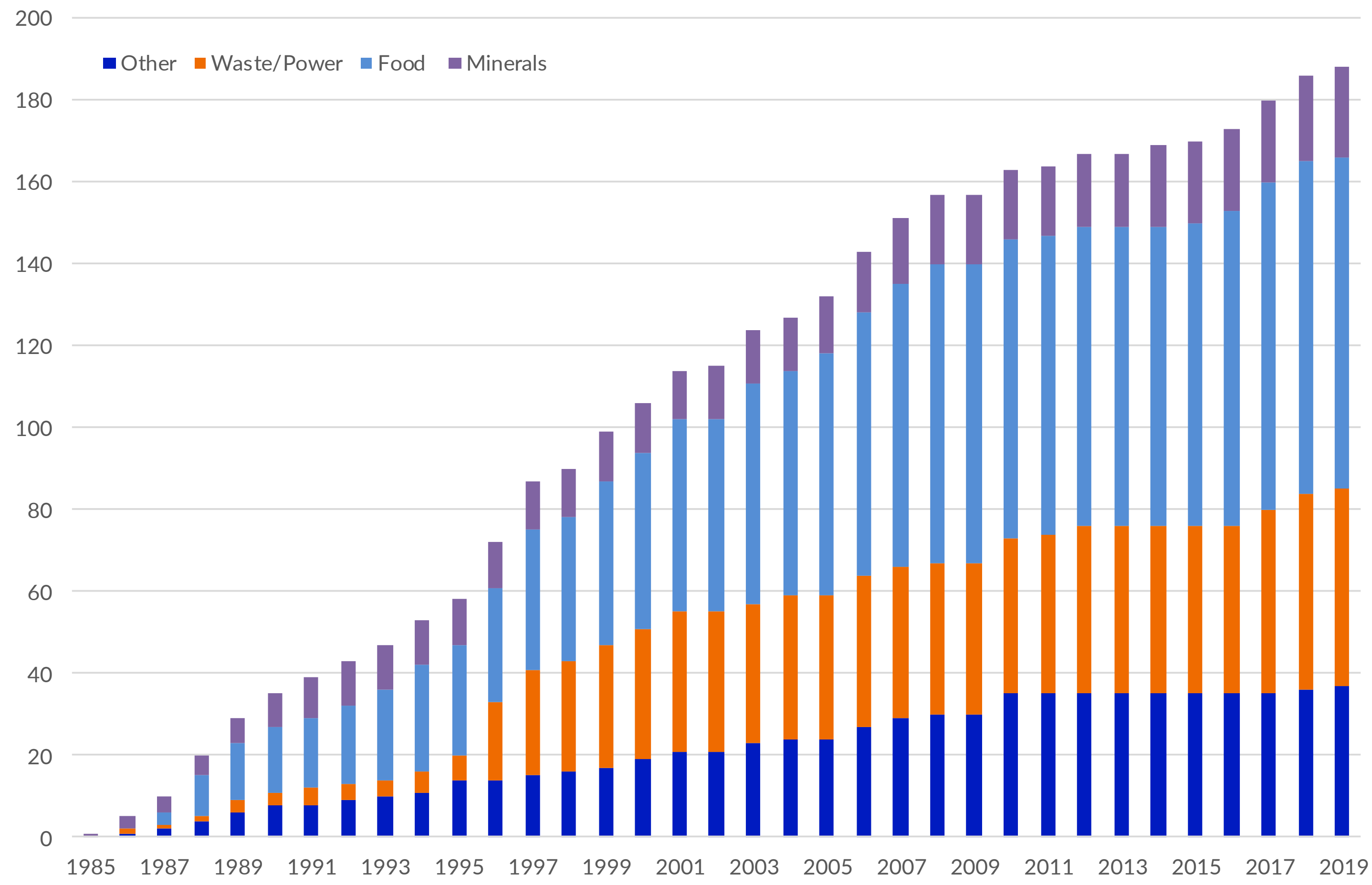
elf, ferminore, Marathon, Total, British Gas, bp, heijmans, Rio Tinto, Veolia, Cochin Shipyard Limited, Lafarge, Comalco

