Energy Innovation Needs Assessment

Sub-theme report: Biomass & bioenergy

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The views expressed in this report are the authors' and do not necessarily reflect those of the Department for Business, Energy and Industrial Strategy.

Acronyms and abbreviations

Table 1. **Key acronyms and abbreviations**

Acronym/abbreviation	Definition
AD	Anaerobic Digestion
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy & Industrial Strategy
CAPEX	Capital Expenditure
CCC	The Committee on Climate Change
EINA	Energy Innovation Needs Assessment
EPCm	Engineering, Procurement, and Construction Management
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute
FOAK	First-of-a-kind
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
HTL	Hydrothermal Liquefaction
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LC	Lignocellulosic
LCOE	Levelised Cost of Energy
MSW	Municipal Solid Waste
OPEX	Operating Expenditure
RHI	Renewable Heat Incentive
RD&D	Research, development, and demonstration
SNG	Synthetic Natural Gas
SRC	Short Rotation Coppice
TINA	Technology Innovation Needs Assessment
TRL	Technology Readiness Level

Glossary

Table 2. **Key terms used throughout this report**

Term	Definition
Learning by doing	Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors, such as the impact of standards which tend to increase in direct proportion to capacity increases.
Learning by research, development and demonstration	Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D); increases with spend in RD&D and tends to precede growth in capacity.
Sub-theme	Groups of technology families that perform similar services which allow users to, at least partially, substitute between the technologies. For example, a variety of technology families (heat pumps, district heating, hydrogen heating) have overlapping abilities to provide low-carbon thermal regulation services and can provide flexibility to the power system.
System value and Innovation value	Estimates of change in total system cost (measured in £ GBP, and reported in this document as cumulative to 2050, discounted at 3.5%) as a result of cost reduction and performance improvements in selected technologies. This is the key output of the EINAs and the parameter by which improvements in different technologies are compared. System benefits result from increasing deployment of a technology which helps the energy system deliver energy services more efficiently while meeting greenhouse gas targets. Energy system modelling is a vital tool in order to balance the variety of interactions determining the total system costs. Innovation value is the component of system value that results from research and development (rather than from 'learning by doing')
Technology family	The level at which technologies have sufficiently similar innovation characteristics. For example, heat pumps are a technology family, as air-source, ground-source and water-source heat pumps all involve similar technological components (compressors and refrigerants). Electric vehicles are also a technology family, given that the battery is a common component across plug-in hybrids and battery electric vehicles.
Gross Value Add	Gross Value Add (GVA) measures the generated value of an activity in an industry. It is equal to the difference between the value of the outputs and the cost of intermediate inputs.

Introduction

Box 1. **Background to the Energy Innovation Needs Assessment**

The Energy Innovation Needs Assessment (EINA) aims to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. Using an analytical methodology developed by the Department for Business, Energy & Industrial Strategy (BEIS), the EINA takes a system-level approach, and values innovations in a technology in terms of the system-level benefits a technology innovation provides.[1] This whole system modelling in line with BEIS's EINA methodology was delivered by the Energy Systems Catapult (ESC) using the Energy System Modelling Environment (ESME^{TM}) as the primary modelling tool.

To support the overall prioritisation of innovation activity, the EINA process analyses key technologies in more detail. These technologies are grouped together into sub-themes, according to the primary role they fulfil in the energy system. For key technologies within a sub-theme, innovations and business opportunities are identified. The main findings, at the technology level, are summarised in sub-theme reports. An overview report will combine the findings from each sub-theme to provide a broad system-level perspective and prioritisation.

This EINA analysis is based on a combination of desk research by a consortium of economic and engineering consultants, and stakeholder engagement. The prioritisation of innovation and business opportunities presented is informed by a workshop organised for each sub-theme, assembling key stakeholders from the academic community, industry, and government.

This report was commissioned prior to advice being received from the CCC on meeting a net zero target and reflects priorities to meet the previous 80% target in 2050. The newly legislated net zero target is not expected to change the set of innovation priorities, rather it will make them all more valuable overall. Further work is required to assess detailed implications.

[1] The system-level value of a technology innovation is defined in the EINA methodology as the reduction in energy system transition cost that arises from the inclusion of an innovation compared to the energy system transition cost without that innovation.

The biomass and bioenergy sub-theme report

This report covers both the production of biomass feedstocks, as well as the conversion of these feedstocks to different energy vectors. It focusses on how innovation could bring down costs and reduce barriers to deploying technologies within the biomass and bioenergy sub-theme. This work focusses on technologies at earlier stages of development rather than mature technologies with lower potential for further innovation.

The technology families in scope of this report are:

Table 3. **Scope of biomass and bioenergy assessment**

Gasification-based routes to gaseous and liquid fuels	• Bio-Synthetic Natural Gas (Bio-SNG) • Biohydrogen ($BioH_2$) • Fischer-Tropsch (FT) Synthesis • Gasification to methanol • Fast pyrolysis and upgrading • Hydrothermal liquefaction
Energy crop production	• Woody and grassy energy crops • Novel oil crops • Microalgae and macroalgae
Hydrolysis and fermentation-based routes for liquid fuel production	• Lignocellulosic (LC) ethanol • Syngas fermentation • Sugars to higher hydrocarbons • Alcohol catalysis
Anaerobic Digestion (AD)	• AD for biogas production

Source: E4tech, Vivid Economics

The report has four sections:

- **Biomass and bioenergy and the energy system:** Describes the role of biomass and bioenergy in the energy system, based on ESME modelling performed by the ESC.
- **Innovation opportunities:** Provides lists of the key innovations available within biomass and bioenergy, and their approximate impact on costs.
- **Business opportunities:** Summarises the export opportunities of biomass and bioenergy, the GVA and jobs supported by these opportunities, and how innovation helps the UK capture the opportunities.
- **Market barriers to innovation:** Highlights areas of innovation where market barriers are high and energy system cost reductions and business opportunities significant.

Key findings

Innovation areas in biomass and bioenergy

The main innovations for the biomass and bioenergy sector are identified below. The list is not a substitute for a detailed cost reduction study. Rather, it is a guide for policymakers and key stakeholders on the main areas to be considered in any future innovation programme design.

The innovation priorities below select individual or groups of the top scoring innovations. Table 4 maps the top scoring innovations to individual technology components, and Appendix 2 sets out the full list of innovations and their scores.

- **The UK can be a leader in the production and use of some types of biomass feedstock**. In particular, the UK has an unexploited resource in the biogenic fraction of Municipal Solid Waste (MSW) where large amounts of materials are not repurposed, recycled or otherwise reduced. A proportion of this could be used for energy. Additionally, the UK could be a leader in breeding of Miscanthus, an energy grass, by building upon the country's current strength in energy crop breeding. Opportunities in short rotation coppice can also be explored.
- **For gasification-based routes to liquid and gaseous fuels, the priority is using today's technologies to build demonstration and early commercial scale plants.** Demonstration and commercial operation of these technologies would provide proof of concept and help de-risk future investments for investors. Gasification-based routes produce a wide variety of energy vectors which could be important in decarbonising transport, heat, and the power sectors, such as liquid fuels, hydrogen, and synthetic natural gas. When combined with Carbon Capture Utilisation and Storage (CCUS) in the form of Bioenergy with Carbon Capture and Storage (BECCS), these could potentially deliver negative emissions.
- **For hydrolysis and fermentation-related routes, priorities are piloting the pre-treatment and hydrolysis steps and developing processes that are tailored to feedstocks**. Currently, the pre-treatment and hydrolysis of lignocellulosic (LC) feedstocks comprise a significant proportion of the overall production costs. Reducing their costs through R&D relating to process design and enzyme development, as well as construction of pilot and demonstration facilities, are key steps for these technologies to reach commercialisation.
- **For anaerobic digestion, the priorities are finding higher value end uses for digestate and enabling the use of alternative feedstocks and co-digestion of different feedstock types.** Both such innovations could significantly improve the economic case for AD, but require investment in terms of further R&D.

Business opportunities for the UK

There are large business opportunities, associated with the export of conversion equipment and related services for advanced bioenergy. In total, exports could directly support up to 11,000 jobs and £1.5 billion GVA per annum by 2050. In the business opportunities section below, GVA and jobs results are set out by component (Table 6).

- **Export opportunities for equipment and services are roughly equal.** Export opportunities arise primarily from the UK's expected competitiveness in gasification-based routes and engineering, procurement, and construction management (EPCm) services associated with the construction of complex infrastructure. Note, expected UK strength in gasification-based routes is in the associated processes, rather than gasification technology itself.
- **The UK's export opportunity is relatively uncertain.** Climate scenarios typically predict 200%-300% increases in global bioenergy demand. However, there is significant uncertainty around which route(s) will dominate the conversion of biomass into energy and biofuels. It is plausible that the largest markets do not match UK competitive strengths.
- **Domestic business opportunities are similar in scale to export opportunities, supporting £1.4 billion in GVA and 15,000 jobs per annum by 2050.** Operation and maintenance, which are unlikely to be exported, is the single largest domestic opportunity.

Market barriers to innovation in the UK

Opportunities for HMG support exist when market barriers are significant, and they cannot be overcome by the private sector or international partners. In the market barriers section below, the barriers are set out by component, where possible (Table 7). The main market barriers identified by industry relate to:

- **Bioenergy routes are not currently cost-competitive with fossil fuels and are therefore reliant on government support to create enough demand.** Particularly for Anaerobic Digestion (AD), there is a lack of outcome-focussed targets and mandates to support market creation. Current pathway focussed support initiatives tend to be complex and prescriptive, making it difficult and costly for industry to comply.

- **Given the wide range of potential biomass uses within and outside the energy sector, there has been debate over how biomass resources should be used.** This uncertainty over long-term biomass resource availability, and the relative greenhouse gas (GHG) and other impacts of different biomass end uses has led to hesitation over bioenergy investment and policy. Recent analysis, such as that carried out by the Committee on Climate Change (CCC), has clarified many of these questions, but a wider consensus is still needed.

- **The return on investment for advanced biofuels is perceived as risky and occurs far into the future; therefore, financing is expensive.** Without policy security over an extended period and the confidence that the market will be of an adequate size, investment will remain high-risk. The sector competes with existing technologies, including fossil fuels, which offer higher and more certain returns. In the absence of risk-sharing by the government, cost of finance for industry will likely remain high, particularly for small innovative developers.

- **Industry perceives processes for determining eligibility of waste feedstocks as unnecessarily complex and costly.**

Key findings by component

Government support is justified when system benefits and business opportunities are high, but market barriers prevent innovation.

Table 4. **Cost and performance in biomass and bioenergy (see key to colouring below)**

Overall statistics for biomass and bioenergy: System value = £96.5 billion (range: £57.6-97.5billion), 2050 export opportunity (GVA) = £1.5 bn, 2050 potential direct jobs supported by exports= 11,000				
Component	**Example innovations**	**Business opportunities**	**Market barriers**	**Strategic assessment**
Feedstocks	Develop seed-based planting for Miscanthus; breed crops with traits tailored to specific end uses	N/A	Moderate	The UK can be a leader in the use and production of some types of biomass feedstock. In particular, the UK could use Municipal Solid Waste (MSW), and could be a leader in breeding of Miscanthus, an energy grass. Energy crops are not considered a major export opportunity for the UK given land constraints and expected domestic demand. Without government intervention, innovation in energy crops will occur, but at a lower scale.
Gasification based routes	Deployment of demonstration and early commercial plants using today's technology; improve syngas cleaning technologies	Medium-high	Severe	For these routes, constructing demonstration and early commercial plants, using today's technologies, is the key priority. Demonstration and commercial operation of such a plant would provide proof of concept and help de-risk future investments for investors. Gasification-based routes provide a significant business opportunity, driven by existing UK strength in key processes within this route, particularly in the use of syngas, such as FT synthesis. This is dependent on gasification-based conversion routes becoming the dominant bioenergy production technique, which remains uncertain. Without government intervention, innovation in gasification-based routes is significantly constrained.
Hydrolysis and Fermentation	Improvement and cost reduction of pre-treatment and hydrolysis steps through pilot plants; Developing processes tailored to specific feedstocks through enzyme R&D	Medium-Low	Severe	For hydrolysis and fermentation-related routes, focussing on piloting the pre-treatment and hydrolysis steps, and developing processes that are tailored to feedstocks are the two key priorities. Currently, the pre-treatment and hydrolysis of lignocellulosic feedstocks comprise a significant proportion of the overall production costs. Reducing their costs through R&D relating to process design and enzyme development, as well as construction of pilot and demonstration facilities, are key steps for these technologies to reach commercialisation. Associated business opportunities could be significant but are expected to be significantly smaller than those from gasification-based routes. Without government intervention, innovation is significantly constrained.

Overall statistics for biomass and bioenergy: System value = £96.5 billion (range: £57.6-97.5billion), 2050 export opportunity (GVA) = £1.5 bn, 2050 potential direct jobs supported by exports= 11,000				
Component	**Example innovations**	**Business opportunities**	**Market barriers**	**Strategic assessment**
Anaerobic Digestion	Focus on finding higher value end uses for the digestate through R&D on better characterisation; Develop methods of utilising alternative feedstocks	Medium-Low	Moderate	For anaerobic digestion, priorities were related to finding higher value end uses for the digestate and the use of alternative feedstocks and co-digestion. Both such innovations could significantly improve the economic case for AD but require investment in terms of further R&D. Export opportunities are appreciable, but this is a relatively mature market where the UK is unlikely to grow its market share significantly in future. Without government intervention, innovation in anaerobic digestion will occur, but at a lower scale.

Source: Vivid Economics, E4tech

Note: The main innovations per component are the innovations that score highest in the innovation inventory. This table only includes component-specific market barriers. Cross-cutting barriers are included in the market barriers section below. We only include export markets in this assessment because it is more directly linked to additional benefits to the UK economy. However, an assessment of the domestic market is included in the report below.

Table 5. **Key to colouring in the key barriers by component**

Business opportunities	**Market barriers**
High: more than £1 billion annual GVA from exports by 2050	**Critical:** Without government intervention, innovation, investment and deployment will not occur in the UK.
Medium-High: £600-£1,000 million annual GVA from exports by 2050	**Severe:** Without government intervention, innovation, investment and deployment are significantly constrained and will only occur in certain market segments / have to be adjusted for the UK market.
Medium-Low: £200-£600 million annual GVA from exports by 2050	**Moderate**: Without government intervention, innovation, investment and deployment will occur due to well-functioning industry and international partners, but at a lower scale and speed.
Low: £0-200 million annual GVA from exports by 2050	**Low:** Without government intervention, innovation, investment and deployment will continue at the same levels, driven by a well-functioning industry and international partners.

Source: Vivid Economics, E4tech

Box 2. **Industry workshop**

A full-day workshop was held on 11th February 2019 with key delegates from the biomass and bioenergy industry, academic community, and research agencies. Key aspects of the EINA analysis were subjected to scrutiny, including innovation opportunity assessment, and business and policy opportunities assessment. New views and evidence were suggested; these have been incorporated into an update of the assessments.

The views of the attendees were included in the innovations assessment and detailed in the section ‘Innovation Opportunities within Biomass and Bioenergy’.

Biomass and the whole energy system

Current situation

Currently, the production of biomass and its use in different energy vectors comprise a key part of the UK's energy system. In total, the use of all forms of bioenergy accounted for 9.5% of UK primary energy production in 2017.[2] Liquid biofuels in transport, biomass combustion for electricity, and anaerobic digestion to produce biogas are the technologies most widely deployed.

- In 2017, renewable electricity generation from bioenergy (including biomass co-firing) reached 32TWh, or 32% of all renewable electricity generation in that year.
- In the period 2017/18, renewable fuels (biofuels) supplied 2.4% of total road and non-road mobile machinery fuel. Of this, 48% was biodiesel and 47% was bioethanol, with a smaller proportion of biomethanol (5%).[3]
- Anaerobic digestion also plays a role, with 2.5TWh of biogas produced in 2017, from around 500MW of installed capacity.[4]

There is potential for further use of biomass, and the use of different biomass pathways, in the UK's energy system. These include different combinations of feedstock, conversion technology, and end use. As a result, there is also early-stage development of a range of newer routes, such as the production of bio-derived synthetic natural gas. There is increasing interest in the UK and globally in the production of biofuels from new feedstock types, such as wastes, residues, and energy crops, which could have low sustainability impacts. This is driven by moves to promote these routes in biofuels policy mechanisms, while limiting the use of many of the current food- and feed-based biofuels.[5]

[2] ONS & BEIS (2018), UK Energy Statistics 2017 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695626/Press_Notice_March_2018.pdf
[3] Department for Transport (2018), Renewable Transport Fuel Obligation statistics: period 10 (2017/18), report 4 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/731060/rtfo-year-10-report-4.pdf
[4] BEIS (2018), Digest of United Kingdom Energy Statistics 2018 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf
[5] E4tech, TRL, Temple and Scarlett Research (2017), Advanced Drop in Biofuels: UK Production Outlook to 2030 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652538/advanced-drop-in-biofuels-uk-production-capacity-outlook-2030.pdf

Future deployment scenarios

Scenarios from the Energy Technologies Institute (ETI) and the CCC show that bioenergy could play an important role in the UK's energy system. Bioenergy could be used in the power, heat, and transport sectors, as well as providing negative emissions through the combination of bioenergy with carbon capture and storage (BECCS).

ETI scenarios have highlighted the possible value of bioenergy in the UK energy system, particularly if BECCS is needed for negative emissions.[6] The overarching message from these scenarios was that the successful deployment of bioenergy is critical to delivering a low-carbon energy system transition in the UK. The use of BECCS to deliver negative emissions is key to enabling more cost-effective decarbonisation across the energy system, by allowing for the offsetting of more expensive decarbonisation measures elsewhere in the energy system. Additionally, a larger amount of emissions savings will be required elsewhere in the energy system, at a higher cost, particularly in the transport sector, if there is a lower amount of bioenergy available for use. If CCUS is not available, then bioenergy can provide the most value in low-carbon fuels and heating applications. Lastly, gasification, to produce clean syngas, is a highly important technology in most scenarios. This is due to the flexibility of the technology, both in terms of the feedstocks it can use and the products it can make.

