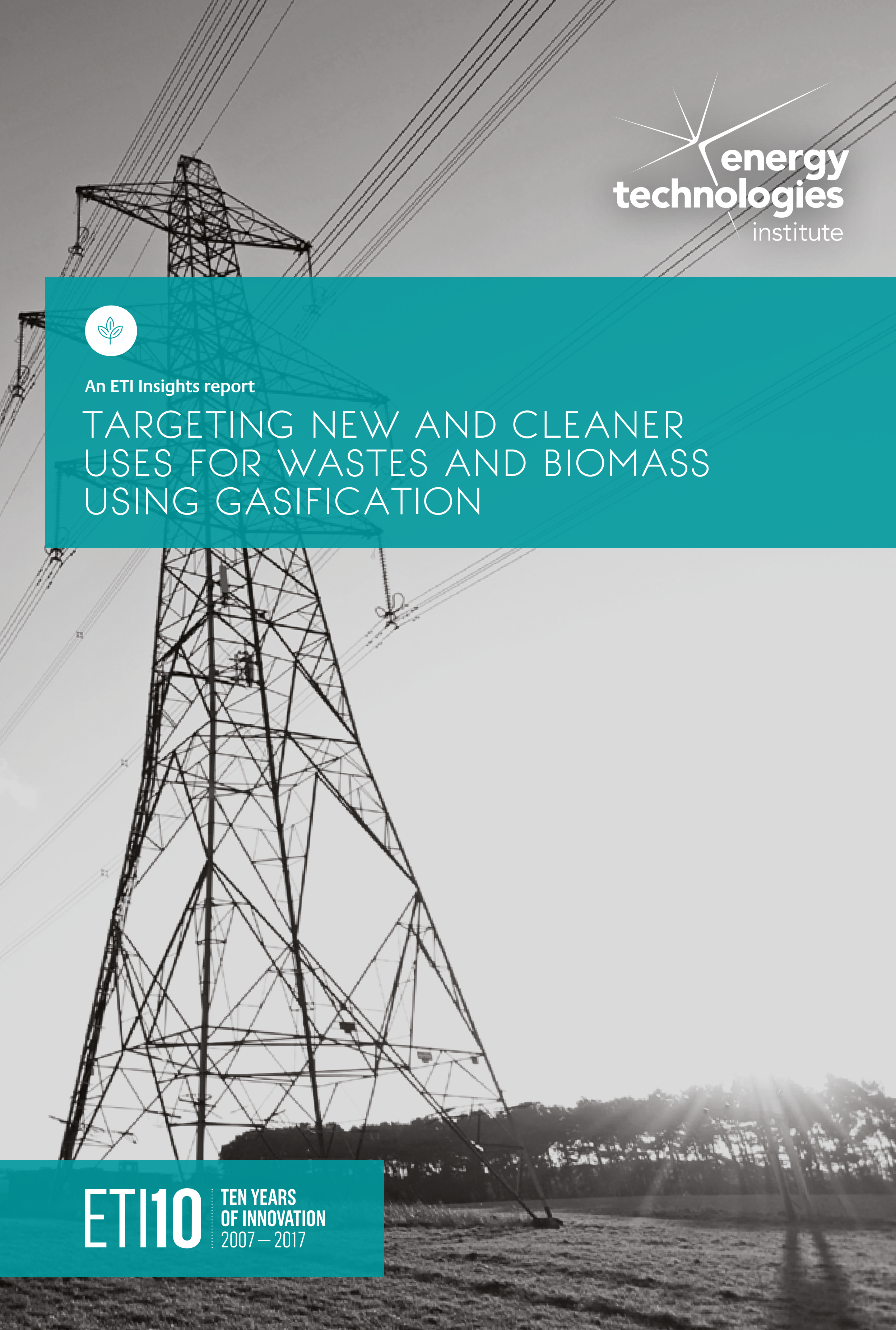
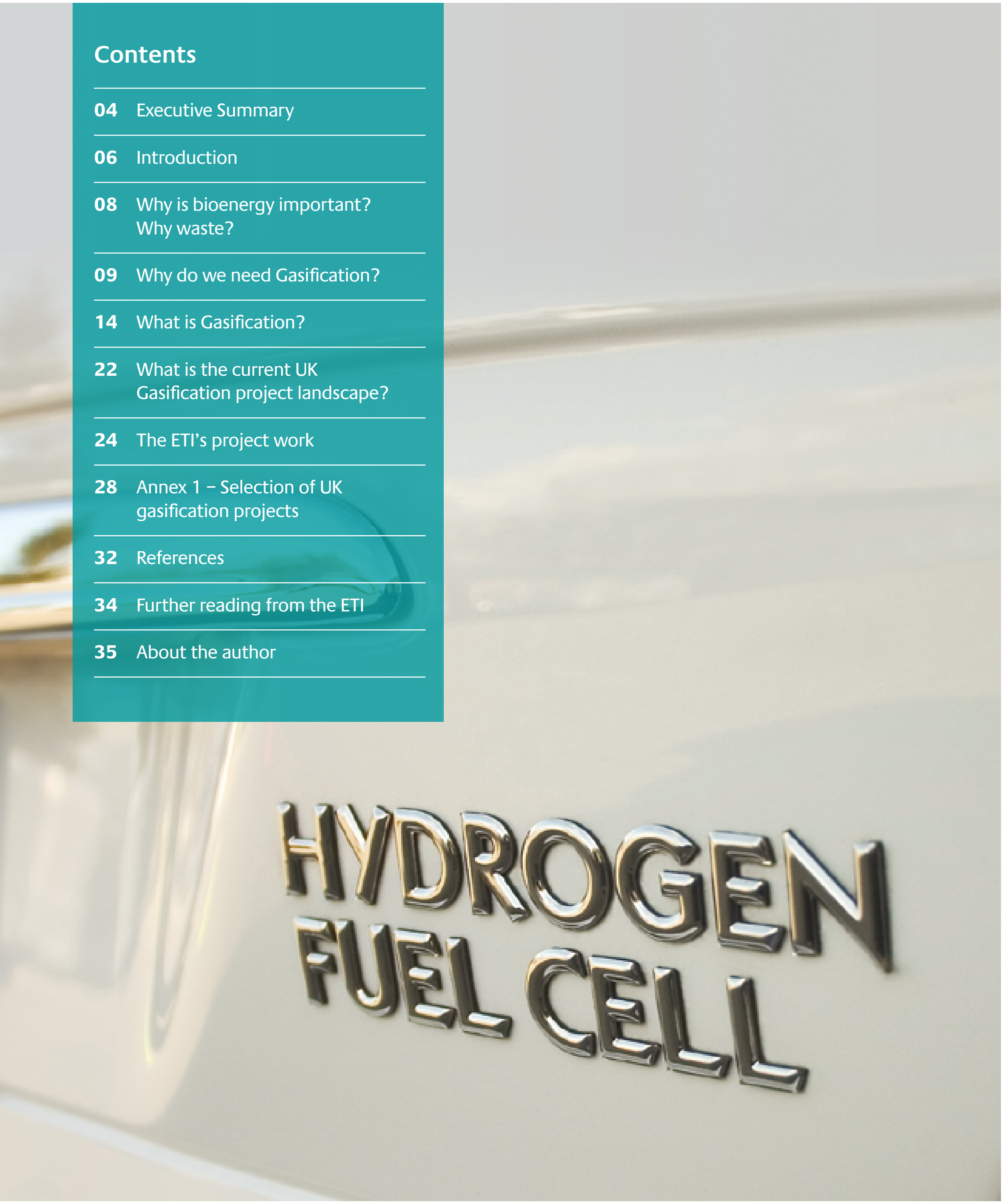


energy technologies institute

An ETI Insights report

TARGETING NEW AND CLEANER USES FOR WASTES AND BIOMASS USING GASIFICATION

ETI10 TEN YEARS OF INNOVATION 2007 — 2017



Contents

ETI estimates Bioenergy can reduce the cost of meeting UK 2050 carbon targets by

more than

1% of GDP

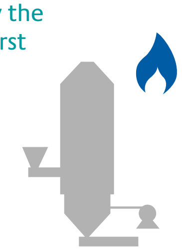
Gasification is a key technology for delivering low carbon energy. It can accept a wide variety of feedstocks -

to yield a wide variety of useful outputs

electricity heat fuels chemicals materials

TARGETING NEW & CLEANER USES FOR WASTES & BIOMASS USING GASIFICATION

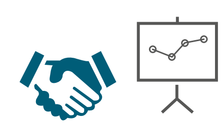
For gasification to operate efficiently and effectively, the gas made by the gasifier should first be cleaned



The cleaned syngas from a gasifier can be used to produce power efficiently, particularly for operation at small scales, for example in towns

The benefits of using gasification in towns (5-20 MWe) come from its ability to operate efficiently at small scales with the waste heat generated being readily available for use in district heating networks to provide heat and power

Gasification projects with integrated syngas clean-up have the potential to be competitive with other sources of renewable power – but support will be required to enable their early deployment

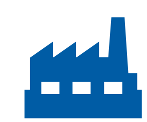


ETI is investing

£5m

in a

1.5MWe



gasification project incorporating syngas cleaning and tar removal in the West Midlands to build confidence in the technology

EXECUTIVE SUMMARY

Gasification with integrated syngas clean-up to remove undesirable components can be used to produce an "ultra-clean" syngas[1] suitable for use in demanding and efficient applications including reciprocating engines, gas turbines, chemical synthesis processes (for example, to produce hydrogen, fuels or chemicals) and/or biological synthesis processes. It offers a number of benefits including:

- flexible in feedstock and outputs (heat, power, liquid and gaseous fuels, and chemicals)
- high efficiencies
- scalable to suit applications in typical UK towns and small cities, in particular at the sub 10 MWe scale
- ability to be combined with CCS to create "negative emissions" which ETI anticipates will be needed to deliver a cost-effective 2050 low carbon energy system

Currently, however, the technology and commercial risks are too high for typical investors and developers. To accelerate the technology to the point where these risks are more acceptable, the ETI has recently announced that it is investing in the construction of a 1.5 MWe waste gasification demonstration project incorporating an engine fuelled by "ultra-clean", tar-free syngas. This paper seeks to present why the ETI thinks this technology is important and how its research has mitigated many of the risks associated in driving this sector forward.

1 The term "Syngas" is a shortening of "Synthesis Gas". Syngas is a combustible gas mixture consisting primarily of carbon monoxide, carbon dioxide, hydrogen and methane, as well as other potential components including nitrogen if air has been used as the oxidant in the gasification step.

Why is bioenergy important?

Bioenergy is a hugely valuable source of low carbon renewable energy because it can be stored and used flexibly to produce heat, power, liquid and gaseous fuels as well as chemicals and materials such as plastics. Combined with carbon capture and storage (CCS), it has the potential to deliver "negative emissions" which ETI anticipates are needed to deliver a lowest cost 2050 low carbon energy system.

Why waste?

As a small, densely populated country, waste is a key UK biomass resource. The gate fees paid for taking waste provide an additional and supportive income stream for gasification projects.

We can already use combustion to get energy from waste – why do we need gasification?

Of the variety of existing and new alternatives for producing energy from biomass and wastes, gasification offers a number of advantages for the UK including:

- Accepts varying feedstock qualities – this is especially important for wastes
- Produces power more efficiently, particularly at the town scale
- By operating at smaller scales, waste miles can be reduced and integration with local heat networks can be facilitated
- Resilient to future uncertainties – it can produce a wide variety of outputs, not just electricity
- Many of these end products from gasification are compatible with existing infrastructures
- It is one of the most efficient ways to generate future "negative emissions" from biomass with CCS

The deployment of gasification now is important to improve resource efficiencies and greenhouse gas savings across the power, heat, transport and industrial (including agricultural) sectors. Using wastes, which bring a supportive gate fee income, is a gateway to delivering these improvements. Deploying waste gasification now will also support the future deployment of larger scale biomass gasification plants integrated with CCS to deliver "negative emissions".

What is gasification and why is ultra-clean, tar-free syngas important?

Gasification converts the energy held within a difficult to use solid fuel into an easier to use gas. To use the gasifier product gas most efficiently and effectively to deliver the advantages described above, this gas, known as "synthesis gas" or "syngas" for short, must firstly be cleaned.