## Sales by Sector and Geography

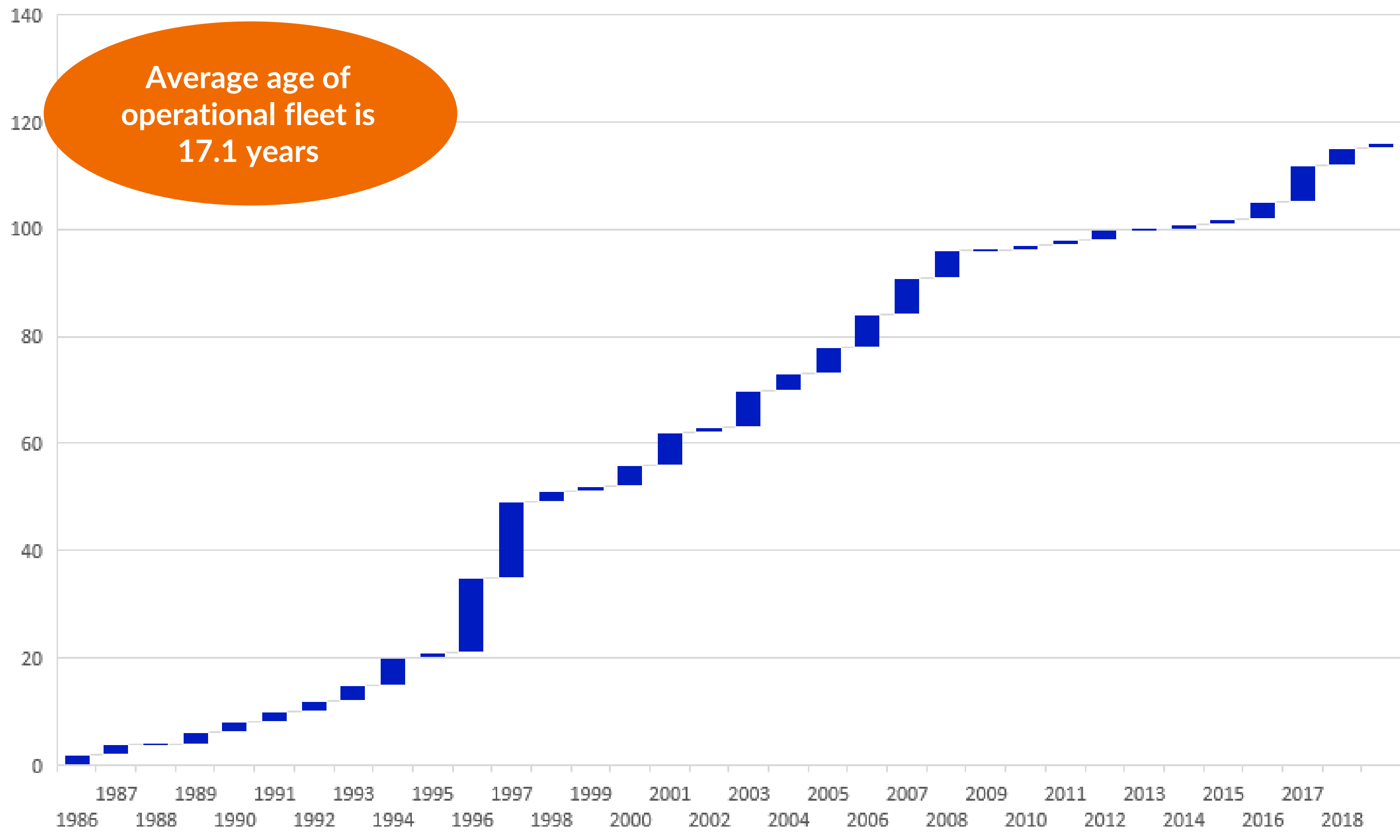


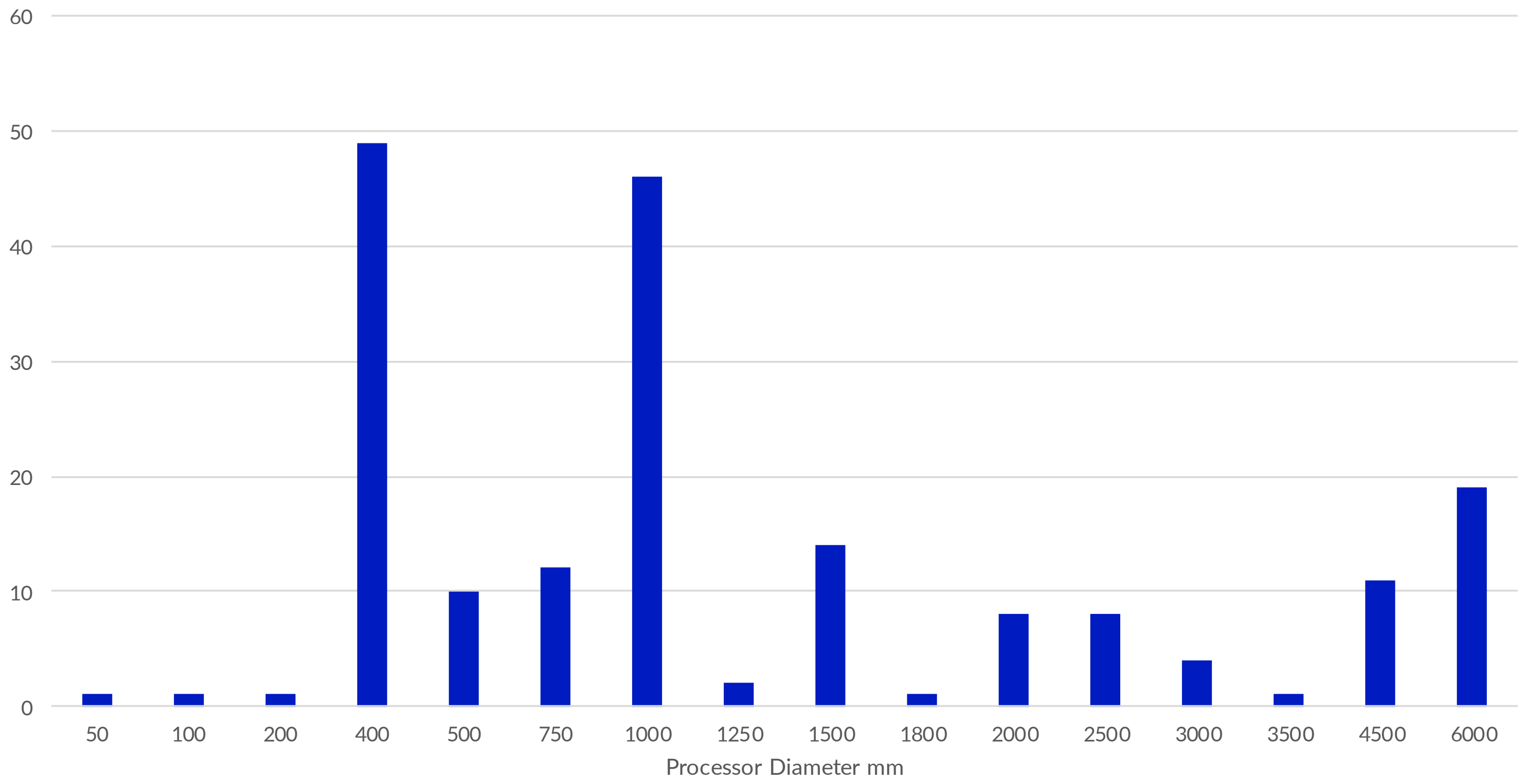
## Cumulative Sales by Sector



## Age of Operational Fleet



## Sales by Size of Processor



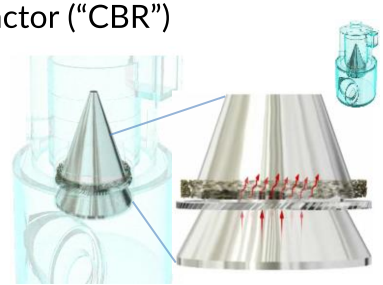
# Appendix II

# The Technology and Why it Works

# The Technology and Why it Works

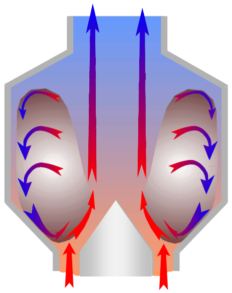
## Two Generic TORBED Reactor Types

- *Compact* Bed Reactor ("CBR")



At its heart, the technology is based on suspension of solids in a fast-moving gas stream. The gas stream, which is directed at an angle, lifts the solids into a shallow compact fluidized bed imparting horizontal motion and subjecting the base layer of the bed to high impact gas velocities and thus high heat and mass transfer rates.

