Low
Carbon
Innovation
Coordination
Group

Technology Innovation Needs Assessment (TINA)

Bioenergy
Summary report

September 2012

Background to Technology Innovation Needs Assessments

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed funding and delivery bodies in the area of 'low carbon innovation'. Its core members are the Department of Energy and Climate Change (DECC), the Department of Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), the Technology Strategy Board (TSB), the Scottish Government, Scottish Enterprise, and the Carbon Trust. The LCICG also has a number of associate members, including the Governments of Wales and Northern Ireland, Ofgem, the Crown Estate, UKTI, the Department for Transport, the Department for Communities and Local Government, the Ministry of Defence, and the Department for Environment, Food and Rural Affairs

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other Government initiatives, in particular those from the Office of Renewable Energy Deployment in DECC and from BIS.

This document summarises the Bioenergy TINA analysis and draws on a much more detailed TINA analysis pack which will be published separately.

The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA.

The TINA analytical framework was developed and implemented by the Carbon Trust with contributions from all core LCICG members, as well as input from numerous other expert individuals and organisations. Expert input, technical analysis, and modelling support for this TINA were provided by E4Tech.

Disclaimer – the TINAs provide an independent analysis of innovation needs and a comparison between technologies. The TINAs' scenarios and associated values provide a framework to inform that analysis and those comparisons. The values are not predictions or targets and are not intended to describe or replace the published policies of any LCICG members. Any statements in the TINA do not necessarily represent the policies of LCICG members (or the UK Government).

Acronyms and Units

i. Acronyms and abbreviations

AD	Anaerobic Digestion
BBSRC	Biotechnology and Biological Sciences Research Council
BTL	Biomass to Liquids (typically a gasification to transport biofuel plant)
BioSNG	Gasification plant producing biomethane
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
ESME	Energy Systems Modelling Environment
ETP	Energy Technology Perspectives
ETI	Energy Technologies Institute
EU	European Union
FT	Fischer Tropsch (Catalyst component on gasification to transport fuel plant)
GHG	Greenhouse Gas
GVA	Gross Value Added
IEA	International Energy Agency
ILUC	Indirect Land-Use Change
IP	Intellectual Property
LCA	Life-Cycle Assessment
LUC	Land-Use Change
R&D	Research and Development
RD&D	Research, Development and Demonstration
TPES	Total Primary Energy Supply

ii. Units of measure

EJ	Exajoule
MW	Mega Watt
GW	Giga Watt
Mha	Million Hectares
bn	Billion
tn	Trillion

Bioenergy is a promising renewable energy source which could contribute significantly to UK gas, power, transport fuel and heat demands. Its relative use across these energy markets is subject to significant innovation and market uncertainties, particularly regarding the availability of Carbon Capture and Storage (CCS). However, across innovation and market scenarios increased levels of sustainable feedstock are found to have consistent need and value.

The value of innovation to the UK from reducing energy system costs is calculated to be £42bn (range £6-101bn). This has a particularly wide range due to the number of early stage conversion technologies with significant future cost reduction potential. International business development is calculated to provide further economic value to the UK of £19 (6-33) bn. Significant market barriers are identified which could restrict the UK from realising these domestic savings and international markets.

The highest gains from increased innovation are estimated to be from increased levels of sustainable feedstock and from select conversion technologies, which are capable of converting wastes and other sustainable feedstocks. Key areas of innovation priority are improvements in woody/grassy crops, advanced biofuels demonstration, proof of integrated gasification systems at scale, and high efficiency biopower systems that are robust to a variety of feedstocks and ready for CCS.

Potential role in the UK's energy system

- Bioenergy is a resource with significant deployment potential in the UK and could meet around a tenth to a fifth of the UK's total primary energy supply by 2050. Innovation can play a key role in achieving this sustainably and at lowest cost
- Bioenergy has several strengths which favour its deployment as a renewable, low carbon technology in the UK. Bioenergy is dispatchable, can use existing infrastructure, can be domestically sourced, and could be used to generate negative emissions via CCS. A further strength of bioenergy is that it could be used to supply heat, power, gas and transport fuel, through several conversion routes, from various feedstocks
- The use of bioenergy in the UK will, however, be limited by several key factors, most prominently sustainability, cost and technical readiness. The UK Government Bioenergy Strategy (2012) states that only sustainable deployment will be acceptable in the UK; innovations that improve sustainability and enable deployment at lowest cost have the greatest potential to increase the penetration of bioenergy in the UK's energy mix
- At present there are significant uncertainties around future bioenergy deployments in the UK, which are driven by multiple overlapping factors, most prominently: sustainability, the availability of imports, the relative performance of different bioenergy technologies, exogenous market conditions, and progress in other low carbon technologies; especially CCS
- Across these uncertainties significant deployment potential was identified for bioenergy as a low carbon provider of each of its potential end products; renewable gas, heat, electricity and transport fuel. Modelling underpinning the Bioenergy TINAs shows that within each of these end use energy markets bioenergy could potentially meet upwards of a tenth of demand by 2050, but not simultaneously, due to limited availability of sustainable feedstock
- Some conversion paths were however found to be more resilient to scenario conditions:
  - *i.* Most consistently, biomethane from anaerobic digestion is expected to be deployed and imports of biofuels are modelled to be accepted to as high levels as can be sustainably supplied
  - *ii.* If CCS is available, biopower in combination with CCS is found to be favoured. If CCS is not available, higher levels of domestic biofuels and bioheat are expected to be produced
- A range of conversion technologies could potentially be used to convert feedstocks into these energy end uses. Significantly, most of these conversion technologies are unproven at scale and are not yet cost-competitive

Cutting costs and increasing deployment through innovation	• Innovation in bioenergy across both feedstocks and conversion technologies could save the UK energy system approximately £42 (6-101) bn cumulatively over 2010-2050 • Greatest gains were found to be from innovations to maximise the yields of dedicated energy crops and innovations to enable reliable operation of early stage conversion technologies at lowest cost (especially if high level of converted imports are expected) • Innovation in feedstock production could reduce their costs and increase sustainable deployment potential for both water grown algal crops and land grown dedicated energy crops. Estimated cost reductions on these feedstocks in the range of 53-80% could save the UK £12 (2-40[1]) bn to 2050, primarily from land grown feedstocks which have significantly greater deployment potential in the UK than algae • Innovations to maximise the yields of woody/grassy crops on marginal land have additional benefits. Firstly, regarding cost reduction, these innovations could enable system-wide cost reduction across the various conversion routes that can process these crops – to biofuels, biomethane, biopower and bioheat. This is therefore a relatively "agnostic" innovation priority. Secondly, these innovations could reduce pressure on land use, which lies at the heart of many sustainability concerns • Sustainable production of woody/grassy feedstocks will require (i) optimisation on marginal lands in a way that does not compromise the delivery of important ecosystem services, (ii) a clear understanding of emissions from land use change, (iii) minimal chemical inputs • Innovation has significant value for each of the possible conversion routes within bioenergy, to overcome the challenges of converting these sustainable feedstocks (as well as wastes) reliably, efficiently and at scale. Highest value is identified for early stage conversion routes: *i.* Earlier stage conversion technologies particularly gasification systems (for either biomethane, power and transport fuels, not heat) and advanced biofuel conversion technologies – have the highest potential for cost reduction of 48-80% by 2050, cumulatively saving the UK energy system £23 (0-78[1]) bn. Proof of concept at scale is the primary innovation need for these technologies, which could realise much of their cost reduction potential over the next decade *ii.* Near commercial conversion technologies (combustion and gasification for heat, combustion for power and anaerobic digestion for biomethane), are estimated as having cost reductions of 12-33% by 2050, cumulatively saving the UK energy system £7 (4-14[1]) bn. The primary innovation needs for these technologies are efficiency gains and component level improvements, which are expected to be achieved incrementally over the next 40 years • Imports (capped at 3% of global supply) enable the majority of savings for advanced biofuels in all scenarios. Realisation of these savings is not guaranteed, as innovation will not necessarily drive down prices, which are also subject to international market factors. This was factored into final innovation programme prioritisation, where savings from imports are separated out • Innovations that also enable facilities to produce multiple output types (e.g. liquid fuels and high value chemicals) also have significant potential to take conversion technologies along the learning cost curve and enable optimal output under different market scenarios
Green growth opportunity	• Global bioenergy markets are estimated to have a cumulative turnover of £2-17 tn, which the UK could seek to capitalise on by building upon world class academic, industrial and commercial strengths • Not all areas of the bioenergy market are optimal for UK engagement due to climatic and geographic factors, plus higher levels of activity abroad. This primarily applies to the export of feedstocks (which due to limited land availability the UK will not have surplus of) and markets such as bioheat (where the UK is a late adopter) • Nevertheless, through targeting areas of particular strength (e.g. plant science, biochemistry, chemical engineering and mechanical engineering) the UK could potentially capture 5-10% of the global market

[1] The high for all of the technologies' potential combined is not the same as the sum of their individual highs as they could not all simultaneously be realised due to feedstock constraints

	within select niches of bioenergy; highest value being found in the export of new energy crops IP, and the development of advanced components for biofuel and biopower conversion technologies • Targeted engagement in key areas of UK strength is estimated to offer £19 (6 - 33) bn to the UK economy over 2010-2050 • Furthermore, if UK innovations can improve the sustainability of feedstock production and the performance of conversion routes that can process them, UK demonstration of best practice and optimal use could also have significant international environmental benefits on top of market leadership opportunities
The case for UK public sector intervention	• Public sector activity is required to unlock these opportunities. There are significant market failures to innovation and the UK cannot rely on other countries to develop the technologies for us • Market failures are identified most strongly for early stage technologies, which struggle to get access to capital. This is attributed to low investor appetite for high capex, high risk, technologies which have potential knowledge spill-overs • Other prominent market failures include policy-dependent market demand (negative externalities), uncoordinated development within bioenergy supply chains where feedstock suppliers and consumers have limited capacity to coordinate development, and a lack of existing infrastructure (especially for large scale bioheat) • In select cases it is not expected that other countries will drive the innovation that the UK could need, to the timelines required, specifically for: developing woody/grassy energy crops optimised to UK conditions and biomethane from gasification
Potential priorities to deliver the greatest benefit to the UK	• Innovation areas with the biggest benefit to the UK are; *i.* Woody/grassy crops with greater yields, which can be grown on marginal land in a way that does not compromise the delivery of important ecosystem services *ii.* Affordable and reliable advanced biofuels from sustainable crops (e.g. gasification systems, liquid pyrolysis fuels and lignocellulosic fermentation) *iii.* High efficiency biopower systems which are robust to a range of feedstocks and CCS requirements • A further priority for UK bioenergy innovation is the continued pursuit of strategic, joined up innovation programmes, which would seek to simultaneously develop sustainable feedstock production alongside advanced conversion technologies • Long term deployment of sustainable bioenergy will also require further understanding of optimal sustainability conditions, especially life cycle assessment emissions • Realising the full benefit from innovation over the following 4-10 years will require significant on-going UK and European Union public sector funding and the scaling up of support for the prioritised set of technology areas in a joined up fashion

Sub-area	Technology	Value in meeting emissions targets at low cost £bn	Value in business creation £bn	Innovation Priorities
New Energy Feedstock	Woody/Grassy Crops	4.7 (2.4 – 13.5)	2.6 (0.7 - 3.8)	▪ Crop cost reductions and improved sustainability through yield increases and capacity to plant on marginal land in a way that does not compromise the delivery of important ecosystem services ▪ Development of crops that are suited to farmers' needs (short maturity times, ease of grubbing up)
	Oily Crops	5.6 (0.0 - 24.3)	0.3 (0.0 - 0.4)	
	Microalgae	1.0 (0.0 – 2.9)	0.4 (0.0 - 3.4)	▪ Cost reductions through increases in yield and harvestable energy content ▪ Risk reduction through development of species robust to production conditions
	Macroalgae	0.3 (0.0 - 3.4)	0.5 (0.0 - 1.1)	▪ Reduction of macroalgae cultivation and conversion costs, improving yields, and proving economical production at scale in UK waters ▪ Improved assessment of environmental impacts and costs
Biomethane	Anaerobic Digestion	2.6 (2.0 - 4.9)	1.1 (0.8 - 1.2)	▪ Development of improved pre-treatment, digestion and gas upgrading components, capable of taking mixed feedstocks
	BioSNG	0.9 (0.0 - 4.8)	1.0 (0.0 - 1.2)	▪ Large scale demonstration of a fully integrated plant ▪ Improved catalysts and syngas clean-up to enable cheaper, more reliable production at a smaller scale
Bioheat	Small Scale	1.7 (0.1 - 3.1)	0.9 (0.4 - 1.2)	▪ Incremental increases in system efficiencies ▪ improved installation techniques and control mechanisms
	Large Scale Heat	0.2 (0.0 - 0.9)	3.6 (1.9 - 6.7)	
Biopower	Combustion	3.0 (1.7 - 4.7)	4.6 (3.1 - 5.7)	▪ Development of advanced boilers and operation systems that are robust to a variety of feedstocks ▪ Establish combustion facilities that are compatible with CCS
	Gasification	1.7 (0.0 - 5.6)	0.6 (0.0 - 1.1)	▪ Large scale demonstration activities, pursuing efficiency increases (especially through modification of high efficiency gas turbines for an H_2–rich fuel) and reliable, durable production, using sustainable feedstocks ▪ Compatibility with CCS
Advanced Biofuels	Gasification Routes	7.9 (0.0 - 67.8)	1.1 (0.2 - 3.6)	▪ Large scale demonstration of a fully integrated plant ▪ Improved catalysts and syngas clean-up to enable cheaper, more reliable production at a smaller scale
	Pyrolysis Derived Fuel	3.9 (0.0 - 65.6)	0.7 (0.0 - 4.8)	▪ Cost reductions through development of co-processing capability in conventional oil refineries ▪ Development of robust fast pyrolysis techniques, capable of utilising mixed feedstock
	Novel Fuels	2.9 (0.0 - 68.1)	0.4 (0.0 - 3.1)	▪ *For biological systems:* Cost reductions and reliability improvements through bacteria and yeast optimisation ▪ *For chemical routes:* Cost reductions and reliability improvements through catalyst optimisation
	Lignocellulosic Ethanol	3.7 (0.0 - 19.5)	0.5 (0.3 - 1.4)	▪ Development and demonstration of the pre-treatment stage to enable improved use of lignocellulosic material in the fermentation process, and maximise co-product revenues or use on-site ▪ Optimisation of hydrolysis and fermentation techniques (especially for butanol fermentation)
	Lignocellulosic Butanol	2.3 (0.0 - 21.8)	0.6 (0.3 - 2.7)	

Figure 1: Bioenergy TINA summary

Benefit of UK public sector activity/investment: Low | Medium | High

1) Bioenergy landscape – TINA scope

A subset of bioenergy technologies were chosen for detailed analysis, based on a high-level review of their plausible future deployment levels, development stage, ability to utilise more sustainable feedstocks, and innovation potential. Figure 2 (below) shows the feedstocks, conversion technologies and energy end uses which were assessed in detail in this TINA.

