A report by the Energy Technologies Institute

THE ROLE FOR BIOENERGY IN DECARBONISING THE UK ENERGY SYSTEM

Findings from the ETI bioenergy programme

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Contents

Executive Summary

Bioenergy, derived from purpose-grown biomass and waste, is currently the largest source of renewable energy in the UK[1]. The Energy Technologies Institute's (ETI) whole energy system analysis consistently highlights the ongoing importance of bioenergy in delivering cost-effective energy system decarbonisation and meeting the UK's 2050 greenhouse gas (GHG) emissions targets. This document integrates findings from the ETI's research programme, delivered over the last 10 years, to set out a vision for bioenergy in a low carbon UK energy system.

From a GHG emissions reduction perspective, the aim of biomass production, waste resource use and bioenergy generation should be to help deliver a global system that produces the lowest emissions overall. In terms of bioenergy, its value is greatest when combined with Carbon Capture and Storage (CCS) to deliver negative emissions (net removal of carbon dioxide from the atmosphere) alongside production of power or hydrogen. There is a growing evidence base that shows that these negative emissions will be a key enabler in delivering a lowest-cost UK energy system decarbonisation transition.

However, while the UK must endeavour to develop a CCS sector, there are currently no CCS plants (either fossil- or biomass-fuelled) in operation or under construction in the UK. In the absence of CCS, bioenergy can still contribute towards lowering emissions and meeting the UK's 2050 GHG emissions target (an 80% reduction in GHGs relative to 1990 levels). However, rather than producing power or hydrogen, the value of bioenergy without CCS is greatest when used in sectors which are otherwise difficult to decarbonise and which have no other readily available, lower carbon alternatives. In the long-term, this is likely to be in industry, or producing liquid and gaseous fuels for use in heavy-duty transport, aviation and/or shipping.

The flexibility of bioenergy, in terms of the different end products it can generate and the range of biomass and waste feedstocks it can be generated from, makes it a valuable part of a range of future energy transition pathways. However, flexibility also adds uncertainty and complexity to investment decisions which may depend on wider energy system decisions for their economic viability. By examining different energy futures, common technologies and feedstocks can be identified which present low-risk choices now and retain options for how bioenergy might be used in the future. Gasification is one such approach as it can take biomass and waste to produce a clean syngas (a mixture of carbon monoxide, hydrogen, carbon dioxide and methane) which can be used with and without CCS to make power, heat, hydrogen, bio-synthetic natural gas (bioSNG) and transport fuels. Investing in the development of gasification now, provides flexibility for the role of bioenergy in a future energy system.

In terms of feedstocks, the bioenergy sector is transitioning from one dominated by waste feedstocks, to one increasingly reliant on imported and UK-grown biomass feedstocks. Increasing the availability of UK-grown biomass can increase resilience to changes in the global biomass market and deliver wider environmental benefits, including increasing the carbon sequestered in soils, if second generation energy crops such as short rotation coppice (SRC) willow and Miscanthus, and forestry are planted in the right locations. UK-grown biomass feedstocks are currently largely derived from existing woodland and arable crops, but work commissioned by the ETI suggests that there is the potential for up to 1.4 Mha of second generation crops to be planted without detriment to current levels of food production, if improvements are made to land management to increase productivity and reduce waste across the agricultural sector. The challenge now is to create market structures and business models which provide the right balance of risk and reward for new growers.

1 BEIS (2017), Digest of UK Energy Statistics (DUKES), Renewables and Wastes: Commodity Balances, Tables 6.1-6.3 [online]. Available at: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes. All information from central UK Government departments (BEIS, DECC, DfT, and Defra) contains public sector information licensed under the Open Government Licence v3.0 [online]. Available at: https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/

Executive Summary
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In summary:

- In the context of UK energy system decarbonisation, the value of bioenergy within the energy system is greatest when combined with CCS to deliver negative emissions. Strategies to develop a CCS sector in the UK must include Bioenergy with CCS (BECCS).
- In the absence of CCS, the value of bioenergy is greatest when producing gaseous or liquid fuels for use in sectors which are otherwise difficult to decarbonise, and where no lower-carbon options are readily available.
- The flexibility of gasification with syngas clean-up makes it resilient to wider energy system decisions. Investment is needed to deploy this technology at a commercial scale.
- The UK has the potential to increase biomass feedstock production in ways which deliver additional environmental benefits. Greater focus is needed on developing markets and business models which encourage new planting in suitable locations.