- *Expanded* Bed Reactor ("EBR")



The EBR expands the bed from the CBR into the reactor chamber (as shown in the picture to the left), which increases the force with which gas and particles are mixed. This creates a faster rate of reaction and thereby allows faster processing in a comparatively restricted space.

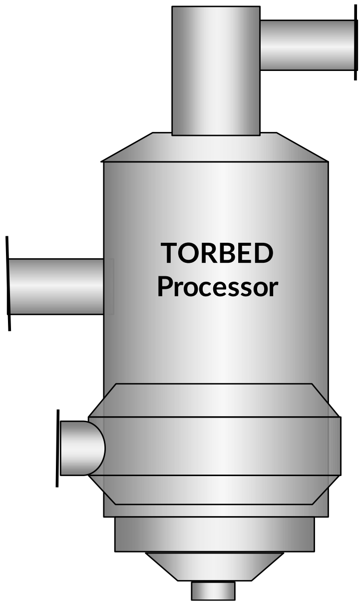

The key to understanding what the TORBED processors have to offer over and against other technologies is that they deliver very thorough processing of a steady stream of material in a very fast moving gas stream. This allows for:

- extremely close real time process control, more so than with competing technologies as there are no large masses of partially processed material;
- ability to process very fine materials;
- low system pressure drop;
- there is no grate or bed on which ash can slag;
- thorough processing and thereby high efficiency; and
- a comparatively small physical footprint and thereby lower capital costs.

In addition, a TORBED has no moving parts, which results in good availability and reduced maintenance costs.

# The Technology and Why it Works

## Key Features




High material processing rate

Low bed mass

Low thermal inertia

Very rapid shut down

Fast start up

Very accurate temperature control

Enhanced safety and operational flexibility

Allows for effective processing of challenging materials, eg:

high carbon conversion in gasification of high alkali metal feedstock; and

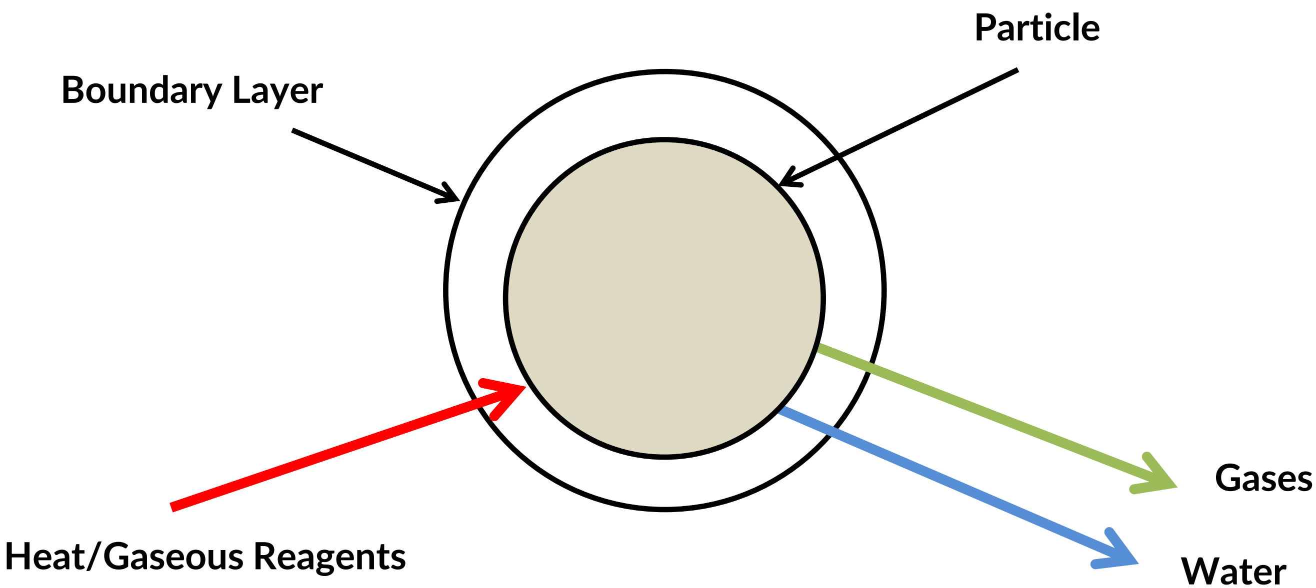
excellent carbon burnout of rice husk without crystalline ash formation.

# The Technology and Why it Works

## The Impact of High Gas Velocities

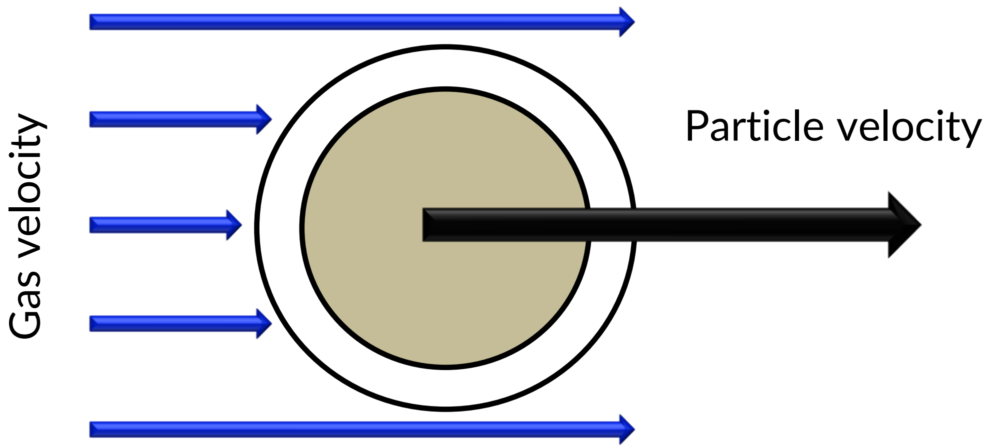
All particles of matter attract a boundary layer of air, which must be penetrated for a reaction to take place. The thicker the boundary layer, the more reaction is inhibited.

The high gas velocities in a TORBED processor strip away the boundary layer, facilitating rapid processing.