The bioenergy technologies assessed can be used to supply energy to power, transport fuel, and heat markets. Biomethane can also be produced, which can act as an energy vector, primarily for the heat market. Anaerobic Digestion and Gasification technologies are assessed as producers of biomethane. Gasification based systems can be used to provide heat, power and transport fuels, by combining a biomass gasifier with different downstream processing technologies. Each of the different downstream gasification technologies are distinct and have unique innovation needs. Alongside gasification, combustion plants are used to provide electricity.

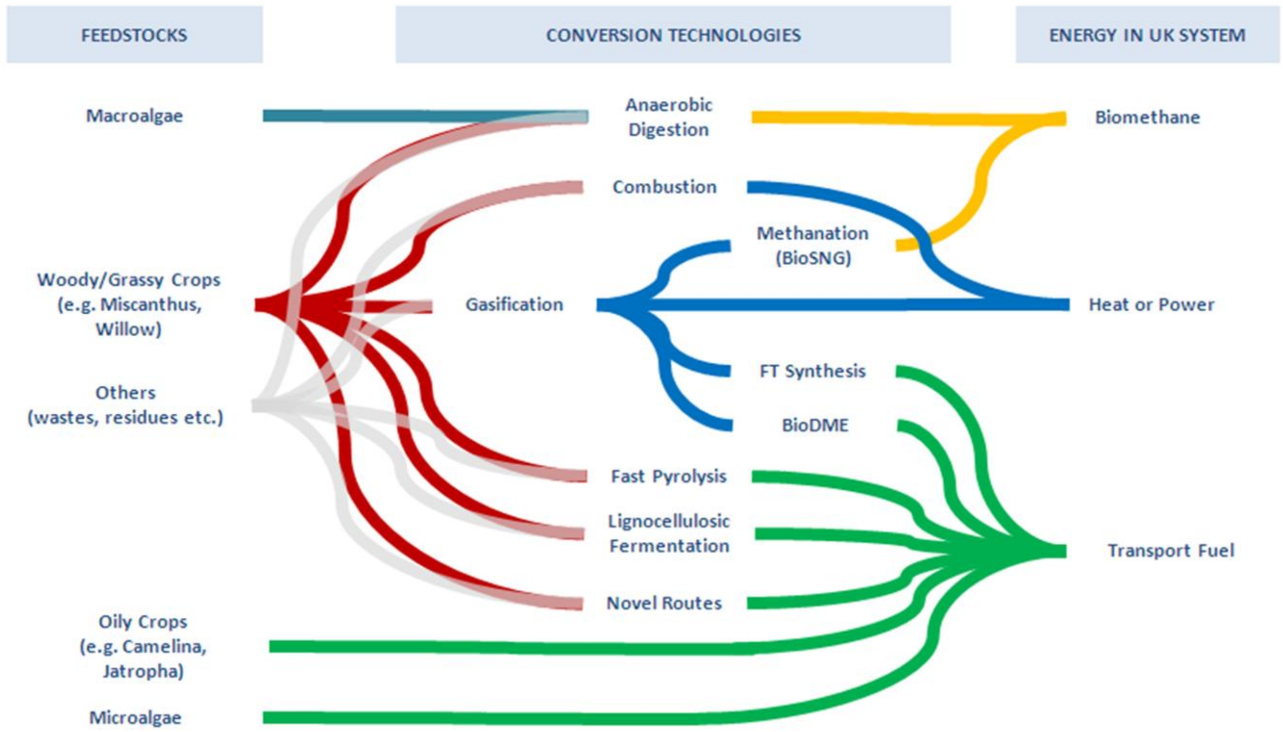
For the production of transport biofuels, in addition to gasification systems, several other conversion technologies are assessed, which use thermochemical, biological or chemical processes to synthesise liquid fuels. The transport fuels assessed are all advanced routes, which are capable of using lignocellulosic feedstocks and wastes.

The feedstocks assessed in detail in this TINA can be grown in water and on land. The land grown, dedicated energy crops are sub categorised as woody/grassy and oily. The aquatic feedstocks are micro- and macro- algae. These were chosen based on a high level assessment of deployment potential and because they have the potential to be grown in areas unsuitable for food crops, which is potentially more sustainable than first generation energy crops. Regarding conversion routes, microalgae is assessed as being used to produce transport fuels and macroalgae (seaweed) is assessed as being used to produce biomethane in adapted anaerobic digestion systems. Fermentation to ethanol is another process that can be applied to macroalgae to produce transport fuels, but that is not assessed in detail in this TINA. Innovations to increase the supply of other feedstocks (e.g. wastes, forestry residues and agricultural residues) are not assessed in detail but, as shown in the table below, technologies that can utilise these feedstocks are assessed.

First generation crops and biofuel conversion processes were not studied, nor were small biomass boilers, hydrotreated vegetable oils (HVO), pre-treatment techniques including chipping, pelletisation and torrefaction, nor modifications to engines for biofuels. Although these areas were identified to have large potential markets, there are comparatively fewer remaining innovation opportunities or challenges to overcome (compared to the chosen subset), hence these areas were not selected for detailed analysis.

Figure 2: Bioenergy flow chart for routes covered within the Bioenergy TINA

(This is not an exhaustive illustration of the complete bioenergy landscape, but simply shows the cross connections of the feedstocks and technologies assessed in this bioenergy TINA)



2) Bioenergy will play an important role in the UK energy system

iii. Overview

Bioenergy resources are very valuable to the UK energy system in comparison with other low carbon alternatives because of their flexibility, cost, suitability to existing infrastructure, and potential to generate negative emissions via CCS.

Bioenergy is derived from a range of feedstocks and converted into different energy end uses i.e.- biomethane (a natural gas replacement), bioheat, biopower and biofuels. Table 1 shows the UK deployment potential for the technologies assessed in this report across these areas.

These figures were generated using energy system modelling exercises to understand the plausible deployment levels for different technology options. We have set low, medium and high deployment ranges reflecting currently available knowledge about the likely 'best use of biomass' across competing routes. The ranges selected are chosen to capture the full range of feasible deployment scenarios for individual technologies, and are neither forecasts for the UK, nor targets for policy makers. While the medium scenario was designed to provide an approximately additive picture of potential deployment across bioenergy technologies, the high scenario is not consistently additive across the different technologies.

While the way bioenergy was used within the UK energy system was found to be susceptible to various exogenous and endogenous conditions, the overall utilisation rates of bioenergy within the models were typically found to be high – provided low embedded emissions.

Method

The deployment ranges were determined using Committee on Climate Change MARKAL runs for the fourth carbon budgets, DECC 2050 calculator scenarios, and customised runs of the ETI's Energy Systems Modelling Environment (ESME) model. The MARKAL and ESME model specifications meet 80% emissions reduction targets by 2050, at lowest cost, with resource constraints, and energy security parameters. Our customised runs varied the performance of exogenous market conditions (e.g. fossil fuel prices, availability of Carbon Capture and Storage, degree of demand reductions) and one endogenous condition, biomass availability.

Sustainable feedstocks

Bioenergy supply is ultimately limited by the availability of feedstocks. The vast majority of bioenergy available within the model was taken up across different model runs, with the availability of feedstock as a key constraint and the core driver of overall deployment.

There are significant sustainability concerns in reaching maximum bioenergy deployment levels, which would have to be monitored and reassessed as higher penetration levels are pursued. Prominent among these concerns are land use change impacts, the use of agricultural land for fuel production, air quality concerns[2], impacts on biodiversity and emissions from land use change.

Given these constraints, it is estimated that bioenergy feedstocks could supply ~400-2000PJ to the UK by 2050 (around a tenth to a fifth of UK total primary energy supply)[3]. By 2050 domestic sources of biomass could supply ~300-700PJ, around 50% of which could be from dedicated woody/grassy energy crops. The rest of the UK's domestic biomass would come from a mix of other smaller sources (e.g. forestry and agricultural residues, sawmill co-products, etc.). Domestic sources of wastes are estimated to supply ~100-170PJ to the UK. The remaining bioenergy feedstock potential is from imports, which could be imported as chipped biomass or refined biofuel, with the UK being estimated to take up to 3% of global supply by 2050.

Sustainability uncertainties are greatest for our high deployment scenarios, due to required land use (see New Energy Feedstocks overview in this section of the document for more detail).

Conversion and energy end uses

Bioenergy feedstocks can be converted into a variety of energy end uses: biomethane, bioheat, biopower and advanced biofuels[4]. Which of these will dominate is uncertain, driven by many factors: predominantly the existence of CCS, the availability of alternative technologies and fossil fuel prices across the different markets.

In all scenarios, biomethane is expected to be deployed, predominantly from anaerobic digestion, which is a mature technology and is well suited to processing wet biomass and low cost wastes. Imports of biofuels are expected to be accepted to as high levels as can be sustainably supplied.

Deployment levels of biopower, domestic biofuels and bioheat are largely dependent on the availability of CCS. If CCS is available, biopower in combination with CCS was found to be favoured due to the low cost of energy production and high carbon savings/negative emissions. If CCS is not available, higher levels of domestic biofuels and bioheat are expected to be produced.

A range of conversion technologies could potentially be used to convert feedstocks into the energy end uses above. Many of these conversion technologies are unproven at scale and not yet cost-competitive.

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[2] Air quality concerns could restrict long term bioenergy use, due to emissions of PM10 and NOx. This issue is not explicitly addressed in this report as it was not identified as a 'game changing' restriction (filters are currently available which have been shown to reduce these emissions by up to 80% in combustion systems).

3 The UK government bioenergy strategy sets 12% as a central estimate of the contribution of bioenergy to the UK's total primary energy demand, within a range of 8-21% - in this report final energy demand was varied across 3 scenarios, leading to slight differences in percent of demand supplied.

[4] Production of biochemicals is analysed separately, in the industrial energy efficiency TINA.

Table 1: Estimates of UK bioenergy deployment for the technologies considered in this report and their potential contribution to the energy market they supply (written as central estimate (low-medium). Percentages of energy market demand are provided for indicative understanding of technology potential. (Significantly, these are subject to the demand profile assumed, which was varied in this analysis). Comparisons of deployment levels to other reports are best done using absolute deployment levels. Deployment levels are not all additive in the high scenarios, owing to feedstock constraints (the focus of this report is on individual technologies' potential, not overall bioenergy markets).

Category	UK Deployment 2020 (PJ)		UK Deployment 2050 (PJ)		Percent of Energy Market Demand Met in 2050		Energy Market Percent is derived from
	Domestic Production	Imports	Domestic Production	Imports	Domestic	Imports	
New Energy Feedstocks							
Woody/Grassy Crops	33 (12 - 47)	8 (0 - 62)	217 (160 - 304)	74 (0 - 470)	3%(3% - 3%)	1%(0% - 5%)	
Oily Crops	0 (0 - 1)	12 (0 - 52)	2 (0 - 35)	46 (0 - 137)	0%(0% - 0.4%)	0.6%(0% - 2%)	
Microalgae	0 (0 - 0)	0 (0 - 0)	0 (0 - 0)	29 (0 - 85)	0%(0% - 0%)	0.4%(0% - 1%)	
Macroalgae	0 (0 - 0)	0 (0 - 0)	8 (0 - 79)	0 (0 - 0)	0%(0% - 1%)	0%(0% - 0%)	
Total:	***33 (12 - 47)***	***21 (0 - 115)***	***227 (160 - 384)***	***149 (0 - 692)***	***3%(3% - 5%)***	***2%(0% - 8%)***	***Primary Energy Supply***
Biomethane							
Anaerobic Digestion	8 (8 - 15)	0 (0 - 0)	103 (58 - 156)	0 (0 - 0)	6%(2% - 11%)	0%(0% - 0%)	
BioSNG	0 (0 - 1)	0 (0 - 0)	41 (0 - 204)	0 (0 - 0)	2%(0% - 14%)	0%(0% - 0%)	
Total:	***8 (8 - 16)***	***0 (0 - 0)***	***193 (103 - 361)***	***0 (0 - 0)***	***8%(3% - 19%)***	***0%(0% - 0%)***	***Gas Demand***
Bioheat							
Small Scale	40 (4 - 40)	0 (0 - 0)	18 (0 - 164)	0 (0 - 0)	1%(0% - 11%)	0%(0% - 0%)	
Large Scale Systems	0 (0 - 0)	0 (0 - 0)	38 (0 - 102)	0 (0 - 0)	3%(0% - 7%)	0%(0% - 0%)	
Total:	***40 (4 - 40)***	***0 (0 - 0)***	***56 (0 - 164)***	***0 (0 - 0)***	***4%(0% - 11%)***	***0%(0% - 0%)***	***Heat Demand***
Biopower							
Combustion	23 (23 - 42)	0 (0 - 0)	120 (15 - 244)	0 (0 - 0)	4%(1% - 13%)	0%(0% - 0%)	
Gasification	0 (0 - 0)	0 (0 - 0)	38 (0 - 136)	0 (0 - 0)	1%(0% - 7%)	0%(0% - 0%)	
Total:	***23 (23 - 42)***	***0 (0 - 0)***	***157 (15 - 244)***	***0 (0 - 0)***	***5%(1% - 13%)***	***0%(0% - 0%)***	***Electricity Demand***
Advanced Biofuels							
Gasification Routes	0 (0 - 0)	4 (0 - 23)	11 (0 - 324)	63 (0 - 417)	1%(0% - 15%)	3%(0% - 20%)	
Upgraded Pyrolysis Oil	0 (0 - 0)	5 (0 - 23)	3 (0 - 324)	19 (0 - 417)	0%(0% - 15%)	1%(0% - 20%)	
Novel Fuels	0 (0 - 0)	3 (0 - 23)	4 (0 - 324)	24 (0 - 417)	0%(0% - 15%)	1%(0% - 20%)	
Lig. Ethanol	0 (0 - 9)	9 (0 - 28)	0 (0 - 127)	33 (0 - 152)	0%(0% - 6%)	2%(0% - 7%)	
Lig. Butanol	0 (0 - 6)	3 (0 - 17)	0 (0 - 127)	24 (0 - 152)	0%(0% - 6%)	1%(0% - 7%)	
Total:	***0 (0 - 9)***	***24 (0 - 28)***	***18 (0 - 324)***	***163 (0 - 417)***	***1%(0% - 15%)***	***9%(0% - 20%)***	***Transport Fuel Demand***

iv. Breakdown by Sub-Area

The sections below further detail the potential for each bioenergy sub-area (New Energy Feedstocks, Biomethane, Biopower, Bioheat and Advanced Biofuels) to 2050, based on the underlying TINA deployment analysis.