The CCC have shown there is the potential to increase the UK's use of sustainable biomass to meet between 5 – 15% of UK energy demand by 2050.[7] The lower end of this range can be achieved by maximising the potential of the UK's organic waste resource. The upper end could be reached by expanding the growth of energy crops to around 1 million hectares of land (7% of current agricultural land), increasing the tree planting rate to 50,000 hectares per year by 2050 and by tripling current import levels. This relies on strong governance of biomass supply chain sustainability in the UK and worldwide.

A strong majority (86%) of Intergovernmental Panel on Climate Change (IPCC) climate scenarios assume that BECCS is used to meet climate goals.[8] This highlights the potential importance of BECCS. According to the CCC, by 2050

[6] Energy Technologies Institute (2018), The Role for Bioenergy in Decarbonising the UK Energy System, https://es.catapult.org.uk/wp-content/uploads/2018/11/FINAL-The-role-for-Bioenergy-in-decarbonising-the-UK-energy-system.pdf
[7] The Committee on Climate Change (2018), Biomass in a low-carbon economy https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf
[8] Muri, H. (2018), Environ. Res. Lett., 13, 044010 https://doi.org/10.1088/1748-9326/aab324

between 20 and 65 $MtCO_{2e}$/yr could be sequestered through BECCS in the UK. This is equivalent to up to around 15% of current UK CO_{2e} emissions.[9]

Sub-theme system integration: Benefits, challenges and enablers

The benefits of bioenergy are the ability to enable negative emissions and the decarbonisation of 'hard-to-treat' sectors (e.g. industry and heat).

The potential for negative emissions could be a key benefit of deploying bioenergy. This could be achieved either through BECCS, or through optimising biomass production so that bioenergy operates alongside use of biomass as a carbon sink. Wood in construction acts as a carbon sink and displaces high-carbon materials such as cement, brick, and steel.

Bioenergy routes can produce fuels that can help reduce emissions in sectors which are viewed as hard to decarbonise. Low-carbon liquid fuels can be produced through numerous bioenergy routes, which is expected to be required for some time in sectors that are hard to decarbonise by other ones. This is particularly relevant for sectors such as aviation, in which there are currently few alternatives[9].

Bioenergy conversion technologies deployed today can form the basis of future supply chains. The commonality of supply chains between biomass routes means that biomass feedstocks and technologies developed and deployed today can form part of future supply chains. For example, feedstock supply chains and gasification plants developed for Bio-SNG projects developed today could be converted into biohydrogen plants in the future, and potentially combined with CCUS.[10]

It is also important to recognise the key challenges within the biomass and bioenergy sector. These include developing a scalable, mature, and sustainable supply chain, visibility of future market demand, and competition from other energy vectors.

Establishing feedstock supply chains at the right scale and level of maturity. This is necessary to ensure a reliable supply of high quality, sustainable feedstocks at the location of conversion to energy.

Demonstrating supply chain sustainability. This is particularly important for feedstock production in order to ensure supply chain impact is minimised, including

[9] The Committee on Climate Change (2018): Biomass in a low-carbon economy https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf
[10] E4tech and Ecofys (2018), Innovation Needs Assessment for Biomass Heat https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf

indirect impacts on other sectors. These impacts could include indirect land use change for crop-based feedstocks, and diversion of feedstocks from other sectors such as wood processing industries and animal feed.

Visibility of future market demand. Given that many bioenergy routes are more expensive than the incumbents, they rely on market demand created by policy.

Competition from other energy vectors. The electrification of transport coupled with the widespread use of wind and solar for power generation could result in a declining demand for liquid fuels.

Box 3. **System modelling: Biomass and bioenergy in the UK energy system**

Following the BEIS EINA methodology, whole energy system modelling was conducted using the ESME^{TM} Version 4.4 to estimate where innovation investments could provide most value to support UK energy system development.

ESME is a peer-reviewed whole energy system model (covering the electricity, heat and transport sectors, and energy infrastructure) that derives cost-optimal energy system pathways to 2050 meeting user-defined constraints, e.g. 80% greenhouse gas (GHG) emissions reduction.[11] The model can choose from a database of over 400 technologies which are each characterised in cost, performance and other terms (e.g. maximum build rates) out to 2050. The ESME assumption set has been developed over a period of over 10 years and is published.[12] ESME is intended for use as a strategic planning tool and has enough spatial and temporal resolution for system engineering design.

Like any whole system model, ESME is not a complete characterisation of the real world, but it is able to provide guidance on the overall value of different technologies, and the relative value of innovation in those technologies.

The EINA Methodology prescribes the approach to be taken to assess the system-level value of technology innovation. This involves creating a baseline energy system transition without innovation (from which a baseline energy system transition cost is derived), and on a technology-by-technology basis assessing the energy system transition cost impact of "innovating" that technology. Innovation in a technology is modelled as an agreed improvement in cost and performance out to 2050.

For the EINA analysis, the technology cost and performance assumptions were derived from the standard ESME dataset[11] as follows:

- In the baseline energy system transition, the cost and performance of all technologies is assumed to be frozen at their 2020 levels from 2020 out to 2050.
- The "innovated" technology cost and performance for all technologies are assumed to follow the standard ESME dataset improvement trajectories out to 2050 (these are considered techno-optimistic).

There is significant value to the UK in continued (and accelerated) innovation in biomass production. This includes increasing availability of domestic biomass to deliver cost reduction in other parts of the energy system.

As part of the modelling work, 'high innovation runs' were carried out to investigate the impact of high, but technically achievable, innovations. In these runs, the greatest system cost impact comes in the run ‘UK Biomass’, which could deliver a cumulative system benefit to 2050 of innovation of £96.5 bn (discounted at 3.5%). One key benefit that is expected is that when more biomass becomes available, more hydrogen based on biomass routes coupled with CCUS can be made. This, in turn, provides negative emissions, without incurring more expensive decarbonisation measures in hard-to-decarbonise sectors, thus leading to a significant system cost benefit.

It should be noted, however, that while the UK already has an abundance of other renewable resources (e.g. wind, tidal), significant effort (including innovation) is required to increase the availability of biomass.

[11] More details of the capabilities and structure of the ESME model can be found at eti.co.uk/programmes/strategy/esme. This includes a file containing the standard input data assumptions used within the model.
[12] The ESME assumption set has been developed is published with data sources at https://www.eti.co.uk/programmes/strategy/esme

Box 4. **Learning by doing and learning by research**

The total system value follows from two types of technology learning:

- **Learning by doing:** Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors, such as the impact of standards which tend to increase in direct proportion to capacity increases.
- **Learning by research:** Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D). It increases with spend in RD&D and tends to precede growth in capacity.

The EINAs are primarily interested in learning by RD&D, as this is the value that the government can unlock as a result of innovation policy. Emerging technologies will require a greater degree of learning by RD&D than mature technologies. Academic work suggests that for emerging technologies around two-thirds of the learning is due to RD&D, and for mature technologies it contributes around one-third.[13]

To reach a quantitative estimate of the system value attributable to RD&D, these ratios are applied to the system value. This implies that, as an emerging technology, around £64.3 billion system value for biomass follows from RD&D efforts (of a total of £96.5 billion system value). Note, this is an illustrative estimate, with the following caveats:

- The learning-type splits are intended to apply to cost reductions. However, in this study, they are applied to the system value. As system value is not linearly related to cost reduction, this method is imperfect.
- In practice, learning by research and learning by doing are not completely separable. It is important to deploy in order to crowd-in investment to more RD&D, and RD&D is important to unlock deployment.

These estimates are used in the EINA Overview Report to develop a total system value that results from innovation programmes across the energy system.

[13] Jamasb, Tooraj (2007). "Technical Change Theory and Learning Curves", The Energy Journal 28(3).

Innovation opportunities within biomass and bioenergy

Introduction

Box 5. **Objective of the innovation opportunity analysis**

The primary objective is to identify the most promising innovation opportunities within biomass and bioenergy and highlight how these innovations may be realised and contribute to achieving the system benefit potential described above. This section provides:

- A breakdown of the costs within biomass and bioenergy across key components and activities.
- A list of identified innovation opportunities, and an assessment of their importance to reducing costs and deployment barriers.

The use of biomass as an energy source in the UK has grown over the past decade. Electricity from biomass combustion, anaerobic digestion, and several biofuels routes are now considered as well established, mature technologies. However, there are several novel technologies, such as advanced biofuel routes, BioH_2, Bio-SNG, and BECCS, which could potentially play an important role in the decarbonisation of the UK energy system. These technologies require innovation as a key component in aiding their path to becoming commercially viable.

The focus of this work is on understanding how innovation could bring down the cost of, and reduce the barriers to, deploying technologies within the biomass and bioenergy sub-theme. This work focusses on technologies at earlier stages of development rather than mature technologies with less potential for further innovation. Additionally, within this sub-theme it is important to recognise that there is a broad range of technologies, many of which have differing innovation needs. Hence, for the purposes of identifying these main innovation needs, the scope was limited to predominantly earlier stage technologies, and divided into groups with common technological needs.

Gasification-based routes

- **Bio-SNG:** Gasification of biomass feedstock to produce syngas, followed by syngas clean-up and conditioning, water-gas shift (WGS) reaction, methanation, and product purification.

- **Biohydrogen ($BioH_2$):** Gasification of biomass feedstock to produce syngas, followed by syngas clean-up and conditioning, water-gas shift reaction and hydrogen separation/purification.
- **Fischer-Tropsch Synthesis:** Gasification of biomass feedstock to produce syngas, followed by syngas clean-up and conditioning, water-gas shift reaction, Fischer-Tropsch catalytic synthesis of long-chain hydrocarbons, and upgrading to fuels.
- **Syngas to Methanol:** Gasification of biomass feedstock to produce syngas, followed by syngas clean-up and conditioning, water-gas shift reaction, and catalytic synthesis of methanol.
- **Fast Pyrolysis & Upgrading, Hydrothermal Liquefaction:** Fast pyrolysis is the controlled thermal decomposition (in the absence of oxygen) of biomass to produce pyrolysis oil. Hydrothermal Liquefaction involves conversion of biomass with water under high pressure conditions to produce a crude bio-oil.

Energy Crops

- **Woody and grassy energy crops:** Miscanthus and Short Rotation Coppice (SRC).
- **Novel oil crops**: Jatropha and Camelina.
- **Microalgae and macroalgae**: Microscopic, single-celled aquatic photosynthetic organisms, and large aquatic photosynthetic crops such as seaweed.

Hydrolysis and Fermentation

- **Lignocellulosic (LC) ethanol:** Pre-treatment and hydrolysis of lignocellulosic feedstock to produce sugars which are subsequently fermented to ethanol.
- **Syngas fermentation:** The fermentation of syngas using anaerobic organisms to produce alcohols.
- **Sugars to higher hydrocarbons:** Pre-treatment and hydrolysis of lignocellulosic feedstock to produce sugars which are subsequently converted by microorganisms to produce lipids, short-chain and long-chain hydrocarbons, which are then upgraded to liquid fuels.
- **Alcohol catalysis:** Dehydration of alcohols to form short-chain alkenes, which are oligomerised to longer-chain hydrocarbons before being upgraded to liquid fuels.

Anaerobic Digestion

- Biomass is broken down by microorganisms in the absence of oxygen to produce biogas.

Cost breakdown

The aim of the cost tables is to provide context for the innovation priorities. The tables provide an overview of which components or areas contribute most to the cost of producing different biomass resources or bioenergy products. By understanding which areas contribute most to cost, these can help to guide the discussion on where best to focus innovation priorities. They are not intended to provide a comparison between technologies.

For the bioenergy conversion routes, the cost structure is comprised of three major components – capital cost, feedstock costs and operational and maintenance costs. For some conversion routes, more granularity is provided for the breakdown of the capital costs. Regarding energy crops, the overall production costs are comprised of planting material, planting operating costs, cultivation and harvest, land rent, and other costs. A full inventory of the cost breakdowns for all technology families is provided in Appendix 2, which is based on the sources listed, with additional input from the workshop attendees.

Feedstock and capital costs are key cost components for all conversion technologies. Feedstock costs and conversion plant capital costs are the priorities for cost reduction. Innovation can significantly bring down feedstock costs through improved yields or utilisation of cheaper feedstocks and can bring down CAPEX through process improvements.

The cost of syngas clean-up is key for most gasification-based routes. The gasifier itself is not seen to have much further scope for cost reduction. However, the clean-up of the syngas is currently challenging, and has scope for further cost reduction. This is particularly important, as it is the starting point to produce all the energy vectors considered in this technology family (except for fast pyrolysis and hydrothermal liquefaction).

The production costs of energy crops are heavily influenced by yield. Priorities include reducing land area and reducing feedstock costs. Crop yield improvement therefore has a large influence on production costs per tonne of feedstock.

Feedstock costs are key in determining the cost of hydrolysis and fermentation routes. For hydrolysis and fermentation routes, feedstock costs make up the largest component of production costs. A large proportion of the feedstock costs is driven by enzyme costs for hydrolysis of lignocellulosic feedstocks.

Capital costs are the most significant factor in anaerobic digestion production costs. Unlike other conversion technologies, feedstock costs do not make up a significant portion of the overall production costs. The CAPEX of the AD plant is the most significant factor, though operating costs also have an impact.

Inventory of innovation opportunities

Innovation priorities were identified through desk research and consultation with industry experts, with the key areas for focus explained below.

The UK could be a leader in both the use of Municipal Solid Waste (MSW) and Miscanthus breeding. In particular, the UK has unexploited resource in biogenic MSW that cannot be repurposed, recycled or otherwise reduced. However, sustainability considerations, with respect to the waste hierarchy, need to be considered. Workshop participants also identified that the UK is a world leader in Miscanthus breeding, and that building upon this strength is a key innovation priority.

For gasification-based routes, innovation priorities are building demonstration and early commercial plants, based on today's technology. Currently, there is insufficient incentive for demonstration and commercial plants to be built for the technologies for the gasification-based routes discussed, given their relatively high technology and market risk. Demonstration and commercial operation of these technologies would provide proof of concept and help de-risk future investments. Such plants would also provide a platform to learn from, thus allowing for improvements in future plant design.

For hydrolysis and fermentation related routes, workshop participants recommended that there should be a focus on piloting the pre-treatment and hydrolysis steps. Additionally, processes should be tailored to feedstocks such as biogenic MSW and crop residues. Pre-treatment and hydrolysis of lignocellulosic feedstocks are critical enablers for the lignocellulosic ethanol and sugars to higher hydrocarbons routes. To reduce the costs of these steps, the workshop participants identified two key innovation needs. Firstly, combining leading academic research with skilled process and chemical engineering to develop cost-effective processes at the pilot scale, followed by the development of pre-commercial demonstration facilities led by industry, is essential. Secondly, processes should be tailored to specific feedstocks, such as MSW and crop residues, rather than being designed to be feedstock-flexible, since plants will likely be cost-optimal if designed for particular feedstocks. To do this, activity in academia and industry is needed to discover and produce enzyme cocktails with the aim of significantly lowering their cost contribution.

For anaerobic digestion, priorities are related to finding higher value end uses for digestate and the use of alternative feedstocks and co-digestion. Currently digestates are used in agriculture for fertilisation and soil conditioning, but there are opportunities to link digestates with several other sectors with higher value end-use applications. This requires R&D into better characterisation of digestates. Improving the understanding of methods of unlocking the energy in hard-to-digest feedstocks (e.g. lignocellulosic ones) and further investigating the synergies in co-digestion of both wet and dry feedstocks were also identified as key innovation needs. They have the potential to boost biogas yields and increase the options for the types of feedstocks that AD can use.

The workshop participants discussed the contents of the table and offered feedback, particularly regarding the key innovation priorities. The updated table was circulated afterwards to participants, who were given the opportunity to provide further comments. In the innovation tables in Appendix 2, the magnitude of the contributions to cost reduction and reducing deployment barriers are described in qualitative terms relative to other innovation opportunities.

Innovation Opportunity Deep Dives: Gasification-based routes

Building demonstration plants and early commercial plants based on today's technology is the key priority. Although many of the building blocks of the technology have been operated commercially in other processes, there is significant innovation in combining them at scale to deploy successful early commercial plants. The UK could benefit from leveraging gasifier technologies that have been developed and deployed elsewhere, for example, in China.

Funding of pilot scale plants is needed to bridge the gap between research council-funded work and industry involvement. For early-stage technology development, after publication and patenting, it can be difficult to find funding. This is often because at this stage of development, the technology has often not been de-risked to the point at which companies would be interested in getting involved. Pilot scale gasification rigs have CAPEX of £300-400k, for which funding is not currently available. Funding pilot scale testing would allow this gap to be bridged, as well as providing opportunities for training for academia and for skilled operators for UK plants. Support for spinouts could also bridge this gap.

Cost-effective, consistent syngas cleaning to a level suitable for downstream applications is needed. Catalytic processes can be highly sensitive to contaminants in syngas, with current syngas clean-up costs being a significant part of overall costs. Thus, innovation in developing cost-effective clean-up is critical to ensuring the commercial viability of multiple syngas-based processes.

The Fischer-Tropsch process would be most effectively enabled by allowing co-processing of FT waxes in existing refineries. This is currently not allowed in any refineries that produce jet fuel (most refineries) and so is a large barrier. Without this, developers today need to build standalone upgrading plants that may not be needed in the future once refinery co-processing is allowed. To address this, ASTM standards for jet fuel produced from refinery co-processing need to be developed.

For fast pyrolysis, further early stage work is needed to obtain a pyrolysis oil that is co-processable. Utilising existing refinery assets to produce finished fuels from pyrolysis oil could result in capital cost savings in comparison with standalone plants.[14] There are ongoing studies looking into how this could be made into a technically viable and commercially attractive opportunity.[15] However, this technology has not been proven on a commercial scale and thus further work is needed.

For Hydrothermal Liquefaction (HTL), a larger reactor is needed, as this has only been investigated at a laboratory scale. Collaboration with industry would also be useful. Private investors have shown interest in this route but there is a gap between the academic research and the scale needed to demonstrate the technology's potential.

Further work is needed on the reverse water-gas shift reaction, which converts CO_2 to CO, to enable CO_2 utilisation in fuels production. This is a shared common innovation need with the Carbon Capture, Utilisation, and Storage sub-theme.

Innovation Opportunity Deep Dives: Energy Crops

An overarching message from the participants was that the UK is a world leader in Miscanthus breeding, and that the UK should consider strengthening its position in this area.[16] While breeding was mentioned several times as a key area for innovation, a range of recommendations were made with respect to the production of energy crops.