What is the current UK gasification project landscape?

Gasification as a technology sector is emerging – waste is currently the preferred feedstock while power is currently the preferred output. These developments will facilitate the future uptake of gasification to produce a broader range of outputs, to use the wider biomass resource pool, and ultimately to combine with CCS.

The ETI's project work

The ETI has taken a stage-wise approach to accelerating the development of gasification for the production of "ultra-clean", tar-free syngas. It is now working with Syntech Bioenergy to build and operate a 1.5 MWe gasification project, incorporating syngas tar removal and cleaning, in the West Midlands. This will be operational from 2018 onwards.

INTRODUCTION

The ETI's analysis of the UK energy system and bioenergy sector in particular, indicates that gasification is a key technology in delivering a low carbon energy system under many different future energy scenarios. This resilience to different future energy scenarios is due to its:

Feedstock flexibility

In being able to process a variety of feedstocks including biomass and wastes, gasification provides both a strong fit against the biomass resource pool available to the UK and an ability to advantageously respond to feedstock changes.

Output flexibility

Syngas is a well-known and already widely used intermediate that can be used to deliver heat, power, fuels, chemicals, materials and combinations of these. To realise these benefits from syngas derived from biomass and wastes, the syngas must firstly be cleaned.

Comparable/better efficiencies

Compared with other technologies, especially at smaller scales, cleaned syngas permits the use of higher efficiency generating processes such as engines. There is innovation headroom to increase efficiencies further.

Scalability

Gasification can be efficiently and effectively deployed across all scales including, and especially, at the smaller town scale (5-20 MWe[2]) or equivalent. By operating at smaller scales, waste miles and site footprint can be reduced and integration with local heat networks can be facilitated.

Potential for integration with Carbon Capture and Storage (CCS)

Pre-combustion capture[3] is an efficient method for carbon capture. Gasification plants incorporating integrated syngas cleaning can in future be linked into carbon capture infrastructure systems [1].

Further, the ETI has identified additional insights through its ongoing analysis and work in waste gasification with its project partners.

Scale-up

A careful and considered approach to scale-up is needed – aggressive scale-up factors should be viewed with caution. The extra financing required for larger scale gasification plants with syngas cleaning has been shown to be difficult to acquire and/or difficult to service at the current innovation level. Additionally, technical issues arising at larger scales not identified or fully addressed through smaller scale work and/or modelling may become significant, will be harder to resolve and will likely need to be resolved within tighter timescales given the larger quantum of financing to service.

Cost competitiveness

Techno-economic analysis indicates that gasification projects with integrated syngas clean-up have the potential to be competitive with other sources of renewable power. As for other forms of renewable power, in the near term and in the absence of a carbon price, support mechanisms are needed to assist early deployment.

Financial returns of gasification projects with gas cleaning steps

These are potentially competitive with other sources of renewable power. However, internal rates of return (IRR), while positive, are currently typically below the rates that would normally be required by investors. There is scope to reduce, in particular, procurement costs and so improve IRRs as experience is gained.

2 MWe is a MW of electricity

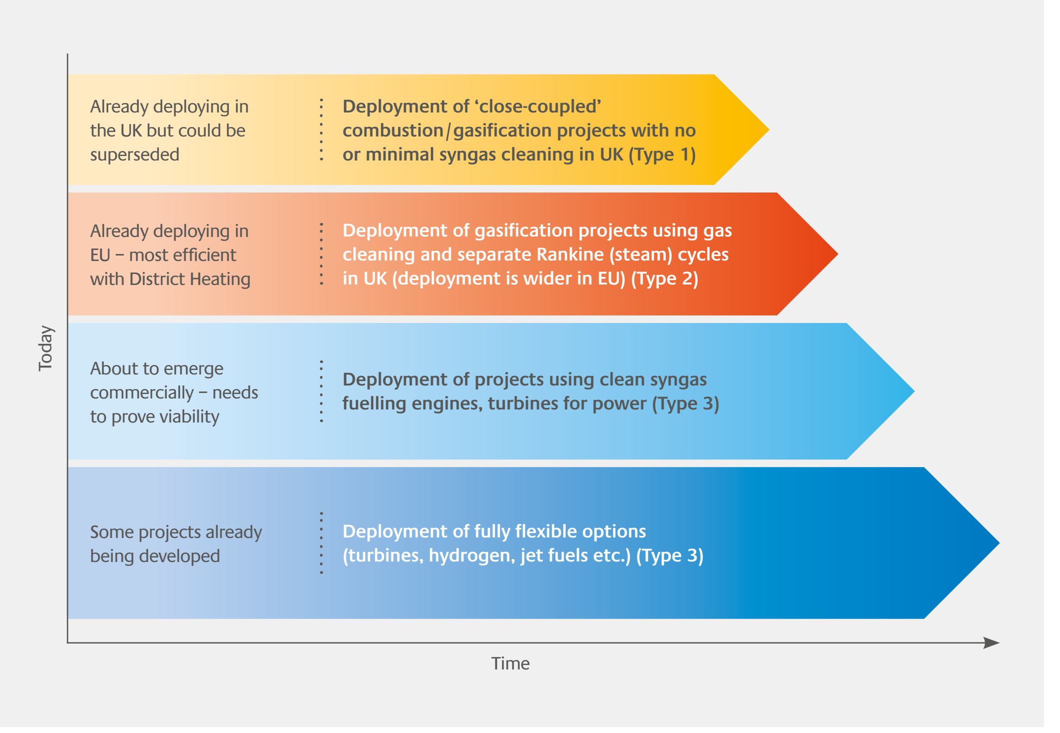
3 A pre-combustion system involves first converting solid, liquid or gaseous fuel into a mixture of hydrogen and carbon dioxide before separating these so that the hydrogen can be used as a fuel and the carbon dioxide stored

A programme approach, or Innovation Runway

To build confidence in financing and delivering successful gasification projects, UK gasification policies should be designed as an integrated programme of stages (i.e. an Innovation Runway) targeting the deployment of gasification projects which incorporate integrated gas cleaning steps which can provide the high efficiencies and flexibilities offered by gasification. These policies should drive a strong pace of innovation balanced with building confidence.

As shown in Figure 1, commercial gasification experience is already being gained by using syngas to raise steam for power and heat [2]. This experience can be leveraged to deliver gasification with integrated gas cleaning in which clean syngas is used directly in engines and gas turbines and subsequently to produce alternative products such as hydrogen. Such an approach will enable the UK "gasification community" to deliver confidence to financiers and policy makers. However, although the technology can provide positive rates of return, there remain some barriers to its adoption. Very few reliable commercial gasification demonstration plants incorporating integral syngas cleaning stages have been built so technical risks still remain, particularly with regard to effective and reliable gas cleaning, technology integration and operability, and in achieving a high degree of plant availability.

Figure 1
Gasification status and programme approach to gasification progress



WHY IS BIOENERGY IMPORTANT? WHY WASTE?

Why is bioenergy important?

Bioenergy is a hugely valuable source of low carbon renewable energy because it can be stored and used flexibly to produce heat, power, liquid and gaseous fuels as well as chemicals and materials such as plastics. Combined with carbon capture and storage (CCS), it has the potential to deliver "negative emissions" which ETI anticipates are needed to deliver a lowest cost 2050 low carbon energy system.

The ETI's internationally peer-reviewed Energy System Modelling Environment (ESME), a national energy system design and planning model, suggests that bioenergy, in combination with Carbon Capture and Storage (CCS), could provide around 10%[4] of projected UK energy demand whilst also delivering net "negative emissions" of approximately -55 million tonnes of CO_2 per year in the 2050s. This is roughly equivalent to half the UK's annual emissions target in 2050 of 105 million tonnes of CO_2 per year and reduces the need for other, more expensive, decarbonisation measures. Even in the absence of CCS, bioenergy alone is still a cost-effective means of decarbonisation and should play an important role in meeting the country's 2050 emissions target.

ETI's analysis shows that bioenergy and CCS are two of the most important options available for decarbonising the UK's energy system. Bioenergy is estimated to reduce the cost of meeting the UK's 2050 carbon targets by more than 1% of Gross Domestic Product (GDP); without it, it is anticipated that it will be difficult to deliver an affordable low carbon energy system.

Why waste?

As a small, densely populated country, waste is a key UK biomass resource. The gate fees paid for taking waste provide an additional and supportive income stream for gasification projects.

There are a variety of non-food related biomasses available to use in the UK for energy, both imported and indigenously produced. These include:

- Forestry products, much of which are currently imported
- Energy crops, which can include:
  - Short Rotation Forestry
  - Short Rotation Coppice e.g. Willow and Poplar
  - Miscanthus
- Agricultural residues of which wheat straw is perhaps of most near-term interest
- Wastes derived from Municipal Solid Wastes, Commercial and Industrial wastes, and waste wood

4 This equates to about 130 TWh of energy per year from biomass sources and is similar to the biomass resource estimates reported by the CCC [41].

WHY DO WE NEED GASIFICATION?

Excluding imported biomass resources, it is unlikely that there will be sufficient volumes of any one kind of UK produced biomass to support the large scale roll-out of bioenergy envisaged, whether that roll-out consists of many smaller facilities or fewer larger facilities. Of these UK biomass resources, and particularly in the nearer term, the largest arisings are waste derived. Waste as a resource is a key UK feature – as a small, densely populated country, large tonnages of wastes arise from densely populated and closely located areas. 54.5 million tonnes of waste from households, commercial and industrial sources were produced in the UK in 2014 [3]. The greater proportion of these wastes arise in England and around 23% is landfilled [3]. ETI analysis agrees with the Green Investment Bank's assessment that around 8 million tonnes/year of suitable additional waste arisings will be available for energy recovery in the near term [4]. Legislation seeks to incentivise its diversion away from landfill through the landfill tax and via landfill diversion targets.

Waste is attractive as a fuel as it brings an additional and helpful income stream to a plant in the form of gate fees. However, the use of wastes is technically challenging. Waste quality varies temporally, both by the season and by year; and geographically. These attributes, along with the possible need to consider processing blended biomass feedstocks in future, are a driver for UK bioenergy technology solutions to be feedstock flexible.

We can already use combustion to get energy from waste – why do we need gasification?

Of the variety of existing and new alternatives for producing energy from biomass and wastes, gasification offers a number of advantages for the UK including:

- Accepts varying feedstock qualities – this is especially important for wastes
- Produces power more efficiently, particularly at the town scale
- By operating at smaller scales, waste miles can be reduced and integration with local heat networks can be facilitated
- Resilient to future uncertainties – it can produce a wide variety of outputs, not just electricity
- Many of these end products from gasification are compatible with existing infrastructures
- It is one of the most efficient ways to generate future "negative emissions" from biomass with CCS

The deployment of gasification now is important to improve resource efficiencies and greenhouse gas savings across the power, heat, transport and industrial sectors. Using wastes, which bring a supportive gate fee income, is a gateway to delivering these improvements. Deploying waste gasification now will also support the future deployment of larger scale biomass gasification plants integrated with CCS to deliver "negative emissions".

WHY DO WE NEED GASIFICATION?
Continued ›

While energy from waste technologies based on combustion already exist and are in commercial use, they are typically large, being greater than about 15 MWe, requiring greater than about 200,000 tonnes/year of wastes and often low efficiency [5]. This makes them regional in scale, often requiring waste to be drawn from more than two counties. This:

- increases waste miles, and hence associated logistical emissions and local disruption
- means, because of scale of operation, that the plants have a high local impact
- makes using heat a challenge, and
- makes waste contracting more challenging, albeit it is well practised

As a comparator, biomass (excluding wastes) combustion processes range from the small domestic kW heater scales up to the GW scale power stations (e.g. Drax power station near Selby).