New Energy Feedstocks

The feedstocks assessed in detail within this report are i) dedicated energy crops which could be grown on marginal land and ii) aquatic crops, which could be grown in water, both in natural conditions (e.g. at sea) or in facilities that could be built on marginal land (e.g. raceway ponds). The land grown dedicated energy crops considered are subcategorised as either woody/grassy crops or oily crops[5]. The aquatic feedstocks assessed are microalgae and macroalgae (see section (1) for more detail on how these crops could feed into the UK energy system).

Collectively, domestic production of these new energy feedstocks could provide ~3-5% of UK primary energy supply by 2050. Imports of liquid biofuels (e.g. from Jatropha or microalgae) and woody/grassy chips could add a further ~8% to UK energy supply. The range of domestic new energy crop deployment levels is primarily driven by yield improvements, increased utilisation of marginal land in a way that does not compromise the delivery of important ecosystem services, and innovation to enable the use of new aquatic feedstocks. Import availability is also dependent upon the development of international markets and the percentage of these markets that can fairly be expected to be available to the UK.

Woody/grassy dedicated energy crops were found to have the greatest and most robust deployment potential. They are estimated to provide over three quarters of new feedstock supply, as they have the most available land, their use is robust to bioenergy end uses and they are proven to work. Their core limiting factor is sustainable use of land.

Most of the remaining deployment is from land-based oily crops, UK production of macroalgae and imports of microalgae. Microalgae is only expected to be available as an import as it is not optimally grown in the UK, due to climatic conditions. Limited UK macroalgae production is estimated by 2050 in the central and high scenarios, due to uncertainties around available sea area and potentially preferable use in other markets, for non-energy purposes.

This TINA estimates up to 0.6Mha of sea would be used to grow macroalgae for energy production, in line with DECC 2050 pathways analysis. Future detailed analysis from the Crown Estate is expected to offer further insights into the area of the UK seabed which macroalgae could be farmed on. Initial insights from this indicate that significantly greater production might be possible, by a factor of two or three. However, increased production will not necessarily mean greater use as an energy source, owing to the higher profitability of macroalgae in pharmaceutical, chemical and food markets.

For the land based crops up to 0.9 Mha of UK land is assumed to be sustainably available for dedicated energy crop production by 2050. This is in line with the UK Government Bioenergy strategy which assumes that 0.3-0.9Mha land could sustainably be available for UK feedstock production[6]. Sustainability concerns and uncertainties are nevertheless a key limiting factor, which would benefit from increased innovation.

Imports can also significantly increase the availability of these new energy feedstocks. Imports of oily crops and microalgae are expected as liquid biodiesel. Woody/grassy crops are expected to be imported as chips. Imports are set to zero in the low scenario, to reflect the possibility of low availability from international markets, which could potentially not develop significantly. In the central and high scenarios the availability of imports is capped using IEA global deployment data. In the central share UK imports are capped at a “fair share” of 1.5% of global production, this share is increased to 3% in the high scenario.

Biomethane

Consistently high levels of biomethane were produced by the model runs, which are estimated to meet 3-19% of UK gas demand by 2050, often for industrial processes, which have few alternatives.

In the central case biomethane provides 8% of UK gas demand, predominantly from Anaerobic Digestion facilities, due to their higher technical readiness and strengths in converting of low cost wet waste, which is expected to be a significant feedstock in all scenarios. The range of gas demand met by bioenergy systems reflects the range of bioenergy availability and the technical uncertainty in the other biomethane producing technology assessed, BioSNG.

BioSNG plants have greater technical uncertainties and optimally use drier lignocellulosic feedstocks, which can be used in a wider range of conversion technologies. Due to their technical uncertainty in the low scenario deployment is set to zero. Therefore, 100% of biomethane is expected to be provided by Anaerobic Digestion in the low scenario.

Typically BioSNG plants were not favoured in model runs, due to the higher carbon saving benefits of centralised biomass power production with CCS. To reflect this, in the central scenario only 10% of UK biomass is used in BioSNG, while to provide a plausible upper limit 50% of UK biomass is allocated to BioSNG plants in their high scenario.

[5] Innovation to increase the supply of waste and other feedstocks is not assessed. The conversion technologies assessed can use these feedstocks though.

[6] The strategy further states that the range of upper estimates of land could technically be used for dedicated energy crop production in England and Wales, without impinging on food production, ranges from 0.93 to 3.63Mha.

The highest levels of production were realised in scenarios with increased constraints on heat and insulation technologies, constrained CCS and high fossil fuel prices. The lowest scenarios are constrained by low biomass availability. No imports were modelled for biomethane.

Biopower

Biomass power is frequently utilised in model runs, to reach emissions targets at lowest cost. Across the three scenarios biomass is used to meet around 1%, 5% and 13% of UK power demand respectively.

Typically the majority of biomass is used in model runs to produce power, due to the carbon benefits of using CCS in conjunction with biomass – in the central scenario, around 84% of domestic biomass goes into power (up to 96% of UK biomass goes to power in the highest scenario).

Low levels of biopower are consequently found in scenarios with low bioenergy availability and reduced emissions savings (either due to the absence of CCS or increased land use emissions). In the lowest biopower scenario, with no CCS and increased land use emissions, 45% of used biomass went to biopower, with around 100PJ remaining unused, due to embedded emission factors.

The technologies modelled to produce biomass power are gasification and combustion systems. Gasification technologies will compete with combustion systems for use of the same feedstocks. Currently combustion systems are significantly more proven and cheaper than gasification plants. This fact is reflected in the low scenario, where gasification systems have zero deployment. Long term cost predictions of gasification systems show them reaching parity with combustion by 2030 and potentially being around 1p/kWh cheaper by 2050. They have the further advantage of having higher biomass conversion efficiencies, 42-56%, in comparison to 30-40% for combustion, which is a significant benefit in a biomass constrained system. High utilisation of combustion systems is nevertheless expected in all scenarios, due to their current deployment levels and proven reliability. Biopower generated via gasification is capped at around 56% in the high scenario by 2050, in line with IEA estimates of global combustion and gasification deployment.

Bioheat

Supply of heat from biomass feedstock was modelled as being supplied for small scale applications, to residential and commercial buildings, and at a large scale for industrial applications and for CHP systems.

A large deployment range was determined for bioheat systems, driven by the relative performance of other low carbon heat technologies, the existence of CCS, overall heat demand, the costs of electricity production, and the existence of district heat networks.

In the central scenario around 11% of UK biomass goes to heat, thereby meeting 4% of UK heat demand. In the high scenario around 30% of UK biomass goes to heat, supplying 11% of UK heat demand by 2050. This scenario had a higher than average costs of electricity production, high availability of biomass and limited competitor technologies (lower heat pump performance, restricted heat networks, limitations on solar hot water installations).

Near zero deployment levels were estimated in the low case, as other competing technologies are found to be favoured, such as heat pumps, electric resistive and district heating, while CHPs are not deployed. Industrial processes are identified as having few low carbon alternatives, however if direct supply of heat from gasification or combustion systems is not used biomethane is expected to be utilised.

Advanced Biofuels

In the majority of model runs *domestic biomass* is only utilised to a limited extent to produce advanced biofuels. Central estimates of domestic production are representative of the majority of model runs and see 1% of UK transport fuel demand met by domestically produced biofuels, using ~5% of available feedstock. *Imports* of biofuels were however found to be utilised to as high levels as could be supplied by international markets – in central estimates 9% of UK transport fuel demand is met by imports.

In the central case the determined advanced biofuel deployments are spread across all the advanced conversion technologies in question, based on current commercial activity and IEA deployment estimates from the IEA Biofuels Roadmap and IEA Bluemap. Each advanced biofuel technology assessed has its own high scenario, in which it has particular success and consequently meets the majority of advanced biofuel demand.

In the low scenario domestic production of advanced biofuels was also set to zero, to further reflect the technical uncertainty of these technologies and because the majority of available biomass was typically used to produce biopower. Imports were also set to zero in the low bioenergy availability scenario, reflecting both the fact that advanced biofuels are still not technically proven, and that international markets may only develop to a limited extent in cases where biomass is preferentially used in other sectors.

In the highest deployment scenario, domestic production of advanced biofuels is equivalent to over three quarters of UK aviation fuel demand by 2050, using half to three quarters of available feedstock, depending on pathway and achieved conversion efficiency.

The high deployment level was produced by select model runs (those with particularly high biomass availability and constrained CCS). This step change in biofuel deployment is significantly higher than the central deployment scenario, which is drawn from a representative scenario that matches the consensus view of the majority of the model runs (NB: CCS with biofuels weren't captured by ESME or MARKAL and are regarded as an innovation to reconsider in future years, following successful innovation in CCS and Advanced Biofuel Conversion processes respectively. Notably, more recent modelling for the UK Government Bioenergy Strategy, did allow CCS with biofuel conversion processes – and also arrived at a comparable deployment level in the high scenario).

Imports of biofuels were accepted to as high levels as possible by the model, with global supply being used to provide 42% of UK transport fuel demand by 2050 in the scenario with highest uptake, limited at a "fair share" of 3% of global supply.

3) Innovating to Realise Bioenergy Potential at Lowest Cost

i. Overview

The two key innovation themes to enable optimal deployment of bioenergy in the UK are increasing feedstock supply sustainably and developing conversion technologies which can economically and efficiently process this feedstock.

Figure 3 and Table 2 show that there are a range of possible feedstocks and conversion technologies with varying innovation needs, spanning Technology Readiness Levels (TRL) 3-9, which have high cost reduction potential.

Innovations for Sustainable Feedstock

Increased levels of sustainable feedstocks require innovation to enable production at sea or on marginal land (land which is not suitable for food production or other important ecosystem services). Enabling large scale deployment of **land grown** crops requires improving the business case for farmers, through lower cost crops, shorter growing cycles and ease of replanting, which will require innovation. Innovation is estimated to have the potential to reduce costs of production by 53-80% across different types of crops. The greatest lever identified to achieve this is yield increases, which are estimated to have a stretch potential of 1.6% per annum. Achieving stretch increases would likely require controversial techniques such as genetic modification or genomics.

Innovations for Conversion Technologies

Highest cost reduction potential is identified for the **earlier stage technologies** which are at or below TRL 7 and have not yet comprehensively been proven at scale. This includes all of the advanced biofuel conversion technologies, BioSNG for biomethane production and large scale gasification systems for biopower. For these technologies cost reductions of 30-50% are estimated over the next decade, as they become more commercially viable through larger scale trialling. A further 20-30% potential cost reduction is estimated to 2050 from component level improvements and efficiency gains. Optimising these systems to produce multiple outputs and also high value chemicals is identified as a way to accelerate them along the learning curve and also to create increased profits, which are more resilient to short term market conditions.

Near commercial technologies above TRL 7, combustion and gasification for bioheat, combustion for biopower and anaerobic digestion for biomethane, are estimated as having cost reductions of 12-33% by 2050. The primary innovation needs for these technologies are efficiency gains and component level improvements, which are expected to be incrementally achieved over the next 40 years.

ii. Breakdown by Sub-Area

The rest of this section details the key innovation needs across the technology sub-areas considered in this report[7].

New energy feedstocks

Dedicated energy crops grown on land and in aquatic conditions are assessed in this report. The innovation needs for these feedstocks broadly fall into two categories: improving plant characteristics and developing improved cultivation techniques; these would ideally be pursued synergistically. The key plant characteristics to improve across all crop types are yield, energy content, quality of land requirements and reduced agrochemical needs. Large-scale deployment will require these characteristics to be optimised to the various geographical regions of the UK. The second category of innovations, the development of improved farming/cultivation techniques, would involve new production techniques and equipment, and the valorisation of co-products.

These innovations would have significant effect throughout the UK energy system because around half of the final energy generation costs from many conversion processes come from the purchase of the feedstock.

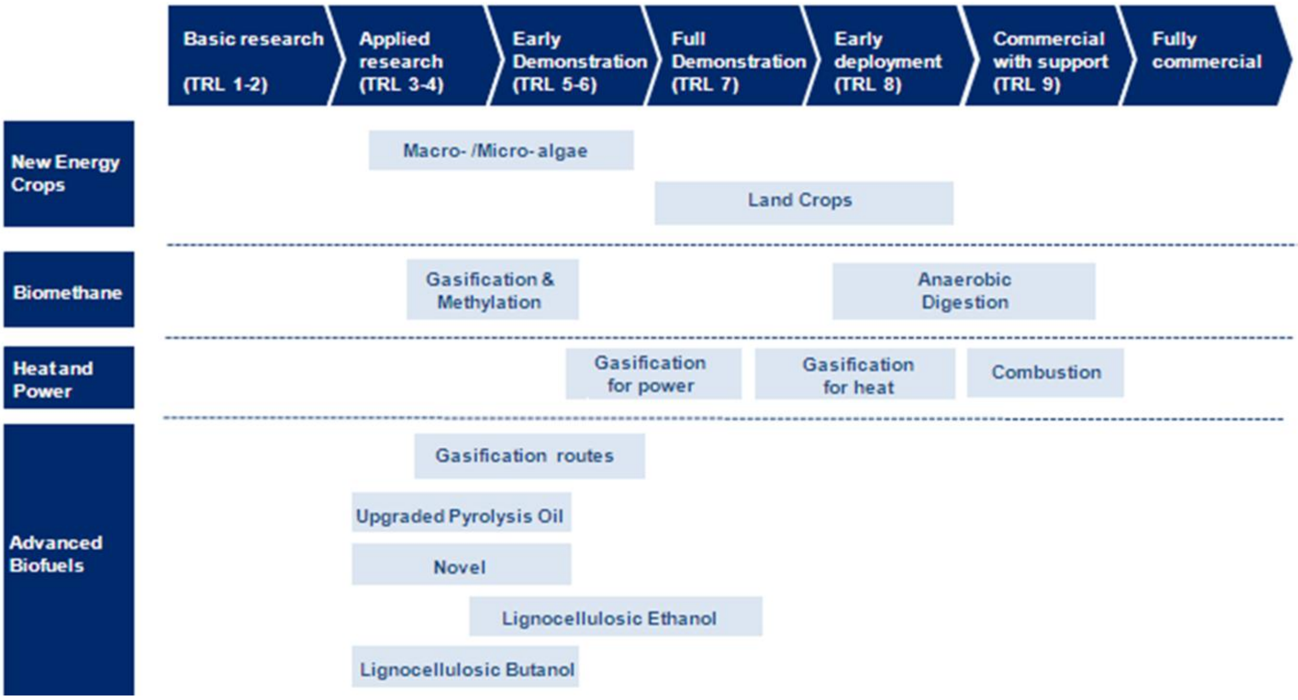
The land based crops considered in this analysis are those which could be grown on marginal land not suitable for food crops or other important ecosystem services. These crops are categorised as 'Woody' (e.g. Poplar, Willow, Eucalyptus), 'Grassy' (e.g. Miscanthus, Swtichgrass, Weed Canary Grass) and 'Oily' (e.g. Camelina and Jatropha[8]). These crops are available at TRL 7-8, see figure 3, but basic research is being undertaken to improved plant characteristics, some of which are being demonstrated at TRL 5-6.