The top priority is research into seed-based planting for Miscanthus, including aspects such as seed coating. The current method of rhizome planting is time-consuming and labour-intensive, as well as being difficult to scale up due to the relatively slow speed of propagation. Hence, developing more efficient and faster propagation methods, such seed-based planting, could significantly lower the cost of miscanthus production.

[14] International Renewable Energy Agency (IRENA) (2018), Innovation Outlook - Advanced Liquid Biofuels.
[15] 4REFINERY: Scenarios for integration of bio-liquids in existing REFINERY processes https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/biofuels/4refinery
[16] The focus on Miscanthus in this report reflects the opportunity described by industry workshop participants. It should be noted that there are other opportunities where the UK have strong capabilities in, such as in SRC. Forest management is outside of the scope of this report.

Identifying and breeding for desirable traits linked to end uses e.g. anaerobic digestion and fermentation, is another key priority. This could increase the potential demand from lower cost and smaller scale applications.

Innovation should focus breeding research and development on resilience and invest in developing improved weed and pest control techniques. Both innovations can give higher average yields and increase the confidence of farmers.

Increasing breeding research and development in the area of water efficiency was identified as being another important consideration. This results in lower water impacts and suitability for growth in drier and drought affected areas. For Miscanthus, future breeds need to be developed which can also be more drought resistant, and process water and nutrients more efficiently. For SRC, increasing SRC willow's ability to grow on marginal lands was identified as another priority by the workshop participants.

Most of the workshop discussion on energy crops focussed on woody and grassy energy crops as detailed above. However, some feedback was provided regarding novel oil crops or macroalgae. Given the international interest in breeding and producing novel oil crops, it was suggested that the UK's expertise in plant breeding could also be applied to this area. Microalgae is unlikely to be of significant interest to the UK as the conditions do not suit its production, and research and innovation are stronger in other countries, such as the USA and Israel. Conditions are more favourable for macroalgae production and the UK does have some research expertise in this area.[17]

Innovation Opportunity Deep Dives: Hydrolysis and Fermentation

Piloting the pre-treatment and hydrolysis steps would aid cost reduction, followed by construction of demonstration scale plants. In the short term, this activity requires combining leading academic research and knowledge in lignocellulosic feedstock with process and chemical engineers capable of developing processes and reactors at a pilot scale. It is important that such pilot facilities be built at appropriate scales and cost and can produce sugars of the right quality. In the longer term, support for pre-commercial demonstration needs to be provided. Projects at this stage were recommended to be industry-led and have substantial industry co-funding. Workshop participants also suggested that work at this stage would be sped up and made more cost-effective if there were suitable open-access

[17] The Scottish Association for Marine Science https://www.sams.ac.uk/facilities/seaweed-farms/

demonstration facilities in the UK. Funding for such a facility would make the UK highly attractive for the development of not only lignocellulosic (LC) ethanol, but also a wide range of sustainable bio-based fuel and chemical industries.

Processes should be tailored to specific feedstocks such as biogenic Municipal Solid Waste (MSW) and crop residues, rather than designed to be feedstock-flexible.
This activity should be focussed on UK feedstock available at a scale and cost that can allow cost-effective bioethanol production. Workshop participants suggested that the work should involve academic researchers working in the area of discovering and improving enzymes for lignocellulose deconstruction, as well as companies looking to produce them. Substantial cost savings can be achieved by reducing the quantity of enzymes used, lowering costs of enzyme production, and developing ways to re-use enzymes where possible. For example, enzyme cocktails should be developed which focus on a lignocellulosic feedstock. Tailored processes are not only more efficient and reliable, but also, from a commercial point of view, most plants would likely be developed with long-term feedstock contracts in place.

Participants made additional observations regarding syngas fermentation.
Firstly, the use of waste gas streams containing CO/CO_2, such as from steel production, should be considered alongside using biomass, particularly for syngas fermentation. Secondly, a comparison of syngas fermentation vs catalytic routes (e.g. FT synthesis) should be made. For routes using syngas, often the syngas clean-up step is the costliest component. Bacteria used in syngas fermentation are more tolerant of contaminants than catalysts, and thus syngas fermentation could offer a cost advantage over catalytic routes.

Innovation Opportunity Deep Dives: Anaerobic Digestion

Finding higher value end uses of digestate could significantly improve the techno-economic case for AD. Currently, digestates are used in agriculture for fertilisation and soil conditioning, but there are opportunities to link digestates with several other sectors which could potentially provide much higher value to the AD/biogas industry. Additionally, the use of digestate in these higher value applications could reduce the potential impacts of its use on land, particularly in nitrate vulnerable zones.[18] However, it should be noted that such work is at an early stage, and further R&D on characterising digestates is needed. This would identify

[18] Stiles (2018), W.A.V. et al., Bioresource Technology 267, 732 - 742
https://doi.org/10.1016/j.biortech.2018.07.100

other valuable compounds such as hormones, proteins, and enzymes which are present in digestates.

Research into utilising hard-to-digest feedstocks and co-digestion could increase the number of deployment opportunities. This involves improving the understanding of methods of unlocking the energy in hard-to-digest feedstocks, and further investigating the potential synergies of co-digesting both wet and dry feedstocks. This could help to optimise existing plants' biogas yields and increase the variety of feedstocks that can be used in AD.

Improving biogas yields could also improve the economic case for AD. This could be achieved via further understanding of microbial cultures and their interactions, as well as improved process monitoring.

Innovation may need to focus on existing assets. The current lack of incentives may slow down new technology deployment and therefore, with fewer new plants being built, opportunities may need to focus on existing plants.

In addition, other important enablers were also discussed during the workshop. A holistic view on policy-making and innovation programme design is needed as AD provides cross-cutting opportunities across many sectors. Examples of such sectors include food production, fertiliser production, and the dairy industry.

Business opportunities within biomass and bioenergy

Introduction

Box 6. **Objective of the business opportunities analysis**

The primary objective is to provide a sense of the relative business opportunities against other energy technologies. To do so, the analysis uses a consistent methodology across technologies to quantify the 'opportunity'; in other words, what *could* be achieved by the UK. The analysis assumes high levels of innovation but remains agnostic about whether this is private or public. This distinction is made in the final section of the report. The two key outputs provided are:

- A quantitative estimate of the gross value added, and jobs supported associated with biomass and bioenergy technology, based on a consistent methodology across technologies analysed in the EINA. Note, the GVA and jobs supported are *not* necessarily additional, and may displace economic activity in other sectors depending on wider macroeconomic conditions.
- A qualitative assessment of the importance of innovation in ensuring UK competitiveness and realising the identified business opportunities. Note, the quantitative estimates for GVA and jobs supported cannot be fully attributed to innovation.

The following discussion details business opportunities arising both from exports and the domestic market. An overview of the business opportunities, and a comparison of the relative size of export and domestic opportunities, across all EINA sub-themes is provided in the overview report.

More detail on the business opportunities methodology is provided in the Appendix.

Globally, biomass and bioenergy are used in a variety of applications, not all of which are likely to be export markets for UK suppliers. Biomass currently accounts for approximately 10% of global primary energy supply.[19] However, half of

[19] Irena (2014). Global Bioenergy Supply and Demand Projects. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

this demand is from Africa and developing Asian economies.[20] Biomass in African and Asian countries is often used directly (e.g. in wood-burning stoves) for cooking or heating, and hence does not present an export opportunity for the UK. However, global demand for modern applications of bioenergy in power, industry, and transport is rapidly growing.[21] Given limited feedstock availability in the UK, the business opportunity for the UK is unlikely to centre on the export of biofuel, but rather exporting equipment and services required for the conversion of biomass into bioenergy.[22] Our focus is on advanced conversion technologies, since this is where innovation could unlock UK competitiveness. For first-generation biofuels, such as conventional ethanol, innovation is likely limited. Furthermore, in the EU, the Renewable Energy Directive II includes limits to significant increases in deployment of these routes. The following sets out the scope of the business opportunity analysis in further detail, before presenting an overview of the potential market, UK competitiveness, and potential GVA and jobs supported if the opportunity is seized.

The business opportunities analysis focusses on UK exports of bioenergy conversion equipment and associated EPCm services. The UK supply chain can leverage a strong research base and a relatively large existing bioenergy industry to innovate in key conversion technologies and demonstrate their domestic deployment. This provides an opportunity to export advanced conversion equipment competitively. In addition, the UK has leading engineering consultancies, who provide a range of support to bioenergy companies, including project development and construction management.[23] Workshop evidence suggests this existing knowledge and skill set can provide a good platform for the UK to capture EPCm contracts during the deployment of advanced bioenergy conversion technologies overseas.

The analysis considers business opportunities across three broad groups of conversion technologies.[24] The three categories cover all the conversion technologies for which innovation opportunities are considered. Service provision, for the types of services the UK is likely to export (e.g. not day to day maintenance), is included within the following three routes.

- **Gasification-based routes:** These include Bio-SNG, bio-H_2, fast pyrolysis, and Fischer-Tropsch synthesis. All stages of each process are included in this

[20] Ibid.
[21] Ibid.
[22] The UK is reflected as a large net importer of biomass for the production of bioenergy. It is conceivable the UK imports biomass, converts it domestically, and exports biofuel. However, this is unlikely to be cost-effective at scale and hence not considered as a business opportunity.
[23] Mott Macdonald website https://www.mottmac.com/power/bioenergy
[24] We recognise there are significant differentiating aspects in each conversion process. However, due to the uncertainty around which process is likely to be most cost-effective (and hence widely taken up) and the broad crossovers in technology, further granularity in the business opportunities analysis is judged to be spuriously accurate. Therefore, the results are presented at this higher level.

analysis, not just the gasification step. For example, Bio-SNG production includes the pre-treatment of the feedstock through to gasification, syngas cleans up, the methanation process, and purification of the product.

- **Hydrolysis and fermentation routes:** The processes included are Lignocellulosic fermentation, syngas fermentation, conversion of sugars to higher hydrocarbons, and alcohol catalysis. As with gasification-based routes, equipment associated with all steps in the process are considered.
- **Anaerobic digestion route:** This includes all equipment associated with anaerobic digestion.

Intellectual property (IP) licensing presents a potentially significant business opportunity but is not quantified in this analysis. Workshop evidence suggests the UK has several opportunities for IP licensing in key conversion technologies and crop breeding. This represents a substantial business opportunity. However, IP generated in the UK and subsequently licensed abroad for production would not lead to substantial additional jobs or GVA in the UK. Given the focus of the analysis on business opportunities which ultimately generate UK jobs, we do not quantify IP-related opportunities.

The business opportunities analysis is set out as follows

- An overview of the global market, with a focus on markets for exports
- A discussion of the UK's competitive position, with a focus on exports
- A discussion of the business opportunities from exports
- A discussion of the UK business opportunities in the UK's domestic market, including a comparison of the relative importance of export and domestic opportunities

Box 7. **The UK's current bioenergy industry**

- UK strengths include the later stages of gasification-based routes, such as syngas conditioning and catalysis; anaerobic digestion; and engineering, procurement, and construction services.
- The UK generated the fifth-highest electricity output from biomass and waste globally in 2016, with a 6% increase in 2017.[25]
- UK producers operate across the supply chain, from the planting of feedstocks to their conversion into final fuels that have a range of applications in the power, transport, buildings, and industry sectors.
- These producers can be smaller businesses, such as farmers, who use 2% of the arable land in the UK to grow crops for bioenergy. Alternatively, larger businesses, such as CoGen, who specialise in the development and deployment of advanced biomass conversion technology; or power plants, such as Drax, who specialise in meeting final energy demands.[26]
- More recently, there has been strong growth in the anaerobic digestion industry, with over 450 plants operational, including 80 biomethane-to-grid plants, and a further 327 planned.[27]

Market overview

Traditional biomass and conventional bioenergy currently dominate the global market, with the size of the bioenergy market within scope relatively small.[28] Although the global bioenergy industry is large, this is predominantly driven by technologies and fuels, such as traditional uses of wood for cooking and conventional biofuels, that are outside the scope of this business opportunities analysis. Many of the technologies considered in this analysis are yet to reach large-scale commercialisation, such as Bio-SNG. This limits the current size of the market,

[25] Irena capacity and generation database http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=54
Biomass magazine (2018) UK bioenergy capacity, generation up in 2017 http://biomassmagazine.com/articles/15200/uk-bioenergy-capacity-generation-up-in-2017
[26] NNFCC (2017) Domestic bioenergy production in the UK poses no threat to food production https://www.nnfcc.co.uk/news-crops-stats
[27] NNFCC (2018) Anaerobic Digestion Deployment in the UK https://www.nnfcc.co.uk/publications/report-anaerobic-digestion-deployment-in-the-uk
[28] As discussed in the Innovation opportunities section and the introduction to the business opportunities, we focus on the market for innovative bioenergy.

along with the associated export opportunities. Nevertheless, there has been commercialisation of some of the technologies and biofuels considered. Anaerobic digestion has been deployed in many territories globally, while advanced ethanol comprises 2% of final bioenergy demand in transport.[29]

As key technologies commercialise, the size of the global advanced bioenergy market is expected to grow substantially. Substitution away from carbon-intensive fuels, such as coal and gas, and innovation in advanced routes to final fuels are expected to drive bioenergy demand. Provided feedstocks are sourced sustainably, then the GHG benefits can be a substantial improvement over fossil fuel use. Overall bioenergy demand could double by 2030, with increased use in power, district heating, transport, and manufacturing.[30] This final fuel demand can drive growth throughout the bioenergy value chain, including at the feedstock and conversion stages. This is expected to create a substantially larger market size by 2050 for the feedstocks, technologies, and fuels within the scope of this analysis**.**

As a result of increases in bioenergy demand, our analysis suggests that market turnover in the global (advanced) bioenergy industry is expected to increase to approximately £120 billion by 2050. Although a large proportion of the overall market is unlikely to be traded, as discussed below, total global capital expenditure on conversion technology is expected to exceed £100 billion annually, driven by increasing demand for bioenergy. This in turn creates a market for tradeable services, chiefly EPCm services, of around £15 billion. Further explanation of the methodology used to estimate market sizes is provided in Appendix 4.

Given many advanced routes have not commercialised, there is significant uncertainty over which ones will dominate the bioenergy industry in 2050. Innovation and local factors, such as relative feedstock availability, will be critical to determine which routes are cost-competitive in 2050. Given its application across various conversion routes, our assessment includes a relatively large market share (of total bioenergy production) for gasification-based routes. Our analysis suggests that the market for these routes is expected to be £65 billion by 2050. This compares to £30 billion and £35 billion for the hydrolysis and fermentation, and anaerobic digestion routes, respectively.

[29] Global Methane Initiative Agriculture Subcommittee (2014) A Global Perspective of Anaerobic Digestion Policies and Incentives https://www.globalmethane.org/documents/tools/a-global-perspective-of-ad-policies-incentives.pdf
[33] IEA (2017) Technology Roadmap Delivering Sustainable Bioenergy https://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf
[30] Irena (2014) Global Bioenergy Supply and Demand Projections https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

EPCm services are likely to be highly accessible for UK exporters, whereas only a fraction of equipment for conversion technologies is likely to be traded. Given the immaturity of the market for advanced biofuel generation equipment and services, the future tradability of goods and services is difficult to establish based on the current sector. However, based on analogous sectors we assume the following:

- **Bioenergy conversion equipment** is assumed to be as tradeable as combustion equipment for power generation (35%). This implies a tradeable market of approximately £40 billion annually by 2050.

- **EPCm services** related to the design and management of the construction of complex infrastructure are assumed to be highly traded, up to 100%. This implies an annual tradeable market of approximately £15 billion by 2050.This excludes wider services, such as maintenance, which are typically provided locally.

Figure 1 **The current and future bioenergy market**

Current market for bioenergy

- *Production:* Global generation from bioenergy conversion technologies is 200TWh in 2017, representing ~£2 bn in turnover.
- *Trade:* Most production is currently for internal markets, such as anaerobic digestion, with global traded turnover of relevant equipment of ~0.5bn.
- *Markets:* The UK is the fifth-largest market for biopower, with increases in biofuels use in recent years from a low base.

Tradability of market

- *Goods:* Equipment and intellectual property is highly traded; feedstocks often locally sourced, but there is substantial trade in wood pellets (the UK is the world's largest importer).
- *Services:* Engineering, procurement, and construction contracts (EPC) are highly traded.
- *Trends:* International trade is expected to increase sharply as the bioenergy market moves towards high-value advanced biofuel production.

Trends in deployment

- *Global:* Biofuel generation is expected to grow over 300% by 2050.
- *Growth pattern:* The rest of the world market will drive growth rather than the EU market, given its larger size.
- *Uncertainty:* If a 2C is exceeded, bioenergy demand is still expected to grow, but significantly less (<200% increase by 2050).

Global and regional market size to 2050

- *Growth trend*: Stronger growth post-2030 following commercialisation of key conversion technologies and high replacement demand.
- *Key markets:* 15% of global demand expected to be EU, with 85% of global demand located in the rest of the world in key bioenergy markets, such as the US, Brazil, and China.

Source: Vivid Economics

UK competitive position

The UK has early-stage strength in some stages of gasification-based routes but requires further innovation to enable competitiveness as the market matures. The domestic supply chain is not thought to be competitive in gasification technology itself. To illustrate, the UK does not have any large-scale pilot gasifiers for R&D, unlike other countries such as Austria.[31] Nevertheless, despite industry weakness, there is academic research on gasification technologies in the UK, which could enable exports of intellectual property. In contrast, the UK is thought to be competitive in equipment for the latter stages of gasification-based routes, such as syngas conditioning and catalytic processes. For example, the UK supply chain is developing technology for biomass-derived syngas purification and conditioning and has existing commercial methanation catalysts available. Given key gasification-based routes are not yet commercial, continued innovation is necessary to maintain existing strengths.