Combustion technology improvements have resulted in improved biomass and waste combustion process efficiencies at the larger scale (nominally above 10-20 MWe). Below about 10-20 MWe, which approximates to the town scale, steam turbine efficiency losses become more significant resulting in reduced overall plant efficiencies. System efficiencies can drop from the more optimal 25-30% at larger scales down to around 20% and below [6]. Overall efficiencies to power are limited by combustion characteristics, steam system metallurgies, rates of fouling, rates of corrosion etc. Higher steam temperatures – and aspirations are to get to 1,000°C – yield higher system efficiencies but require more and more exotic materials. However, metallurgical improvement opportunities are now tending to a limit. Current energy from waste plant efficiencies are of the order of 14-27% on a site basis [7] with potential improvement opportunities up to around 29-35% possible if steam temperatures can be raised and combustion conditions improved [8] [9]. Much higher overall efficiencies are available if heat is produced and used as well as power. However, it must be noted, and depending on the type of steam turbine used, that as the heat supply rate rises, power production falls. Additionally, using the heat available from large waste to energy facilities in the UK, often located away from users, can be difficult.

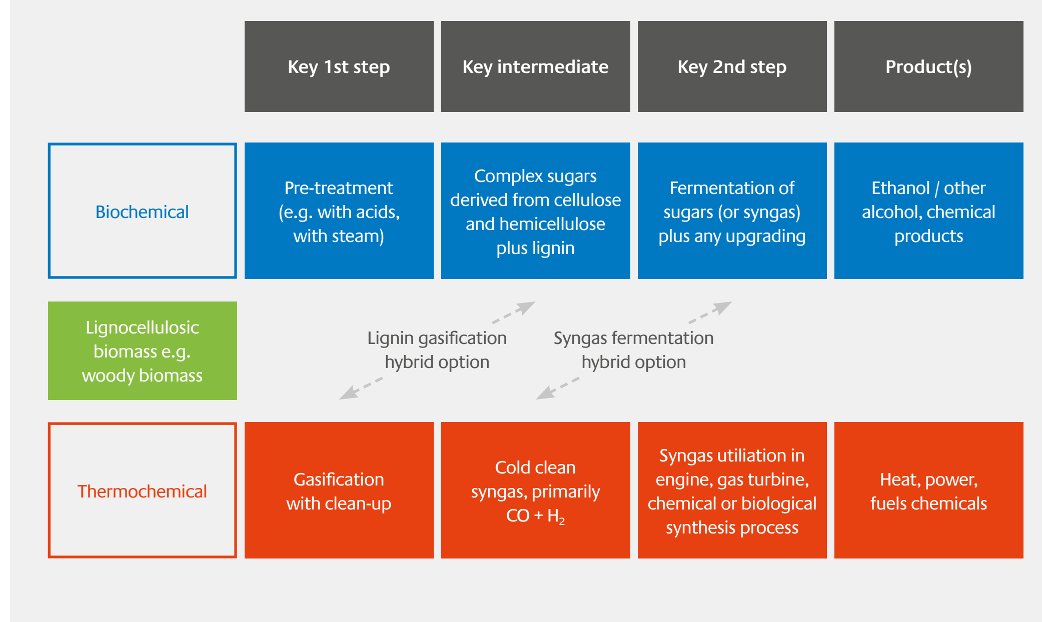
There is, therefore, a potential opportunity to develop high efficiency waste fuelled power plants, particularly at the smaller, town scale. Additionally, there are also opportunities to develop processes that produce a wider variety of end energy vectors from biomass and wastes such as bio synthetic natural gas (bioSNG), hydrogen and jet fuel. There are also longer term opportunities to integrate both power and alternative end vector routes with Carbon Capture and Storage (CCS) infrastructures.

Previous ETI research has sought to assess the scale of the waste to energy opportunity. By taking a top down approach, this work identified potential for around 50-100 town scale plants in the UK at the 50,000 to 200,000 tonnes/year range (approximating to 5-20 MWe), each directly employing around 25-40 people. At these smaller scales, waste miles can be reduced, local impact is minimised, options for heat utilisation can be opened up and opportunities for alternative applications explored such as private wire[5] supply.

There are two key pathways plus a hybrid of these to take advantage of this opportunity to convert lignocellulosic[6] biomass and wastes into heat, power, fuels and/or chemicals (Figure 2):

- "Second generation[7]" biochemical – these processes include a biological transformation step. Typically, a high intensity process is firstly used to convert the complex sugars present in biomass cell walls into more easily fermentable sugars. Once released, these sugars can be biologically upgraded to produce fuels and chemicals, for example ethanol. These processes will typically reject lignin which can be used to provide process energy or else for other purposes (e.g. as a source of natural aromatics).
- Thermochemical – high temperatures, sometimes combined with elevated pressures, and chemical transformations are used to yield an energy carrying gas or liquid, e.g. combustion products, syngas, pyrolysis oil. When this energy carrying gas or liquid consists primarily of chemical energy, then it can be burnt directly in a boiler or engine, or upgraded, for example to hydrogen or jet fuel (Figure 3).
- Hybrid – high temperature processing (e.g. gasification of biomass) combined with biological first (e.g. fractionation of biomass to yield lignin for subsequent gasification plus sugars) or second step (e.g. fermentation of syngas).

Figure 2
Two key pathways with examples for converting lignocellulosic biomass



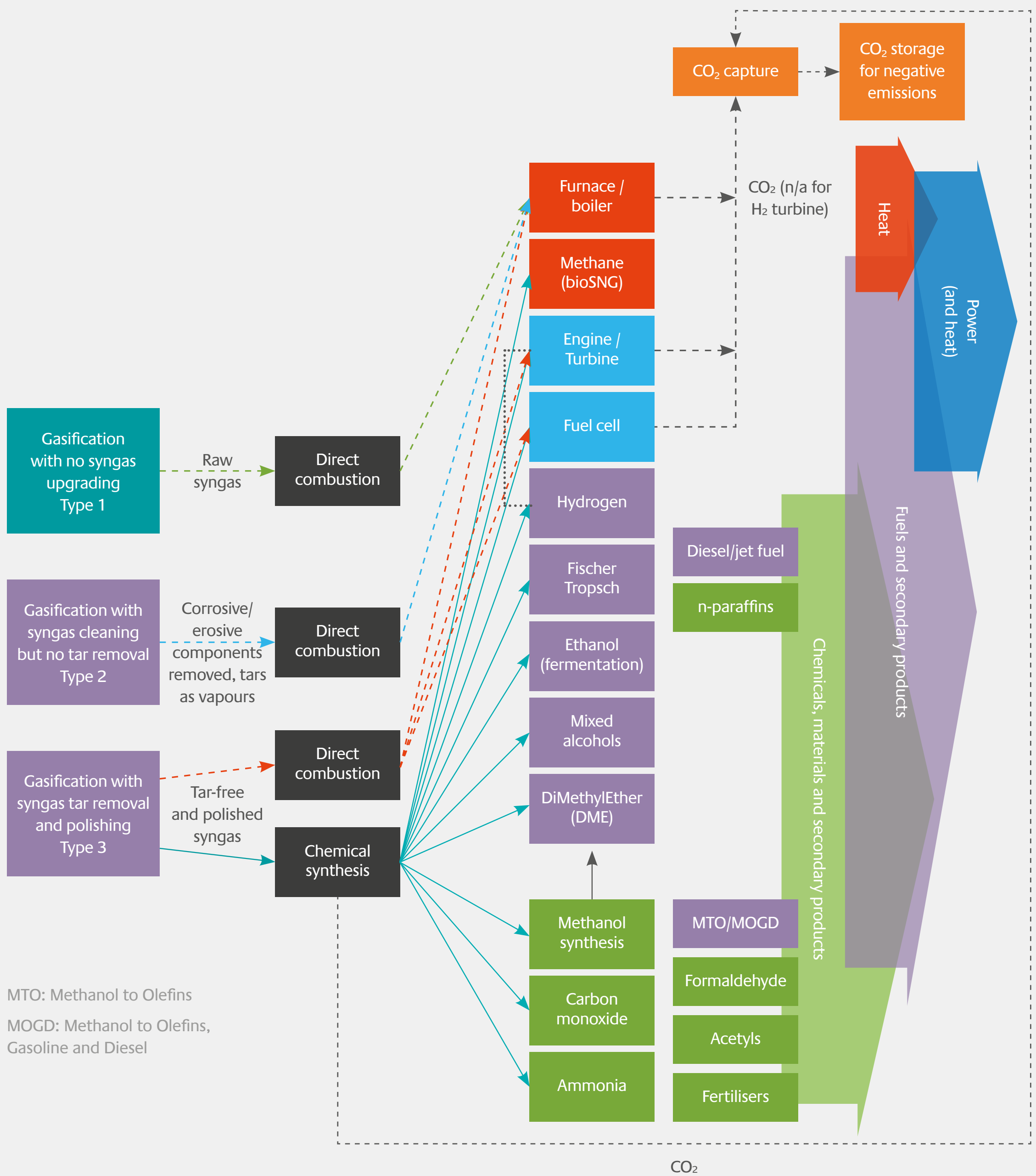
5 Private wire systems are localised electricity grids, that although connected to the local distribution networks have privately owned central plant that produces electricity. This enables it to operate a stand-alone supply in the event of the national grid failing.

6 Lignocellulosic biomass (often shortened to LC biomass) refers to plant biomass that is composed of cellulose interwoven with hemicellulose and lignin. Examples include woody biomass such as from forestry, Miscanthus and the biomass part of waste materials. The lignocellulose structures have evolved to give plants and trees mechanical strength and protect them from pests and diseases – this makes the chemical utilisation of biomass challenging.

7 Where "first generation" refers to the use of food-based crops to produce, for example, bioethanol.

WHY DO WE NEED GASIFICATION?
Continued ›

Figure 3
Variety of outputs available from syngas (courtesy NNFCC*)



* See www.nnfcc.co.uk

Of these two pathways, the thermochemical pathway, and in particular gasification combined with syngas cleaning to yield an ultra-clean, tar-free, syngas, offers some key advantages with respect to deployment in the UK:

- Thermochemical technologies are more accepting of changing feedstock qualities – this enables the more effective use of wastes and the variety of biomass types that might be available from across the UK.
- Once the output syngas has been cleaned, it can be used to provide a variety of end vectors, many of which are not available via combustion i.e. heat, power, fuels and/or chemicals, as shown in Figure 3. Many of the output options are identical to (or highly compatible with) existing fossil derived products, for example aviation jet fuel.
- For power production, and particularly at the smaller town scale, higher efficiencies to electricity can be delivered by using "ultra-clean", tar-free syngas fuelled engines and gas turbines compared to conventional combustion processes using steam turbines. At larger scales, efficiency differences can become less marked.
- The UK can build on its strong and broad experience of combustion engineering and the types of technologies used in gasification, for example fluidised bed reactors.
- The UK can build on its experience of syngas production and utilisation, for example BP's Saltend site near Hull and the Teesside chemicals complex (ex ICI site).
- In future, gasification can potentially be integrated with Carbon Capture and Storage (CCS) to create "negative emissions" which ETI anticipates will be needed to deliver a cost-effective 2050 low carbon energy system.

There is interest both in the UK and abroad in the biochemical route to process non-food biomasses including waste feedstocks. However, to date, biochemical processes have been best suited to single source feedstocks and so will not cope as well with changing feedstock qualities. Additionally, biochemical processes are primarily focused on producing biofuels and/or biochemicals and are less able to provide the end use energy flexibility offered by thermal processes.

There is also interest in the use of pyrolysis for liquefaction to produce primarily a high density liquid oil from biomass. Pyrolysis oil potentially offers some attractive opportunities including feeding the oil into an existing oil refinery, liquefying biomass to facilitate logistics and to provide peak load power via engines and gas turbines. However, pyrolysis oil properties are very different to existing fossil fuels and developers have struggled to deliver a commercially usable and competitive product oil although some are developing pyrolysis projects to deliver heat and/or power plus recovery of value added products. Although development work is ongoing, liquefaction by pyrolysis with the primary aim of producing a liquid fuel product is a longer term opportunity compared to gasification, is narrower in application and is not as good a fit with CCS which is of particular interest to the ETI.

WHAT IS GASIFICATION?

What is gasification and why is ultra-clean, tar-free syngas important?

Gasification converts the energy held within a difficult to use solid fuel into an easier to use gas. To use the gasifier product gas most efficiently and effectively to deliver the advantages described above, this gas, known as "synthesis gas" or "syngas" for short, must firstly be cleaned.