Innovations to improve plant characteristics are estimated to enable cost reductions of up to 47% and 56% for woody/grassy crops and oily crops respectively. Achieving this would require (i) adaptation for cultivation on marginal lands in a way that does not compromise the delivery of important ecosystem services (ii) yield increases on these marginal lands (iii) lower cost of inputs, primarily from reduced use of agrochemicals (iv) the development of species that are less susceptible to pathogens; and (v) crops with increased energy contents. Yield improvements are found to source up to 80% of estimated cost reductions. Stretch yield improvements are estimated to be 1.6% p.a. based on historical trends and expert opinion on achievable tonnes per hectare.

[7] The overall cost reduction potential for each technology is detailed in Table 2 which is drawn from supporting TINA evidence packs.

[8] Jatropha is not expected to be deployed in the UK – it is an example of a crop which would be grown in warmer climates

Figure 3: Bioenergy technology readiness levels



The innovations to improve *plant characteristics* would be pursued through increased deployment activities and research in plant science and agronomy (e.g. through genomics and selective breeding). Stretch yield improvements would require genetic modification which has significant public acceptance issues in the UK and regulatory constraints.

Innovations to improve the *farming techniques* of land grown crops are required to enable lowest cost production, improve the business case for farmers and to determine how to close the gap between lab and farm yields. Improvements to farming practice could be achieved by: optimising production/distribution systems to both farmers' and consumers' needs, which could be done with pre-processing/densification systems at the farm level, which could potentially enable cheaper product distribution, by reducing overall transport costs, result in a more useful and consistent product, and have reduced storage requirements. Precision farming techniques could also be adapted to lower the costs of production.

There is a need to carry out lab based activities in tandem with deployment activities, to ensure that yield improvements are also achieved on the farm and to pursue increased understanding of different species needs to enable optimal selection of plants in specific geographical conditions. Further to this, deployment can also be increased by developing crops which are more suited to farmers' business models, with shorter maturity times, and increased ease of grubbing up.

The aquatic crops analysed in this TINA are microalgae and macroalgae, which are at TRL 3-6. These require a series of innovations to enable lower costs and efficient production at scale.

Macroalgae is expected to be deployed in the UK, while microalgae is not, due to climatic constraints. Innovation to enable increased deployment of microalgae at lower cost could still enable greater supply of bioenergy imports.

Innovation on **microalgae** could enable up to 67% cost reductions by 2050, predominantly by enabling cheaper cultivation, which represents the majority of costs. Innovations on species *characteristics* are required to increase yields and energy content, keeping an optimal growth/energy storage balance. Innovation is also needed to develop species that are robust to a variety of conditions and less susceptible to contaminants/pathogens. Laboratory stage research on species types as well as from trial deployment activities could enable this. Innovation to improve laboratory processes could also enable quicker cataloguing of species types, speeding up the analysis of microalgae strains and selection of those with advantageous traits.

Improved cultivation and harvesting *techniques* are also required to farm microalgae at scale. These include algal cultivation methods (e.g. photobioreactors), dewatering processes (e.g. improved centrifugation, flocculation), pre-treatment/hydrolysis processes (e.g. ultrasound and use of enzymes) and oil extraction techniques.

Macroalgae innovation could reduce costs by up to 80% by 2050 and is needed to develop farming techniques for UK regional conditions. The majority of cost reductions are from improvements to cultivation and harvesting, from improvements to species characteristics and farming processes. Yield increases, achieved predominantly through lab research, are calculated to significantly reduce the costs of cultivation. Other key *characteristics* to improve are moisture content, carbohydrate content and photosynthetic conversion efficiencies. Improved identification systems for new algae strains would facilitate the pursuit of these innovations.

Sea farming *techniques* and infrastructure would have to be developed for local conditions, if development is to be achieved in the UK. Cultivation techniques could utilise horizontal or vertical lines, with potential synergies to offshore wind farms, and could build upon current activity in farming macroalgae for food and the cosmetics industry.

Biomethane

The upgrading of biogas produced by Anaerobic Digestion technology and the methanation of syngas thereby producing biomass-derived synthetic natural gas (BioSNG) are considered in this report as potential technologies for producing biomethane for gas grid injection.

Anaerobic Digestion is a proven technology, around TRL 8-9. Significant innovation potential still exists through component level improvements, seeking to (i) lower costs, (ii) utilise a wider range of feedstocks, (iii) use digestate residues, (iv) monitor process performance, and (v) optimise bacterial strains. Based on the commercial nature of this technology this component level innovation could be pursued through deployment activities.

Energy production costs are estimated as being reduced by up to 34% by 2050, from innovations across system components. The pre-treatment, digestion steps all have high improvement potential, from a swathe of possible developments offering up to 45% of the potential cost reductions and the capacity to use more feedstock types. Up to 51% of cost savings are estimated to be from improved gas upgrading and injection systems, potential technologies for this are Pressure Swing Absorption, Membrane Separation and Cryogenic Separation.

BioSNG is an unproven technology at full scale, currently around TRL 4 - 5, which requires innovation to reduce costs and integrate various components from other applications into a full scale plant. By 2050 up to 67% cost reductions are estimated, around a third of which will be enabled by conversion efficiency improvements from 64% to 70%. The majority of the remaining reductions are from improved syngas cleaning and catalytic methanation processes (33%) and full system integration (26%).

Improved syngas clean-up and synthesis is a key area of innovation need, as these steps are prone to spoiling from contaminants (such as tars). Hot gas clean-up and improved catalysts are potential solutions to this, which can also lower costs. This area of innovation is further elaborated upon in the advanced biofuels discussion (below) for similar gasification technologies.

Increased deployment of this technology could potentially be enabled by advanced plant designs which could enable smaller scale reactors than are currently required by economies of scale. This would enable lower feedstock delivery costs, increased sustainability, and potentially have higher yields, efficiency and reduced equipment costs.

Bioheat

Bioheat systems are modelled as meeting demand for small scale residential and commercial facilities, large scale industrial facilities and CHPs. These are currently commercially deployed with support (TRL 8-9) and most possible innovations focus on reducing costs in functioning systems. A lack of local heat networks in the UK is identified as a limitation to deployment. Targeted innovation could lower the costs of heat networks, through reducing component costs and pursuing optimum system design.

Bioheat conversion technologies are typically combustion based, which is commercially available for heat application. Gasification systems can also be used for small scale heat and CHP applications, which are commercially deployed with support in some countries. The innovation needs for these conversion technologies are fewer than for power application, since heat production is a simpler process, not requiring power generators after a boiler or gasifier. For gasification systems lower grade syngas can also be used, enabling the use of updraft and downdraft fixed bed reactors.

By 2050, innovation across the sub areas of bioheat systems is estimated to reduce the levelised costs of energy generation by up to 14% for small scale systems and 12% for large scale systems. The majority of this is achieved by overall efficiency improvements, which reduce feedstock purchase requirements. Stretch efficiency improvements across the production system (to 85 - 90% by 2050) are estimated to reduce costs of bioheat production by 44% for small scale systems and 53% for large scale systems.

Bioheat deployment can also be increased from innovations to technology components other than the conversion technology, such as installation method, distribution and production control systems and heat delivery methods. 24% of cost reductions can be driven by innovation on these components.

Biopower

Combustion and gasification technologies are assessed in this report to produce electricity from biomass.

Combustion is already a commercial technology for coal feedstocks and is commercial with support in the UK when co-firing or using biomass feedstocks only. The innovation opportunities for combustion focus on incremental improvements to current systems, increasing efficiencies and developing boilers which are robust to a wider range of feedstocks. This could be achieved using Organic Rankine Cycle power generation systems and adapting boiler technology from coal systems (e.g. circulating fluidised bed boilers). Innovation is estimated to enable efficiency improvements from 30% now to 40% by 2050 and levelised cost of electricity reductions of about 15%.

Large scale biomass **gasification to power** is at the demonstration stage, reaching TRL 6-7. Technical challenges have hindered past projects, all of which are no longer operational. Further technology development requires demonstration of efficient reactors at scale, which are robust to a variety of feedstocks and resilient to slagging, corrosion and agglomeration of reactant. Novel approaches for biomass reaction, which currently range from TRL 1-4, could present breakthrough improvements.

Costs of energy generation are estimated as being reduced by 48% for gasification to power by 2050. Around one third of these estimated reductions are from improved reactors and syngas clean up systems. This could be achieved with hot gas clean up and by reducing the costs of oxygen separation. Around half of the estimated cost reductions are from improved power generators; in particular gas turbines, which need to be adapted from natural gas to use syngas, which has lower calorific values. Efficiency improvements (from a baseline of 42%, potentially reaching 56% by 2050) are estimated as driving further cost reduction, through reducing required feedstock input costs, per unit of electricity. Hydrogen turbines or large scale stationary fuel cells could potentially be used to achieve stretch efficiencies.

Innovation is also required to enable these technologies to work with CCS technology, which could have significant effects on deployment through enabling negative emissions. This will require the development of CCS systems as well as their modification to bioenergy use, a topic covered in a separate CCS TINA.

Advanced Biofuels

Advanced conversion techniques are required to enable the production of liquid biofuels from wastes and feedstocks that can be produced on non-arable land. There are currently a range of technologies for this, which are between TRL 3-7 and are yet to be sufficiently demonstrated at scale. The technologies assessed are gasification routes, upgraded pyrolysis oil routes, novel chemical and biological routes, lignocellulosic ethanol, and lignocellulosic butanol. Cost reductions are necessary for each of these, to enable large-scale use.

A range of transport fuels can be produced from **gasification routes,** utilising technical knowledge and developments which have been proven for other applications (e.g. coal syngas), but need to be adapted to biomass systems. At TRL 4-6 pilot plants have been constructed for gasification processes to transport fuels, predominantly for FT synthesis, producing middle distillates (which can be upgraded to diesel, gasoline and/or kerosene). Other plants have produced BioDME, fermented syngas to ethanol and produced ethanol catalytically. FT and

Table 2: Potential impact of innovation levels on levelised cost of energy production, from supporting TINA evidence packs

Bioenergy System	Units	Current LCOE Estimate	Stretch % LCOE reduction 2010-2020	Stretch % LCOE reduction 2020-2050	Stretch LCOE 2050	Note on Cost Calculation Assumptions
New Energy Feedstocks						
Woody/Grassy Crops	£/GJ	7	14%	40%	3	*Don't include conversion to other energy forms*
Oily Crops	£/GJ	41	18%	37%	18	*Converted to biodiesel*
Microalgae	£/GJ	47	26%	42%	15	
Macroalgae	£/GJ	47	37%	44%	9	*Calculations for biogas*
Advanced Biofuels						
FT Synthesis	£/GJ	33	46%	20%	11	*Modelled for woody feedstock at $4/G, which is held constant throughout 2010-2050*
BioDME	£/GJ	37	32%	27%	15	
Upgraded Pyrolysis Oil	£/GJ	43	50%	24%	11	
Novel Fuels	£/GJ	39	41%	35%	9	
Lig. Ethanol	£/GJ	35	52%	16%	11	
Lig. Butanol	£/GJ	43	49%	31%	9	
Biomethane						
Anaerobic Digestion	£/GJ	14	19%	14%	9	*Feedstock costs just from transport*
BioSNG	£/GJ	21	51%	22%	6	*Same feedstock as Adv. Biofuels*
Bioheat						
S/M Residential	£/MWh_{th}	120	8%	6%	102	*Same feedstock as Adv. Biofuels*
S/M Commercial	£/MWh_{th}	55	5%	7%	49	
Industrial Process Heat	£/MWh_{th}	46	6%	6%	40	
District CHP	£/MWh_{th}	35	7%	10%	29	
Biopower						
Combustion	£/MWh_e	66	9%	6%	56	*Same feedstock as Adv. Biofuels*
Gasification	£/MWh_e	89	14%	34%	46	

BioDME plants were used for detailed analysis in this TINA, as the technologies generally share common innovation needs and advanced fermentation routes were assessed within lignocellulosic ethanol and butanol.

The key needs for gasification fuel routes are demonstration that syngas can reliably be produced and converted to fuel from biomass at scale, in a fully integrated plant, without spoiling delicate catalytic components. Cost reductions are also required, which will predominantly come from plant integration and intensification of catalyst processes.

Syngas conversion to fuel from biomass feedstock has proved to be a key technical barrier in previous development and is therefore identified as a lynchpin area of innovation need. Reliable production of syngas and its conversion to fuel requires innovation on syngas cleaning, conditioning, and processing. Possible technologies to enable this are microchannel reactors and hot gas clean-up.

Costs can be reduced by innovation in gasification to fuel systems by up to 50% by 2050. Around a quarter of these cost reductions could come from biomass conversion efficiency increases (maximum estimated efficiency is 58%), which would reduce the amount of feedstock required per unit of fuel produced. Full plant integration is estimated to provide around 30% of the cost reductions, enabling optimal use of heat, power and other products generated on-site. Process intensification of the catalysis step, and to a lesser extent, higher efficiency syngas clean-up, can also provide around 30% of the required cost reduction.

New system designs, using novel reactor technologies which could be used at much smaller scales than current technology, with higher yields, efficiency and reduced equipment costs, could potentially enable significantly higher uptake rates.

Gasification systems can also be specified to produce BioDME. BioDME is a non-drop in fuel, which is a gas at room temperature and pressure, but a liquid at >5bar. Widespread use of fuels of this nature would also require widespread engine conversion and fuel infrastructure development, to enable widespread uptake (not assessed here).

Upgraded pyrolysis oil (UPO) can be produced using technologies which have been developed originally for heat, power, and food industry applications and are at an initial demonstration stage. Application of these technologies to produce transport fuel is at TRL 3-5. The two key steps in the production of UPO are fast pyrolysis followed by oil upgrading. Upgrading could be carried out in stand-alone plants, or integrated within oil refineries, benefiting from onsite hydrogen availability and energy integration.