The UK is less competitive in the hydrolysis and fermentation-related routes but does have research strength. Historically, UK companies have not had strength in hydrolysis and fermentation routes. The low domestic availability of lignocellulosic feedstocks may contribute towards the UK supply chain's limitations in these routes. Despite limited industry competitiveness in hydrolysis and fermentation, there is research strength at universities. For example, the UK is a major research hub for syngas fermentation.[32] Innovation could enable the UK supply chain to become competitive in hydrolysis and fermentation routes and unlock export opportunities. An opportunity may exist in tailoring these processes to more readily available domestic feedstocks such as municipal solid waste.[33]

The UK has competitive strength in anaerobic digestion, supported by an expanding domestic market. The UK's anaerobic digestion industry has grown by more than 350% in the last 10 years.[34] There are a wide range of suppliers to support the domestic industry, with UK firms successfully exporting specialist components in Europe, as well as to the rest of the world.[35] Workshop evidence suggests that UK firms are competitive in re-exporting assembled components using their own IP, as well as exporting specialist components.

The key international competitors for the UK across the bioenergy value chain are Germany, the US, and China. Trade data is not disaggregated at the level of

[31] E4tech (2018) Innovation Needs Assessment for Biomass heat https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf
The Austrian pilot large-scale gasification project is at Güssing https://biomasspower.gov.in/document/flipbook-pdfdocument/Biomass%20gasification%20based%20combined%20heat%20and%20power%20plant%20at%20G%C3%BCssing,%20Austria.pdf
[32] Synbiochem website http://synbiochem.co.uk/national-synthetic-biology-research-centres/
[33] Compared to, for example, Scandinavian countries with large lignocellulosic supplies.
[34] Expert evidence and mrw (2018) 'Supercharge' AD for boost in jobs and exports says ADBAhttps://www.mrw.co.uk/latest/supercharge-ad-for-boost-in-jobs-and-exports-says-adba/10036196.article
[35] AnaerobicDigestion.com https://anaerobic-digestion.com/biogas-products/
https://www.biogasproducts.co.uk/projects/#

bioenergy conversion technology and does not exist for technologies which have not reached commercialisation. Therefore, as the next best alternative, trade data at the lowest level of aggregation and workshop evidence are used to determine the UK's key international competitors.[36] For equipment usage in the bioenergy industry, Germany is the leading exporter in the world market with a 20% market share, while the US and China have market shares of 11% and 8%, respectively.

In the EU market, the UK's key competitor is Germany; however, Sweden, Finland, and Denmark are also important competitors in specific areas of the value chain. According to trade data, Germany has a leading 36% share in purification machinery in the EU market, which could be leveraged to develop strength in gasification-based routes. It also has a 32% market share in distilling plant, likely to be applicable to hydrolysis and fermentation routes; and a 35% share in the wider export category containing anaerobic digestion. Sweden has strength in gasification, especially using forestry residues as feedstocks; and plant breeding, which may compete against the UK's IP exports in this area.[37] Furthermore, there is academic research in Denmark on pre-treatment technologies, and existing gasification strength in Finland.[38]

Unlike the EU market, no country has a clear competitive advantage in the rest of the world market. Germany, China, and the US maintain export strength in technology and equipment applicable to many advanced routes to final biofuels. For example, for gas generator exports in the rest of the world market, which is assumed to indicate strength in gasification-based routes, Germany, China, and the US have market shares of 5%, 9%, and 15%, respectively. For distilling plant, which is assumed to indicate strength in hydrolysis and fermentation routes, Germany, China, and the US have market shares of 12%, 31%, and 5%, respectively.

[36] A subset of the following HS codes was used to determine country-level conversion technology market shares: 730900, 741999, 761100, 8405, 841931, 841940, 842129, 842139, and 847989.
[37] E4tech (2018) Innovation Needs Assessment for Biomass Heat https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf
[38] E4tech (2018) as above.
AutomationWorld (2013) Finland Open's World's Largest Biomass Gasification Plant https://www.automationworld.com/article/industries/power-generation/finland-opens-worlds-largest-biomass-gasification-plant

Figure 2 **The UK's competitive position in trade in goods**

Current UK competitiveness

- *Market shares* (GBR, HFR, AD):
  EU *(excl. UK)* ~ 7%, 3%, 5%
  RoW ~ 4%, 3%, 3%
- *Strengths:* Leading engineering and research base; gasification skills developed from waste management and power applications.
- *Weaknesses:* Limited land availability is a barrier to domestic deployment, which may be key to learning-by-doing.

Competitor- Germany

- *Market shares* (GBR, HFR, AD):
  EU ~ 31%, 24%, 33%
  RoW ~ 12%, 9%, 14%
- *Strengths*: Strong manufacturing base in similar technologies such as gas generation and purification; Miscanthus research.

Competitor - China

- *Market shares* (GBR, HFR, AD):
  EU ~ 1%, 2%, 2%
  RoW ~ 14%, 15%, 10%
- *Strengths*: Use of straw in anaerobic digestion; research on pre-treatment technologies and biological hydrogen production.
- *Weaknesses:* Limited presence in the EU market.

Competitor– USA

- *Market* shares (GBR, HFR, AD):
  EU ~ 3%, 2%, 4%
  RoW ~ 18%, 11%, 12%
- *Strengths:* Gasification, strong bioenergy research base, and available learning-by-doing from deployment in large domestic market.
- *Weaknesses:* Distilling and rectifying plant.

**Market shares of content by value*

Note: *Market shares based on analysis of HS Codes: 730820, 730890, 841280, 841290, 8482, 848340, 850231, 850300, 850400, 853720, and 854460. GBR is gasification-based routes; HFR is hydrolysis and fermentation routes; and AD is anaerobic digestion.*

Source: *Vivid Economics*

Box 8. **Industry workshop feedback regarding business opportunities**

- Domestic deployment is key to enable innovation in bioenergy technology in the near term. Without it, there will be lower learning and scale effects, and therefore lower domestic competitiveness.
- Intellectual property exports are a strong business opportunity for the UK. Furthermore, there are good opportunities in catalysis and plant breeding, particularly Miscanthus.
- The UK has good business opportunities to import components for conversion technologies, assemble them using its IP, and then re-export. UK firms are already active in this area for anaerobic digestion equipment.
- There was consensus for the UK not having export opportunities in feedstocks due to the limited land availability in the UK.

Table 6. **Export market shares and innovation impact – biomass and bioenergy**

Component	Tradeable market 2050 (£bn)	Current market share of related goods and services	2050 outlook with strong learning by research			
			Market share*	Captured turnover (£m)	Captured GVA from exports (£m)	Rationale for the impact of innovation on exports of related equipment and services
Gasification-based routes (equipment)	**EU: 1.2** RoW: 11	**EU: 7%** RoW: 4%	**EU: 16%** RoW: 6%	**Total: 900**	**Total: 360**	The UK market share increases significantly, to half that of Germany's current market share. This is driven by the UK supply chain leveraging existing strength in technologies applicable to gasification-based routes, such as syngas conditioning and catalysis to drive innovation.
Hydrolysis and fermentation routes (equipment)	**EU: 0.7** RoW: 8.1	**EU: 3%** RoW: 3%	**EU: 6%** RoW: 4%	**Total: 420**	**Total: 170**	The UK market share increases significantly, to a quarter of Germany's current market share. The smaller increase reflects the UK's relative weakness in this route compared to gasification-based ones. The increase can be driven by innovation in pre-treatment and hydrolysis of lignocellulosic feedstocks, and tailoring processes to be able to use feedstocks that are more readily available in the UK, such as the biogenic fraction of MSW.
Anaerobic digestion (equipment)	**EU: 1.3** RoW: 8.9	**EU: 5%** RoW: 3%	**EU: 5%** RoW: 3%	**Total: 310**	**Total: 130**	The UK's market share is assumed to remain constant given the relative maturity of this market. Maintaining this market share will likely require the UK supply chain to offer innovative solutions in the component assembly process.

Component	Tradeable market 2050 (£bn)	Current market share of related goods and services	2050 outlook with strong learning by research			
			Market share*	Captured turnover (£m)	Captured GVA from exports (£m)	Rationale for the impact of innovation on exports of related equipment and services
EPCm Services						
Gasification-based routes (services)	**EU: 0.5** RoW: 4.8	**n/a**	**EU: 11.8%** RoW: 11.8%	**Total: 630**	**Total: 350**	The UK's ability to capture EPCm-related services is assumed to be similar across different routes. A market share of 11.8% is thought to be feasible, based on the UK's market share for similar services in the oil and gas sector.
Hydrolysis and fermentation routes (services)	**EU: 0.3** RoW: 3.4	**n/a**	**EU: 11.8%** RoW: 11.8%	**Total: 440**	**Total: 240**	
Anaerobic digestion (services)	**EU: 0.6** RoW: 3.8	**n/a**	**EU: 11.8%** RoW: 11.8%	**Total: 510**	**Total: 280**	

Note: *The possible market share of the UK, and rationale for the impact of innovation are based on stakeholder input gathered in the workshop. Key technologies cannot be perfectly matched against trade data because it is not available at the required level of disaggregation. Therefore, current market shares are indicative of the most disaggregated UN COMTRADE category the technology sits within. A subset of the following HS codes was used for each technology depending on applicability: 730900, 741999, 761100, 8405, 841931, 841940, 842129, 842139, and 847989.*

Source: *Vivid Economics*

UK business opportunities from export markets

Box 9. **Interpretation of business opportunity estimates**
The GVA and jobs estimates presented below are *not* forecasts, but instead represent estimates of the potential benefits of the UK capturing available business opportunities. The presented estimates represent an unbiased attempt to quantify opportunities and are based on credible deployment forecasts, data on current trade flows, and expert opinion, but are necessarily partly assumption-driven. The quantified estimates are intended as plausible, but optimistic. They assume global climate action towards a 2 degree world and reflect a UK market share in a scenario with significant UK innovation activity.[39] More information on the methodology, including a worked example, is provided in Appendix 4, and a high level uncertainty assessment across the EINA subthemes is provided in Appendix 5.

Our analysis suggests that growth of UK exports could add £1.5 billion to GVA per annum and support 11,000 jobs by 2050, primarily through opportunities associated with gasification-based routes, as shown in Figure 3 and Figure 4.[40] For advanced bioenergy, the 2050 global tradeable turnover is expected to be over 8 times that of the 2015 level. This is driven by commercialisation of the gasification-based, and hydrolysis and fermentation routes to final biofuels, as well as continued growth in the anaerobic digestion market. Gasification-based routes are expected to support £0.7 billion in GVA and 5,500 jobs per annum by 2050, which is the highest of all routes to final biofuels. For this reason, there is a deep dive on gasification-based routes in the section below. Additionally, there is also a deep dive on EPCm service exports because these are expected to support £0.9 billion in GVA and 5,600 jobs per annum by 2050.[41]

Overall opportunities for the UK will significantly depend on whether growth in the advanced biofuels and bioenergy market aligns with UK strengths. As shown in Table 6, the UK is expected to capture a large share of the tradeable value of the gasification-based routes market. Improved UK competitiveness in this area,

[39] Note, other IEA climate scenarios were also used as a sensitivity. Where the level of global climate action has a meaningful impact on market size, this is highlighted in the market overview section. Full results are available in the supplied Excel calculator.
[40] These figures are from the IEA's 2 degrees scenario, which is the standard for business opportunities. GVA and jobs figures are robust to climate scenario. The IEA's reference to technology scenario is expected to lead to £1.5 billion in GVA and 12,000 jobs by 2050, while the below 2 degrees scenario is expected to lead to £2 billion in GVA and 15,000 jobs by 2050.
[41] EPCm services contributes towards GVA and jobs in the gasification, hydrolysis and fermentation, and anaerobic digestion routes.

combined with the large expected market, is a key driver of the substantial estimated business opportunities. If demand for gasification-based fuel production is relatively small by 2050, UK business opportunities will be substantially reduced because it is in these routes that the UK is expected to be most competitive.

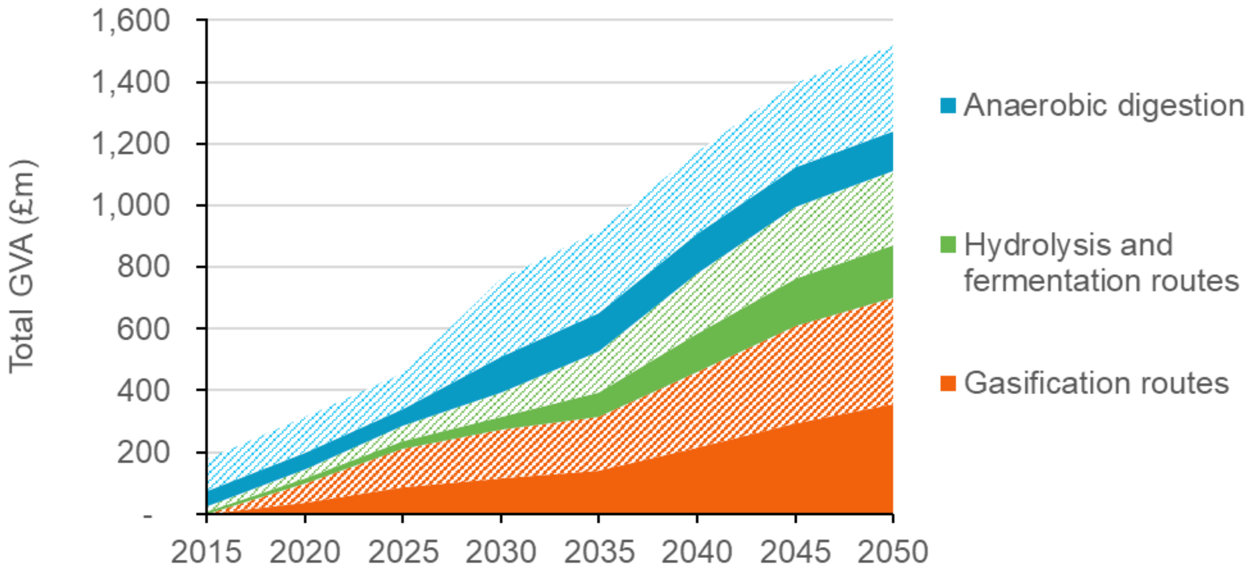
Hydrolysis and fermentation-associated routes are expected to contribute £0.4 billion in GVA and 3,000 jobs per annum by 2050. Opportunities in gasification-based routes are expected to be substantially greater than hydrolysis and fermentation routes by 2050. Combined with the lower expected UK market share, a key driver of these lower opportunities for hydrolysis and fermentation routes is the smaller expected tradeable market. Many conversion technologies in this category, such as alcohol catalysis, are not likely to meet a high volume of the overall biofuel demand by 2050. For example, the International Energy Agency (IEA) forecasts that biojet fuel will comprise 20% of final transport biofuel demand by 2050.[42] However, only a fraction of this is expected to come from alcohol catalysis because a variety of routes will be required to substitute for kerosene entirely.[43] This leads to low GVA and jobs numbers for alcohol catalysis because the process is only meeting a relatively small volume of the overall bioenergy fuel demand. Similar reasons can explain relatively low GVA and jobs numbers for many other routes in this category.

Anaerobic digestion routes are expected to contribute £0.4 billion in GVA and 2,800 jobs per annum by 2050. The UK has an existing strength in anaerobic digestion which can be leveraged to maintain competitiveness. Although the UK is not expected to increase its market share because this is a mature industry, international growth in the anaerobic digestion market will likely increase UK business opportunities. This leads to expected GVA and jobs figures in 2050 being more than double those of the 2015 figure. GVA opportunities grow more strongly than jobs opportunities because of expected productivity gains up to 2050, driven by scale economies, learning-by-doing, and further innovations.

[42] IEA (2017) Technology Roadmap Delivering Sustainably bioenergy https://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

[43] Reuters (2016) From green slime to jet fuel: algae offers airlines a cleaner future https://www.reuters.com/article/us-airbus-germany-biofuels/from-green-slime-to-jet-fuel-algae-offers-airlines-a-cleaner-future-idUSKCN0Z117F

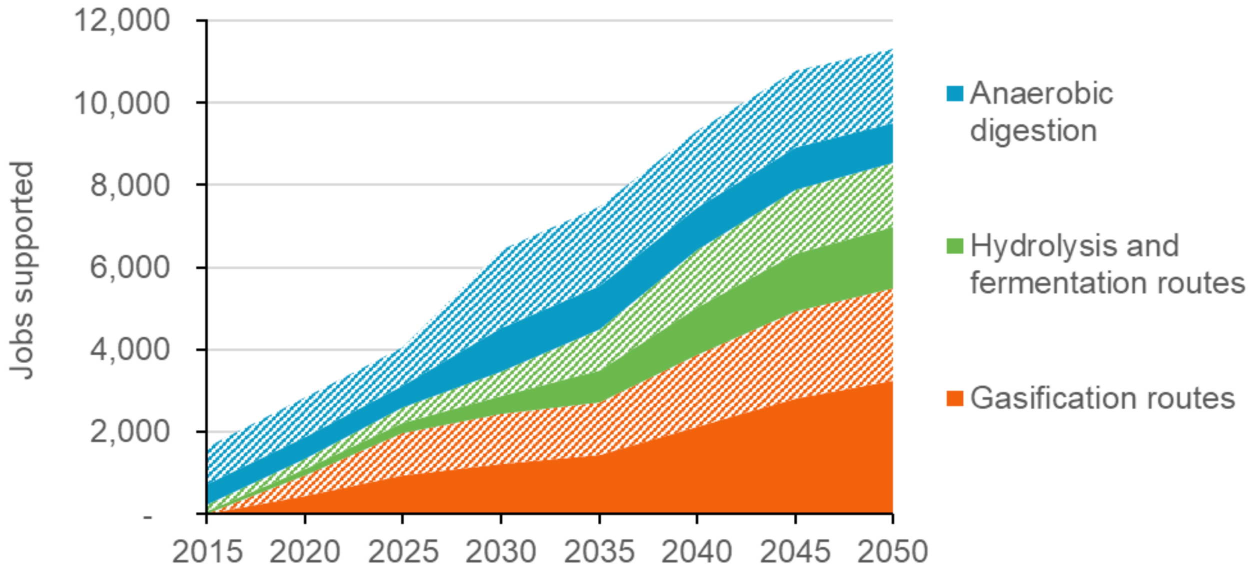
Figure 3 **GVA per annum from export markets by route – biomass and bioenergy**



Note: *The solid line represents equipment opportunities while the patterned line represents EPCm service opportunities.*

Source: *Vivid Economics*

Figure 4 **Jobs supported per annum from export markets by route – biomass and bioenergy**



Note: *The solid line represents equipment opportunities while the patterned line represents EPCm service opportunities.*

Source: *Vivid Economics*

UK business opportunities from domestic markets

Discussion

The transition to low-carbon and negative-emissions technologies can drive domestic business opportunities throughout the biomass and bioenergy value chain. As with the export analysis, the domestic analysis sizes opportunities associated with the production of advanced biofuels. Bioenergy could meet between 5% and 15% of the UK's energy demand by 2050 compared to 7% in 2017.[44] Although greater biomass use will drive UK domestic business opportunities in agriculture, the Committee on Climate Change (CCC) anticipates the UK's limited land availability will necessitate substantial imports.[45] Despite large expected feedstock and bioenergy conversion equipment imports, there are large domestic business opportunities in services with low tradability, for example O&M, feedstock production and high value components.