Although gasification, as a process, is closely related to both pyrolysis and combustion, there are some key differences:

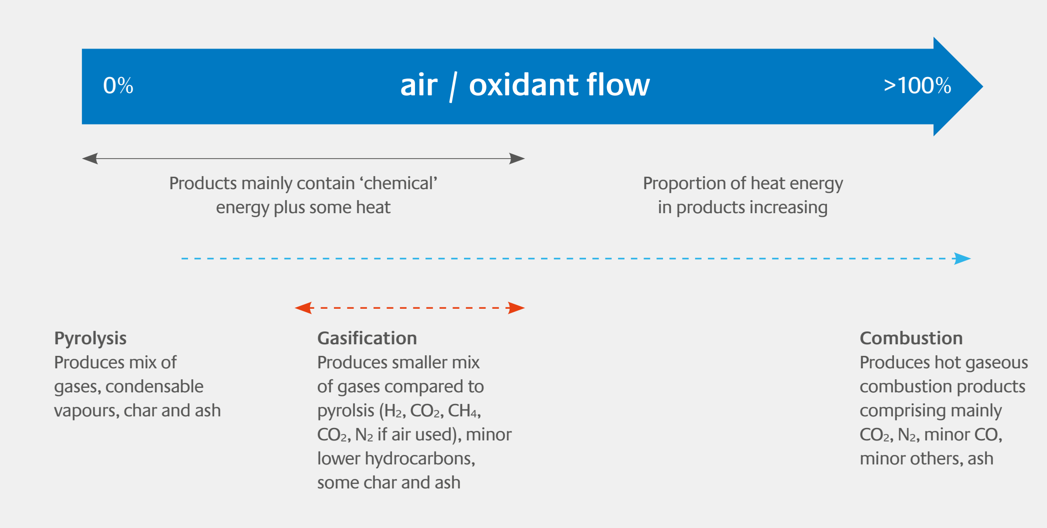
- Combustion converts the chemical energy held within the input fuel into heat energy only. As much as possible of the chemical energy contained within the input fuel should be retained as heat in the form of gaseous hot combustion products to maximise efficiency. This heat energy can then be used to deliver power (through heating water to make steam for use in a steam turbine) and/or heat. As the chemical energy available in the fuel was converted to heat only, combustion cannot be used to produce, for example, a fuel or a chemical feedstock.
- Gasification, including "gasification by pyrolysis", converts chemical energy held within the input fuel into chemical energy held in a more useful, gaseous form (i.e. syngas)[8]. As much as possible of the chemical energy that was contained within the input fuel should be retained in the gaseous form to maximise efficiency. Compared to combustion, gasification provides additional functionality. As well as being able to use the gaseous energy carrier to provide power (for example, in a gas turbine) and/or heat, it can also be used to provide hydrogen, fuels and/or chemicals (Figure 3). However, to realise these benefits, the syngas must firstly be cleaned and conditioned to meet the requirements of the syngas conversion process, be that an engine, a gas turbine or a chemical synthesis process.

Gasification can take place either by thermal degradation of a solid fuel in the absence of air or oxygen leaving behind a char (gasification by pyrolysis) or, more usually, by the partial combustion of a solid fuel to yield a product gas containing usually carbon monoxide, hydrogen, carbon dioxide, methane, other lower hydrocarbons and, if air is used as the oxidant, nitrogen (Figure 4). The proportions of these constituents will depend on the gasification conditions used.

The gas produced by gasification is usually called "synthesis gas" or "syngas". Its name suggests a gas to synthesise other products (e.g. diesel) – however, the term is nowadays generally employed more widely to include a range of fuel gases used in the variety of end use options available including, for example, engines and Fischer Tropsch synthesis (Figure 3).

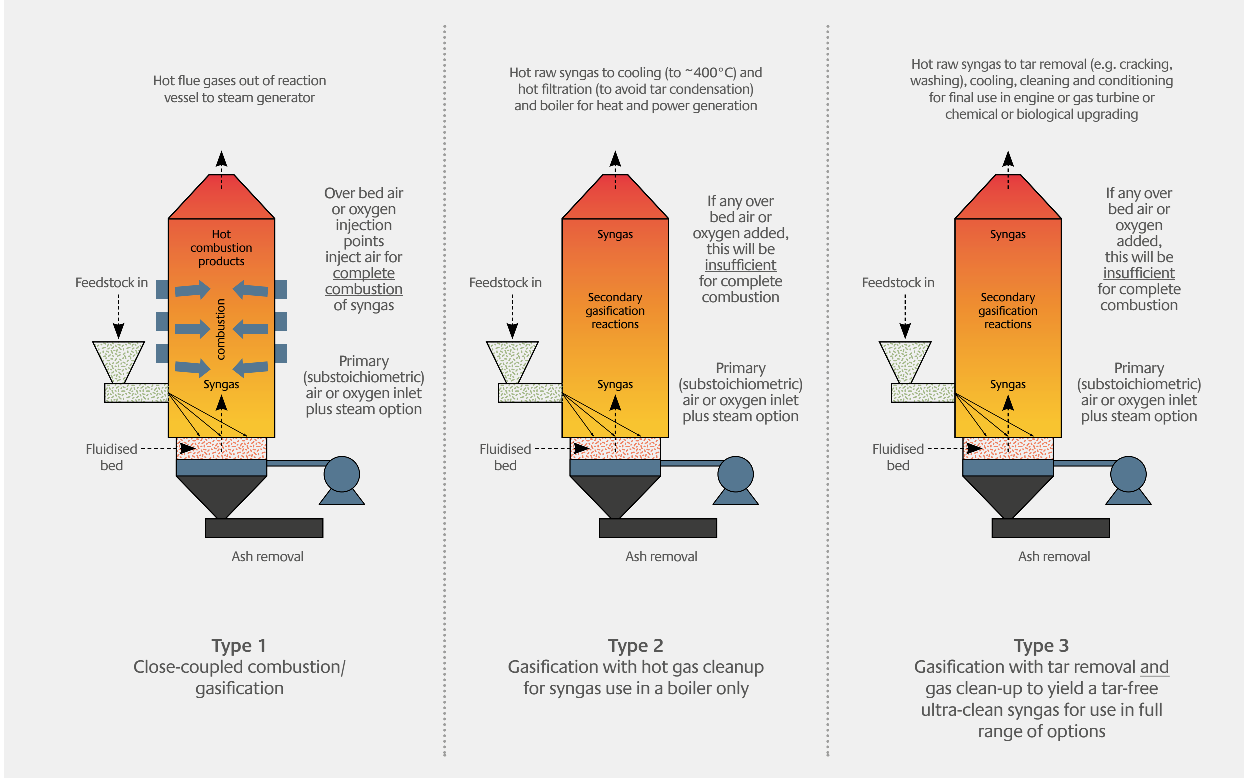
Gasification can take a number of forms. For the purposes of this report, it has been categorised in three ways, each of which is described in further detail below and illustrated in Figure 5:

Figure 4
Differences between pyrolysis, gasification and combustion



8 Some "gasification by pyrolysis" processes and developers are working to enable the production of chemical side products recovered from the gases and vapours produced by the pyrolysis process.

Figure 5
Type 1, 2 and 3 gasifier configurations, using a fluidised bed reactor as an example



WHAT IS GASIFICATION?
Continued ›

- **Type 1:** Two-stage close-coupled combustion/gasification for steam raising only – minimal, if any, syngas cleaning takes place
- **Type 2:** Gasification with use of cleaned syngas (with tars retained in the syngas as vapours) in a separate unit for steam raising
- **Type 3:** Gasification to produce an "ultra-clean", tar-free syngas suitable for use in engines, gas turbines, chemical and biological upgrading processes

While categorisation can be helpful in describing the different ways gasification can be applied, it must be understood that there will be, in practice, technologies which do not exactly fit these categories.

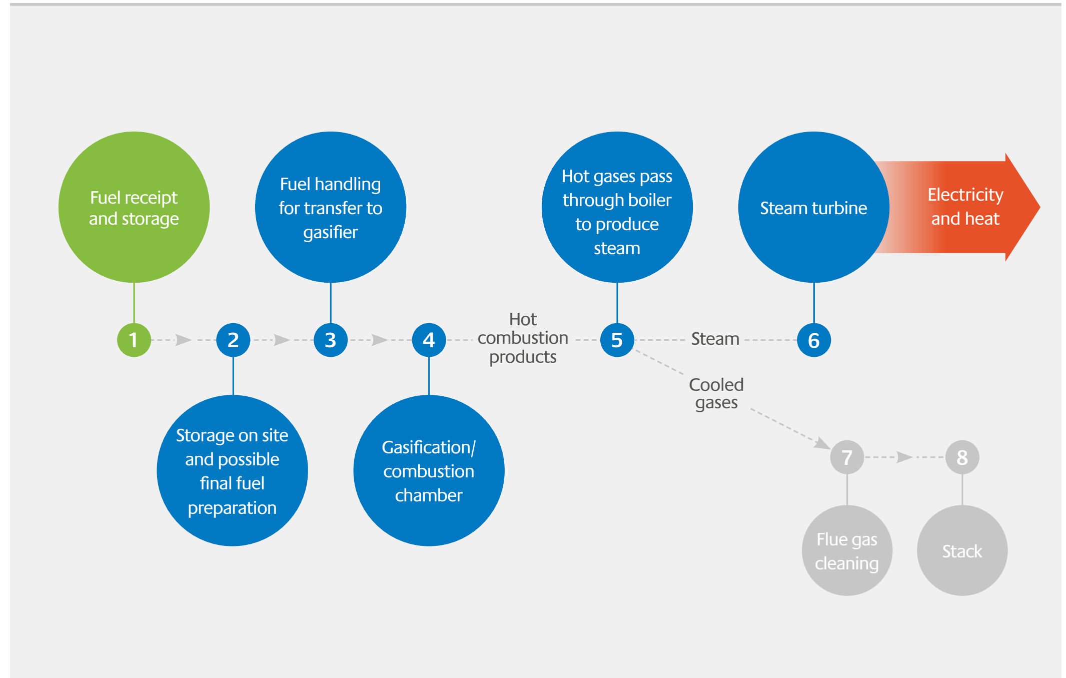
Two-stage close-coupled combustion/gasification (Type 1):

As with combustion, the chemical energy within the fuel to a two-stage close-coupled combustion/gasification process is converted into heat energy only. This technology option can therefore only be used to deliver power and/or heat. It has been classified as "gasification" as it meets the requirements of the definition of gasification as given in the Renewables Obligation [10]. A benefit it has realised, having been termed "gasification", is that financiers and others have started to understand that "gasification can work" and experience of designing, installing and operating gasification type reactors is being gained in the UK.

In the two-stage close-coupled combustion/gasification process, waste (or biomass if desired) is initially burnt sub stoichiometrically[9], for example in a bubbling fluidised bed (Figure 5) or on some form of grate. As such, gasification "occurs" immediately prior to the introduction of additional combustion air either within the gasifier vessel itself as over bed air or in a second "closely coupled" vessel. This additional air results in the complete combustion of the "syngas". The raw syngas is not cleaned before it is used and hence there is no opportunity to use the syngas to produce the variety of output options offered by gasification (Figure 3).
As noted above, the output from this type of "gasifier" is the same as from combustion plants, i.e. hot gaseous combustion products which are immediately used to raise steam for power and heat (Figure 6). As with conventional energy from waste plants, the flue gases from two stage combustion/gasification plants are cleaned prior to release to atmosphere to meet or exceed the required standards. Hence, flue gas clean-up processes must be sized and designed to accept the larger volumes of flue gases expected[10].

As a partial combustion process, and particularly at smaller scales, system efficiencies to power can be low, in the range of 10-20% on a site basis [11].

Figure 6
Typical stages in two-stage close-coupled combustion/gasification process (Type 1) – see also Figure 7 and Figure 8



Gasification with syngas cleaning in separate unit for use in steam raising only (Type 2):

Type 2 gasification systems, unlike the Type 1's, include an integral syngas cleaning step following the gasification step (Figure 7). The objective of syngas cleaning in Type 2 systems is to reduce boiler fouling and corrosion and to permit an increase in system performance by enabling higher steam temperatures to be used. Tars, which are a feature of raw syngases produced from biomass and wastes and which have high calorific value, can be accepted by boilers providing they are in the vapour state. Therefore, they are typically not removed by the gas cleaning step in Type 2 plants. Leaving the tars in the syngas, however, means that Type 2 gasification plants can only produce power and heat via steam.