By 2050 cost reductions of up to 75% are estimated for UPO systems. Feedstock costs are reduced in this case through plant conversion efficiency improvements up to 84%[9]. However, the majority of cost reductions, around 63%, are from the upgrading process. Innovation can reduce costs for the upgrading process by enabling co-processing of pyrolysis oil in conventional refinery units, enabling use of existing infrastructure and commercial technologies. Improved processes could also reduce the costs of pyrolysis oil upgrading, including hydrotreating, catalytic upgrading and fractionation.

Novel chemical routes to fuels are at TRL 3-5 and their innovation need is concept demonstration. These fuels are produced by the use of specially designed catalysts which convert sugars to a range of potential biofuels (isoprenoids, iso-butanol, esters, furanics, alkanes or other synthetic hydrocarbon). Development and optimisation of these catalysts in a means that is suitable to scalable production is a key need of this technology. Costs are least certain for these less developed fuel routes, but parity with other advanced fuel routes is predicted by companies developing them.

Novel biological routes are at a similar stage of development, TRL 3-5. These routes produce fuels from sugars using select bacteria and yeasts. Innovation using synthetic biology and genetic modification is required to continue the development of these biofuels. Companies developing these routes also predict parity with other advanced fuels, as is shown in Table 2. Both of these novel routes are likely to require adaptation to optimally extract sugars from lignocellulosic material via pre-treatment technologies (as for lignocellulosic alcohol routes), although some developers are looking at producing fuels directly from lignocellulosic material without going via sugars.

Lignocellulosic fermentation processes range from TRL 3-7. Ethanol fermentation techniques, based on common first generation systems, are more developed than for butanol, which requires further developments for fermentation bacteria. Lignocellulosic ethanol systems are currently TRL 5-7, while lignocellulosic butanol technologies are currently at TRL 3-5. Both share the key need of reliable and affordable pre-treatment and hydrolysis techniques to enable effective use of lignocellulosic material. Research is at an early R&D stage on new pre-treatment techniques, e.g. ionic liquids, or biological pre-treatment using fungi. Stretch innovation on crucial pre-treatment techniques can also lead to ~34% cost reductions for fuel production.

Innovation on the ethanol and butanol hydrolysis and fermentation steps can reduce production costs and enable optimal use of all sugar types (e.g. C5 sugars). There are several commercial or near commercial hydrolysis processes for this (e.g. dilute acid hydrolysis), although these currently use homogeneous rather than mixed feedstocks. Biological hydrolysis (using enzymes) of biomass is at the later stages of R&D, although some developers are starting to demonstrate these routes at a larger scale.

[9] Efficiency doesn't include H_2 energy input

Development of Consolidated BioProcessing (CBP), which unifies enzyme production, hydrolysis & fermentation into one reactor is an innovation which could address many of these issues and reduce overall costs.

In current systems, the alcohol produced in the fermentation reaction is typically separated from water by distillation, an energy intensive process which can significantly affect the plant energy balance and economics. New processes using membranes and molecular sieves offer potential improvements to the required alcohol separation step.

By 2050, these improvements, alongside efficiency improvements from 31% to 42%, could lower costs by up to 71% for lignocellulosic butanol and 63% for lignocellulosic ethanol.

The production of biofuels through the routes considered here can also be used to produce various co-products in a "bio-refinery": syngas can be used to produce various organic chemicals; separated lignin from lignocellulosic ethanol and butanol processes can be used to generate heat and power, and acetone is also a potential co-product of butanol fermentation. Further understanding the potential of co-products for these conversion routes could lead to high value biochemicals which could have a significant effect on overall plant economics.

4) Value in meeting emissions and energy security targets at lowest cost

The value of innovation to the UK energy system, from bioenergy use, is estimated as £42 (6 - 101)bn[10]. There are two key drivers of this value, increasing the amount of bioenergy deployable, and decreasing the levelised cost of energy production, through system cost and efficiency improvements. Significant contributors to overall value are imported biofuels, and land grown energy crops, as shown in the technology by technology breakdown in table 3. In terms of imported bioenergy, table 3 shows that the vast majority of the value from advanced biofuels, oily energy crops, and micro-algae will likely come in the form of imports, owing to domestic resource limitations. Similar to our analysis of domestic bioenergy feedstock availability, if we believe that UK innovation in bioenergy feedstocks could also increase the amount of imported bioenergy available, the value to the UK in meeting emissions and energy savings targets at lowest costs would be in the tens of billions of GBP. This again strengthens the case for innovation in new energy feedstocks.

However, in the case of imported bioenergy, the estimated value of innovation must be tempered by the fact that the UK may have trouble capturing this value. The estimates in table 3 that the cost reductions estimated for fuel and feedstock production will be reflected in lower market prices. However, it is possible that the cost of production will not be the key driver of price in the international biofuels and crops markets, and that the exporting countries will capture the majority of the value enabled by these savings. In such a case, the savings estimated from imports (e.g. the £41bn for advanced biofuels) would be a significant overestimation. Given the uncertainty of future market developments, we have not tried to estimate this effect, but it should be strongly taken into account when comparing innovation opportunities.

On the whole, considering the impact of bioenergy availability (both domestic and imported), would considerably strengthen the case for innovation in bioenergy feedstocks (especially domestically suitable woody/grassy crops) while potentially reducing the case for innovation in advanced biofuels and imported energy feedstocks.

Calculation method

The savings were calculated using a detailed analysis of the potential for cost reduction from technology innovation and the potential deployment rates for each technology (assuming successful innovation), as overviewed in sections (2) and (3)) respectively. The estimated cost savings to the UK energy system resulting from innovation were calculated against a counterfactual case specific to each broad technology area (e.g. new energy feedstocks, advanced biofuels, etc.). The counterfactual case was one in which no innovation occurs, such that costs remain at those for the best alternative option in that technology area[11]. We then refine this to look at a counterfactual where 'learning by doing' occurs independently from 'learning by research' (see below).

Savings from cost reductions

Realisation of the value to the UK energy system would require continual cost and efficiency improvements in line with the potential outlined in section (3).

These reductions include maximum innovation potential, combining 'learning by research' (driven by RD&D spending) and 'learning by doing' (achieved through the incremental learning associated with increased deployment alone)[12].

[10] This total is a rough estimation because all technologies considered cannot simultaneously reach their highest deployment scenarios. The upper bound on potential saving is calculated by adding the high of: woody/grassy crops, macroalgae, imported advanced biofuels fuels, Anaerobic Digestion and domestic biofuels. The high of BioSNG, Bioheat and Biopower savings were not added to avoid double counting biomass use.

[11] While this 'inflexible deployment' method accounts for competition/alternatives within a broad technology area, it does not allow for complex interactions across technology areas (e.g. substitution between deployment of advanced biofuels and biopower in the context of alternative developments in electric vehicle and renewable electricity technologies). While technically possible, a more sophisticated 'perfect system optimisation' counterfactual would add enormous complexity, and would not substantively affect our central case and the conclusions of this report. Moreover, while this estimation method potentially overestimates innovation value (see Offshore Wind and Marine Energy reports), in the case of the bioenergy technologies as a whole, such overestimation is likely to be nil/small, since the driving constraint to bioenergy deployment is biomass availability, and not the relative success of non-bioenergy technologies.

[12] As defined in Jamasb, T. (2007), Technical Change Theory and Learning Curves: Patterns of Progress in Energy Technologies, The Energy Journal, Vol. 28, Issue 3, 45-65.

Table 3: Savings to the UK energy system from technology innovation by domestic production and imports. These figures are not additive in their high scenarios due to feedstock constraints.

Category	Savings 2010-2050 (£bn)[13] Domestic	Imports	Total
New Energy Feedstocks			
Woody/Grassy	3.5 (2.4- 4.8)	1.2 (0 - 8.7)	4.7 (2.4 - 13.5)
Oily	0.4 (0 - 4.7)	5.2 (0 - 19.6)	5.6 (0 - 24.3)
Microalgae	0 (0 - 0)	1.1 (0 - 2.9)	1.1 (0 - 2.9)
Macroalgae	0.3 (0 - 3.4)	0 (0 - 0)	0.3 (0 - 3.4)
Total:	***4 (2- 9)***	***7 (0 - 31)***	***12 (2- 40)***
Biomethane			
Anaerobic Digestion	2.6 (2.0- 4.9)	0 (0 - 0)	2.6 (2.0- 4.9)
BioSNG	0.9 (0 - 4.8)	0 (0 - 0)	0.9 (0 - 4.8)
Total:	***3 (2- 10)***	***0 (0 - 0)***	***3 (2- 10)***
Bioheat			
Small Scale Heat	1.7 (0.1- 3.1)	0 (0 - 0)	1.7 (0.1- 3.1)
Large Scale Heat	0.2 (0 - 0.9)	0 (0 - 0)	0.2 (0 - 0.9)
Total:	***2 (0 - 3)***	***0 (0 - 0)***	***2 (0 - 3)***
Biopower			
Combustion	3.0 (1.7- 4.7)	0 (0 - 0)	3.0 (1.7- 4.7)
Gasification	1.7 (0 - 5.6)	0 (0 - 0)	1.7 (0 - 5.6)
Total:	***5 (2- 9)***	***0 (0 - 0)***	***5 (2- 9)***
Advanced Biofuels			
Gasification routes	0.6 (0 - 26.4)	7.3 (0 - 41.5)	7.9 (0 - 67.8)
UPO	0.3 (0 - 26.0)	3.7 (0 - 39.7)	3.9 (0 - 65.6)
Novel Fuels	0.3 (0 - 27.8)	2.6 (0 - 40.3)	2.9 (0 - 68.1)
Lig. Ethanol	0 (0 - 7.0)	3.7 (0 - 12.5)	3.7 (0 - 19.5)
Lig. Butanol	0 (0 - 7.9)	2.3 (0 - 13.8)	2.3 (0 - 21.8)
Total:	***1 (0 - 28)***	***20 (0 - 41)***	***21 (0 – 68)***

For the more commercialised technologies (bioheat, combustion for biopower and to a smaller extent anaerobic digestion) only incremental cost reductions are expected, predominantly from learning by doing improvements on different technology components, as well as system-level conversion efficiency increases. The sheer scale of deployment is therefore the key driver of the value calculated for these technologies.

Cost savings from innovation are a greater driver of value for the remaining conversion technologies and feedstocks. Levelised costs of energy production can decrease by over 50% for each of these. Therefore, technology specific innovation is critical to unlocking potential value.

See table 3 for a summary by technology area of the value in meeting emissions and energy security targets at lowest cost (i.e. the value of cost savings to the energy system).

The potential value of innovation can be further broken down for each technology's subcomponents, the reader is directed to the supporting TINA packs for this level of detail.

[13] Medium (Low – High) deployment scenarios, discounted at 3.5% to 2035, and 3.0% between 2035 and 2050, in line with HMT guidelines

Value from increased bioenergy availability

Increased levels of bioenergy availability are a lynchpin factor which can unlock the value from innovation across the production chain. This is true both for the availability of domestic biomass, and the availability of imported bioenergy (in the form of bioenergy feedstocks or bioenergy products like biofuels).

The critical constraint on the domestic deployment of bioenergy conversion technologies (and the related bioenergy products) is the amount of domestic bioenergy feedstocks available. Hence, the availability of sustainable bioenergy feedstock is a key enabler of the deployment of conversion technologies, and innovation in bioenergy feedstocks has *additional* enabling value not fully captured in the cost-savings calculation in table 3. This additional value can be roughly assessed by looking at the value to the energy system from loosening this constraint on biomass. For example, innovation is considered critical to moving from our low to our high deployment scenario for domestic bioenergy crops. The estimated value to the system of such an increase in biomass availability would be >£50bn to 2050 (cumulative discounted). This represents an order of magnitude greater impact than that found by looking at cost-savings potential alone, and it further strengthens the case for innovation in new energy feedstocks.

In terms of imported bioenergy, table 3 shows that the vast majority of the value from advanced biofuels, oily energy crops, and micro-algae will likely come in the form of imports, owing to domestic resource limitations. In the high scenario for woody/grassy crops two thirds of the savings are expected to come from imports.

Similar to our analysis of domestic bioenergy feedstock availability, if we believe that UK innovation in bioenergy feedstocks could also increase the amount of imported bioenergy available, the value to the UK in meeting emissions and energy savings targets at lowest costs would be in the tens of billions of GBP. This again strengthens the case for innovation in new energy feedstocks.

However, in the case of imported bioenergy, the estimated value of innovation must be tempered by the fact that the UK may have trouble *capturing* this value. The estimates in table 3 that the cost reductions estimated for fuel and feedstock production will be reflected in lower market prices. However, it is possible that the cost of production will not be the key driver of price in the international biofuels and crops markets, and that the exporting countries will capture the majority of the value enabled by these savings. In such a case, as mentioned earlier in this section, the savings estimated from imports (e.g. the £41bn for advanced biofuels) would be a significant overestimation. Given the uncertainty of future market developments, we have not tried to estimate this effect, but it should be strongly taken into account when comparing innovation opportunities.

On the whole, considering the impact of bioenergy availability (both domestic and imported), would considerably strengthen the case for innovation in bioenergy feedstocks (especially domestically suitable woody/grassy crops) while potentially reducing the case for innovation in advanced biofuels and imported energy feedstocks.

5) Green growth opportunity

i. Overview

A large global bioenergy market

Significant growth is expected in bioenergy markets globally. Innovation could create additional economic value by helping UK-based businesses to develop competitive advantage and compete successfully in these markets.

By 2050 global production of the feedstocks considered in this report is estimated at 12-151EJ/yr[14], deployment of the conversion technologies covered is estimated at 14-87 EJ/yr. These feedstock and conversion technologies are estimated to have a cumulative global market turnover of £2-14tn to 2050, which could add £6-33bn[15] to the UK economy.

IEA BLUE map and IEA Reference Scenarios were used to estimate global deployment ranges, alongside potential technology ramp-up rates and bottom up estimates of international development activity. Key drivers of global deployment are the availability of bioenergy feedstocks, the scale of worldwide efforts to tackle climate change, final energy demand, fossil fuel prices and the development of other competing or complementary technologies, such as wind and CCS. These factors will not only affect the overall levels of bioenergy used but also the energy market in which it is used, for example increasing constraints on CCS would reduce biopower deployments and lead to increased biofuel or biomethane production. Hence the deployment ranges established are not additive across the high scenarios, due to the limited availability of biomass.