In addition to the technologies considered in the export analysis, the domestic opportunities include installation and O&M services. These are typically supplied domestically, hence they do not present a major export opportunity, but can support significant domestic GVA and jobs. Given the UK is likely to be a net importer of bioenergy feedstocks, new energy feedstocks are excluded from the export analysis, but are included for the domestic analysis. As in the export analysis, the domestic analysis considers three broad groups of bioenergy conversion processes: gasification-based routes, hydrolysis and fermentation routes, and anaerobic digestion.

[44] Committee on Climate Change (2018) Biomass in a low carbon economy https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf.
[45] Ibid.

Box 10. **The UK's domestic demand for bioenergy**

The need for negative emissions is likely to be a key driver of business opportunities associated with bioenergy in the UK. Harvested biomass typically contributes most to climate change if emissions are sequestered while also providing energy services.[46] Given the UK's limited availability of biomass and the amount of negative emissions required for net-zero, it's plausible all of the UK's advanced bioenergy business opportunities are driven by negative emissions applications.

The business opportunities analysis is anchored in a scenario where most biomass use in the UK is for hydrogen production with CCS. This is based on the ESME modelling underpinning the EINAs. Biomass gasification coupled with CCS to produce hydrogen has two core climate benefits: hydrogen will displace fossil fuels in the energy mix and by coupling biomass with CCS the process creates negative emissions. Notably, BECCS for power generation is another plausible use of biomass in the future UK energy system. A scenario where BECCS in power is more dominant would yield similar, but likely lower, results. Key technologies (such as gasification) are shared across the technologies, however there are likely to be more retrofit applications for BECCS in power, with e.g. old coal fired units converted for BECCS use.

Domestic opportunities for advanced biofuel use in the road transportation sector are likely limited. This is in line with ESME modelling and CCC analysis, which as discussed, concludes the most effective use of limited biomass is for negative emissions applications. Limited biofuel use in the transport sector would substantially limit the business opportunities associated with hydrolysis and fermentation routes, for example lignocellulosic ethanol fermentation, as these routes are vital to produce biofuels for transport. Biofuels could be a key enabler for aviation decarbonisation, but this is outside the scope of the EINAs.

Across the technologies considered, the shares UK firms capture of the domestic market are outlined in Table 7 and detailed below:

- **Equipment for gasification-based routes, hydrolysis and fermentation routes and anaerobic digestion:** The UK can grow its domestic market share in these routes from a low base to 47% by 2050, in line with the domestic

[46] Ibid.

share of combustion equipment for power generation.[47,48,49] For gasification-based routes, the UK can grow market share primarily in the later stages of the route, for example catalysis, rather than earlier stages such as gasification.

- **Installation and O&M services:** these services have low tradability; the analysis assumes a 95% domestic market share to allow for minor imports
- **EPCm services:** The UK captures 77% of the domestic market for EPCm services across bioenergy conversion technologies, in line with the current domestic share for EPCm services in the oil & gas sector. This market share is assumed to remain constant up to 2050 as engineering consultancy strength in the UK continues.
- **New energy feedstocks:** The UK captures a 60% domestic market share in new energy feedstocks by 2050, in line with estimates for UK new energy feedstock domestic production and imports.[50]

Domestic business opportunities within biomass and bioenergy can support £1.4 billion in GVA and 15,000 jobs per annum by 2050, as shown in Figure 7 and Figure 8. These domestic business opportunities are roughly equal to export opportunities in 2050, as shown in Figure 5 and Figure 6; with exports supporting £1.5 billion in GVA and 11,000 jobs per annum by 2050.[51] The inclusion of new energy feedstocks in the domestic analysis leads to bioenergy exports being associated with more productive jobs; nevertheless, domestic opportunities can produce highly skilled jobs also as new energy feedstocks contributes less than one third of overall domestic opportunities in 2050.

Despite domestic opportunities peaking in the 2030s, overall opportunities peak in 2050, as shown in Figure 5 and Figure 6. Domestic bioenergy demand ramps up by 2030 which drives substantial growth in equipment for hydrogen production with CCS in the mid-2030s. As demand rises, UK firms capture EPCm and installation services and equipment value for gasification-based biomass routes to hydrogen leading to a peak of GVA and jobs in 2035. Domestic business opportunities fall after 2035 with growth in new capacity slowing; as the industry matures towards 2050, business opportunities transition towards O&M services and replacement demand, contributing to a second smaller peak in GVA and jobs in

[47] For the equipment used in natural gas and coal routes to hydrogen, domestic production and trade data codes are not well-matched, leading to an unreliable calculation for domestic market share.
[48] Domestic share for equipment used in power generation combustion equipment uses UK investment in combustion equipment in 2017 (calculation uses BEIS' figures) and subtracts combustion equipment imports using HS codes: 840681, 840682, 841620, 842139, 850161, 850162, 850163, 850164
[49] We recognise there are technical differences between combustion equipment for power generation and future bioenergy conversion technologies. Production and trade data for existing bioenergy conversion routes in the UK is not well-matched and could not be used as a proxy technology.
[50] This market share is based on Low Carbon Innovation Coordination Group (2012) Technology Innovation Needs Assessment https://www.carbontrust.com/media/190038/tina-bioenergy-summary-report.pdf
[51] Although exports support a higher domestic GVA than the domestic market, jobs supported are lower because they have a higher GVA/worker ratio associated with them. The inclusion of new energy feedstocks in the domestic analysis drives this.

2050. Although domestic opportunities are relatively volatile, contributing to sizeable employment swings, overall opportunities follow a smoother upward trajectory: growth in export opportunities after 2035 can reduce any employment slack in the bioenergy sector associated with a slowdown in domestic opportunities.

Services contribute the greatest domestic business opportunities by 2050, with the contribution from new energy feedstocks and equipment substantially lower, as shown in Figure 7 and Figure 8. ESME optimisation estimates no advanced biofuels use in transport; accordingly, there are no business opportunities identified for hydrolysis and fermentation routes. Business opportunities by sub-sector are outlined in Table 7, and detailed below:

- Services support £0.8 billion in GVA and 7,900 jobs per annum by 2050; O&M contributes the largest service opportunity, supporting £0.6 billion in GVA and 6,100 jobs per annum by 2050. Installation and EPCm services contribute the remainder of the service opportunities.
- New energy feedstocks can support £0.4 billion in GVA and 5,000 jobs per annum by 2050; wood/grassy crops, for example Miscanthus, contribute most of these opportunities, supporting £350 million in GVA and over 4,000 jobs per annum by 2050.
- Equipment opportunities can support £0.2 billion in GVA and 1,600 jobs per annum by 2050; equipment for gasification-based routes contributes 65% of these opportunities, with equipment for anaerobic digestion contributing the remainder.
- Domestic business opportunities for conversion equipment are relatively more uncertain than services as a greater share of their value is traded and hence more exposed to competition.

Quantitative results

Table 7. **Domestic market shares and innovation impact – biomass and bioenergy**

Technology	Domestic market 2050 (£bn)	Current share of related UK market	2050 outlook with strong learning by research			
			Market share (%) *	Domestic turnover captured (£m)	GVA (£m)	Rationale for the impact of innovation on domestic deployment of related equipment and services
Gasification-based routes' equipment	0.7	N/A	47%	330	130	The UK market shares grows to 47% by 2050, in line with the UK's current domestic market share in combustion equipment for power generation. The UK leverages strength in anaerobic digestion and the later stages of gasification-based routes to innovate in bioenergy conversion technologies.
Hydrolysis and fermentation routes' equipment	0	N/A	47%	0	0	
Anaerobic digestion equipment	0.3	N/A**	47%	160	70	
O&M services	1.4	95%	95%	1,300	590	The UK captures 95% of the market for O&M and installation services as these services have low tradability.
Installation services	0.3	95%	95%	310	140	
EPCm services	0.2	77%	77%	160	90	The UK captures 77% of the EPCm services value associated with bioenergy conversion technologies, in line with the existing EPCm domestic share in the oil & gas

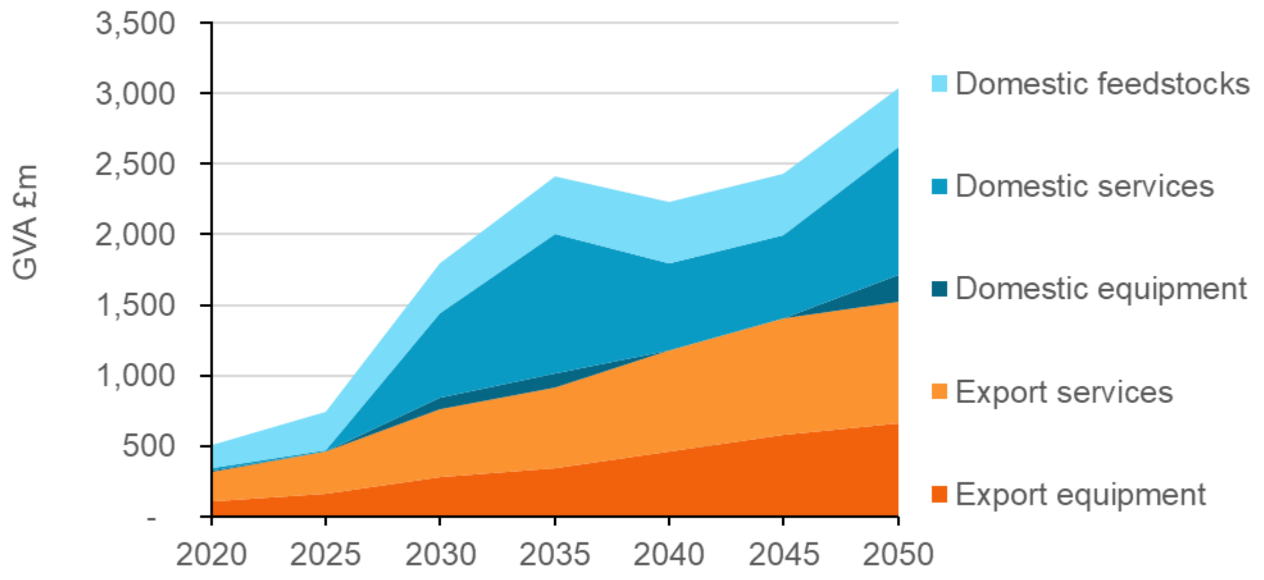
Technology	Domestic market 2050 (£bn)	Current share of related UK market	2050 outlook with strong learning by research			
			Market share (%) *	Domestic turnover captured (£m)	GVA (£m)	Rationale for the impact of innovation on domestic deployment of related equipment and services
						sector. The UK builds on leading engineering consultancy strength to successfully expand into bioenergy technologies.
`New energy feedstocks	0.8	N/A	60%	760	420	The UK market share grows to 60% by 2050. Leading Miscanthus research across several UK universities drives an uptake in domestic new energy feedstock production and yields.

Note: ** Future market shares are not a forecast, but what UK business opportunities could be potentially in the context of the EINAs. The possible market share of the UK, and rationale for the impact of innovation, are based on PRODCOM analysis and additional market research. N/A indicates data is not available.*

*** Although anaerobic digestion has commercialised, poorly matched production and trade codes does not permit the computation of current market share.*

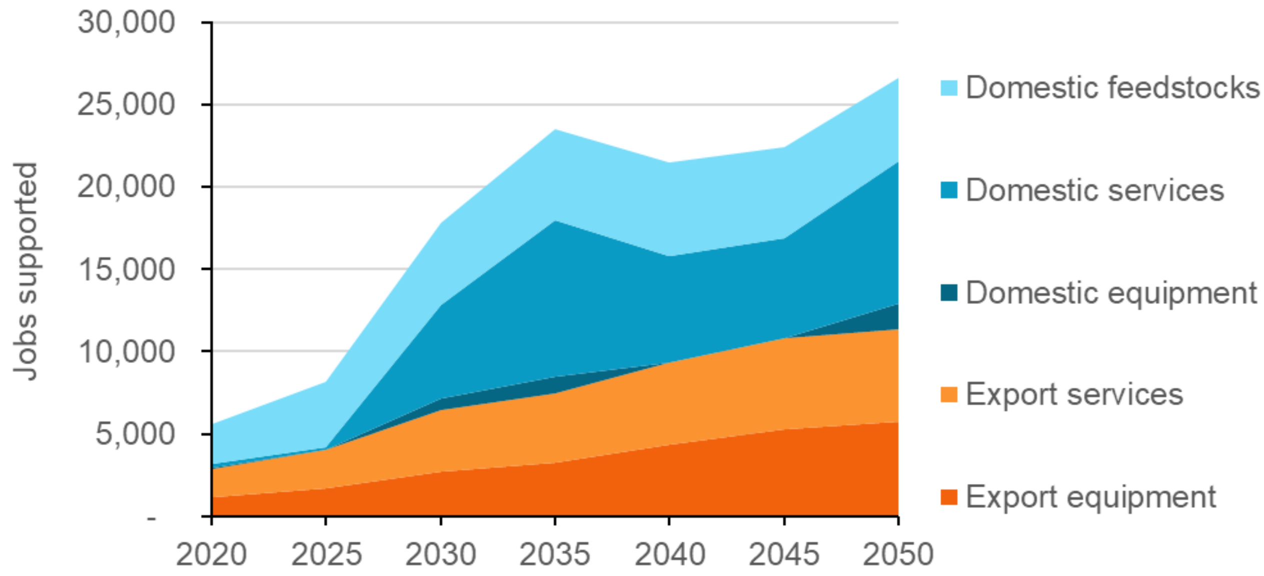
Source: *Vivid Economics*

Figure 5 **GVA per annum from export and domestic markets – biomass and bioenergy**



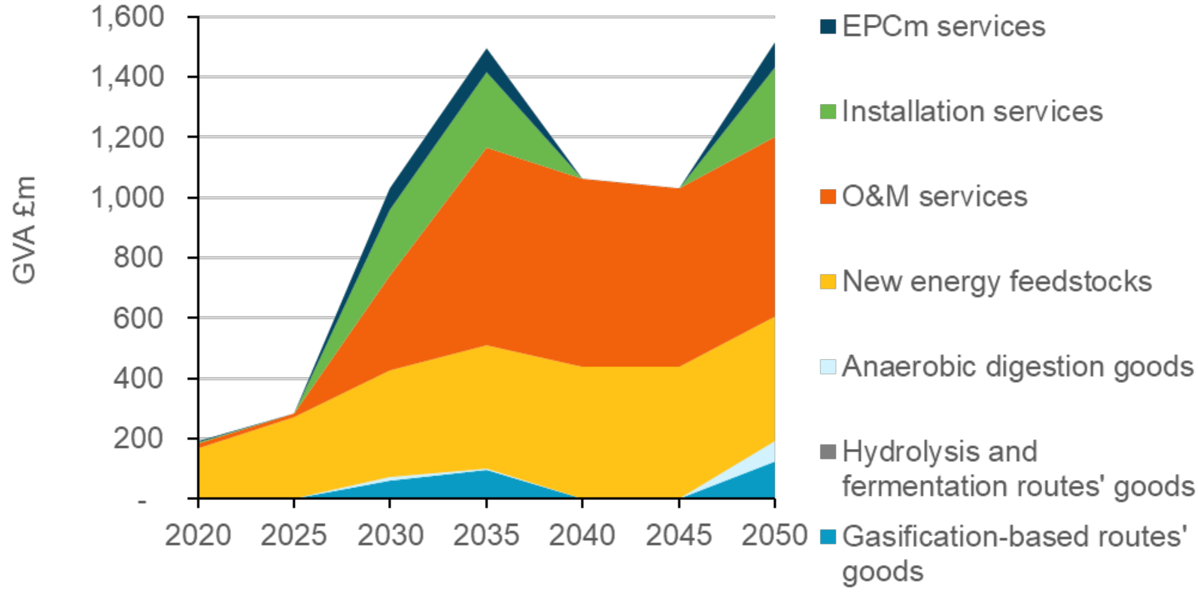
Source: Vivid Economics

Figure 6 **Jobs supported per annum from export and domestic markets – biomass and bioenergy**



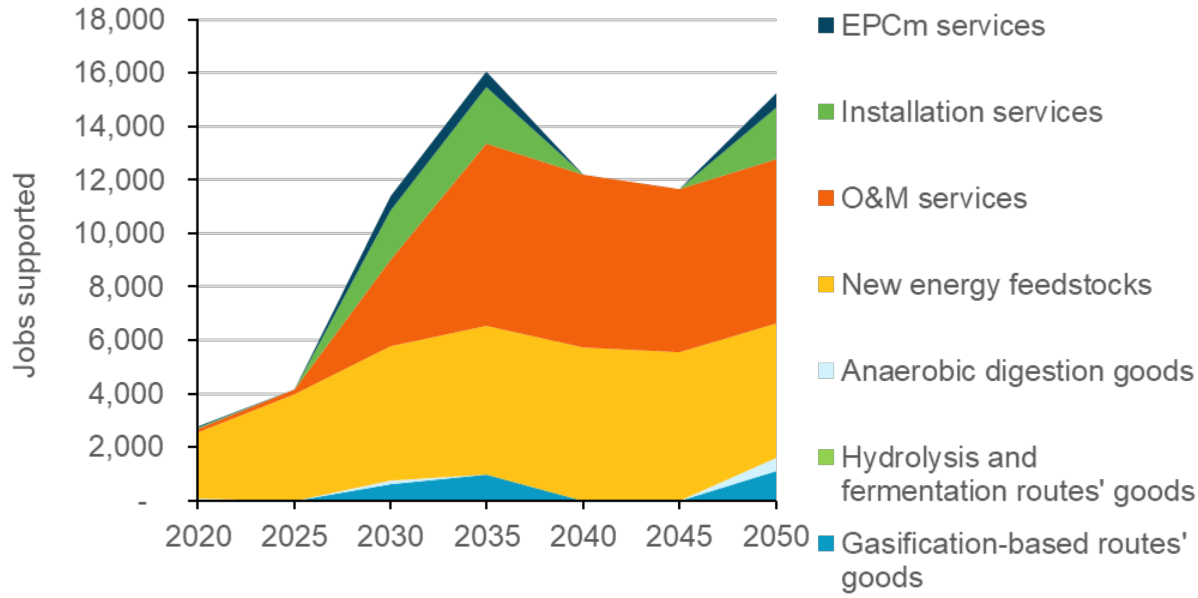
Source: Vivid Economics

Figure 7 **GVA per annum from domestic markets by component – biomass and bioenergy**



Source: Vivid Economics

Figure 8 **Jobs supported per annum from domestic markets by component – biomass and bioenergy**



Source: Vivid Economics

Business opportunity deep dive: Gasification-based routes

Exports of the equipment for gasification-based routes can contribute £0.4 billion in GVA and 3,300 jobs per annum by 2050. These figures are robust to climate scenarios, with a GVA range of £0.9 billion to £1.1 billion and the number of jobs supported ranging from 7,000-9,000.[52] This is based on the strong assumption that the UK can capture 16% of the EU and 6% of the rest of the world gasification-based routes market by 2050.[53] These market shares are half the size of Germany's current share in similar existing technologies.[54] Its unlikely gasifier exports will be the primary driver of these business opportunities because of the UK's relative weakness in gasification technology. Rather, given existing strengths, later stages of gasification-based routes, such as syngas conditioning and catalysis, are likely to drive opportunities.