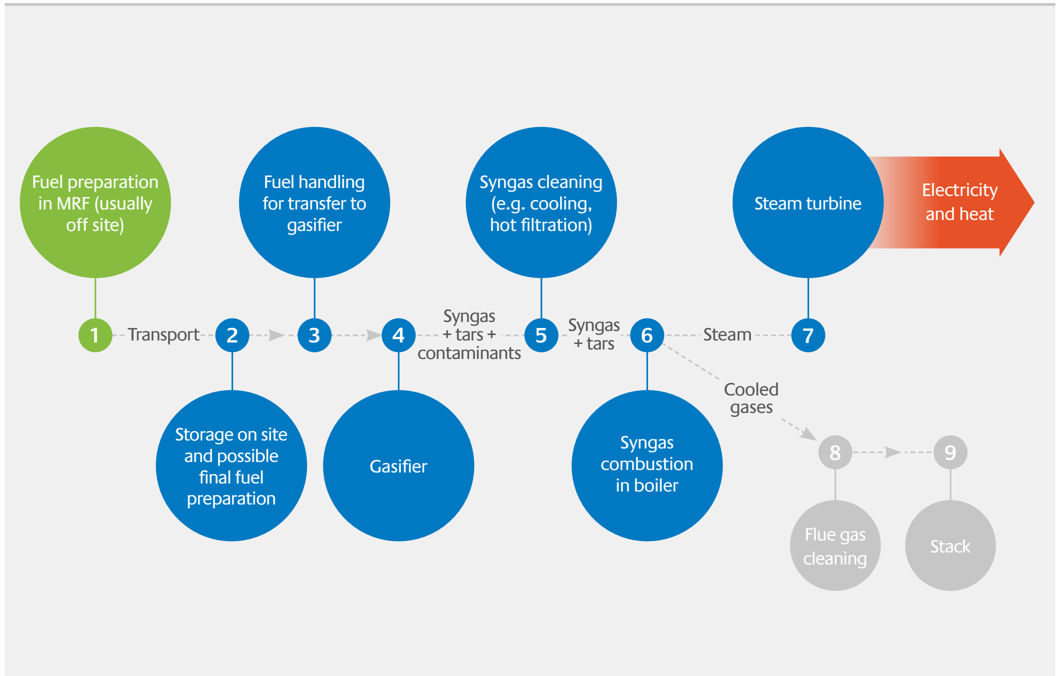
Type 2 gasification is particularly attractive for use in district heating schemes. The 160 MW Lahti plant in Scandinavia is an example of the successful deployment of this kind of gasification [2].

9 Stoichiometric combustion is the theoretical combustion of the whole amount of a quantity fuel when mixed with the theoretical amount of air (oxygen) to yield exhaust products of only CO_2 and water. Hence, sub stoichiometric combustion is the burning of a quantity of fuel with insufficient air or oxygen for complete combustion.

10 The volume of input syngas will be lower than the volume of flue gases post combustion as flue gases will contain nitrogen brought in with the combustion air.

WHAT IS GASIFICATION?
Continued ›

Figure 7
Stages in gasification with syngas cleaning in separate unit for use in steam raising only (Type 2) – see also Figure 6 and Figure 8



These Type 2 gasification systems, where the objective is to produce steam only, will consist of a chain of unit operations which must be made to work together since there is not usually the opportunity to use intermediate storage or buffering (Figure 7):

› Feedstock preparation to homogenise the waste feed, storage and handling – these are straightforward processes but must be carefully designed to ensure system reliability. Often, much of the feedstock preparation takes place in an offsite supplier's materials recycling facility (MRF). There will sometimes be a "mini" MRF on site to provide final fuel treatment, for example to guard against any unwanted materials such as stray metal objects which may cause downstream damage.

› Gasifier vessel, can be, for example, a circulating fluidised bed [12], a bubbling fluidised bed (Figure 5) or a fixed bed reactor. The choice of reactor will require, amongst other things, knowledge of:

  – the end use requirement
  – feedstock to be used
  – the planned scale of operation
  – local design and operational experience
  – supplier demonstrated experience

› Integral syngas cleaning step – the objective of gas cleaning in this instance is to produce a syngas which can be used more efficiently, compared with the "Type 1" case described above, in a boiler only. The aim is to retain the maximum chemical and heat energy contained within the syngas while removing problematic contaminants which cause corrosion and erosion in downstream boilers, but not tars as these have high calorific values. By removing these undesirable components, higher steam temperatures and pressures are achievable and maintenance requirements will be reduced. An example of this type of syngas cleaning is provided by Valmet from Finland. This process firstly cools the syngas to around 400°C [12] [13]. This cooling is sufficient to cause corrosive compounds such as alkali chlorides present in the syngas to condense onto ash particles carried out of the gasifier with the syngas but is not sufficient to condense out the high energy content tars. Following cooling, the syngas is filtered at high temperature to remove the ash particles holding the condensed undesirable components. Through this process, the energy content of the syngas, consisting of both heat and chemical energies, is maximised while at the same time removing harmful constituents down to tolerable levels such that steam temperatures and pressures can be maximised. This system is particularly suited to larger scale Combined Heat and Power applications – although Valmet quote scales down to around 7 MWe (equivalent) [13]. This approach can also be used to convert existing boilers and furnaces to waste or biomass firing while leaving the existing fuelling systems available as a back-up [14] [15].

› Combustion of the syngas (which still contains tars in the vapour state) in a steam boiler followed by power generation via a steam turbine. Following use in the steam turbine, the exhausted steam is condensed to convert it back into boiler feed water.

› Flue gas cleaning processes sufficient to meet or exceed emissions requirements prior to flue gas discharge.

As noted above, steam systems lend themselves to the upper end of the scale range, in particular starting at about 20 MWe. At these larger scales, high gasification efficiencies of around 31% on a site basis (excluding any MRF loads) are reported by Valmet [12].

Gasification for the production of "ultra-clean", tar-free clean syngas (Type 3):

Of the technologies described here, gasification with integral syngas clean-up and conditioning to remove undesirable components including tars, is the only one capable of delivering the range of alternative syngas upgrading options beyond straightforward combustion to raise steam (Figure 3). The level of gas clean-up and conditioning needed is generally defined by the end use application with the quality of stringency requirements increasing in the following general order (lowest to highest): steam raising, reciprocating gas engine, gas turbine, biological syngas upgrading, chemical synthesis. To date, the ability to achieve these levels of cleaning, especially for chemical synthesis, has not been robustly demonstrated to enable widespread commercial roll-out.

In the nearer term, therefore, the use of syngas cleaned to the less demanding levels required by engines compared with other new applications should provide a first, lower risk, stage of delivering processes to produce "ultra-clean", tar-free syngas. This use of syngas in engines provides the opportunity to produce power at high efficiencies, in particular at smaller scales, and on smaller site footprints. The smaller site footprint benefit is especially important for many private wire applications, for example on industrial sites.

As with Type 2 gasification systems which produce steam only, gasification systems which produce an "ultra-clean", tar-free syngas typically consist of a chain of unit operations which must be made to work together (Figure 8). These elements usually include:

› Feedstock preparation to homogenise the waste feed, storage and handling – this will be the same as for Type 2 described above. To reiterate, these processes must be carefully designed to ensure system reliability.

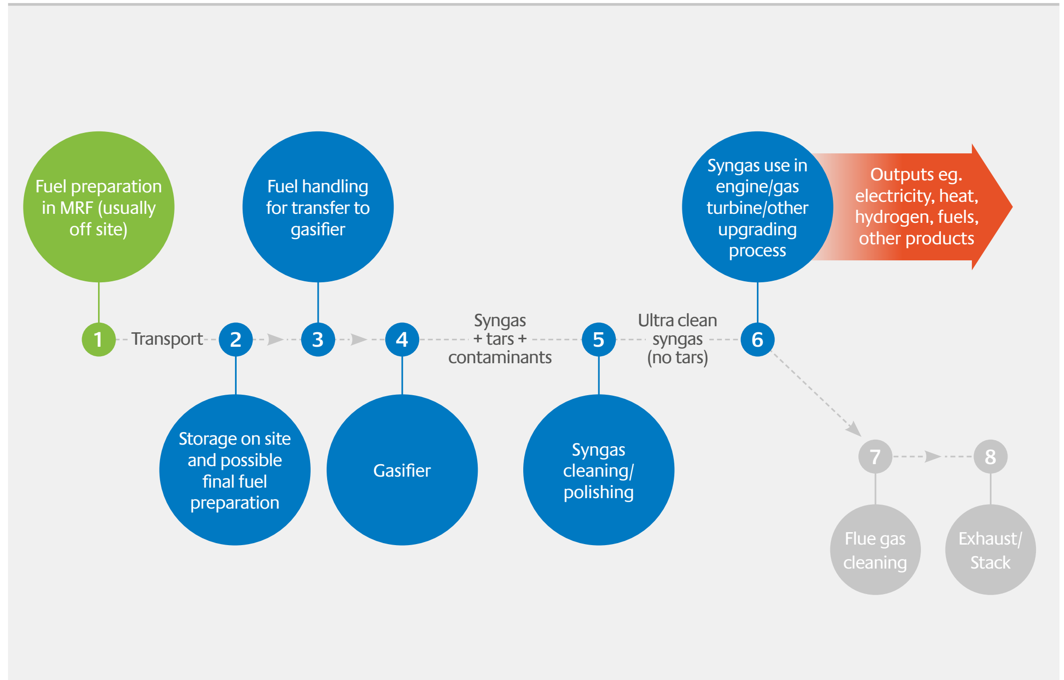
› Gasifier vessel, often a bubbling fluidised bed with others such as fixed bed reactors available. In principle, a similar gasifier type to

WHAT IS GASIFICATION?
Continued ›

that used for "Type 2" gasification described above might be used (Figure 5). The design process will require the same considerations and choices as for Type 2.

- The objective for syngas cleaning in this type of gasification is to produce an "ultra-clean", tar-free syngas which can be used in the variety of end uses offered by gasification to deliver power, heat, fuels and/or chemicals (Figure 3). These output options have a more challenging set of syngas quality specifications and acceptable levels are typically more stringent compared with syngas use in a boiler (Figure 9). A key difference between this and the Type 2 systems described above, is that as well as removing undesirable components, tars must also be removed from the syngas prior to utilisation. The tar removal processes can take a number of forms but can typically be categorised into high-temperature and low-temperature based systems, followed by polishing/conditioning steps. High-temperature based systems will typically include a second stage high temperature thermal treatment step at about 1200°C to crack (or split) the heavy tars into lower molecular weight components, followed by cooling and polishing/conditioning steps to remove components such as sulfur and ammonia. Low-temperature based systems typically include a set of scrubbing stages to remove and collect tars and other contaminants. Examples include the technologies provided by Advanced Plasma Power and Royal Dahlman [16] [17].
- End use (e.g. reciprocating gas engine, gas turbine, chemical synthesis process such as a water gas shift unit to produce hydrogen, biological synthesis process).
- Final flue gas treatment as required to meet or exceed environmental requirements. As the syngas is "ultra-clean" before use, then the flue gas treatment needed will be more limited than in Type 1 or 2.

Figure 8
Stages in Type 3 gasification process for the production of "ultra-clean", tar-free syngas – see also Figure 6 and Figure 7



Overall efficiencies to power of Type 3 gasification systems vary between about 25% and 35% from prepared feedstock to net electricity output with innovation headroom to get up towards around 40%. Current reciprocating engine technologies are reaching about 43% engine efficiency on natural gas with about 35% on syngas. With development and experience, it should be possible to increase engine efficiencies to about 40%. Where gasification systems are designed to produce fuels, for example by the Fischer Tropsch process to produce jet fuels or by methanation to produce bioSNG, then overall site energy efficiencies (from prepared feedstock to fuel or gas) of the order of 40-45% and 65-70% respectively, are anticipated.