Global deployment figures are used to estimate the potential gross value added (GVA) contribution to the UK economy across each technology area and its subcomponents (e.g. boilers and generators are subcomponents for biopower combustion systems). Firstly turnover figures are calculated by using global deployment scenarios and expected technology costs. Turnover figures are then converted to GVA figures based on known turnover-to-GVA ratios for similar industries (e.g. basic manufacturing, agriculture, high tech services, etc.) which range from 10-65%. Next, we estimate the proportion of the global market that might be accessible (or 'tradable') to UK based companies. Finally, the proportion of the globally accessible market that the UK can capture is estimated based on its competitive advantage. The UK's competitive advantage is graded from low to high, which is used to estimate a percentage of the available market which the UK could potentially be expected to take. ~1% of the market is attributed for areas of low competitive advantage, ~4% for areas of medium advantage and ~8% for areas of high advantage. Within each subcomponent market these numbers are adjusted to account for the specific nature of the UK's strengths.

The UK has key strengths across the different markets

Due to limited land area constraints and consequent feedstock availability it is not expected that the UK will be able to capitalise significantly on the bioenergy market through exports of end-use bioenergy products. However the UK is capable of capitalising on select markets where it has relevant skills and experience. High value to the UK is identified from targeting the design and development of select conversion technologies as well as other areas with high value IP, such as crop development. These are discussed below, for each bioenergy category. Final international business development values are provided in Table 4.

£ 6 – 33 bn net contribution to the UK economy

The successful capture of global business opportunities could generate billions of GBP in value for the UK in each of the bioenergy sectors assessed in this report (see Table 4). The sum value of these different sectors is roughly estimated[16] at £12 (38- 67)bn.

It may be appropriate to apply an additional displacement effect since part of the value created in the export market will be due to a shift of resources and thus partly cancelled out by loss of value in other sectors. Expert opinion has roughly assessed this effect to be between 25% and 75%, so we have applied a flat 50%. Including this displacement factor, bioenergy is estimated to still make a cumulative contribution of ~£19 (6 - 33)bn [11] to 2050.

[14] Further feedstocks from forestry, agricultural residues and wastes could also be used by the conversion technologies in this report. Around 10-19EJ are estimated for these feedstocks.

[15] Discounted at the social discount rate of ~3% and accounting for economic displacement effects.

[16] This is a rough estimate as *all* of the bioenergy sectors will not be able to simultaneously reach their maximum deployment levels due to limited feedstock availability. Cumulative figures are calculated by summing the maximum value of woody/grassy feedstock, microalgae, macroalgae, advanced biofuels, anaerobic digestion and bioheat.

ii. Breakdown by Sub-Area

The GVA that the UK is calculated as being able to derive from international markets, 19 (6 - 33)bn to 2050, is determined from activity across the bioenergy sub areas. The UK's specific strengths across these areas are explained in further detail in this section for New Energy Feedstocks, Biomethane, Bioheat and Biopower.

New Energy Feedstocks

New Energy Feedstocks are estimated to provide £4 (1 - 8) bn in GVA to the UK by 2050. Feedstock production, for both land and aquatic crops, at large deployment requires the selection and development of quality crops, which then have to be distributed, cultivated, harvested and converted to end uses. High value is identified for the UK at the harvesting/cultivation steps due to their overall market sizes and for crop development/selection because of the UK's high competitive advantage. Woody/grassy crops are found to have the highest value, because of their high expected deployments and UK research capabilities.

For **woody/grassy** crops around two thirds of the business value to the UK is estimated to come from crop development, selection and plant material supply, where c.70% of the market is expected to be accessible to international competition. The UK is assessed to have medium-high competitive advantage, based on wide ranging research covering Short Rotation Coppice, Miscanthus and other areas and the world class research programmes and facilities at the BBSRC Research Institute at Rothamsted and various Universities (Aberystwyth, Southampton, Cambridge, Durham, Edinburgh, Exeter, Glasgow, Leeds, Imperial, Nottingham, Oxford, Sheffield, Warwick and York). In addition, the UK could derive competitive advantage as an earlier adopter with some of the largest Willow plantations in Europe. Based on this, the UK is estimated as having medium-high competitive advantage in the crop development and selection market

The other third of the business value that the UK can capture from woody/grassy crops is from cultivation and harvesting activity. Only 10% of the cultivation/harvesting market is expected to be internationally accessible as national production is generally expected to be dependent on local labour. High tech agricultural equipment sales would be the main means of taking advantage of these markets, which the UK is identified as having medium strength in.

For **oily crops,** around 45% of the business value to the UK is expected from crop development and selection, for which the UK is assessed to have medium-high competitive advantage based on commercial activity on Jatropha (e.g. from Quinvita). 55% of the business value is expected from cultivation/harvesting activities, for which UK competitive advantage is assessed as low-medium, with some UK based companies active abroad (Sun Biofuels Ltd, Sustainable Agroenergy, Kerfoot).

For **macroalgae,** 80% of the business value to the UK is estimated from cultivation, where 15% of the market is estimated to be internationally accessible. Medium-high competitive advantage is assessed for the UK in this early stage industry because of research capabilities at the Scottish Academy of Marine Sciences, plans for development trials on 30 ha of UK coastline by the crown estate, and because of offshore engineering expertise gained from the oil and gas industry.

For **microalgae** around 90% of the business value is from cultivation, harvesting and pre-treatment, of which on average 30% of the market is expected to be internationally traded. The UK is identified as having medium advantage for these sectors, based on active research programmes at various universities, including Manchester, Plymouth, QMU, Coventry and Southampton.

Biomethane

Biomethane systems are estimated to provide £2 (1 - 2) bn in GVA to the UK by 2050. The routes considered to biomethane, BioSNG and Anaerobic Digestion are technologically distinct, but for both of these paths high tech markets are expected to offer highest value creation potential, due to the UK's capabilities and the exportability of these technologies. The UK has overall low to medium competitive advantage in these industries, but some key capacities that could be areas of strength. Anaerobic Digestion routes have higher value to the UK, as they are more likely to be widely deployed, however, key developments for BioSNG, including syngas treatment and catalytic conversion are particular areas of UK strength.

For **Anaerobic Digestion** 50% of the business value is identified at the digestion step, with the remaining value evenly split between pre-treatment and upgrading. 40% of the digester market is expected to be internationally tradable, which is lower than for the other components (both expected to be 60% internationally tradable) based on current market activity, where large digestion equipment is sourced regionally. For pre-treatment and digestion the UK is assessed to have low-medium competitive advantage as the majority of the UK's technology is imported from abroad. However, it does have relevant strength from the water industry, active research at places such as the University of Southampton and The CPI's National Anaerobic Digestion Development Centre, and growing commercial activity.

For **BioSNG** over 70% of the business value estimated is from the syngas clean-up, methanation and upgrading. 80% of these component markets are estimated to be internationally tradable, based on the exportability of the technologies. The UK is estimated as having medium-high strength in syngas methanation and upgrading because of strong commercial activity in these chemical engineering dependent routes, which are directly relevant to gasification routes to transport fuels. In the UK Commercial methanation catalysts are available from companies such as Johnson Matthey. Further, the Velocys micro-channel reactor, being developed by Oxford Catalysts, is applicable to methanation process intensification.

Bioheat

Bioheat systems are estimated to provide £4 (2-8) bn in GVA to the UK by 2050. Global bioheat markets will develop around feedstock supply and preparation, system design, installation and control, and energy conversion and distribution systems. Highest business development value to the UK is estimated for energy conversion and collection systems, due to the overall size of the markets. Highest value is possible for large scale systems, due to their significantly greater global deployment. The UK is estimated to have low to medium competitive advantage for the various bioheat submarkets, but overall business creation value is in line with other conversion routes because of the expected scale of global bioheat deployment.

For both **large scale** and **small scale** heat systems around 90% of the business creation value to the UK is expected to be from energy conversion and collection technologies, which represent around 80% of global markets. 75% of these markets are expected to be internationally tradable. UK competitive advantage is assessed as low-medium for them, based on a few firms that make heat exchangers (e.g. Bowman and Thermex) and a handful of steam turbine manufacturers (e.g. Turbine Bladings and Rolls-Royce), against larger multinational activity abroad.

Table 4: Estimates of global bioenergy deployment ranges in 2050, market turnovers over the next 40 years and potential UK market capitalisations. These are not all additive across the scenarios, especially for bioheat, owing to feedstock constraints, totals are therefore rough estimates.
Source: E4tech, Carbon Trust, expert interviews

Category	Global Deployment[1] by 2050 (EJ)	Turnover 2010 -2050 (£bn)	UK Gross Value Added, 2010-2050 (£bn)	
			Without Displacement	With Displacement
New Energy Feedstocks				
Woody/Grassy Crops	69 (12 - 128)	1,601 (422 - 2,332)	5.2 (1.4 - 7.6)	2.6 (0.7 - 3.8)
Oily Crops	4 (0 - 5)	445 (0 - 692)	0.5 (0.0 - 0.8)	0.3 (0.0 - 0.4)
Microalgae	3 (0 - 8)	134 (0 - 1,040)	0.8 (0.0 - 6.7)	0.4 (0.0 - 3.4)
Macroalgae	4 (0 - 14)	134 (0 - 336)	0.9 (0.0 - 2.3)	0.5 (0.0 - 1.1)
Sub-Total:	***81 (12 - 151)***	***2,313 (422 - 3,707)***	***8 (1 - 17)***	***4 (1 - 8)***
Biomethane				
Anaerobic Digestion	4 (3 - 4)	380 (291 - 434)	2.1 (1.6 - 2.5)	1.1 (0.8 - 1.2)
BioSNG	7 (0 - 8)	236 (0 - 271)	1.8 (0.0 - 2.1)	0.9 (0.0 - 1.1)
Sub-Total:	***11 (3 - 13)***	***615 (291 - 705)***	***4 (2 - 5)***	***2 (1 - 2)***
Bioheat				
Small Scale	4 (1 - 5)	1,025 (559 - 1,419)	1.6 (0.9 - 2.2)	0.9 (0.4 - 1.2)
Large Scale Systems	27 (12 - 42)	4,042 (2,324 - 7,690)	5.0 (3.8 - 10.1)	3.6 (1.9 - 6.7)
Sub-Total:	***31 (12 - 47)***	***5,067 (2,324 - 9,109)***	***9 (4 - 16)***	***4 (2 - 8)***
Biopower				
Combustion	6 (4 - 8)	1,214 (808 - 1,503)	9.2 (6.1 - 11.5)	4.6 (3.1 - 5.7)
Gasification	2 (0 - 3)	109 (0 - 212)	1.4 (0.0 - 2.7)	0.7 (0.0 - 1.3)
Sub-Total:	***8 (4 - 9)***	***1,322 (808 - 1,425)***	***11 (6 - 12)***	***5 (3 - 6)***
Advanced Biofuels				
Gasification Routes	5 (1 - 14)	254 (49 - 831)	2.2 (0.5 - 7.2)	1.1 (0.2 - 3.6)
Upgraded Pyrolysis Oil	1 (0 - 14)	119 (0 - 791)	1.5 (0.0 - 9.5)	0.7 (0.0 - 4.8)
Novel Fuels	2 (0 - 14)	91 (0 - 754)	0.7 (0.0 - 6.2)	0.4 (0.0 - 3.1)
Lig. Ethanol	2 (1 - 5)	162 (91 - 430)	1.1 (0.6 - 2.8)	0.5 (0.3 - 1.4)
Lig. Butanol	1 (1 - 5)	119 (67 - 525)	1.2 (0.7 - 5.4)	0.6 (0.3 - 2.7)
Sub-Total:	***11 (2 - 19)***	***745 (207 - 1,355)***	***7 (2 - 15)***	***3 (1 - 7)***
Total:	***61 (14 – 87)***	***10,063 (2,332 - 16,591)***	***38 (12 - 67)***	***19 (6 - 33)***

1: Total deployment is given just for conversion technologies, also accounting for further feedstocks, such as forestry and agricultural residues. All deployment and GVA figures are additive in the central scenario.
2: Discounted at a social discount rate of 3.5% to 2035, and 3.0% between 2035 and 2050, in line with HMT guidelines

Biopower

Biopower systems are estimated to provide £5 (3 -6) bn in GVA to the UK by 2050. The process of power production from both combustion and gasification involves the pre-treatment of feedstock, which is processed in reactors/boilers to produce an energy vector which is converted to power in a generator. The majority of the value the UK can capitalise on from these steps is in the market for power generators and combustion boilers. Higher expected deployment values for combustion systems offer higher business value potential to the UK.

For **Combustion** systems 60% of the estimated value is from boilers and 30% is from power generation systems, which is predominantly driven by the relative sizes of these markets. 60% of both these markets are expected to be internationally tradable. The UK is assessed to have low-medium competitive advantage for boilers. Active research exists under the SUPERGEN programme and ~15 projects are in development, however most of the recent UK dedicated biomass power plants have used imported boiler technology. The UK has only one major boiler developer, Doosan Babcock, and there are many developers active in other countries. Doonsan are however one of the few global technology providers able to convert coal plants to 100% biomass. For power generation systems the UK is assessed to have medium competitive advantage based on the research already stated, and on the fact that the developer Alstom still has a steam turbine and generator presence in the UK.

For **Gasification** to power systems two thirds of the business value to the UK is from power generation systems, while one third is from gas clean-up technology, both of which are expected to be 60% internationally tradable. The UK is assessed to have medium competitive advantage in gas clean-up for power systems based on university research at various institutions, and tangential commercial developments in advanced biofuels by Johnson Matthey and others. UK competitive advantage for gasification power generation systems is graded as medium-high because of academic research and commercial UK-based activity by Biossence, APP, Siemens Industrial Turbo machinery, Rolls-Royce and ITP Engines UK.

Advanced Biofuels

Advanced biofuel systems are estimated to provide £3 (1 -7) bn in GVA to the UK by 2050. The production chain of advanced biofuels includes a wide variety of potential processes for the conversion of feedstocks to fuel. Highest value to the UK is found in specific high tech component processes, which are more exportable, protectable through IP and well-aligned with the UK's academic and commercial strengths. In central cases highest value is identified for gasification routes, based on their large deployment potential and key UK strengths in catalytic fuel synthesis. However, *all* of the advanced biofuels have the *potential* to create large business value, reflecting their relative early stage of development and the high uncertainty about which specific technologies will "win", as well as the UK's broad capacities in this arena.

For **gasification routes** the highest value is predicted for processes involving FT synthesis, which have high global deployment. For this production route 75% of UK business value is identified from the syngas clean-up and FT synthesis steps. 80% of these high tech markets are expected to be internationally tradable and the UK is identified as having medium competitive advantage in gas clean-up and medium-high in FT synthesis. This is based on significant UK industrial and research activity, since Johnson Matthey is one of the three main FT catalyst suppliers globally, and Oxford Catalysts have successfully piloted their Velocys micro-channel reactor. Further, the UK has strong active university research programmes, for example at Newcastle, Nottingham and Sheffield.