The UK supply chain will need to establish partnerships with international suppliers of gasification technology to fully access business opportunities in gasification-based routes. UK firms are more likely to export specialised equipment at later stages of gasification-based routes, such as syngas conversion to Bio-SNG, compared to earlier stages, such as gasification, because the domestic supply chain has greater expertise in the later stages. Therefore, for the UK supply chain to export in areas of its competitive strength, they may need to establish partnerships with foreign suppliers of gasifiers and create an international supply chain. Without such an agreement, UK firms may struggle to maximise export opportunities because they are unlikely to have the prerequisite expertise to export the entire value chain. UK firms are already demonstrating their capability to sign agreements with foreign suppliers of gasifiers for the domestic market, indicating they are well-placed to replicate these agreements in an overseas market.[55]

The UK is a leader in catalysis science, which can enable export opportunities for IP. Workshop evidence suggests that the UK is an international leader in catalysis, with strong research at firms and universities. Catalysis is important in many gasification routes, such as Bio-SNG and Fischer-Tropsch synthesis.

[52] The 3 climate scenarios used in this analysis are the IEA's ETP reference technology, 2 degrees, and beyond 2 degrees scenarios.
[53] The UK's potential market share figures were driven by assuming by 2050 the UK captures a share in this market half that of Germany's in existing, relevant technology.
[54] The HS codes used for gasification-based routes are 730900, 741999, 761100, 842139, and 8405. Izaak Wind (2009) HS Codes and the Renewable Energy Sector https://www.ictsd.org/sites/default/files/downloads/2009/09/hs_codes_and_the_renewable_energy_sector_izaak_wind.pdf
[55] Energy Technologies Institute (2017) Work starts on ETI backed innovative waste gasification commercial demonstration plant in the West Midlands https://www.eti.co.uk/news/work-starts-on-eti-backed-innovative-waste-gasification-commercial-demonstration-plant-in-the-west-midlands

Therefore, there is a clear opportunity for existing catalysis strength to unlock high-value export opportunities for the UK supply chain. UK firms are already doing this, by developing innovative catalysis solutions in Fischer-Tropsch synthesis.[56] This intellectual property can then be licensed internationally, with offshore manufacturing of catalysts expected.

Business opportunity deep dive: EPCm services

EPCm services can contribute £0.9billion in GVA and 5,600 jobs per annum by 2050. EPCm contracts are a common form of contract in the construction industry. They are signed between an end-user of a facility, the client, and an outside expert firm, the contractor. This agreement gives the contractor, usually an engineering firm, complete responsibility for the design, construction, delivery, and risk of the project.[57] Our analysis suggests such EPCm services could contribute £0.3 in GVA and 2,200 jobs per annum for gasification routes. A further £0.5 billion of GVA and 3,400 jobs are associated with both hydrolysis and fermentation, and anaerobic digestion.

The UK can leverage its leading engineering services sector to export EPCm services overseas. Traditionally, UK firms possess strength in engineering consulting. Although they have often operated in markets other than bioenergy, their brand recognition and scale can enable their entry into the bioenergy industry. There is evidence of some leading UK engineering consultancies doing this already, suggesting a movement to bioenergy is feasible.[58] However, Engineering UK has estimated a domestic shortfall of at least 22,000 graduate-level engineers annually.[59] This can limit the extent to which UK firms are able to pursue new growth opportunities, such as in EPCm management services for the bioenergy industry.

Innovation in bioenergy conversion technology, and strong domestic deployment, would help to develop the UK's bioenergy service exports. Domestic innovation in gasification-based, hydrolysis and fermentation, and anaerobic digestion routes to final biofuels will increase the value of the knowledge and skills of UK workers in the bioenergy industry. Furthermore, strong domestic deployment helps to build the required expertise. Given commercialisation for key

[56] Johnson Matthey website https://matthey.com/products-and-services/chemical-processes/core-technologies/fischer-tropsch-technology
[57] EPCm Engineer website https://www.epcengineer.com/definition/132/epc-engineering-procurement-construction
[58] Mott McDonald bioenergy website https://www.mottmac.com/power/bioenergy
[59] Engineering UK (2018) Synopsis and recommendations https://www.engineeringuk.com/media/1576/7444_enguk18_synopsis_standalone_aw.pdf

routes is still in the future, there is limited evidence to assess the importance of domestic deployment and innovation on the UK's competitiveness in EPCm services. However, domestic deployment and innovation in the oil and gas sector was crucial for UK firms to develop the skills and knowledge base in order to serve clients abroad.[60] Similarly, it is also likely domestic deployment and innovation in key bioenergy routes will be crucial to fully unlock export opportunities.

[60] Oil and Gas Authority (2016) Supply Chain Strategy https://www.ogauthority.co.uk/media/2834/supply_chain_strategy_1016.pdf

Market barriers to innovation within biomass and bioenergy

Introduction

Box 11. **Objective of the market barrier analysis**

Market barriers prevent firms from innovating in areas that could have significant UK system benefits or unlock large business opportunities. These barriers can either increase the private cost of innovation to levels that prevent innovation or limit the ability of private sector players to capture the benefits of their innovation, reducing the incentive to innovate.

Government support is needed when market barriers are significant, and they cannot be overcome by the private sector or international partners. The main market barriers identified by industry are listed in Table 8, along with an assessment of whether HMG needs to intervene.

Market barriers for biomass and bioenergy

Bioenergy makes up 9.5% of the total primary energy production in the UK.[61] HMG has given bioenergy an important role in decarbonising the energy system and provided long-term support measures. Innovation priorities focus on bioenergy as an input substitute within the current energy infrastructure.[62]

Table 8 lists the main market barriers in biomass and bioenergy, along with an assessment of whether the government needs to intervene. For each identified market barrier, an assessment of the need for government intervention is provided. The assessment categories are low, moderate, severe, and critical.

- **Low** implies that without government intervention, innovation, investment, and deployment will continue at the same levels, driven by a well-functioning industry and international partners.

[61] BEIS (2018) UK Energy Statistics, 2017 & Q4 2017 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695626/Press_Notice_March_2018.pdf
[62] Levidow et al. (2013) Innovation priorities for UK bioenergy: technological expectations within path dependence http://oro.open.ac.uk/39162/

- **Moderate** implies that without government intervention, innovation, investment, and deployment will occur due to well-functioning industry and international partners, but at a lower scale and speed.
- **Severe** implies that without government intervention, innovation, investment, and deployment are significantly constrained and will only occur in certain market segments or must be adjusted for the UK market.
- **Critical** implies that without government intervention, innovation, investment, and deployment will not occur in the UK.

Table 8. **Market barriers**

Market barrier	Need for HMG support
Policy-dependent demand and uncertain government support levels limit incentives for innovation: policy focus on pathways (particularly for AD) rather than outcomes and lack of clear metrics for industry targets	Critical
High perceived risk, and returns for advanced biofuels far in the future, reduce access to finance: requirement for financial returns above those of existing technologies	Severe
Costly feedstock classification processes reduce innovation on conversion methods: unclear classification of waste and non-waste residue	Severe
Lack of business models to make financial case prevents both access to finance and realising returns on innovation: particularly problematic for first-of-a-kind (FOAK) deployment at scale	Moderate
Disjointed innovation and lack of coordination across the supply chain prevents synergies of innovation; lack of coordination between waste and bioenergy industry	Low

Source: Vivid Economics analysis and stakeholder input

Box 12. **Industry workshop feedback**

Industry experts raised several areas that require HMG support:

- **Bioenergy routes are not currently cost-competitive with fossil fuels and are therefore reliant on government support to create enough demand.** Support is designed based on either outcome targets or pathways. For example, the transport industry has outcome-based targets as per the Renewable Transport Fuel Obligation, while the AD industry and the power industry use feed in tariffs.[63] Particularly for AD, there is a lack of outcome-focussed targets and mandates to support market creation. Current pathway-focussed support initiatives tend to be complex and prescriptive, making it difficult and costly for industry to comply. This barrier is more severe for small innovative schemes.

- **Given the wide range of potential biomass uses within and outside the energy sector, there has been debate over how biomass resources should be used.** This uncertainty over long-term biomass resource availability, and the relative GHG and other impacts of different biomass end uses, has led to hesitation over bioenergy investment and policy. Recent analysis, such as that carried out by the CCC, has clarified many of these questions, but a wider consensus is still needed.[64]

- **The return on investment for advanced biofuels is perceived as risky and occurs far into the future, therefore financing is expensive.** Without policy security over an extended period and the confidence that the market will be of an adequate size, investment will remain high-risk. The sector competes with existing technologies, including fossil fuels, which offer higher and more certain returns. In the absence of risk-sharing by the government, cost of finance for industry will likely remain high, particularly for small innovative developers.

- **Some attendees considered that the processes for determining eligibility of waste feedstocks were unnecessarily complex and costly.** Policy gaps on industrial waste and unclear rules for eligibility of sustainable feedstock in the future were raised as priority areas to address.

- **There is a lack of a clear business model and revenues occur far into the future.** Small companies innovate but are unable to take their innovations to market, partly due to unclear future market conditions. This barrier prevents moving from first-of-a-kind innovation to deployment at scale. As a result, larger players buy small developers once they have developed new technologies, reducing competition in the market.

- **Disjointed innovation and lack of coordination across the supply chain slows innovation.** For example, there is little coordination between the waste and the bioenergy industry despite potential areas of synergy. Dialogue between these industries in the US was referenced as a positive international example.[65]

International opportunities for collaboration

There are potential international opportunities to innovate collaboratively.

- Collaborating or co-working with large-scale research facilities in Europe and the USA through research partnerships or cooperation agreements could speed up innovation in the UK. For example, test facilities in Austria and in the Netherlands have been instrumental for innovation in gasification.[66] The UK can build on the strength of other countries in gasifiers to innovate in the latter steps of gasification-based routes.
- International research collaborations in areas where the UK is already strong can also support innovation. For example, the UK is a global leader in Miscanthus research and collaboration with international partners has contributed significantly to advancement in Miscanthus breeding in recent years.[67]
- For regulatory frameworks, workshop participants referenced the US framework for waste and fuel as a potential model for the UK as well as Denmark's policy position on cost of emission and outcome-based targets.[68]

[63] HMG (2012) Renewable Transport Fuel Obligation https://www.gov.uk/guidance/renewable-transport-fuels-obligation; Ofgem (n.d.) Domestic Renewable Heat Incentive https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi ; Ofgem (n.d.) Feed-in Tariffs (FIT) https://www.ofgem.gov.uk/environmental-programmes/fit

[64] CCC (2018) Biomass Review https://www.theccc.org.uk/comingup/new-ccc-report-bioenergy-review/

[65] Waste and residues are directly included in the definitions of 'renewable biomass' and as such not treated different from other biomass feedstocks. See: NL Agency (2011) Sustainability requirements for biofuels and biomass for energy in EU and US regulatory frameworks https://english.rvo.nl/sites/default/files/2013/12/Report%20EU%20and%20US%20biomass%20legislation%20-%20Partners%20for%20Innovation.pdf

[66] ECOFYS (2018) Innovation Needs Assessment for Biomass Heat https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf

[67] Ibid.

[68] City of Copenhagen (2016) CPH 2025 Climate Plan https://kk.sites.itera.dk/apps/kk_pub2/pdf/1734_96fbb137c683.pdf; IEA (2018) IEA Bioenergy Countries' Report – Update 2018 https://www.ieabioenergy.com/wp-content/uploads/2018/10/IEA-Bioenergy-Countries-Report-Update-2018-Bioenergy-policies-and-status-of-implementation.pdf

Appendix 1: Organisations at the workshop

- Anaerobic Digestion & Bioresources Association
- Department for Business, Energy & Industrial Strategy
- Dorset Biosolutions Ltd
- Energy Technologies Institute
- Engineering and Physical Sciences Research Council
- Forestry Commission
- Future Biogas
- Johnson Matthey
- Progressive Energy
- Rubus Scientific Ltd
- Surrey University
- Terravesta
- UK Centre for Process Innovations
- University of Newcastle
- University of Nottingham
- University of York
- Velocys

Appendix 2: Innovation tables

The workshop participants discussed the contents of the innovation tables and offered feedback, particularly regarding the key innovation priorities. The updated tables were afterwards circulated amongst workshop delegates with the opportunity to provide further comments, which were included.

In the innovation tables below, the magnitude of the contributions to cost reduction and reducing deployment barriers are described in qualitative terms relative to other innovation opportunities:

- Significantly above average = 5
- Above average = 4
- Average = 3
- Below average = 2
- Significantly below average = 1

An indicative timeframe for each innovation is provided. The timeframe given relates to the year the technology is deployed commercially at scale (gaining 10-20% market share).

Table 9. **Innovation mapping and workshop discussion for all gasification-based routes**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
All Gasification-based routes						
Scale	**Plant scale-up** - larger gasification plants will benefit from economies of scale (up to an optimum scale given the distribution of the feedstock resource). Construction of larger scale plants will likely be reliant on the increased deployment of smaller scale ones	5	5	BioH_2, Bio-SNG, FT synthesis, Syngas to Methanol	BECCS	2025
Deployment	**Construction of multiple plants** would bring multiple benefits independent of scale-up, such as process optimisation, improved reliability, experience with different feedstock mixes, CAPEX reduction through replication and standardisation, and reducing the perceived level of risk associated with these projects	5	5	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2025

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Link to CCUS	**Link to CCUS** – the UK is well suited for siting CCUS, which gives an opportunity for early deployment of gasification plants with CCUS, creating an export opportunity for plants and skills	1 (CCUS will increase costs of fuels, but has benefits)	5 (Driver for BECCS could drive deployment)	$BioH_2$, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2035
Renewable hydrogen	**Injecting additional renewable hydrogen** into the methanation reactor could increase the yield of Bio-SNG (and reduce the need for water-gas shift reactions). Oxygen byproduct from electrolysis can partially displace oxygen from air separation unit. Can lower GHG emissions NB: Applies to all gasification routes except BioH2	3	3	Bio-SNG, FT synthesis, Syngas to MeOH	Electrolysers, BECCS	2035

Source: *Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018*

Table 10. **Innovation mapping and workshop discussion for gasifiers**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Gasifier						
Feedstock	**Improved feedstock handling** can increase plant availability (but requires skilled operators and higher cost equipment)	4	4	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2025
Gasifier	**Increased feedstock flexibility** will allow for cheaper feedstocks to be used, increase the supply potential of derived products, may reduce pre-processing costs and allow access to more sustainable feedstocks	4	5	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2030
	High-pressure gasification can reduce the overall levelised cost by reducing the need for energy-intensive gas compression, reduced capex in refractory lining, easier CO_2 separation, and through smaller downstream equipment	4	2	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	Sorption-enhanced gasification (absorption enhanced reforming, AER) allows for CO_2 to be removed in the gasifier as it is formed, giving a higher hydrogen concentration and lower tar concentration, which could eliminate need for WGS step and reduce cleanup requirements	3	2	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2035
	Gasification with reduced CO_2 output – design of new gasifiers with different conditions that would reduce CO_2 output and increase CO output, enabling higher product yields. Low tar and impurities also needed. Not favourable for BECCS but would improve product economics in absence of BECCS	4	2	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	-	2030
Syngas cleanup	**Tar cleanup at higher temperatures** to reduce heat losses (currently carried out after syngas is cooled)	4	4 (this is still seen as difficult)	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2030

Source: *Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018*

Table 11. **Innovation mapping and workshop discussion for BioH2 and Bio-SNG**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
BioH_2 and Bio-SNG						
Water-Gas Shift (WGS) Reaction	**Sorption-enhanced water-gas shift (SEWGS)** combines the water-gas shift reaction with CO_2 capture in a single process, operating at high temperature and pressure. This may obviate the need for WGS catalysts, reduce need for syngas cooling, and allow for waste heat to be used elsewhere. In addition, a SEWGS reactor could be more tolerant to syngas contaminants	4	5	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2040
	Water-gas shift membrane reactors, wherein a H_2-selective membrane is integrated into the WGS step, thereby eliminating the need for a separate hydrogen	4	3	BioH_2, Bio-SNG, FT synthesis, Syngas to MeOH	BECCS	2040

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	purification step, which reduces overall plant CAPEX and OPEX					
Bio-SNG						
Methanation	**More robust methanation catalyst** with improved thermal stability and resistance to sulphur poisoning can reduce production costs, improve reliability, and reduce GHGs associated with process	4	2	Bio-SNG	-	2025