Driving for higher efficiencies is, however, a potential barrier to the commercial roll out of new gasification projects at this time in the UK. Across all energy from waste technologies, there is a tension between gate fee income and efficiencies – higher efficiencies can reduce waste throughput and hence drive down financial returns in the nearer term. There is, though, a potential financial resilience risk to projects following a low efficiency / high waste throughput strategy as gate fees may be liable to fluctuate as waste arisings change and additional energy from waste capacity comes on line. Gasification plants incorporating gas cleaning will be less reliant on gate fee incomes as they can generate a higher proportion of their income streams from products such as electricity. Hence, this may be a potential mitigation against this risk.

WHAT IS THE CURRENT UK GASIFICATION PROJECT LANDSCAPE?

Figure 9
Illustrative syngas quality ex gasifier compared with requirements for use in engines and chemical synthesis process [18]

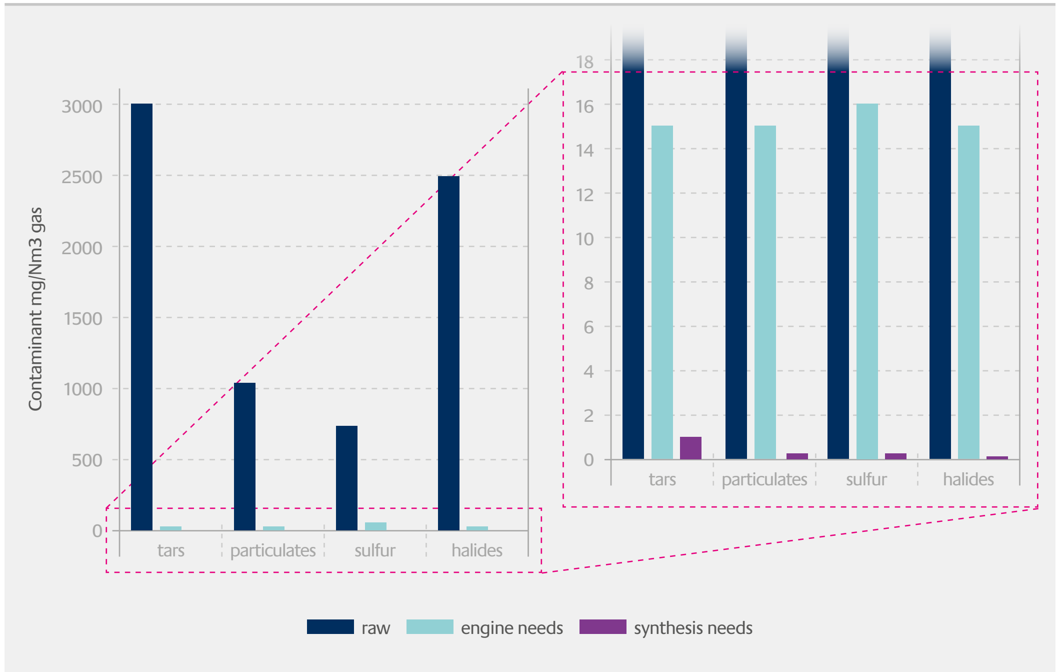
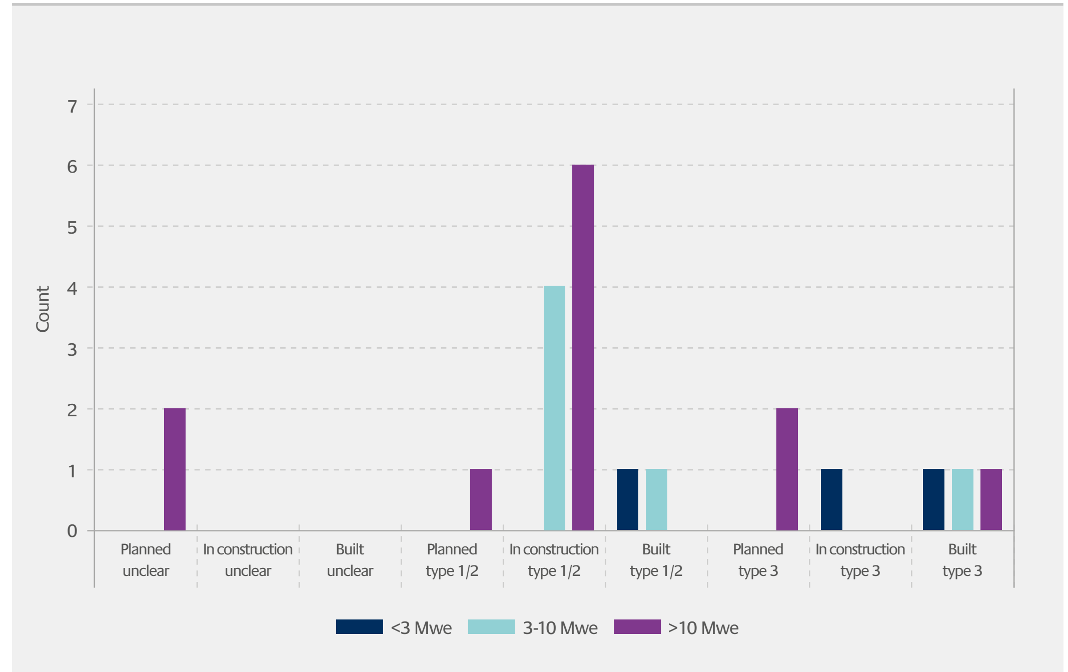


Figure 10
Numbers of UK gasification projects by type*



*Small downdraft type projects, non-electricity producing projects, university research projects, Arbre (see Annex 1) are excluded.

What is the current UK gasification project landscape?

Gasification as a technology sector is emerging – waste is currently the preferred feedstock while power is currently the preferred output. These developments will facilitate the future uptake of gasification to produce a broader range of outputs, to use the wider biomass resource pool, and ultimately to combine with CCS.

As noted above, the "Type 1" close-coupled combustion/gasification type and other gasification projects where electricity is generated via a steam turbine (Type 2) are emerging in the UK while gasification incorporating gas cleaning (Type 3), in which a purified syngas with tars removed ready and usable for upgrading is produced, is beginning to be demonstrated at commercial scale. A selection of UK gasification projects in various stages of development are listed in Annex 1 and summarised in Figure 10.

The list in Annex 1 and Figure 10 indicate a current project skew to the larger scales and to the steam raising/close-coupled combustion/gasification technology (mainly Type 1's). These gasifiers are currently considered relatively "bankable" but are unable to deliver the flexibility opportunity sought from gasification.

Few Type 3 gasification projects are being developed, albeit that some projects offer a technology that could be Type 3 [19].

Despite the encouraging numbers of gasification projects shown in Figure 10, the UK's more recent experience with gasification has been one of mixed successes. The high numbers of planned projects shown in Figure 10 are perhaps a reflection of, and outcome from, these mixed successes. Moving forwards, the gasification industry needs to gain stronger experience in designing and using gasification equipment and systems while investors and policy makers need to gain confidence in gasification, in particular gasification with integral syngas cleaning. To mitigate the risks in developing gasification projects with integral gas cleaning, UK gasification policies should be designed as an integrated programme of stages, or Innovation Runway, moving, step by step, towards the delivery of Type 3 gasification projects incorporating syngas tar removal and cleaning and which can provide the high efficiencies and flexibilities offered by gasification (as illustrated in Figure 3). These policies should drive a strong pace of innovation and development balanced with confidence building, particularly for the finance community. As shown in Figure 1, commercial gasification experience is already being gained, for example in the design, building, commissioning and operation of fluidised bed reactors, by using syngas to raise steam for power and heat [2]. This experience can be leveraged for Type 3 gasification in which an "ultra-clean", tar-free syngas is used directly in engines and gas turbines and subsequently alternative products such as hydrogen (Figure 3).

THE ETI'S PROJECT WORK

The ETI's project work

The ETI has taken a stage-wise approach to accelerating the development of gasification for the production of "ultra-clean", tar-free syngas. It is now working with Syntech Bioenergy to build and operate a 1.5 MWe gasification project, incorporating syngas tar removal and cleaning, in the West Midlands. This will be operational from 2018 onwards.

There is a need to understand and demonstrate how to deliver reliable Type 3 gasification projects capable of delivering an "ultra-clean", tar-free syngas with the capability to be used to deliver multiple output options. This is needed to provide confidence to investors, policy makers and other stakeholders.

The ETI has assessed the potential of three different Type 3 gasification configurations through its Phase 1 Waste Gasification project. These three configurations used two distinct types of medium temperature gasifier combined with three types of high and low temperature syngas treatment systems (Table 1).

Separate investor-ready proposals were presented to the ETI in February 2014 by Advanced Plasma Power (APP), Broadcrown Limited (BREL) and Royal Dahlman (RD). These three companies had been commissioned to develop their proposals from a total of 16 responses to the ETI's April 2012 Waste Gasification Project Request for Proposals. This request for proposals set out that the proposed energy from waste plant must meet the following requirements:

- Demonstrate the key technologies required for a 5–20 MWe facility operating on typical UK waste streams (for example, a demonstrator might be built at the 0.5-3 MWe scale range);
- A net electrical efficiency of greater than 25% over the whole plant, including all parasitic loads and including those used in the upstream Materials Recycling Facility (MRF) whether onsite or offsite, and with no shared allocation of parasitic loads to other MRF outputs;
- Operationally robust – greater than 80% plant availability.

The proposals presented to the ETI included results and findings from pilot scale studies; plant designs with associated capital and operating costs; sites with planning permissions and authorisations from the Environment Agency; and business plans for the commercial operations of the plants and follow on larger scale deployment of the technologies in the UK.

Table 1
High level profiles of ETI's three Phase 1 Waste Gasification Projects

	Advanced Plasma Power [16]	Broadcrown	Royal Dahlman [20] [21]
Proposed demonstrator net output	4.9 MWe	3.3 MWe	7.0 MWe
Location	Tyseley, West Midlands	Wednesbury, West Midlands	Grimsby, North Lincolnshire
Gasification type	Directly heated, oxygen blown fluidised bed (medium temperature) gasifier	Directly heated, oxygen blown fluidised bed (medium temperature) gasifier	Indirectly heated fluidised bed (medium temperature) gasifier
Gas clean-up type	High temperature plasma treatment	High temperature thermal cracking	Low temperature washing
Primary power generation	Reciprocating engines	Reciprocating engines	Gas turbine

The Phase 1 Waste Gasification project demonstrated to the ETI that gasification of waste and use of the resulting syngas in an engine is technically feasible. It also demonstrated that, in particular, the efficiency target of at least 25% (to include fuel preparation in the MRF) could be met. The developers were each able to demonstrate that Refuse Derived Fuel (RDF) is readily available to such projects despite the widespread use of long-term waste management contracts which are used by local authorities in particular.

Identification of sites, gaining planning and environmental permissions were all relatively straightforward, each taking about six months. Planning constraints were reasonable, and mainly concerned noise, odour and traffic movements. An observation was that it is important and beneficial to engage and consult early with the local authority and the community prior to formal planning to help identify the key issues and to highlight key benefits.

The plants were accepted as representing Best Available Techniques (BAT) by the Environment Agency (EA). The EA assessed the plants against either parasitic load or energy recovery per tonne of waste and all three comfortably met the requirements. One of the developers, Broadcrown, sought and obtained end of waste designation for their syngas which is an important step towards paving the way to using the syngas as a raw material in the manufacture of other products.

The impacts of investor confidence in the form of discount factor, gate fee, availability and scale were clearly shown by the techno-economic

THE ETI'S PROJECT WORK
Continued ›

analyses. At the larger 10-20 MWe scale, the data indicate that the proposed 'first of a kind' plants could be competitive with alternative low carbon technologies, having a Levelised Cost of Energy (LCOE) in the £65-£75/MWh range. At the smaller scale (5-10 MWe), LCOE's were around the £100/MWh mark which is still competitive given the characteristics of these plants. For nth of a kind plants, estimated LCOE's ranged between £50 and £80/MWh. These figures indicate that waste gasification, for the present, requires support mechanisms to develop but, over time, increasing investor confidence will reduce risk and cost of capital.