# The Technology and Why it Works

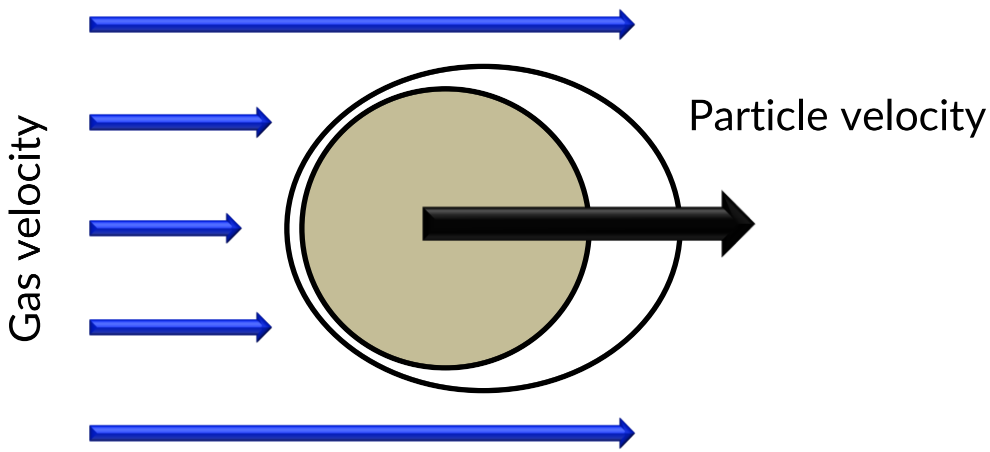
## Slip Velocity




Gas velocity ≈ Particle velocity

Slip Velocity ≈ 0

Stable boundary around particles lead to slow reaction rates.