Source: Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018

Table 12. **Innovation mapping and workshop discussion for Fischer-Tropsch Synthesis**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Fischer-Tropsch Synthesis						
FT Catalyst	**Developing an FT catalyst which is more tolerant of contaminants** such as sulphur, can improve process reliability and reduce pre-treatment requirements **Develop FT catalysts which are more selective** towards desired fuels, thereby improving overall process yields	3 (Much has already been done here)	4	FT synthesis	-	2025
FT reactor	**Improve FT reactor design to increase catalyst lifetime and performance**. Reactor design has an impact on the rate of carbon deposition on the catalyst (fixed bed) and the entrainment of catalyst fines from the reactor (fluidised bed)	2 (Much has already been done here)	2	FT synthesis	-	2025

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Upgrading	**Co-processing Fischer-Tropsch waxes at existing crude oil refineries** would allow utilisation of existing assets and thus reduce capital intensity of overall process.	4	5	FT synthesis	-	2025

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 13. **Innovation mapping and workshop discussion for Syngas to Methanol**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Syngas to Methanol						
Overall Process	Existing technology is very good, and it is difficult to improve on. Although there will be continuous improvement there are no innovation needs	N/A	N/A	Syngas to MeOH	-	Now

Source: *Comments from workshop*

Table 14. **Innovation mapping and workshop discussion for Fast Pyrolysis and Upgrading, Hydrothermal Liquefaction**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Fast Pyrolysis and Upgrading, Hydrothermal Liquefaction						
Fast Pyrolysis	**Improve pyrolysis oil yield.** Only the liquid fraction is converted to liquid transport	5	3	Fast Pyrolysis	-	2025

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	fuels. Maximising liquid production is therefore necessary to realise the potential yields					
	Decrease pyrolysis oil, water and oxygen content, which will prevent catalyst deactivation in the pyrolysis oil upgrade steps. A reduction in acidity and tendency to polymerise would also be beneficial	4	5	Fast Pyrolysis	-	2025
	Catalyst introduction for pyrolysis step, which can reduce oxygen content in the product and promote higher selectivity of desired alkanes	2	5	Fast Pyrolysis	-	2030
Co-processing of pyrolysis Oil	**Prove commercial scale co-processing in Fluidised Catalytic Crackers**, which would allow for existing assets to be	4	4	Refinery Co-processing	-	2025

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	utilised and thus reduce capital investment requirements					
HTL	**Reduce corrosive nature of HTL bio crude**, which can aid downstream processing	3	4	HTL	-	2040
	Improvement of feedstock handling technologies, like pumps and stirrers for feedstock slurries with high water content, would improve the reliability of hydrothermal upgrading processes.	4	4	HTL	-	2040

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 15. **Innovation mapping and workshop discussion for Woody & Grassy Energy Crops - SRC & Miscanthus**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Woody & Grassy Energy Crops - SRC & Miscanthus						
Breeding & Crop R&D	**Seed-based hybrids (seed plugs) to increase Miscanthus planting rate** while decreasing planting cost. Current rhizome planting is relatively labour-intensive and is difficult to scale up due to slow propagation	5	3	Woody & Grassy Energy Crops	-	2030
	Develop higher yielding Miscanthus and SRC breeds (per hectare)	5	2	Woody & Grassy Energy Crops	-	2025
	Develop breeds with improved water efficiency, resistance to pathogens, and environmental characteristics Miscanthus - future breeds being developed can also be more drought	3	5	Woody & Grassy Energy Crops	-	2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	resistant, and process water and nutrients more efficiently SRC - increasing SRC willow's ability to grow on marginal lands					
	Develop breeds adapted for cultivation on marginal lands in a way that does not compromise the economic viability, and that provides important ecosystem services	2	4	Woody & Grassy Energy Crops	-	2035
	Identifying and breeding for desirable traits tailored to applications e.g. digestion and fermentation routes	2	4			2030
Growing and harvesting, improving agronomics	**Accelerating early growth for Miscanthus** may provide cash return earlier to farmers (but may not improve overall returns)	2	4	Woody & Grassy Energy Crops	-	2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	Improve planting, fertilising, and weed / pest control techniques. For example, for SRC, planting material constitutes around 50% of the establishment cost of SRC, and so reducing cuttings material could lead to a significant reduction in establishment cost.	5	4	Woody & Grassy Energy Crops	-	2025
	Optimise harvesting techniques and machinery to specific supply chains. This is more important for SRC, as harvesting machinery for SRC must be customised whereas Miscanthus can take advantage of general machinery	4	3	Woody & Grassy Energy Crops	-	2025

Source: Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018

Table 16. **Innovation mapping and workshop discussion for Novel Oil Crops**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Novel Oil Crops						
Breeding & Crop R&D	**Adaptation for cultivation on marginal lands** in a way that increases yield and does not compromise the delivery of important ecosystem services	4	5	Novel Oil Crops		2030
	Breeding of species that are less susceptible to pathogens and with increased energy contents	5	3	Novel Oil Crops		2030
Growing and harvesting, improving agronomics	**Cultivation which allows reduced use of agrochemicals** can reduce cultivation costs	3	4	Novel Oil Crops		2035

Note: *Not discussed in detail during the workshop*

Source: *Technology Innovation Needs Assessment (TINA) - Bioenergy Summary Report, Carbon Trust & E4tech, 2012*

Table 17. **Innovation mapping and workshop discussion for Microalgae and Macroalgae**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Microalgae						
Species characteristics	**Improve species characteristics**: increase yields, energy content, resilience to variety of conditions, reduced susceptibility to pathogens, optimal growth/energy storage balance	4	3	Microalgae	-	2040
Species identification	**Improve laboratory processes to enable quicker cataloguing** of species types, speeding up the analysis of microalgae strains and selection of those with advantageous traits	3	4	Microalgae	-	2030

Macroalgae						
Species characteristics	**Yield increases, achieved predominantly through lab research**, are calculated to significantly reduce the costs of cultivation	4	3	Macroalgae	-	2035
	Improvements to species characteristics: photosynthetic conversion efficiency, moisture content, carbohydrate content	3	3	Macroalgae	-	2035

Note: Not discussed in detail during the workshop. Macroalgae is expected to be deployed in the UK, while microalgae are not, due to climatic constraints.

Source: Technology Innovation Needs Assessment (TINA) - Bioenergy Summary Report, Carbon Trust & E4tech, 2012

Table 18. **Innovation mapping and workshop discussion for lignocellulosic feedstock pre-treatment, hydrolysis and lignocellulosic ethanol production**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Lignocellulosic feedstock pre-treatment & hydrolysis						
Pre-treatment	**More cost-effective pre-treatment processes.** Pre-treatment processes operating at lower temperatures and pressures will result in lower CAPEX and O&M costs	4	3	LC ethanol, sugars to higher hydrocarbons		2030
	Reduce inhibitor make/ reduce their impact. Through optimisation of pre-treatment conditions, reduce degradation product formation which would otherwise inhibit downstream fermentation. This applies to certain technologies, such as hot acid pre-treatment	4	3	LC ethanol, sugars to higher hydrocarbons		2030
Hydrolysis	**Develop enzymes tailored to feedstocks.** Enzymes which can process a wider range of feedstocks	4	2 (Lower since feedstock	LC ethanol, sugars to higher hydrocarbons		2035

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	are less likely to be optimal from the cost and performance perspectives.		flexibility not recommended)			
	Integrate enzyme production with LC ethanol production, which lowers enzyme production costs. This uses a small enzyme production plant fed with the LC sugars (which are much cheaper than glucose).	3 (Not as big an impact as initially thought)	4	LC ethanol, sugars to higher hydrocarbons		2030
	Improve quality of hydrolysates from LC feedstocks, focussing on attaining higher sugar concentrations	4	2	LC ethanol, sugars to higher hydrocarbons		2035
Lignocellulosic ethanol						
Overall process	**Increase solid loading through optimisation of pre-treatment and hydrolysis steps.** Solid loading is often limited, resulting in low product concentrations and large mass flows to be treated	5 (Expected to have biggest impact)	2	LC ethanol, sugars to higher hydrocarbons		2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	downstream, resulting in higher CAPEX and OPEX					

Source: Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016

Source: Johnson, E., 2016. Integrated enzyme production lowers the cost of cellulosic ethanol. Available at: https://onlinelibrary.wiley.com/doi/epdf/10.1002/bbb.1634

Table 19. **Innovation mapping and workshop discussion for Sugars to Higher Hydrocarbons and Syngas Fermentation**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Sugars to Higher Hydrocarbons						
Reactor	**Improve mass transfer, e.g. improved aeration in aerobic reactor design.** As oxygen is only sparingly soluble in aqueous broths, continuous aeration is needed to maintain aerobic conditions. Improved reactor design can thus improve vapour-liquid mass	3	2	LC ethanol, aerobic fermentation	-	2035

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	transfer, and thus reduce OPEX and CAPEX					
	Improve yields by utilising CO_2 produced in process. Currently, production of CO_2 constitutes major yield loss, which, if captured and re-used, could improve process yields	5	2	Aerobic fermentation	-	2035
Syngas fermentation						
Pre-treatment	**Improve syngas clean-up.** More efficient removal of contaminants will result in improved process reliability	4	3	Syngas fermentation	-	2030
Reactor	**Increase concentration of product in fermentation broth.** Bacteria cannot tolerate high product (e.g. ethanol) concentrations, resulting in a product of low titre and high downstream separation costs. Thus, increasing the concentration (e.g. through more	5	4 (due to lower wastewater impact on environment)	Syngas fermentation	-	2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	resistant bacterial strains) will reduce energy and CAPEX associated with product separation steps. Furthermore, this will help to reduce amount of waste water required to be processed.					
	Improved or novel reactor design which increases mass transfer efficiency, leading to higher conversion rates per unit volume. This then reduces equipment sizes and thus CAPEX, and OPEX through reduced gas bubbling	4	2	Syngas fermentation	-	2025
Bacteria	**Develop resilient bacterial strains and reactor systems with reduced susceptibility to contamination**; Greater tolerance to contaminants in the syngas is likely to help process reliability	3	5	Syngas fermentation	-	2035

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	Genetically engineer or breed more efficient bacteria strains, which can have better product yields	3	3	Syngas fermentation	-	2035

Source: E4tech DfT advanced drop-in biofuels E4tech, 2017. Future fuels for flight and freight competition – Feasibility study
J. Holladay et al. (2014) "Renewable routes to jet fuel".
Available at http://aviation.u-tokyo.ac.jp/eventcopy/ws2014/20141105_07DOE%EF%BC%BFHolladay.pdf
Source: Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016

Table 20. **Innovation mapping for Alcohol Catalysis**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Alcohol Catalysis						
Hydrotreating	**Reduce hydrogen consumption in hydrogenation step**, to reduce operating costs	1	1	Alcohol Catalysis	-	2025
Catalyst	**Improved resilience to trace contaminants**, leading to longer catalyst life and improved process reliability	4	4	Alcohol Catalysis	-	2030
Alternative routes	**Production of fuels from alternative feedstocks.** Syngas fermentation can also produce compounds such as acetaldehyde, which can then in turn be catalysed to produce fuels such as jet-Synthesised Paraffinic Kerosene	3	4	Alcohol Catalysis	-	2035

Note: *Not commented on in workshop.*

Source: *Review of Biojet Fuel Conversion Technologies, NREL, Wang et al., July 2016; The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison, De Jong et al., 2015*

Table 21. **Innovation mapping and workshop discussion for Anaerobic Digestion – Pre-treatment**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Feedstock Pre-treatment						
Pre-treatment	**Investigate and optimise pre-treatment technologies for straw**, perennial energy grasses, and recalcitrant feedstocks. Doing so will broaden AD feedstock portfolios and increase disposal routes for local organic waste / residues.	3	4	Anaerobic Digestion	-	2025-2030
	Homogenise difficult feedstocks for multiple AD plants. Centralised blending of animal slurry and commercial waste (chicken litter, commercial industry waste) will allow them to be used in existing AD plants that lack difficult feedstock pre-treatment capabilities	4	5	Anaerobic Digestion	-	2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	Novel concept that couple's pre-treatment with hydrogen production by biological routes. Biological hydrogen production (proven in lab, TRL4), starts with fermentation of biomass to give H_2 and acetate. Acetate could then be fed to AD to produce Methane. Producing hydrogen as well as methane through the fermentation plus AD route has been shown to lead to a greater conversion efficiency from biomass to energy than AD alone.	1	2	Anaerobic Digestion	Hydrogen & Fuel cells	2040

	Compacting and use of ensiling additives during storage has been noted to minimise feedstock waste, which directly contributes to conversion efficiency. More scientific evidence and research on optimisation techniques will help improve biogas yield	3	2	Anaerobic Digestion	-	2025

Source: Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018

Table 22. **Innovation mapping and workshop discussion for Anaerobic Digestion – Digester**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Digester						
Digestion	**Develop new AD reactor types that can use lignocellulosic materials.** There is the potential for improved biogas yield and rate through designing the pre-	4	2 (likely few new AD plants)	Anaerobic Digestion	-	2025

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	treatment and AD together in a combined reactor.					
	Better understanding of microbiology community in digesters. Research and knowledge on causes and effects of microbe interaction will help digestion optimisation.	3	4	Anaerobic Digestion	-	2025
	Understanding co-digestion options of different types of feedstocks. This can maximise gate fees and biogas yields, and develop uniform feeding technologies for drier biomass (e.g. energy crops)	4	5	Anaerobic Digestion	-	2030
	Increase biomass retention in digesters by integrating with attached media	3	4	Anaerobic Digestion	-	2030

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	Membrane use in digesters can enable higher conversion rates	3	4	Anaerobic Digestion	-	2030
	Reduction of viscosity of substrates via particle size reduction treatment can reduce OPEX costs by reducing parasitic energy requirements of associated plant such as pumps and mixers	3	4	Anaerobic Digestion	-	2030
	Real-time process monitoring, diagnostic, analytics, and control system that allows better management and optimisation of plant.	3	4	Anaerobic Digestion	-	2020-2025

Source: *Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018. Technology Innovation Needs Assessment (TINA) - Bioenergy Summary Report, Carbon Trust & E4tech, 2012*

Table 23. **Innovation mapping and workshop discussion for Anaerobic Digestion – Integration and Valorisation of digestate**

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
Digester						
Scale	**Large-scale Centralised AD (CAD) plants** offer greater feedstock aggregation opportunities, homogenisation of wastes, and less variable biogas output over the year	3	5	Anaerobic Digestion	-	2020
Biogas upgrading & injection	**Improved removal of CO_2, H_2S, siloxanes, and water**. Currently these technologies result in methane losses, and there is scope for reduction of energy consumption	1	1	Anaerobic Digestion	-	2030
Integration						
Integration	**Integrating AD with the reformer and fuel cell** could increase plant	1	4	Anaerobic Digestion	Hydrogen & Fuel cell	2025

Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
	electrical output with higher conversion efficiency					
Integration	**AD for demand-side response.** On-site gas storage could provide demand-side response service, providing base-load or demand response	3	4	Anaerobic Digestion	Smart system	2025
Valorisation						
Valorisation	**Valorisation of digestate's role in energy, food, and environmental system**: Consider AD's total impact benefit including fertiliser production (replacing carbon-intensive synthetic fertiliser), carbon capture, and soil structure improvement	4	5	Anaerobic Digestion	-	2025

Source: *Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018*
Technology Innovation Needs Assessment (TINA) - Bioenergy Summary Report, Carbon Trust & E4tech, 2012

Appendix 3: Technology family cost breakdowns

Gasification based routes

Table 24. **Cost Model of Bio-SNG**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Fuel receipt and drying	5	% of CAPEX	
Gasification	26	% of CAPEX	
Oxygen production	7	% of CAPEX	
Methanation	14	% of CAPEX	
OSBL, Civils, Power, Grid Connection	21	% of CAPEX	
Construction, EPC risk, others	28	% of CAPEX	
CAPEX	60	% of total	315GWh/yr scale, FOAK
OPEX	40	% of total	Nat gas price = £19/MWh, Efficiency = 64%
Total	23.1	£/GJ	**Hurdle rate = 12%**

Note: *Not discussed in detail during workshop*

Source: *The Renewable Heat Incentive: A reformed and refocused scheme - Response to Consultation. Advanced Plasma Power: 26th April 2016; Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018*

Table 25. **Cost Model of BioH2**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Fuel prep	1	% of CAPEX	
Gasification, cooling, bulk cleaning	28	% of CAPEX	
Compression	5	% of CAPEX	
Water-gas shift	14	% of CAPEX	
OSBL, Civils, Power, Grid Connection	23	% of CAPEX	
Construction, EPC risk, others	27	% of CAPEX	
CAPEX	53	% of total	62MW (RDF input), FOAK, no CO_2 sequestration, not transport grade
OPEX	47	% of total	Feedstock to biohydrogen efficiency = 78%
Total	20.5	£/GJ	**12% discount rate**

Note: *Not discussed in detail during workshop*

Source: *Biohydrogen: Production of hydrogen by gasification of waste, Cadent, Advanced Plasma Power and Progressive Energy, July 2017. https://gogreengas.com/wp-content/uploads/2015/11/Biohydrogen-Cadent-Project-Report-FINAL-3.pdf*

Table 26. **Cost Model of Fischer-Tropsch Synthesis**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Capital costs	35	%	750MWinput
Feedstock costs	48	%	Conversion efficiency = 40.5% (MJfuel/MJfeedstock)
O&M costs	16	%	
Total	19	£/GJ	**2020 LCOE**

Note: *Not discussed in detail during workshop*

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 27. **Cost Model of Gasification to Methanol**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Capital costs	25	%	
Feedstock costs	58	%	Conversion efficiency = 44% (MJfuel/Mjfeedstock)
O&M costs	18	%	
Total	13	£/GJ	**2020 LCOE**

Note: *Not discussed in detail during workshop*

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 28. **Cost Model of Fast Pyrolysis & Upgrading**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Capital costs	13	%	400MW input
Feedstock costs	48	%	Conversion efficiency = 50% (MJfuel/MJfeedstock)
O&M costs	39	%	
Total	19	£ (2014)/GJ	**2025 LCOE**

Note: *Not discussed in detail during workshop*

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Energy Crops

Table 29. **Cost Model of Miscanthus**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Planting material	18	%	
Planting operating costs	19	%	
Cultivation + Harvest	28	%	Crop harvested annually
Land rent	32	%	2014/15 UK general cropping average. Yield = 10.79odt/ha/yr
Other	2	%	
Total	67	£/odt	**odt = 0% moisture**

Source: *E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013; Land rent rates - 2014 and 2015 average for general cropping from* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/604210/fbs-farmrents2015-30mar17.pdf

Table 30. **Cost Model of Short Rotation Coppice**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Planting material	11	%	
Planting operating costs	19	%	
Cultivation + Harvest	34	%	Crop harvested every 3 yrs
Land rent	33	%	2014/15 UK general cropping average. Yield = 8.54 odt/ha/yr
Other	3	%	
Total	79.62	£/odt	**odt = 0% moisture**

Source: *E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013; Land rent rates - 2014 and 2015 average for general cropping from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/604210/fbs-farmrents2015-30mar17.pdf*

Novel Oil Crops, Microalgae and Macroalgae

Cost Tables were not provided during the industry workshops for Novel Oil Crops or Microalgae and Macroalgae as past studies have indicated that these areas are not a priority for the UK[69] and were thus not a major focus of this work. However, these areas were briefly discussed in the Innovation Opportunities within Biomass & Bioenergy section.