While, the estimated financial returns from these three projects were forecast to be positive, they were, at around 10%, unfortunately below the rate that would normally be required by investors for innovative technology projects such as these where technical risks can be high. It is expected that as operational experience is gained, costs, and in particular procurement costs, will reduce such that financial returns will rise.

Although the technologies selected for use by the three projects were necessarily sourced globally, they included some key elements from the UK. Some additional UK strengths were demonstrated indicating that, despite the fact that there are limited numbers of UK gasification technology providers, the UK is particularly well suited to developing gasification projects, particularly when waste fuelled. These strengths include:

- Project management. There is a need to bring in, at the right time, companies with project management and delivery skills gained from a wide cross-section of projects
- Specialist engineering contractors with experience in constructing high technology content projects
- Fabrication companies for the production of vessels etc. to relevant codes and standards
- Highly skilled workforce – this is most strongly leveraged if the gasification and associated technologies used are related to technologies already in use in the UK, for example bubbling fluidised bed reactors
- Support from a highly-regarded research community with relevant expertise

Lessons learned from beyond the Phase 1 project highlighted the importance of ensuring the project is led from a business perspective and assembling an appropriate project delivery team to develop business cases and plant proposals to time and budget. The ideal team will contain expertise in the process operations, engineering project management, strong UK knowledge and commercial and financial acumen. A skills shortage in one of these areas is likely to lead to project delays, unrealistic costs and schedules and difficulty assembling a financially viable business plan. Understanding the commercial drivers for the project will influence key early decisions such as identifying sites in areas with strong local gate fees, selecting waste types that generate the strongest revenues and balancing project risks with costs so that both match the expectations of investors.

Lessons were also learnt in comparing project performance on a like-for-like basis given variations in project assumptions and available technical data. These challenges are of particular importance for future techno-economic analyses and for policy work.

Ensuring a careful and considered approach is taken to scale-up was also highlighted. Indications are that aggressive scale-up factors should be avoided. However, this can be a challenge, particularly for waste fuelled plants where gate fees are an important income stream, and where there will be a strong driver to build larger scale plants sooner. Further, as noted above, a programme approach (Figure 1) is needed for the development of gasification in the UK such that longer term data sets, especially on performance and carbon savings, can be generated and project developers, manufacturers, Engineering Procurement Construction (EPC) designers and operators can learn by doing in increasingly challenging stages and so deliver confidence to financiers and policy makers that this technology is commercially viable and can play an important role in delivering a low carbon energy sector.

The ETI's work in gasification is now culminating in a £5million investment in a 1.5 MWe gasification project which incorporates syngas cleaning with tar removal in Wednesbury, to the north west of Birmingham, in order to build investor confidence in this technology and drive wider take-up.

The £10.5 million Syntech Energy Centre (SEC) project (formerly Broadcrown) will convert about 40 tonnes/day of post recycling, locally produced refuse derived fuel (RDF) into an "ultra-clean", tar-free, syngas. This syngas, to be equivalently clean to natural gas, will be converted into power using a modified high efficiency gas engine. Waste heat from the engine will be available to heat a local leisure centre amongst other potential uses. Uniquely, at ETI's request, this project will incorporate a syngas test facility which will allow other innovative uses for tar-free clean syngas to be tested and trialled. It is anticipated that initial interest in this test facility will be to test alternative engines and processes to produce, for example, aviation fuel from wastes.

The Project is being led by Syntech Bioenergy UK who are based in Aldridge in the West Midlands. Project Management is being led by MACE (London); engineering, procurement and construction is being led by Otto Simon (Cheshire). The gasification technology is being provided by Frontline Bioenergy (Iowa) and is being built in the UK. Around 100 construction jobs and 25 permanent operations jobs will be created in this one project with further projects planned.

Construction at the Syntech Bioenergy Centre site started in March 2017 and will complete in early 2018. Following commissioning, a set of proving trials using a variety of waste derived feedstock types will be run to establish baseline data and to provide knowledge to support, in particular, UK gasification policy development and to drive the gasification industry forward.

ETI is also pleased to continue supporting both Advanced Plasma Power and Royal Dahlman in their work to deploy their gasification technologies. Advanced Plasma Power, working with Progressive Energy, and supported by the UK's Department for Transport, Ofgem and National Grid, has started construction of a 22GWh/year plant (approximately equivalent to an electricity generation plant capacity of 1-2 MWe) to produce biosynthetic natural gas (bioSNG) from wastes for use in heat and transport [16] [22]. This plant is expected to be in operation from 2018 onwards. Royal Dahlman is also building a plant to produce bioSNG from wastes – this plant, to be built in Alkmaar in the Netherlands and also to be operational from 2018 onwards, is supported by the Investment Fund Sustainable Economy North-Holland (PDENH), ENGIE, the Dutch energy research centre ECN and Gasunie New Energy [23].

Updates on the ETI's project are available from: www.eti.co.uk.

ANNEX 1 – SELECTION OF UK GASIFICATION PROJECTS

Location	Developer / key project lead	Technology	Feedstock	Technology information	Status (planned / in construction / operational / other)	Output
Aberdare [24] [25]	Enviroparks Hirwaun generation	CHO Power	Wastes	Potential to use syngas cleaning stage. Uses plasma gas polishing process	Planned	11 MWe
Belfast [24] [26]	RiverRidge Energy	Biomass Power	Wastes	Unknown technology. Steam raising.	In construction	15 MWe
Birmingham [27]	Birmingham BioPower	Nexterra	Wastes	Updraft gasifier. Steam raising only. Syngas cleaning being developed in US	In construction	10 MWe
Bristol [24]	Avonmouth BioPower	Syngas Products Group (formerly New Earth Technology)	Wastes	Gasification by pyrolysis using screw reactor. Steam raising process.	Built	7.5 MWe
Cardiff [28]	Lockheed Martin/CoGen	Concord Blue	Wastes	Moving bed type reactor. Likely to use syngas cleaning stage.	Planned	15 MWe
Cheshire [24]	CoGen/Peel Environmental	Outotec	Waste wood	Two-stage close-coupled combustion/gasification	In construction	21.5 MWe
Derby [24]	Interserve/Shanks	Energos	Wastes	Two-stage close-coupled combustion/gasification	In construction	11 MWe
Doncaster [29]	BH Energygap	Not stated	Wastes	Not stated	Planned	12 MWe
Dorset (Cranford) [30]	Syngas Products	Syngas Products	Wastes	Staged pyrolysis/gasification	Demonstrator – built	1 MWe
Eggborough (Arbre) [31]	First Renewables & TPS Termiska Processer AB	TPS Termiska Processer AB	Energy crops	Integrated gasification combined cycle	Built – out of use	8 MWe
Glasgow (Polmadie) [24]	Viridor	Energos	Wastes	Two-stage close-coupled combustion/gasification	In construction	11 MWe
Hoddesdon [32]	Bouygues Energies & Services	Biomass Power	Wastes	Unknown technology. Steam raising process.	In construction	10 MWe

ANNEX 1 – SELECTION OF UK GASIFICATION PROJECTS
Continued ›

Location	Developer / key project lead	Technology	Feedstock	Technology information	Status (planned/in construction/ operational/other)	Output
Hull [24]	Spencer Group	Outotec	Wastes	Two-stage close-coupled combustion/gasification	In construction	25 MWe
Isle of Wight [33]	Energos	Energos	Wastes	Two-stage close-coupled combustion/gasification	Unclear	2.3 MWe
Levenseat [24] [34]	Levenseat Renewable Energy	Outotec	Wastes	Two-stage close-coupled combustion/gasification	In construction	12 MWe
Milford Haven [35]	Egnedol	Not stated	Waste wood & farmed wood	Gasification by pyrolysis. State will use engines	Planned	50 MWe
Milton Keynes [24]	Amey Cespa	Energos	Wastes	Two-stage close-coupled combustion/gasification	In construction	7 MWe
Plymouth [36]	O-Gen Plymtrek Ltd	O-gen	Waste wood	Air blown fixed bed downdraft gasifiers fuelling engines	Built	3.5 MWe (estimated)
Royal Wootton Bassett [37]	Swindon Energy	Refgas	Waste wood	Air blown fixed bed downdraft gasifiers fuelling engines	In construction	6 MWe
Shepperton [38]	Suez	Outotec	Wastes	Two-stage close-coupled combustion/gasification	In construction	3.7 MWe
Swindon [16]	Gogreengas	Advanced Plasma Power	Wastes	Oxygen blown gasification for production of bioSNG	In construction	22 GWh bioSNG, equivalent to about 2-3 MWth
Tees Valley [24]	Air Products	AlterNRG	Wastes	Plasma gasification to fuel gas turbines	Built	50 MWe gross
Wednesbury	Syntech Bioenergy/ETI	Frontline Bioenergy	Wastes	Bubbling fluidised bed/engines	In construction	1.5 MWe
Walsall [39] [24]	BH Energygap/Sener	Kobelco	Wastes	Unknown	Planned	20 MWe

Nb: small (sub 1MWe or equivalent) and university projects are excluded.

REFERENCES

[1] G. Newton-Cross and D. Gammer, "The evidence for deploying bioenergy with CCS (BECCS) in the UK," 2016. [Online]. Available: http://www.eti.co.uk/insights/the-evidence-for-deploying-bioenergy-with-ccs-beccs-in-the-uk. [Accessed 16 January 2017].

[2] "Lahti Energia," Lahti Energia, [Online]. Available: http://www.lahtigasification.com/. [Accessed 6 January 2017].

[3] Defra, "Digest of Waste and Resource Statistics – 2017 Edition," March 2017. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/601470/Digest_of_Waste_and_Resource_Statistics__2017.pdf.

[4] Green Investment Bank, "The UK residual waste market (A market report by the UK Green Investment Bank)," July 2014. [Online]. Available: http://www.greeninvestmentbank.com/media/25376/gib-residual-waste-report-july-2014-final.pdf [Accessed 16 January 2017].

[5] WRAP, "List of energy from waste sites," February 2013. [Online]. Available: http://www.wrap.org.uk/content/list-energy-waste-sites. [Accessed 23 January 2017].

[6] "Energy from waste," British Plastics Federation, [Online]. Available: http://www.bpf.co.uk/sustainability/efw.aspx. [Accessed 24 September 2016].

[7] Defra, "Incineration of Municipal Sold Waste," February 2013. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221036/pb13889-incineration-municipal-waste.pdf. [Accessed 24 September 2016].

[8] A. Main and T. Maghon, "Concepts and experiences for higher plant efficiency with modern advanced boiler and incineration technology," 11-13 May 2010. [Online]. Available: http://www.seas.columbia.edu/earth/wtert/sofos/nawtec/nawtec18/nawtec18-3541.pdf. [Accessed 24 September 2016].

[9] A. Sigg, ""Mass Burn" is Advanced Conversion Technology," 16 September 2014. [Online]. Available: http://www.rwmexhibition.com/files/alfred_sigg__hitachi_zosen_innova.pdf. [Accessed 24 September 2016].

[10] DECC, "Renewables Obligation Order 2009 as amended by the Renewables Obligation (amendment) Order 2014," 4 August 2014. [Online]. Available: https://www.gov.uk/government/publications/renewables-obligation-order-2009-as-amended-by-the-renewables-obligation-amendment-order-2011--2. [Accessed 24 September 2016].

[11] "Energos awarded Advanced Conversion Technology contract for Derby," 12 September 2014. [Online]. Available: http://www.energ-group.com/energos/information-centre/news/2014/09/energos-awarded-advanced-conversion-technology-contract-for-derby/. [Accessed 24 September 2016].

[12] F. Ligthart, T. Luomaharju and J. Isaksson, "Advanced thermal conversion solutions for Energy from Waste," [Online]. Available: http://pennwell.sds06.websds.net/2014/cologne/rewe/papers/T2S6O40-paper.pdf. [Accessed 6 February 2017].

[13] "Gasification for biomass and waste," Valmet, [Online]. Available: http://www.valmet.com/products/energy-production/gasification/. [Accessed 16 December 2016].

[14] "Fuel conversion for power boilers: Vaskiluodon Voima Oy, Vaasa, Finland," Valmet, [Online]. Available: http://www.valmet.com/media/articles/all-articles/fuel-conversion-for-power-boilers-vaskiluodon-voima-oy-vaasa-finland/. [Accessed 16 December 2016].