**With a TORBED**

Gas velocity >> Particle velocity

Slip Velocity ≈ Gas velocity

Boundary layer stripped from particle leading to fast reaction rates

# Appendix III

# Technology Comparisons

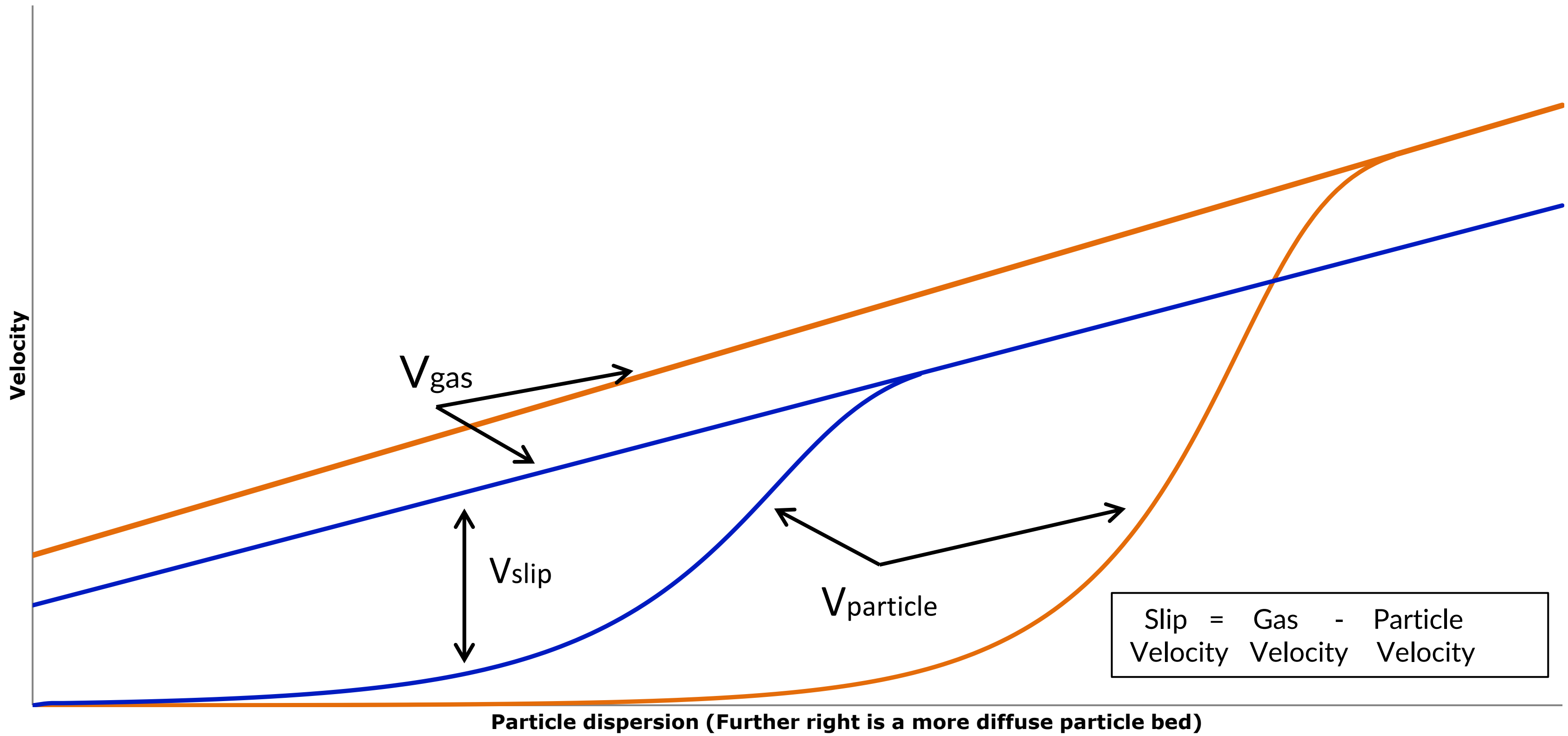
# Technology Comparisons

## Gasification

| Aspect | TORBED EBR | Circulating Fluid Bed (CFB) | Bubbling Fluid Bed | Down & Up Draft Systems |
|---|---|---|---|---|
| **Feed Particle Size** | Can accept wide range of particle sizes with many different shape factors, including fines | Can only accept narrowly sized particles with not much variability in shape factors | Can only accept very narrowly sized particles with very little variability in shape factors | Can handle large particles >10mm |
| **Solids Recirculation** | Solids are separated by centrifugal force directly within the processor and re-circulated internally with no requirement for a cyclone | Normally external to the reactor by cyclone with solids returned to the base of bed for recirculation | Not Done | Not Done |
| **Gas Recycling** | Cost effectively done due to low $\Delta P$ | Difficult due to high $\Delta P$ | Difficult due to high $\Delta P$ | Possible |
| **Pressure drop ($\Delta P$)** | Low (as low as 4" water gauge = 1 kPa). | High (up to 10kPa) | Medium | Low |
| **Gasification Efficiencies** | High (Improved with hot recycle gas and hot air used) | High | Reasonable | Reasonable |
| **Temperature Control Response** | Real-time / Excellent | 5 – 60 seconds | 1 – 2 minutes (Danger of hot-spots) | 5-10 minutes (Danger of hot-spots) |
| **Plant Foot Print** | Smallest | Small, but tall | Large | Large |