For **Upgraded Pyrolysis Oils** 63% of the business value to the UK is estimated to come from the upgrading market, primarily driven by the sheer size of this market, of which 40% is expected to be internationally tradable. The UK is identified as having medium competitive advantage in upgrading as well as in the fast pyrolysis step, based on capabilities manifest in the Carbon Trust's Pyrolysis Challenge, university level research (e.g. at York, Aston, Imperial and others), and wider commercial activity by e.g. Rotawave and Catal International.

For **Lignocellulosic Ethanol** around half of the available business value to the UK is expected to be from the ethanol separation processes, the rest being from the pre-treatment, hydrolysis and fermentation steps. Around 60% of each of these markets is expected to be internationally accessible, owing to the exportability of technology and IP for this pathway. This value is expected to come from the hydrolysis and fermentation markets, because of UK strengths and from the separation market, due to its size. The UK is assessed to have medium competitive advantage in the hydrolysis and fermentation steps, based on fermentation research at BSBEC and the presence of companies such as TMO, Biocaldol and Green Biologics. The UK is assessed to have medium competitive advantage for the separation step, its capacities in this process are based on leading chemical engineering and process engineering groups and activity on key novel membrane technology, by companies such as WhiteFox. The UK is ranked at low-medium for the pre-treatment process, as its activity is primarily academic.

For **lignocellulosic butanol** the markets are categorised in the same way as lignocellulosic ethanol and are expected to be equally tradable. However around 40% of the value is expected from the fermentation step for this pathway. The UK's competitive advantage is ranked as high for butanol fermentation based on academic research at Nottingham, Napier and Aberystwyth, and the fact that the UK possesses three of only a handful of butanol developers worldwide: Butamax, Green Biologics and Solvert. High value is again found at the separation step, which is estimated to provide 40% of the business value to the UK, primarily because of the large expected market size.

For **Novel Chemical Routes** all of the value is expected to be from the development of the conversion processes and technologies. 60% of this market is expected to be internationally tradable and the UK is assessed to have low-medium competitive advantage, having no large technology developers, but relevant research at CoEBio3 and various universities.

For **Novel Biological Routes** the development of new conversion routes is also where the UK is expected to draw business value, again with 60% of this market expected to be internationally tradable. The UK's competitive advantage is again assessed as low-medium, with a few potentially applicable bioscience research and companies (e.g. John Innes Centre, Novacta, Ingenza, NCIMB).

6) Market failures impeding innovation

A range of market failures were identified by stakeholders which hold innovation back across the bioenergy production chain. Some failures apply to just specific elements of single technologies, but most apply across the technologies and bioenergy markets. The prominent markets failures hindering the development of bioenergy are: policy dependent demand (with uncertain support levels), coordination/network failures across a diffuse supply chain, challenges to retaining the IP benefits from early stage RD&D, and conflicting regulatory regimes.

These failures are particularly critical for early stage technologies which are not yet proven at scale as they have a significant effect on reducing investor confidence and access to capital.

Policy dependent demand and uncertain support levels

A range of support mechanisms exist to incentivise and enable bioenergy utilisation (the Renewable Obligation, Renewable Heat Incentive and Renewable Transport Fuel Obligation). Nevertheless, these mechanisms are not fully aligned across bioenergy uses, the market does not yet have the confidence that they will offer sufficient support levels in the period required for significant RD&D investments.

Sustainability concerns are identified as a key driver of uncertainty for government support. Moreover, energy policy does not adequately distinguish between more and less sustainable feedstocks, and there remains high uncertainty about how effectively policy can do this.

Even in the case of perfectly designed support, there always remains uncertainty and perceived project risk owing to potential changes through future review processes.

Coordination/network failures across a diffuse supply chain

Innovations from both crop production and crop development are necessary to unlock the potential of bioenergy. Achieving this requires bioenergy markets for feedstock production, transport and conversion all to develop symbiotically. New, sustainable feedstocks and the conversion technologies which utilise them have to be developed hand in hand, to create an integrated, functioning, market. Due to high transaction costs across the diverse bioenergy supply chain, this does not happening sufficiently, restricting the extent and effectiveness of RD&D activity.

Challenges to retaining the IP benefits from early stage RD&D (spill-over effects)

Spill-over effects reduce the benefits of engaging in early stage RD&D, due to the challenges of retaining IP benefits, and gaining the full market value from these investments. Investors are hence less willing to invest sufficiently in these pre commercial technologies, creating an investment 'valley of death' in the area of RD&D between early stage conceptual technologies and commercial application.

Conflicting Policy Regimes

Climate, energy, environment and planning regimes are not perfectly aligned for the development of bioenergy technologies.

In the case of planning permission, obtaining it can be a lengthy process which has considerable risk of non-acceptance, due to factors such as local opposition to development. This has the effect of significantly increasing market risks and raising the costs of capital for developers.

7) Can we rely on other countries?

Across the majority of the bioenergy landscape there is a large amount of international activity, particularly in the USA, Brazil, Western Europe and South East Asia. These regions have large potential biomass resources and have significant commercial activity and research programmes across the bioenergy areas considered here.

For some bioenergy conversion technologies and feedstocks current global activity cannot be relied upon to enable the required innovations for the UK. This is the case for technologies that must be adopted to UK conditions, and in the case of technologies that will not be available in the timeframe required.

Technologies that must be adopted to UK conditions

For woody/grassy crops and macroalgae it is not expected that international developments will produce crops which are able to produce sufficient yields on marginal land in UK conditions, in the timeframe required. Crops will have to be developed which are not only suited to national conditions but also to local regions within a nation. The UK is not expected to be able to rely on others for this level of development.

In the case of macroalgae farming, domestic production in the UK's waters will require the development of local infrastructure, skilled labour, and an understanding of optimal environmental performance in UK waters which international developments are not guaranteed to deliver. It is also not clear if international developments in harnessing macroalgae crops for energy production will produce strains which are optimal for UK waters. Current developments in Scandinavian waters are most likely to generate insights which can be extrapolated to the UK.

Technologies that will not be available in the timeframe required

The majority of potential bioenergy technologies which the UK can use are expected to be pursued internationally. This is not the case for BioSNG and BioDME systems where there is very limited international activity (only three international developers were identified between them). Importantly, low activity on these in particular is partially attributed to limited interest, due to high complexity and a poor compatibility with CCS systems.

The majority of the sub elements of these technologies are expected to be developed for bioenergy application for transport fuel and electricity production. Nevertheless limited activity was identified for the integration of these technologies at scale.

8) Potential priorities to deliver the greatest benefit to the UK

A number of priorities come out strongly from the analysis although there remains high uncertainty. Existing public sector activity broadly addresses some of these areas and is outlined in this section. Additional activities could be undertaken to gain the full benefits of innovation priority areas. An integrated, whole system, approach is identified as being particularly able to unlock value across the bioenergy supply chain.

i. Innovation areas with the biggest relative benefit to the UK

Key areas of innovation need identified in this report are:

- Sustainable woody/grassy energy crops that have increasing yields, suitable for growth on marginal land in a way that does not compromise the delivery of important ecosystem services and are adapted to regional conditions
- Advanced biofuels at lower cost, that can operate reliably at commercial scale
- Gasification routes to power that can operate efficiently and reliably at scale, potentially with CCS

The following criteria were used to identify these priorities, based on the above analyses:

- Value in meeting emissions targets at lowest cost
- Value in business creation
- Extent of market failure
- Low opportunity to rely on another country

Table 6 summarises these criteria by technology and the consequent prioritisation, showing that a high priority was allocated to woody/grassy crops and a medium-high priority was given to advanced biofuels and gasification routes to power.

Innovation in woody/grassy crops was allocated a high priority because of its value in reducing costs, the presence of critical market barriers, limited capacity to rely on others and its value in enabling greater biomass availability (a prerequisite for high deployment of bioenergy conversion technologies).

It is important to note that the value of technology innovation support for both UK energy cost savings and business creation is found to be subject to significant uncertainties and dependent on the success of innovations, which are not guaranteed. There is therefore significant benefit to the UK from adopting an innovation support strategy that is robust to a range of scenarios and continually monitored as the market evolves.

ii. Existing innovation support for priority areas

The majority of UK bioenergy support funding passes through DECC, Defra, BIS, Department for Transport, the EU, the Carbon Trust, the Energy Technologies Institute (ETI) and the Research Councils. A range of push, pull and enabling activities are carried out by these bodies, which span the bioenergy priority areas highlighted in this report (Table 5).

The UK's **market pull** mechanisms cover all of the bioenergy sectors assessed directly (the Renewable Obligation, Renewable Heat Incentive, Renewable Transport Fuel Obligation). These policies (and their successor policies) will be critical to driving forward deployment of bioenergy, and serve to create a general market environment more conducive to innovation. However, as their focus is on deployment of existing technologies, their impact on UK innovation priorities will be secondary.

Significant **technology push** activities are identified mostly through research programmes, with some demonstration activity.

Prominent **cross cutting** research is carried out by a range of bodies, through the Research Councils, the ETI and the Carbon Trust. The BBSRC funds a range of research programmes including, the virtual BBSRC Sustainable Bioenergy Centre (BSBEC) and the Energy Grasses and Biorefining programme at IBERS, University of Aberystwyth. Projects investigating feedstock optimisation, biological conversion and fermentation technologies to bioethanol and biobutanol, in addition to the use of hydrocarbon, artificial photosynthesis and enzymology underpinning biogas have been funded through this portfolio. The EPSRC, through the Research Council UK Energy Programme fund the *SUPERGEN* Bioenergy Hub (a consortia of academic, research and industrial organisations lead by the Tyndall Centre, University of Manchester), which will initially address 10 research projects ranging from turning biomass into transport fuels to capturing carbon dioxide from burning biomass feedstocks.

Push activities for **woody/grassy** crops have researched yields and been established to encourage deployment. Research on yields is carried out at a variety of universities and research centres, most prominently at Rothamsted Research at Harpenden, Southampton University and the Institute of Biological, Environmental and Rural Sciences at Aberystwyth.

Deployment activity support is targeted through the Energy Crops Scheme, which offers grant funding to establish Energy Crop plantations, but has had low uptake.

No prominent RD&D activities were identified that specifically looked to increase the use of UK marginal land across its regions. Although the ETI and the BBSRC Cropping Carbon Project are undertaking important research investigating the impact of land use change on soil carbon stocks and GHG emissions when converting land to produce energy crops.

Table 5: Summary of existing UK public sector activity/investment

Market pull (demand side)	**Technology push** (supply side)	**Enablers**
Cross Cutting: EU Renewable Energy Directive ***New Energy Crops***: RO ***Biomethane***: RHI, FiT ***Bioheat***: Renewable Heat Incentive (RHI) , Bioenergy Capital Grants Scheme, FiT ***Biopower***: Renewables Obligation (RO), Carbon price, via the EU Energy Trading Scheme (ETS) ***Advanced Biofuels***: Renewable Transport Fuel Obligation (RTFO), Preferential tax regime, Fuel Quality Directive	***Cross Cutting****:* University research - primarily funded through the research councils (especially BBSRC and EPSRC, whose funding predominantly goes to BSBEC and SUPERGEN respectively), ETI, TSB, TSEC, EU FP7, EIBI, Regional Growth Fund ***New Energy Crops***: BBSRC/DEFRA Miscanthus improvement programme, Rothamsted national Willow collection, ENERGYPOPLAR funded by the FP7, SAMs algae research programmes, Energy Crops Scheme ***Biomethane***: Waste & Resources Action Programme (WRAP) ***Bioheat***: Carbon Trust Biomass Heat Accelerator ***Biopower***: ETI waste from energy programme and CCS biopower engineering research ***Advanced Biofuels***: Carbon Trust Pyrolysis Accelerator, CoEBIO3, Select project development support (e.g. Ineos Bio)	– Centre for Process Innovation (CPI) – Energy Technologies Institute (ETI) **Representative Bodies:** – National Farmers Union (NFU) – National Non-Food Crops Centre (NNFCC) – Forestry Commission – Renewable Energy Association (REA) – National Industrial Symbiosis Programme (NISP)

Source: Carbon Trust, E4tech, ETI, DECC

Push activities for **advanced biofuels** are carried out through a variety of research programmes and deployment support activities, covering gasification, pyrolysis, novel chemical and biological routes and lignocellulosic ethanol and butanol.

Gasification and pyrolysis systems are researched by the *SUPERGEN* Bioenergy consortium, lead by the Tyndall Centre in partnership with Aston University and by researchers at the University of Cranfield. In addition, the Carbon Trust Pyrolysis Challenge is designed to turn prototype research into a commercial vehicle. Project development support has also been provided to these technologies (e.g. the Ineos Bio biofuels project received feasibility assessment funding from DECC).

Catalysts relevant to novel chemical routes are researched through the CoEBIO3, using the facilities at the CPI (detailed under enabling activities).

Lignocellulosic ethanol and butanol, and novel biological routes are researched though BSBEC, with associated programme members Newcastle University and TMO renewables. No UK demonstration support activities were identified.

UK push activities for **biopower** cover research at universities and have involved demonstration support. Prominent research under the SUPERGEN project, by the University of Leeds, targets biomass combustion. The ETI are also leading an engineering research programme on biomass to power with CCS. Limited on-going push activities to assist deployment were identified for biopower gasification, possibly due to previous experience with the DTI supported ARBRE plant. Future intended activity was however identified, with the ETI planning to fund the construction of a waste to power demonstration plant focussing on gasification technology.

Enabling activities through **testing sites** are performed by the CPI, primarily for advanced biofuels, which is an open access trial and development centre available to developers between TRL 4-7, with fermentation, gasification and pyrolysis equipment available for use.

Enabling activities through **representative bodies** are carried out through the NNFCC, the National Farmers Union, the Renewable Energy Association and the Forestry Commission, which span the bioenergy business sectors. No single trade body was identified for bioenergy acting throughout the value chain (e.g. equivalent to the British Wind Energy Association for the wind industry).

iii. Potential Innovation Support Priorities

Table 7 overviews the areas of high innovation need across the bioenergy sectors identified as having medium priority upwards. Scale up of current innovation activity across the prioritised areas could require many tens of millions of pounds, but has the potential to unlock billions from each technology analysed over the next 40 years.