[69] Innovation Needs Assessment for Biomass Heat - Final Report, E4tech & Ecofys, 22nd January 2018; Technology Innovation Needs Assessment (TINA) – Bioenergy Summary Report, Carbon Trust & E4tech, March 2016.

Hydrolysis & Fermentation

Table 31. **Cost Model of Lignocellulosic (LC) ethanol**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Capital costs	24	%	690MW input
Feedstock costs	50	%	Conversion efficiency = 37.6% (MJfuel/Mjfeedstock)
O&M costs	26	%	
Total	28	£ (2014)/GJfuel	**2015 LCOE**

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 32. **Cost Model of Syngas Fermentation**

Cost Element	**Levelised cost of production**	**Unit**	**Other factors affecting deployment**
Capital costs	26	%	750MW input
Feedstock costs	42	%	Conversion efficiency = 49.6% (MJfuel/Mjfeedstock)
O&M costs	32	%	
Total	19	£ (2014)/GJfuel	**2020 LCOE**

Source: *Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 33. **Cost Model of Sugars to Higher Hydrocarbons**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Capital costs	26	%	750MW input
Feedstock costs	26	%	Conversion efficiency = 30% (to produce fatty acids) (MJfuel/Mjfeedstock)
O&M costs	47	%	
Total	64	£ (2014)/GJfuel	**2025 LCOE**

Source: *The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison, De Jong et al., 2015; Innovation Outlook - Advanced Liquid Biofuels, International Renewable Energy Agency (IRENA) 2016*

Table 34. **Cost Model of Alcohol Catalysis**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Capital costs	5 - 15	%	
Feedstock costs	70 – 90	%	Conversion efficiency (mass input/mass output) = 96+%. Using LC ethanol LCOE
O&M costs	5 - 15	%	
Total	31.50	£ (2014)/GJfuel	**2020 LCOE**

Source: *Review of Biojet Fuel Conversion Technologies, NREL, Wang et al., July 2016; The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison, De Jong et al., 2015*

Anaerobic Digestion

Table 35. **Cost Model of Anaerobic Digestion**

Cost Element	Levelised cost of production	Unit	Other factors affecting deployment
Feedstock	10	%	Plant efficiency = 70%, Feedstock price = £0.83/GjfuelCan be higher if energy crops used
Pre-treatment	10	%	
Digestion	45	%	2.5MW_{Gas}
Upgrading & injection	35	%	
Total	14	£/GJ	**2020 Costs**

Source: Technology Innovation Needs Assessment (TINA) - Bioenergy Summary Report, Carbon Trust & E4tech, 2012 https://www.fre-energy.co.uk/pdf/RASE-On-Farm-AD-Review.pdf

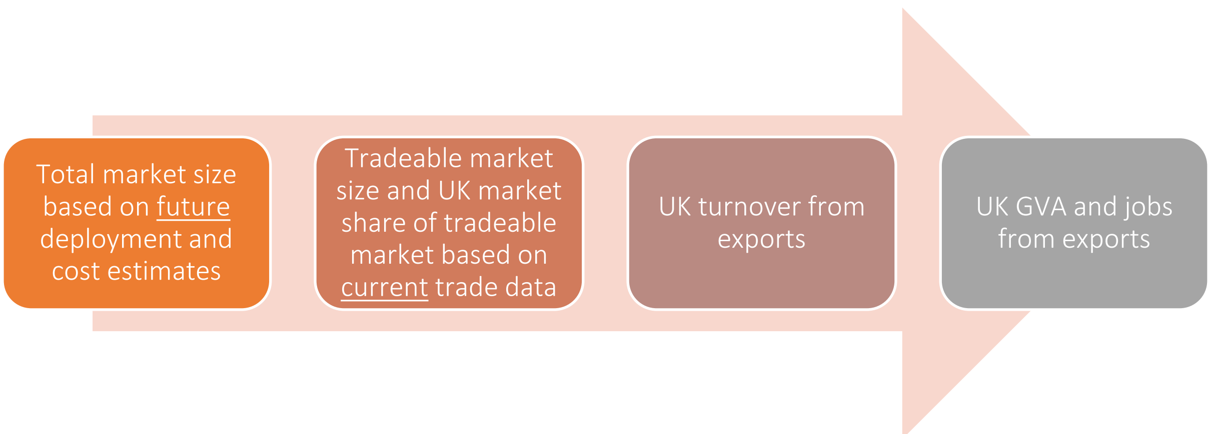
Appendix 4: Business opportunities methodology

Methodology for export business opportunity analysis

In identifying export opportunities for the UK, the EINA process uses a common methodology to ensure comparability of results:

- The **global and regional markets** to 2050 are sized based on deployment forecasts, which come from the IEA when available. For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market.
- The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs created**.

Figure 9 **Methodology for assessing export opportunities**



Source: Vivid Economics

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

Export business opportunities for goods

- Current market shares of UK goods are evaluated based on existing trade data, where available. If the technology is immature or export levels are low, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to reach a market share in the EU and RoW by 2050. The potential future market share is intended as an ambitious, but realistic, scenario. It is triangulated using:
    - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
    - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
    - The importance of innovation in the technology.
- Market share assumptions are validated at a workshop with expert stakeholders and adjusted based on stakeholder input.

Export business opportunities for services

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The EINA methodology does not quantify opportunities associated with installation and operation and maintenance as these are typically performed locally. Exceptions are made if these types of services are specialised, such as in offshore wind.
- The key services to consider are based on desk research and verified through an expert workshop.
- The services considered in the CCUS EINA export analysis are EPCm services, transport and storage services.

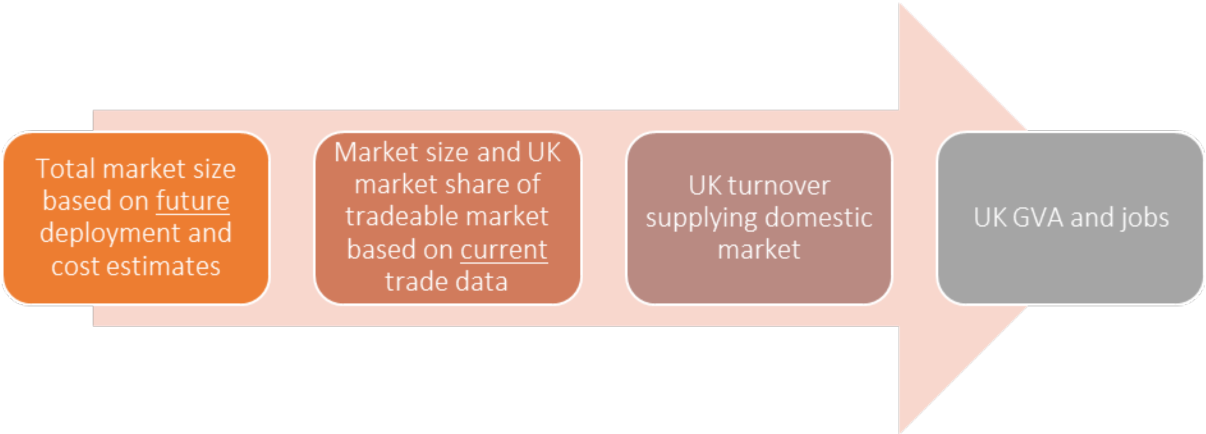
Methodology for domestic business opportunity analysis

To estimate the size of domestic business opportunities for the UK, the EINA methodology, as developed to size export opportunities, is adapted. The domestic analysis leans heavily on insight gleaned from the export analysis, particularly in estimating UK competitiveness and ability to capture market share in its domestic market. To estimate the domestic opportunity, the following methodology is used:

- The **domestic market** to 2050 is sized based on deployment and cost estimates. Deployment estimates are based on ESME modelling used for the EINAs and cost estimates are equal to those from the export work, and based on analysis for each of the EINA sub-themes.[70] For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the UK's market is likely accessible for foreign firms (e.g. electric vehicles), and how much is likely to be exclusively provided by UK companies (e.g. heat pump installation).
- For the traded share of the UK market, the UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- To estimate **UK captured turnover** the traded and non-traded markets are summed.
  - The UK's captured turnover of the UK traded market is estimated by multiplying the tradeable market by the UK's market share.
  - The UK's turnover from the non-traded market is equal to the size of the non-traded market.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs supported**.

[70] For detail on cost estimates used, please refer to the Excel calculators provided for each sub-theme, and the individual sub-theme reports.

Figure 10 **Methodology for assessing domestic business opportunities**



Source: Vivid Economics

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

Domestic business opportunities for goods

- Current market shares of UK goods are evaluated based on existing trade (import) and domestic production data, where available. If the technology is immature, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to potentially increase its market share in its domestic market. This estimate is informed by the previously performed export analysis. It is triangulated using:
    - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
    - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
    - The importance of innovation in the technology.

Domestic business opportunities for services

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The domestic assessment explicitly quantifies services such as O&M and installation, which are typically not traded but can support a large number of

jobs associated with e.g. heat pumps. For these services, the estimate of potential service jobs supported is based on:
  - An estimate of the total turnover and GVA associated with the service
  - A ratio of GVA/jobs (adjusted for productivity increases) in analogous existing service sectors based on ONS data.
- The key services to consider are based on desk research, verified through stakeholder workshops.

Worked example

1. The **global and regional markets** to 2050 are sized based on illustrative deployment forecasts, which come from ESME when available.[71] For example, deployment of nuclear power (37 GW by 2050) is multiplied by O&M costs (~12% of total plant costs) to obtain annual turnover for the nuclear O&M market (~£2.5 billion by 2050).
2. The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market. In the case of nuclear O&M, tradability is 0% being as it is not tradeable. For the domestic analysis, tradability does not directly feed into our model, but is vital to provide insight on the share of the domestic market UK firms will capture.
3. The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below. For example, for nuclear O&M the UK domestic market share is 100% because the component is not tradeable and therefore foreign firms do not capture some of the value.
4. The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**. For nuclear O&M, market turnover (~£2.5 billion) is multiplied by the UK market share (95%) of O&M to obtain UK-captured turnover (~£2.5 billion by 2050).
5. The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by labour productivity figures for that sector to obtain **jobs supported**. For example, appropriate Standard Industrial Classification (SIC) codes are chosen for nuclear O&M. This leads to a GVA / turnover multiplier (49%) that is multiplied by market turnover (~£2.5 billion) to isolate GVA (~£1 billion by 2050), which is then divided by labour productivity (~70,000 GVA / worker by 2050) to isolate jobs supported (~16,000 jobs by 2050).

[71] If deployment information is not available from the IEA, alternative projections from, for example, Bloomberg are used. Please see individual sub-theme reports for further detail.

Additional notes

The below lists areas where the analysis under the EINA Biomass and Bioenergy subtheme deviates from the general approach and highlights any major caveats.

New energy feedstock domestic deployment: ESME outputs biomass production in the UK up to 2050, however this is not disaggregated for new energy feedstocks. Accordingly, new energy feedstock deployment for 2020 and 2050 comes from the Technology Innovation Needs Assessment (2012) for bioenergy.[72] Linear extrapolation determines data points between 2020-2050.

[72] Low Carbon Innovation Coordination Group (2012) Technology Innovation Needs Assessment

Appendix 5: Assessment of business opportunities uncertainty

The assessment of business opportunities in the long term, associated with new technologies is uncertain. This assessment does not attempt to forecast what *will* happen. Instead, the business opportunity assessment attempts to provide a realistic and consistent assessment, based on current information, on the business opportunities that *could* be captured by the UK. Whether these opportunities are indeed realised depends on domestic and international developments, political decisions, macro-economic conditions, and numerous other complex variables.

As this assessment is not intended as a full forecast, a formal quantitative sensitivity analysis has not been performed. the below provides a high-level qualitative assessment of the uncertainty associated with the sized opportunity. Note, this is *not* an assessment of how likely the UK is to capture the opportunity, rather it is an assessment of the uncertainty range around the size of the opportunity. The assessment is based on three key factors driving the assessment

1. *The level of future deployment of the technology*. Technologies such as offshore wind are deployed at scale across different energy system modelling scenarios and hence considered relatively certain. In contrast, there is more uncertainty for e.g. hydrogen related technologies. The export analysis is based on 3 IEA scenarios (with numbers provided for the IEA ETP 2 degree scenario). Domestic analysis is based on a single ESME run used across the EINA process.
2. *The potential domestic market share* the UK can capture. This assessment attempts to estimate a plausible market share for the UK across relevant markets. Where this can be based on longstanding trade relationships and industries, this assessment is considered more robust.
3. *Future technology costs and production techniques* are a key driver of the future turnover, gross value added and jobs associated with a technology. For immature technologies for which manufacturing techniques may, for example, become highly automated in future, future costs and jobs supported by the technology may be significantly lower than assessed.

The ratings in the table below are the judgement of Vivid analysts based on the above considerations. The analysts have worked across all sub-themes and the ratings should be considered as a judgement of the uncertainty around the size of the opportunity relative to other sub-themes. As a rough guide, we judge the uncertainty bands around the opportunity estimates as follows:

- **Green**: Size of the opportunity is clear (+/- 20%). Note, this does not imply the UK will indeed capture the opportunity.
- **Amber:** Size of the opportunity is clear, but there are significant uncertainties (+/- 50%).
- **Red:** There are large uncertainties around market structure and whether the technology will be taken up at all in major markets. The opportunity could be a factor 2-3 larger or smaller than presented.

Table 36. **Assessment of uncertainty in business opportunities across sub-themes**

Sub-theme	Uncertainty rating	Comments
Biomass and bioenergy		• **Deployment**: Moderate deployment uncertainty; BECCS can produce negative emissions that have high value to the energy system under a deep decarbonisation pathway; there is moderate uncertainty as to whether BECCS will be used for hydrogen production, as in the ESME modelling, or for power generation. • **UK market share:** Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services and feedstocks. • **Costs and production techniques:** Relatively certain costs with most opportunities associated with labour input rather than immature technologies.
Building fabric		• **Deployment:** Depends on levels of retrofit that greatly exceed those seen to date. • **Market share:** Speculative for traded. However, majority of market untraded, highly likely captured domestically. • **Costs and production techniques:** High share of labour costs (independent of uncertain tech cost).
CCUS		• **Deployment:** Moderate deployment uncertainty; decarbonisation scenarios anticipate rapid uptake of CCUS, though there are few large-scale facilities today. • **Market share:** Moderate market share uncertainty; the UK is likely to be competitive in the storage of CO2 and EPCm services while component market shares are less certain given numerous technology choices and lack of clear competitors. • **Costs and production techniques:** Moderate cost uncertainty; the lack of large-scale facilities today makes estimating future costs difficult.
Heating and cooling		• **Deployment**: Expected to be deployed in most UK buildings by 2050. • **Market share:** some uncertainties, immaturity in markets such as for hydrogen boilers. • **Costs and production techniques:** Relatively certain given relative maturity of boilers and heat pumps. • **Deployment of hydrogen boilers or heat pumps** lead to similar opportunities for UK businesses, while heat networks present a 50 per cent smaller opportunity per household.

Hydrogen and fuel cells		• **Deployment**: Highly uncertain future deployment with a wide-range of 2050 hydrogen demand estimates across scenarios, particularly for export markets. • **UK market share**: Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services. • **Costs and production techniques:** Although deep uncertainty in future hydrogen production costs, for example electrolysis, most domestic costs are associated with labour input rather than equipment.
Industry		• **Deployment**: Relative certainty in deployment as it is based on the 2050 Roadmaps • **UK market share**: Some uncertainty due to poor quality of trade data that may not be representative of technologies within scope. • **Costs and production techniques:** Some uncertainty in costs, particularly for less mature technologies.
Light duty transport		• **Deployment**: Certainty in deployment; low-carbon vehicles will be required in any deep decarbonisation scenario. • **UK market share**: Speculative market share for a relatively immature market; a small number of uncertain future FDI investment decisions generates high uncertainty in overall business opportunities. • **Costs and production techniques:** Highly uncertain future costs, with substantial falls in battery costs a key enabler of BEV uptake.
Nuclear fission		• **Deployment**: Moderate uncertainty in future deployment with some proposed nuclear plants recently cancelled • **UK market share**: Relatively certain market shares based on robust estimates of current nuclear activity; market share growth is dependent on uncertain development of UK reactor IP; however, most business opportunities are associated with untraded activity or areas where the UK has existing strength • **Costs and production techniques:** Uncertain costs for nuclear new build, with dangers of construction overrun; deep uncertainty in costs for immature nuclear technologies, for example SMRs and AMRs.
Offshore wind		• **Deployment**: Offshore wind will be required in any deep decarbonisation scenario, with clear government commitments. • **UK market share**: Expected growth in current market shares given commitments and progress to date. • **Costs and production techniques:** Costs are relatively certain, with clear pathways to 2050.
Tidal stream		• **Deployment**: Global sites for tidal stream are relatively limited, and hence the potential market size well established. • **UK market share**: Although the market is immature, the UK has a an established (and competitive) position. • **Costs and production techniques:** Costs are relatively certain, although the impact of potential scale production is hard to anticipate.
Smart systems		• **Deployment**: High deployment uncertainty given immaturity of smart system market today and evolving business models and regulatory framework. • **UK market share**: Moderate uncertainty given immaturity of the market today and scalable nature of digital smart

		technologies, though there is UK leadership in aggregation services and V2G charging. • **Costs and production techniques**: Moderate uncertainty of cost reductions of batteries and V2G and smart chargers, though costs are expected to continue to fall.

Source: *Vivid Economics*

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