[15] N. Koh, "Renewable power from biomass and waste - Valmet solutions," 5 June 2014. [Online]. Available: http://www.entechpollutec-asia.com/portals/0/seminar/4_RenewablePower_ValmetSolutions_Nelson%20Koh.pdf. [Accessed 24 September 2016].

[16] "Advanced Plasma Power," [Online]. Available: http://advancedplasmapower.com/. [Accessed 27 September 2016].

[17] "Dahlman," [Online]. Available: http://www.royaldahlman.com/renewable/home/tar-removal/olga-technology/. [Accessed 26 September 2016].

[18] Progressive Energy and CNG Services, "BioSNG: Feasibility Study. Establishment of a Regional Project," 2010. [Online]. Available: http://www.biogas.org.uk/images/upload/news_7_Bio-SNG-Feasibility-Study.pdf. [Accessed 7 February 2017].

[19] Nexterra, "Nexterra's gasification technology," [Online]. Available: http://www.nexterra.ca/files/gasification-technology.php. [Accessed 19 March 2017].

[20] Royal Dahlman, "Gasification," [Online]. Available: http://www.royaldahlman.com/renewable/home/gasification/. [Accessed 19 March 2017].

[21] Royal Dahlman, "Olga Technology," [Online]. Available: http://www.royaldahlman.com/renewable/home/tar-removal/olga-technology/. [Accessed 19 March 2017].

[22] Gogreengas, "Home," [Online]. Available: http://gogreengas.com/. [Accessed 26 March 2017].

[23] Royal Dahlman, "News Release Ambigo," [Online]. Available: http://www.royaldahlman.com/news/news-release-ambigo. [Accessed 26 March 2017].

[24] M. Brown and A. Baddeley, "Investment in Advanced Conversion Technologies (ACT)," November 2016. [Online]. Available: http://www.eunomia.co.uk/reports-tools/investment-in-advanced-conversion-technologies-act/. [Accessed 11 January 2017].

[25] "Our technology," CHO Power, [Online]. Available: http://www.cho-power.com/en/our-technology.php. [Accessed 11 January 2017].

[26] "Renewable energies: Bouygues Construction to build a new waste-to-energy gasification point in Belfast," Bouygues Construction, 12 August 2015. [Online]. Available: http://www.bouygues-construction.com/en/press/release/renewable-energies-bouygues-construction-build-new-waste-energy-gasification-point-belfast. [Accessed 11 January 2017].

[27] "Birmingham Bio Power Ltd. (BBPL), Tyseley, UK," Nexterra, [Online]. Available: http://www.nexterra.ca/files/BBPL-project.php. [Accessed 11 January 2017].

[28] "Lockheed Martin and CoGen to Build Energy-from-Waste Plant in Wales," Lockheed Martin, 11 October 2016. [Online]. Available: http://www.lockheedmartin.com/us/news/press-releases/2016/october/mfc-101116-lm-and-cogen-to-build-energy-from-waste-plant-in-wales.html. [Accessed 11 January 2017].

[29] "Project – The 3Rs @ Sandall Stones Road, Doncaster," bhenergygap, [Online]. Available: http://www.bhenergygap.co.uk/projects-doncaster/#_overview. [Accessed 11 January 2017].

[30] "Creating value from waste derived fuels," Syngas Products, 2017. [Online]. Available: http://www.syngas-products.com/. [Accessed 16 March 2017].

[31] B. Paterson and A. Weeks, "Progress achieved in the ARBRE BIGCC project and prospects for the future," 2003. [Online]. Available: https://books.google.co.uk/books?id=d-ZryW07MCgC&pg=PA115&lpg=PA115&dq=arbre+gasification+plant+MW&source=bl&ots=n3Z-SUv6VF&sig=4xhZPzaGQCQg61t8LOb7jf1NUWg&hl=en&sa=X&ved=0ahUKEwiYyMyMyoXTAhUlKcAKHYfEBPEQ6AEIKzAD#v=onepage&q=arbre%20gasification%20plant%2. [Accessed 2 April 2017].

[32] "Bouygues to build £82m Hoddesdon incinerator," Construction News, 8 April 2015. [Online]. Available: http://www.theconstructionindex.co.uk/news/view/bouygues-to-build-82m-hoddesdon-incinerator. [Accessed 11 January 2017].

[33] "Isle of Wight remains 'committed' to gasification," Letsrecycle.com, 26 July 2016. [Online]. Available: http://www.letsrecycle.com/news/latest-news/isle-of-wight-remains-committed-to-gasification/. [Accessed 11 January 2017].

[34] Fichtner Consulting Engineers Ltd, "Levenseat Gasification Plant Supporting Information," 23 December 2014. [Online]. Available: https://www.sepa.org.uk/media/162417/supporting-information.pdf. [Accessed 11 January 2017].

[35] "Power Generation," 2015. [Online]. Available: http://www.egnedol.wales/power-generation.html. [Accessed 3 February 2017].

[36] "Uncertainty surrounds Plymouth waste wood energy plant," letsreycle.com, 17 February 2015. [Online]. Available: http://www.letsrecycle.com/news/latest-news/uncertainty-surrounds-plymouth-waste-wood-energy-plant/. [Accessed 11 January 2017].

[37] "Refgas," [Online]. Available: https://books.google.co.uk/books?id=d-ZryW07MCgC&pg=PA115&dq=arbre+gasification+plant+MW&hl=en&sa=X&ved=0ahUKEwjl2NidiprUAhVSZFAKHWvxBFEQ6AEIJjAA#v=onepage&q=arbre%20gasification%20plant%20MW&f=false. [Accessed 5 April 2017].

[38] "Eco Park Surry," Suez, July 2016. [Online]. Available: https://www.ecoparksurrey.uk/. [Accessed 11 January 2017].

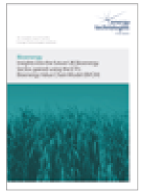
[39] "Sener - Waste-to-energy project in the United Kingdom," [Online]. Available: http://www.revistanoticias.sener/en/news/waste-to-energy-project-in-the-united-kingdom/49/. [Accessed 25 November 2016].

[40] Committee on Climate Change (CCC), "The 2050 target - achieving an 80% reduction including emissions from international aviation and shipping," April 2012. [Online]. Available: https://www.theccc.org.uk/archive/aws/IA&S/CCC_IAS_Tech-Rep_2050Target_Interactive.pdf.

FURTHER READING FROM THE ETI

Public Perceptions of Bioenergy in the UK

www.eti.co.uk/insights/public-perceptions-of-bioenergy-in-the-uk



Insights into the future UK Bioenergy sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)

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The evidence for deploying bioenergy with CCS (BECCS) in the UK

www.eti.co.uk/insights/the-evidence-for-deploying-bioenergy-with-ccs-beccs-in-the-uk

Bioenergy crops in the UK: Case studies on successful whole farm integration evidence pack

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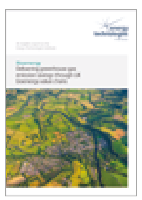

Delivering greenhouse gas emission savings through UK bioenergy value chains

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An ETI Perspective – Bioenergy crops in the UK. Case studies of successful whole farm integration

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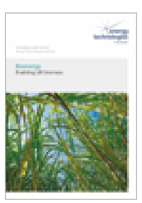

Enabling Biomass in the UK

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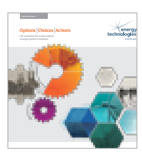

Options | Choices | Actions

www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system

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Geraint is a Chemical Engineer with 30 years' experience in the energy industries, having worked across the coal, oil and biomass sectors. Geraint leads the ETI's bioenergy programme where he is responsible for the delivery and exploitation of the ETI's bioenergy portfolio. This portfolio includes a number of studies, technology development projects and demonstration projects designed to accelerate the bioenergy sector, from production through to utilisation. These projects have a combined value of around £23.5m and include the ETI's multi-million pound investments in waste gasification. Prior to joining the ETI, he worked as Head of Biofuels and Bioenergy at the NNFCC and in a number of close plant support and marketing roles in the oil and coal industries. Geraint holds a Bachelor of Engineering in Fuel and Energy Engineering from the University of Leeds and a PhD in Chemical Engineering from the University of Aston in which he studied biomass gasification. Geraint is a Chartered Engineer, a Fellow of the IChemE and Member of the Energy Institute.

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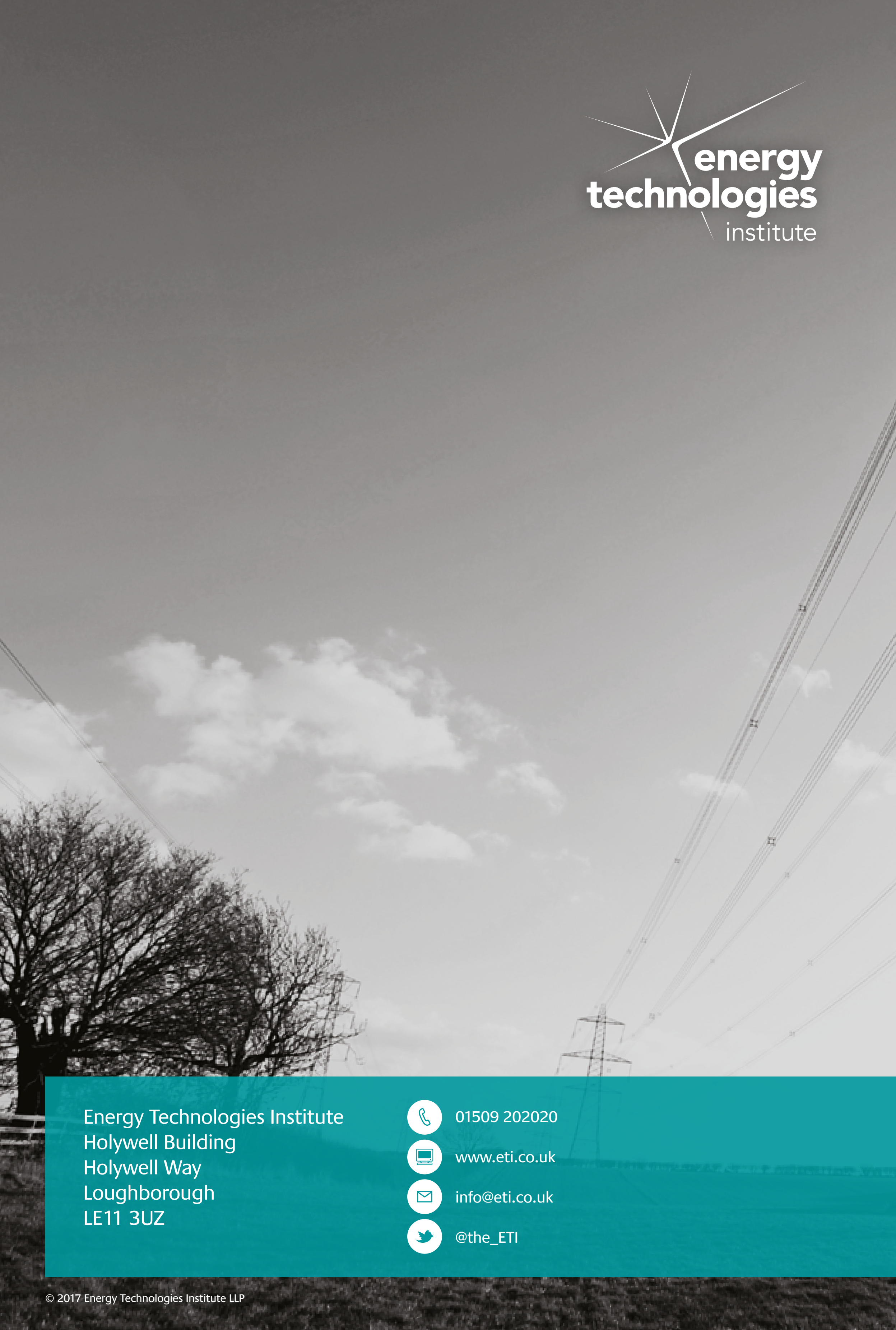

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