To develop and expand the UK bioenergy sector sustainably and in a way which is strategically valuable to the UK's decarbonisation efforts, action must be taken to develop sustainable feedstocks supplies and demonstrate the technical and commercial viability of key technologies. This report sets out four key recommendations to help the UK capitalise on key opportunities to develop the bioenergy sector:

- **Recommendation 1:** Create the right environment for BECCS in the UK, which through deployment can significantly reduce the cost of meeting the UK's 2050 emissions targets and increase the likelihood that the UK can deliver net-zero emissions.
- **Recommendation 2:** Develop gasification for the production of clean syngas from biomass and wastes to enable the bioenergy sector to remain robust to changes elsewhere in the energy system.
- **Recommendation 3:** Increase biomass production and the supply of sustainable biomass for bioenergy in the UK, and maximise the use of appropriate residual waste resources for energy, to enable the delivery of greater emissions savings at a system level, through:
  - o Making greater use of residual waste resources in efficient Energy from Waste (EfW) applications.
  - o Increasing the quantity of UK-grown second generation bioenergy crops, to deliver benefits to both the energy system and to the UK supply chain.
  - o Increasing resilience to changes in global biomass availability by exploring new supply chains for demonstrably sustainable imported biomass.
- **Recommendation 4:** Deliver more physically and chemically consistent feedstocks to end users, through improvements in plant breeding and pre-processing, and/or develop conversion technologies more resilient to variations in feedstock composition.

Summary of recommendations and recommended actions

Table 1
Recommendations and recommended actions to maximise the value of biomass production and bioenergy use

Recommendation 1: Create the right environment for BECCS in the UK, which through deployment can significantly reduce the cost of meeting the UK's 2050 emissions targets and increase the likelihood that the UK can deliver net-zero emissions.

	Recommended actions	Path forward
1.1	The UK Government commits to supporting the commercial-scale development of a UK CCS sector as soon as possible. This could take the form of a sector deal, similar to that agreed with other industries, bringing together expertise from a number of sectors.	A sector deal would require commitment from the Energy and Construction Industries, Investors, Academia and Local and National government.
1.2	Public and private sector investors collaborate to develop appropriate business models and risk-sharing mechanisms for Carbon Capture, Transport and Storage (separately or as a group). These should take into account the longer-term potential for individual CCS projects (both biomass- and fossil-fuelled) to develop into regional clusters using a 'start small and build' approach.	Negotiations will primarily be between UK Government (Treasury and Department(s) with responsibility for energy and climate change policy), and developers and investors associated with new UK (BECCS) projects.
1.3	Ensure that incentives to capture and store carbon distinguish between emissions from fossil fuels and those from systems delivering negative emissions (e.g. BECCS). This will need to align with other GHG reduction incentives to ensure there is no double counting of emissions.	An incentive will need to be implemented by government, but developed with views from industry, investors and specialists in carbon accounting and bioenergy life cycle assessments (LCAs).
1.4	Deliver initial cost-reductions through deploying, at a commercial scale, the most advanced carbon capture technologies (amines and pre-combustion). Sequential deployment of the same technology can drive cost reductions through risk-reduction and learning by doing.	The Liverpool-Manchester Hydrogen Cluster and the Oil and Gas Climate Initiative (OCGI) CCS project are two examples of commercial scale projects under development. Delivering these (or similar) projects will require the previous three actions to be resolved and project-specific support from Industry, Investors, Government and Academia.
1.5	Demonstrate the technical and commercial viability of pre- and post-combustion carbon capture technologies using biomass and waste feedstocks. This would remove one of the few remaining technical uncertainties surrounding the application of CCS to bioenergy production.	Demonstration projects should be supported by dedicated Research and Development (R&D) funding from the public sector (such as the Department for Transport's (DfT's) Future Fuels for Freight and Flight competition (F4C)) and Industry (such as Drax's collaboration with C-Capture).