Technology Innovation priorities

Increased activity on woody/grassy energy crops could unlock innovation savings and enable wide spread uptake. This would involve increased research on crop characteristics, seeking to create strands optimised to farmers' needs, to unlock deployment potential. Targets for this activity would be cost reductions (through increased yields and reduced input requirements), crops which could be deployed on marginal land, and crops with characteristics that are more suitable to farmers' needs (shorter time to harvest, greater ease of grubbing up). Monitoring activity of deployment could also be used to pursue the development of crops which are best suited to farmers' needs and to learn from deployment activities.

For advanced biofuels a range of technologies are under development, which are not sufficiently proven at scale but have high potential value. Increased development and demonstration activities could unlock the value of these technologies, by accelerating the commercialisation of reliable, low cost fuel supply, at scale.

Gasification technologies are shown to have significant value for heat, power, fuel and biomethane application. The component technologies in each of these have been proven, either in demonstration or for other applications (e.g. coal to liquids). A fully integrated, large-scale demonstration plant aiming to reliably produce and utilise syngas from a range of different bioenergy feedstocks could unlock much of the value across these technologies.

Whole Systems, Integrated Approach

Bioenergy feedstock and conversion technology markets are intertwined and their collective development has the potential to magnify the value from innovation across the supply chain. UK public sector intervention could therefore leverage increased innovation benefits by adopting an integrated approach across feedstock and conversion technologies.

Such a strategy would require joined up research and demonstration activities. Increased levels of technical coevolution could be enabled by "bio-refineries", which could use common feedstocks and technical components to produce a variety of outputs. Gasification processes are a prominent potential example of this, with potential co-production of fuels, power and biomethane, all having significant overlapping innovation needs and potential gains from co-products.

The Research Councils have already begun to develop a strategic whole systems approach through their Cross Research Council Bioenergy Strategy Coordination Group. Further integrated activity could involve multiple purpose demonstration facilities (a "bioenergy hub") with joint and/or co-located RD&D capacity for both crops and conversion technologies. This could enable simultaneous pursuit of multiple innovation goals at lower cost through the use of shared resource. Such a site could be set up to lower project risk for developers by guaranteeing feedstock sales/supply, energy distribution equipment and sales, and monitoring of regulation compliance.

Table 6: Benefit of UK public sector activity/investment by sub-area and technology type

Category		Savings Domestic (£bn)[i]	Savings Imported (£bn)[i]	GVA (£bn)[ii]	Can We Rely On Someone Else	Critical Market Barrier?	Innovation Priority Area?
New Energy Feedstocks							
New Woody/Grassy Crops		3.5 (2.4 - 4.8)	1.2 (0.0 - 8.7)	2.6 (0.7 - 3.8)	No	Yes	High
New Oily Crops		0.4 (0.0 - 4.7)	5.2 (0.0 - 19.6)	0.3 (0.0 - 0.4)	Yes	Yes	Medium
Microalgae		0.0 (0.0 - 0.0)	1.1 (0.0 - 2.9)	0.4 (0.0 - 3.4)	Yes	Yes	Low
Macroalgae		0.3 (0.0 - 3.4)	0.0 (0.0 - 0.0)	0.5 (0.0 - 1.1)	Partially	Yes	Low - Medium
	***Total*:**	***4 (2 - 14)***	***7 (0 - 31)***	***4 (1 - 8)***			
Biomethane							
Anaerobic Digestion		2.6 (2.0 - 4.9)	0.0 (0.0 - 0.0)	1.1 (0.8 - 1.2)	Yes	No	Medium
BioSNG		0.9 (0.0 - 4.8)	0.0 (0.0 - 0.0)	1.0 (0.0 - 1.2)	Not soon enough	Yes	Medium
	***Total*:**	***3 (2 - 10)***	***0 (0 - 0)***	***2 (1 - 2)***			
Bioheat							
Small Scale Systems		1.7 (0.1 - 3.1)	0.0 (0.0 - 0.0)	0.9 (0.4 - 1.2)	Yes	No	Low
Large Scale Systems		0.2 (0.0 - 0.9)	0.0 (0.0 - 0.0)	3.6 (1.9 - 6.7)	Yes	No	Low
	***Total*:**	***2 (0 - 3)***	***0 (0 - 0)***	***4 (2 - 8)***			
Biopower							
Combustion		3.0 (1.7 - 4.7)	0.0 (0.0 - 0.0)	4.6 (3.1 - 5.7)	Yes	No	Medium
Gasification		1.7 (0.0 - 5.6)	0.0 (0.0 - 0.0)	0.6 (0.0 - 1.1)	Yes	Yes	Medium-High
	***Total*:**	***5 (2 - 9)***	***0 (0 - 0)***	***5 (3 - 6)***			
Advanced Biofuels							
Gasification routes		0.6 (0.0 - 26.4)	7.3 (0.0 - 41.5)	1.1 (0.2 - 3.6)	Yes	Yes	Medium-High
Upgraded Pyrolysis Oil		0.3 (0.0 - 26.0)	3.7 (0.0 - 39.7)	0.7 (0.0 - 4.8)	Yes	Yes	Medium-High
Novel Fuels		0.3 (0.0 - 27.8)	2.6 (0.0 - 40.3)	0.4 (0.0 - 3.1)	Yes	Yes	Medium-High
Lig. Ethanol		0.0 (0.0 - 7.0)	3.7 (0.0 - 12.5)	0.5 (0.3 - 1.4)	Yes	Yes	Medium-High
Lig. Butanol		0.0 (0.0 - 7.9)	2.3 (0.0 - 13.8)	0.6 (0.3 - 2.7)	Not soon enough	Yes	Medium-High
	***Total*:**	***1 (0 - 28)***	***20 (0 - 41)***	***3 (1 - 7)***			

i) From UK deployment over 2010-2050, discounted at social discount rate.
ii) From global deployment over 2010-2050, after displacement effects, discounted at social discount rates.
Source: E4tech, Expert interviews, Carbon Trust analysis

Table 7: Potential bioenergy innovation priorities and support

	Potential innovation priorities	Current activities/investments	Future potential activities	Indicative scale of public funding[1]
New Energy Feedstocks ▪ Woody/Grassy	▪ Crops that have lower costs and increased sustainability: ▪ Increasing yields on marginal lands in a way that does not compromise the delivery of important ecosystem services ▪ Reduced agrochemical inputs ▪ Higher Energy Content and accessibility ▪ Crops that are well suited to farmers' growing needs: ▪ Shorter time to harvest ▪ Greater ease of grubbing up	▪ Structured research programmes from the research councils, through BBSRC, SUPERGEN and a variety of universities ▪ Energy Crops Scheme Grant covering 50% of establishment costs ▪ Farm level deployment on ~ 3000ha SRC, ~8000ha Miscanthus ▪ Defra/Natural England Defra loan facilities ▪ Indirect: RO, RHI, RTFO	▪ Crop research, development and deployment activities, focusing on improving characteristics on marginal land ▪ Multiple farm level demonstration sites monitored and assessed by research institutions to optimise best practise, continue species improvement through widespread use and determine optimum characteristics for farmers ▪ Improved farm level financial incentives to encourage early adoption of sustainable woody/grassy crops, potentially through a loan scheme ▪ Enabling activities to encourage long term supply-demand relationships, further expanding trade representation bodies representing actors across the value chain	▪ Tens of millions ▪ Tens of millions to high tens of millions ▪ High tens of millions ▪ Millions
Gasification Routes to: ▪ Biopower ▪ Bioheat ▪ Biofuels (FT Synthesis and BioDME) ▪ Biomethane (BioSNG)	*All gasification routes:* ▪ Successful demonstration of a fully integrated plant ▪ Adaptation of reactor technology to a range of feedstocks, to enable wide scale production ▪ improved syngas clean-up systems to remove impurities, such as tar ▪ Production of high value co-products *Biofuels /Biomethane*: ▪ Lower cost, reliable catalyst components which are capable of reliable production of hydrocarbons ▪ Development of catalyst processes which could be produced in small scale components	*All gasification routes:* ▪ CPI multi-mode gasification technology platform (1-500kW units) ▪ SUPERGEN programmes on Thermodynamic conversion processes ▪ *Biopower*: ▪ Potential ETI waste to power gasification project *Biopower/Biofuels*: ▪ Ineos Bio Project Development Support (Feasibility Studies) *Biofuels/Biomethane*: ▪ CoEBIO3 biocatalyst research programme	▪ *All*: Güssing style wood fuelled pilot gasification plant (~10MW) which could demonstrate reliable production of heat and/or power and also be available to test new syngas clean-up technologies ▪ *Biopower*: Pilot plant (~10MW) to improve plant efficiencies, demonstrate reliability (especially regarding syngas clean-up) and reduce plant costs (e.g. through development of low calorific value gas turbines and reduced costs of oxygen separation). ▪ *Biofuels/ Biomethane*: Research programmes targeting Catalyst intensification and improvement ▪ *Biofuels/ Biomethane*: Fully integrated plant at +10MW, demonstrating reliable operation using lignocellulosic or waste feedstocks	▪ High tens of millions ▪ High tens of millions ▪ Tens of millions ▪ High tens of millions

Source: Expert interviews, Carbon Trust analysis

1: Provides an order of magnitude perspective on the scale of public funding (existing and future) over the next 5 to 10 years for programmes targeting the listed innovations

	Potential innovation priorities	Current activities/investments	Future potential activities	Indicative scale of public funding
Biomethane ▪ Anaerobic Digestion	▪ Systems capable of co-processing mixed feedstocks ▪ Optimisation of novel pre-treatment and digestion components	▪ Renewable Heat Incentive ▪ CPI Anaerobic Digestion Test Platform	▪ RD&D funding for new production techniques and their commercial development	▪ Tens of millions
Biopower ▪ Combustion	▪ Development of boiler technology which is robust to a range of feedstocks ▪ Adaptation of biomass combustion technology to CCS	▪ Commercial deployments supported through the RO ▪ SUPERGEN bioenergy programme research led by the University of Leeds	▪ Increased activity to convert existing coal boilers to biomass, possibly targeting plants which will come offline with the IED ▪ Biomass CCS research programme	▪ Tens of millions ▪ Millions
Advanced Biofuels ▪ Upgraded Pyrolysis Oil	▪ Pyrolysis upgrading techniques which are reliable and affordable with a range of feedstocks ▪ Capability to co-process conventional pyrolysis oil in conventional refinery units ▪ Improved fast pyrolysis systems, e.g. Microwave pyrolysis	▪ Carbon Trust Pyrolysis Accelerator ▪ CPI pyrolysis trial facilities (can take up to 350kg) ▪ SUPERGEN Bioenergy Research on Thermodynamic Processes, led by Aston University ▪ Renewable Transport Fuel Obligation ▪ Preferential Tax Regimes ▪ Fuel Quality Directive	▪ RD&D funding for novel pyrolysis techniques ▪ Research programmes on pyrolysis oil upgrading in conventional refineries	▪ Tens of millions ▪ Millions
▪ Lignocellulosic Alcohols	▪ Development of robust and affordable lignocellulosic pre-treatment technologies ▪ Hydrolysis processes capable of utilising mixed feedstocks ▪ Improved fermentation techniques to enable use of all sugar types (e.g. C5 sugars) ▪ Consolidated BioProcessing facilities to unify production steps ▪ Robust butanol fermentation techniques	▪ Multiple research programmes, including BSBEC, Newcastle University and TMO renewables ▪ Renewable Transport Fuel Obligation ▪ Fuel Quality Directive	▪ Research and demonstration programmes for lignocellulosic treatment ▪ RD&D funding for new production techniques and their commercial development	▪ Millions ▪ Tens of millions
▪ Novel Fuels	*Cross ranging:* ▪ Development of robust and affordable lignocellulosic pre-treatment technologies ▪ Development of techniques which go directly from lignocellulosic material to fuels, without requiring intermediary sugar production *Biological*: ▪ Optimisation of enzymes and bacteria for routes through sugars *Chemical*: ▪ Optimisation of catalysts for routes through sugars	▪ Renewable Transport Fuel Obligation ▪ Fuel Quality Directive ▪ BSBEC research on use of novel bacteria to synthesise fuels ▪ CoEBIO3 biocatalyst research programme	▪ Research and demonstration programmes for lignocellulosic treatment ▪ RD&D funding for new production techniques and their commercial development	▪ Millions ▪ Tens of millions

	Potential innovation priorities	Current activities/investments	Future potential activities	Indicative scale of public funding
Whole Systems, Integrated Programme	▪ Simultaneous development of sustainable feedstocks and conversion processes which can utilise them, seeking to: ▪ Optimise feedstock characteristics to conversion processes ▪ Disseminate knowledge to consumers and producers of feedstock	▪ BBSRC research activities at BSBEC span sustainable feedstock production and conversion processes ▪ The EPSRC SUPERGEN programme has assessed the production of different types of feedstocks and their use in thermochemical processes ▪ LCICG TINA research programme seeks to create joined up understanding across innovation support communities and bioenergy developers ▪ The Research Council's Cross Bioenergy Strategy Coordination Group is seeking to establish whole system practices	▪ Bioenergy Scale Up: Establishment of a facility where feedstock is produced at scale and used firstly in established technologies (e.g. CHP) and subsequently in conversion technologies under development ▪ Increased coordination, knowledge dissemination and knowledge sharing activities	▪ + 100 million (staged development) ▪ Sub 1 million
Macroalgae	▪ Reduction of cultivation costs, through: ▪ Improved biomass yields with higher carbohydrate content. ▪ Optimise anaerobic digestion and fermentation processes for macroalgae feedstock ▪ Improved assessment of costs and environmental impacts at whole system level ▪ Proof of concept at scale, demonstrating reliable production of macroalgae systems at scale which are resilient to extreme weather events	▪ Cultivation and strain improvement is researched by the Scottish Association of Marine Sciences (SAMS), who hold the largest algal culture collection in Europe and are carrying out selective breeding to maximise production volatile solids in algae strains ▪ Conversion of macroalgae to energy is researched by ▪ ITI Energy Seaweed Anaerobic Digestion (SAD) programme pursuing cost effective exploitation of macroalgae to gas ▪ SAMS, in partnership with other organisations, through the BioMara project ▪ Scottish Sustainable Partners, investigating bioethanol from seaweed ▪ Napier, within the national biofuels programme ▪ Within the Supergen II marine biomass research programme	▪ University grants to develop improved R&D strain development techniques, specifically improved strain selection and development techniques ▪ Detailed system studies of macroalgae cultivation, on plant economics and environmental performance ▪ Support for pilot demonstration of macroalgae (tens of ha) farming at scale in UK waters, combined with conversion facilities, using the feedstock in an anaerobic digester, combined with wastes	▪ Low millions ▪ Low millions ▪ Tens of millions

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