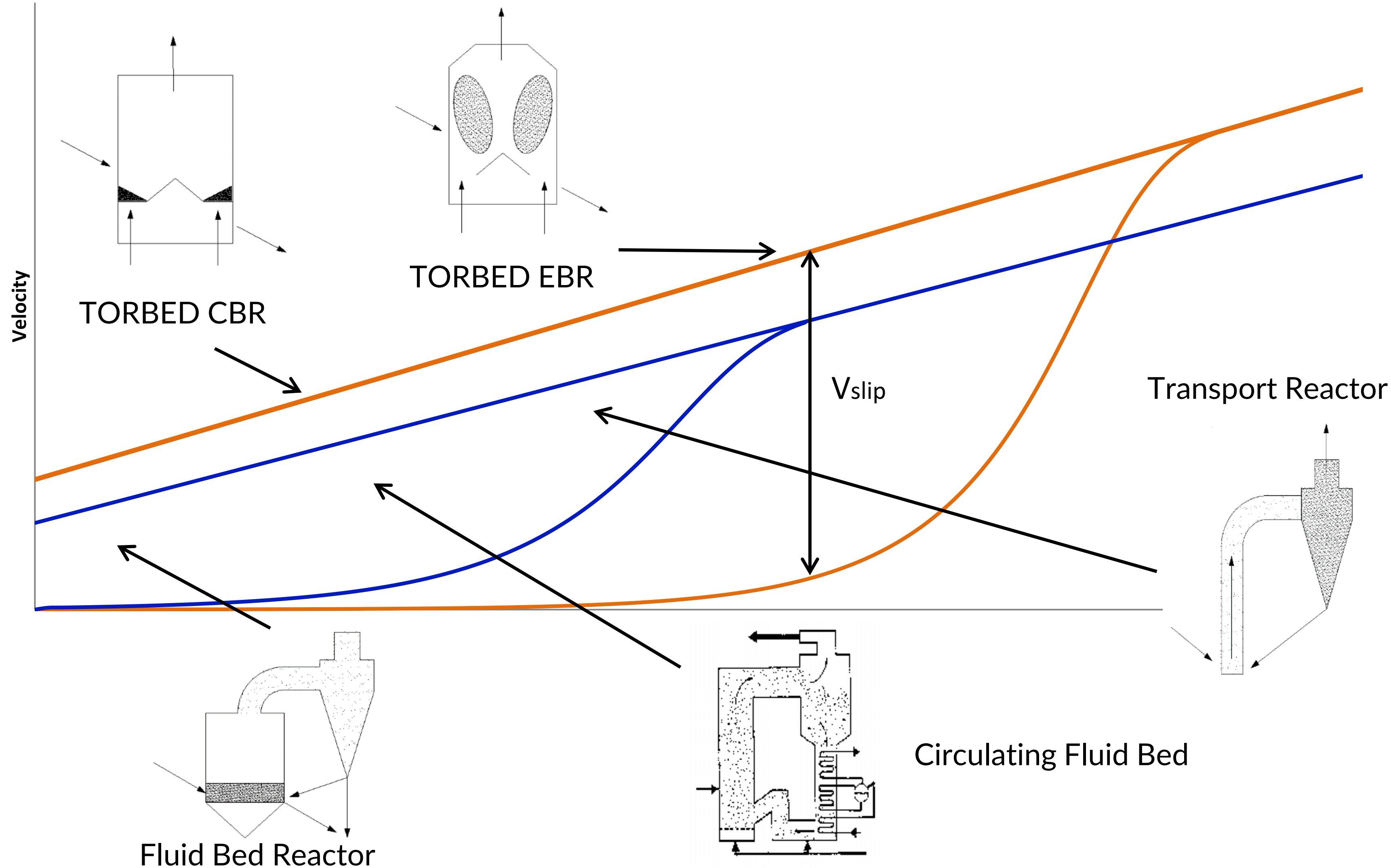
## Higher Slip Velocity

Blue lines indicate conventional technology with particle entrainment at lower speeds.
Orange lines indicate TORBED technology, where very high slip velocity is achieved.



# TECHNOLOGY COMPARISONS

## Processor Slip Velocity Comparisons



# TECHNOLOGY COMPARISONS

## TORBED Processor's Advantages

**In the context of local generation of electricity or heat from biomass or waste, either through gasification or combustion, the TORBED Processors have significant advantages over traditional grates and boilers**

| | | |
|---|---|---|
| Very Wide Multi-fuel Capability → | Reduced fuel risk exposure → | Enhanced energy security |
| Comparatively small scale → | Reduces land requirement → | Lower capex and increased flexibility |
| Can handle irregular and widely graded feedstock → | Less need for pre-processing → | Lower opex and possibly capex |
| High Heat transfer rates → | Smaller unit → | Lower capex |
| Simple to operate and automate → | Real time control → | Minimal energy wastage while avoiding slagging |
| Low pressure drop → | Easy process gas recirculation/ Reduced parasitic load → | Enhanced thermal efficiency |
| Very rapid start-up → | Flexible operation and reduced down time → | Increased revenues |
| No sand bed → | → | Reduced maintenance cost |
| No moving parts in processors → | → | Reduced maintenance cost |
| Potential high turndown ratio → | Operational flexibility → | Reduced operational costs |