Summary of Recommendations and recommended actions
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Recommendation 2: Develop gasification for the production of clean syngas from biomass and wastes to enable the bioenergy sector to remain robust to changes elsewhere in the energy system.

	Recommended actions	Path forward
2.1	To fully realise the flexibility of gasification, R&D funding and support should continue to be provided to develop and commercialise new syngas upgrading technologies to produce, for example, hydrogen and liquid fuels.	A number of commercial demonstration projects are under way, including under the DfT's Advanced Biofuels Demonstration Competition (ABDC) and F4C which provide grant funding for the demonstration of new methods of producing low carbon transport fuels. R&D funding bodies should plan for future development support to capitalise on the learnings from current gasification projects and avoid development stalling.
2.2	Learn and share lessons from early commercial-scale projects to maximise the learning from R&D investments. Apply these in subsequent projects to drive efficiency improvements and cost reductions.	Knowledge exchange between Industry, Academia, and the public sector could be coordinated through networks such as the Knowledge Transfer Network (KTN) or SUPERGEN Research Hubs.
2.3	Ensure that the definition of Advanced Conversion Technology (ACT) used in government incentive schemes encourages the types of technology best able to deliver cost-effective emissions savings and flexibility to the bioenergy sector.	The definition was produced by the Department for Business, Energy and Industrial Strategy (BEIS) who consulted on the definition in 2018. Further consultation following this initial feedback is necessary to ensure the definition aligns with what is needed for incentives to be allocated effectively.
2.4	Gasification is supported under Contracts for Difference (CfD, electricity), Renewable Transport Fuels Obligation (RTFO, transport fuels) and Renewable Heat Incentive (RHI, heating, including bioSNG injection). This is not problematic while the sector is in its infancy but, as the use of gasification expands, it is important to ensure that incentives are directed towards end uses where it will deliver the greatest emissions savings.	Government (BEIS and DfT) and Industry make use of findings from whole energy systems analysis to maintain up-to-date understanding of best uses of biomass.

Recommendation 3: Increase biomass production and the supply of sustainable biomass for bioenergy in the UK, and maximise the use of appropriate residual waste resources for energy, to enable the delivery of greater emissions savings at a system level, through:

Making greater use of residual waste resources in efficient energy from waste (EfW) applications.

	Recommended actions	Path forward
3.1	Increase the frequency and coverage of waste arisings data, with a particular focus on providing up-to-date data on the quantity, composition and location of commercial and industrial (C&I) wastes. This will lower one of the barriers to entry for new entrants who aren't able to access longer-term contracts and therefore need to assess the risk of feedstock shortages. The methodology for collecting this data needs to balance the potential gain from better utilisation of waste resources, with any additional burden placed on waste collectors to generate these data.	Develop robust waste data collection methods for C&I waste and update these data at least annually. These data should be publicly accessible (via Department for Environment, Food and Rural Affairs). The development of these statistics will require collaboration between Government (Defra), the waste management industry and academics working in waste management.
3.2	Encourage the development of Energy for Waste (EfW) plants which are more economically and technically resilient to reductions in waste availability and changing composition by focusing on improving efficiency and processes which can manage feedstock variability.	Planning and permitting authorities and government departments in charge of EfW incentives ensure that their incentives, policies and procedures (including the procurement of waste management services) enable and incentivise the waste management industry to deliver best practice.

Increasing the quantity of UK-grown second generation bioenergy crops, to deliver benefits to both the energy system and to the UK supply chain.

	Recommended actions	Path forward
3.3	Continue to develop the knowledge base around the environmental impacts of energy crop planting and use this to inform best practice guidelines for energy crop planting and incentives for the delivery of public goods.	R&D funding bodies include energy crop research in their research programmes, and collaborate with Academia, Farmers & Foresters to prioritise research needs and establish/maintain long-term monitoring plots. Responsibility for incorporating findings into best practice updates should sit with the industry or a third party such as the Environment Agency or Government (Defra).

Summary of recommendations and recommended actions

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3.4	To encourage energy crop planting, and develop a stable, spatially explicit financial incentive which values the public goods energy crops deliver.	Energy crop planting should be included in agricultural support mechanisms as a means of delivering wider public goods. This is an emerging area of policy – policy makers will need to work with the energy crops industry and academics to develop a mechanism to quantify the value of different environmental benefits. This should also highlight where there continue to be knowledge gaps and research needs.
3.5	Invest in research of new establishment and harvesting techniques to reduce the cost of biomass feedstock production. Encourage collaboration and learning between farmers and across disciplines.	R&D funding bodies work with Academia, Foresters and Farmers to identify research needs in the biomass supply chain.

To increase resilience to changes in global biomass availability by exploring new supply chains for demonstrably sustainable imported biomass.

	Recommended actions	Path forward
3.6	Ensure lessons are learnt regarding biomass handling, storage and transport.	Industry and the Health & Safety Executive (HSE) should work together to identify lessons learnt from, for example, existing biomass import facilities and incorporate this into best practice guidance.
3.7	Continue to assess potential availability of sustainable biomass imports and collaborate across industry to ensure timely expansion of import infrastructure if needed.	Timely investment in import logistics infrastructure requires clarity on the future demand for imported biomass. Identifying and responding to future needs requires ongoing dialogue between the Biomass Industry, Port Authorities, Government, Academia and Investors.

Recommendation 4: Deliver more physically and chemically consistent feedstocks to end users, through improvements in plant breeding and pre-processing, and/or develop conversion technologies more resilient to variations in feedstock composition.

	Recommended actions	Path forward
4.1	Invest in demonstrating new pre-processing technologies (e.g. water washing) at a commercial scale to understand whether the improvements they deliver in feedstock quality outweigh the additional cost of the pre-processing step.	R&D funding bodies should include pre-processing technologies within their energy crop research programmes and collaborate with the biomass supply industry and academia to support commercial-scale demonstration projects.
4.2	Continue research in plant breeding, focused on developing characteristics suited to energy end use applications.	R&D research programmes on plant breeding should continue to work with biomass growers, users and the wider academic community to prioritise and fund research needs.
4.3	Invest in developing conversion technologies which can be optimised for different feedstock types or which can accept a wider change of chemical characteristics.	R&D funding bodies should include conversion technologies within their energy crop research programmes and collaborate with the biomass industry and academia to prioritise research needs and fund demonstration projects.

Introduction

The Energy Technologies Institute (ETI) was established in 2007 as a 10-year partnership between the UK Government and industry to identify and accelerate the development and demonstration of low carbon technologies which can help the UK address its long-term greenhouse gas (GHG) emissions reduction targets, as well as deliver nearer-term benefits. Through its Bioenergy and Carbon Capture and Storage (CCS) programmes it has delivered research and technology development and demonstration projects which have increased understanding of the role sustainable bioenergy can play within the UK energy system, and helped to de-risk the commercial roll-out of key technologies.

This insight report sets out the ETI's vision for bioenergy in a low-carbon UK energy system out to 2050, based on the evidence base it has developed over 10 years, identifying the future opportunities, challenges and actions needed to deliver this vision. Finally, it signposts additional information from the ETI and other organisations who continue to work in bioenergy research and the development of the bioenergy sector.

The ETI's whole energy system analysis has consistently identified how growing and using biomass sustainably, along with waste, can be a valuable mechanism for cost-effectively reducing emissions. However, their optimal role in an energy system varies depending on the demand for different energy vectors (power, heat, fuels), the relative abundance of alternative low carbon energy sources, and the rate of development and deployment of low-carbon technologies and CCS.

While a range of biomass feedstocks and bioenergy technologies are commercially exploited today, developing the sector to maximise its contribution to cost-effective emissions reductions requires an increase in sustainably-sourced feedstocks and the commercial deployment of new technologies able to produce the energy vectors needed (and capture the carbon dioxide produced). In addition, it is important to have access to robust, spatially explicit data on the impacts of growing and using biomass to have confidence in calculations of the life cycle GHG emissions associated with these supply chains.

The ETI's Bioenergy Programme has drawn on expertise from industry and academia to develop and commission projects which were identified as having the potential to add the most value to the bioenergy sector. These projects focused on increasing understanding by filling data gaps and building sophisticated tools to examine bioenergy sector scenarios, as well as developing and demonstrating technologies at a commercial scale (Figure 1).

Key findings from the ETI's Bioenergy Programme have been previously published in a series of Insights reports available on the ETI's website[2]. Alongside these, the ETI has also published data and reports from individual projects which can be accessed via the ETI's Knowledge Zone[3] on the ETI's website.

2 ETI Insights [online]. Available at: http://www.eti.co.uk/insights
Other reports, perspectives and presentations from the Bioenergy Programme are available via the ETI's Reference Library [online]. Available at: http://www.eti.co.uk/library?programme=bioenergy&type=&y=

3 ETI Knowledge Zone, Bioenergy Programme: http://www.eti.co.uk/programmes/bioenergy

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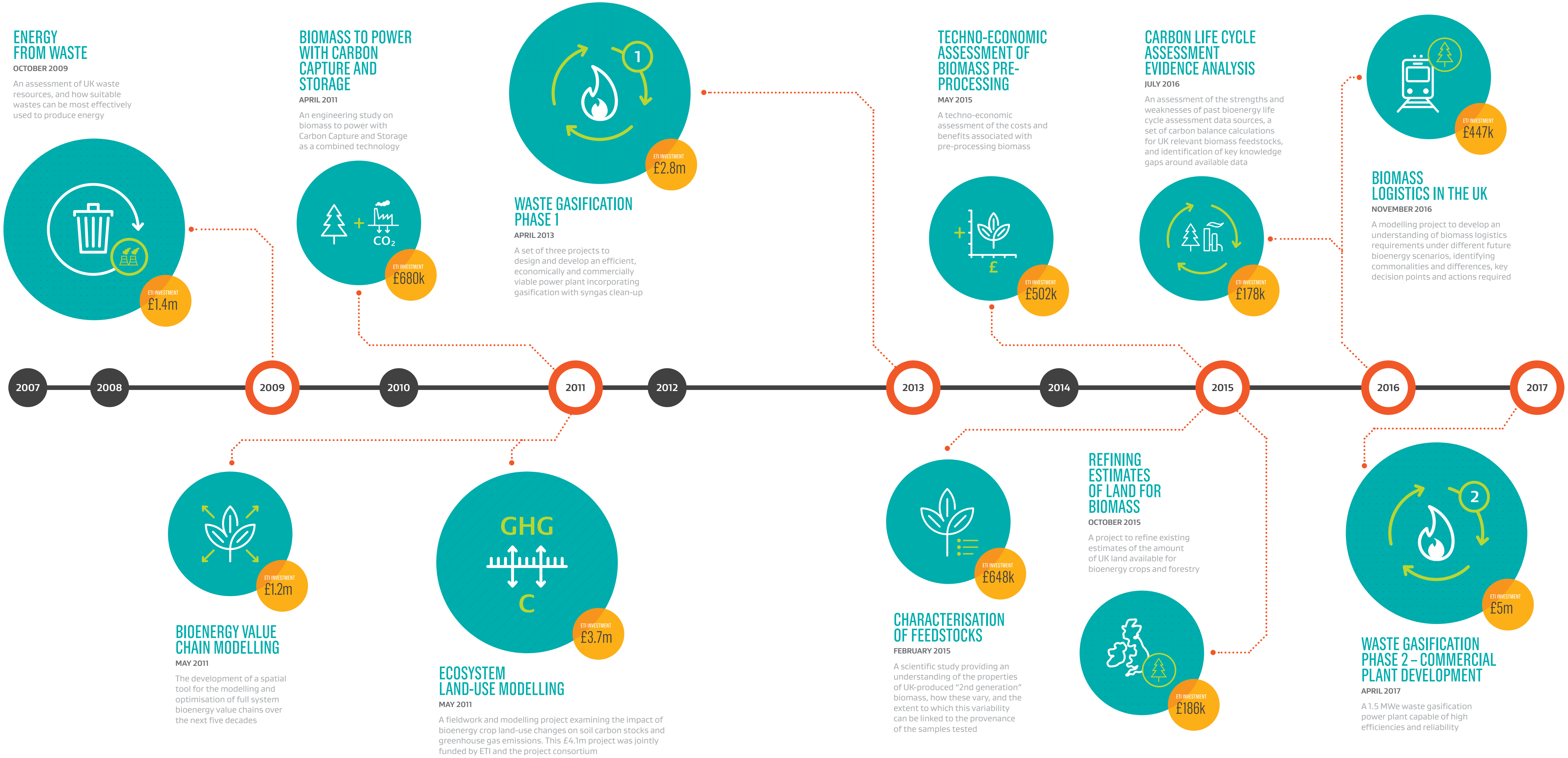
Figure 1
Timeline of the ETI Bioenergy Programme[4]



4 A timeline of the ETI's CCS Programme can be downloaded from the ETI website. Available at: http://www.eti.co.uk/library/10-years-of-innovation-carbon-capture-and-storage

2. The strategic value of biomass

The 2015 Paris Agreement, which was ratified by the UK Government in November 2016[5], is an international agreement to limit global warming to well below 2°C above pre-industrial levels and to pursue efforts to limit it to 1.5°C. Prior to the Paris Agreement the UK had already introduced a target to reduce GHG emissions by 80% from 1990 levels by 2050. To limit warming to 1.5°C, analysis by the Committee on Climate Change (CCC) suggests that the world will need to reach net-zero GHG emissions between the 2060s and 2080s[6].

Given this global challenge to restrain total GHG emissions (including those from both energy and land use) to net-zero, the aim of biomass production and bioenergy use should be to help deliver a global system that produces the lowest emissions overall.

It will be near impossible to remove all sources of anthropogenic GHG emissions, therefore some means of greenhouse gas removal (GGR) from the atmosphere will be required to deliver negative emissions. There are a range of potential GGR technologies under development, including negative emission fuel cells and direct air capture, but these cannot be cost-effectively deployed today[7]. Therefore, the greatest strategic value of biomass production and bioenergy is to deliver net negative emissions.

Biomass has the potential to deliver negative emissions because it absorbs carbon dioxide (CO_2) from the atmosphere as it grows, providing that the rate of new biomass growth exceeds the rate of biomass removed (due to harvesting, fires etc), and that this additional carbon stock is maintained through sustainable land management, growing biomass (e.g. afforestation) and can deliver net negative emissions. Using harvested wood in construction can continue to store carbon for the duration of a building's lifetime, however maintaining the size of this carbon sink requires new wood in construction to continue to at least match the quantity of construction wood disposed of each year (e.g. following demolition).

While afforestation and wood in construction are established techniques, they require continual monitoring to maintain the level of carbon stored. Deployment of Bioenergy with CCS (BECCS)[8] provides permanent storage of carbon, and is consistently highlighted by the ETI and others[9] as a strategically valuable technology in meeting the UK's 2050 targets cost-effectively.

BECCS delivers negative emissions by using biomass to generate energy, capturing the carbon dioxide emissions from combustion and permanently sequestering them in geological storage. Producing electricity or hydrogen using BECCS technologies maximises the potential percentage of carbon dioxide that could be captured. CCS technologies could also be added to gaseous or liquid biofuel plants but the proportion of carbon captured would be much lower, as between a third to a half of the carbon is retained in the final product.

Without CCS, increasing demand for bioenergy can encourage more biomass production but the emissions released at the point of combustion are not sequestered. Where a bioenergy vector is the lowest carbon practicable alternative to fossil fuels (such as aviation biofuels), it can help reduce energy system emissions, but without CCS it will not deliver the net negative emissions which are ultimately needed to reach net-zero. The role for bioenergy under different future energy scenarios is discussed further in Section 4.

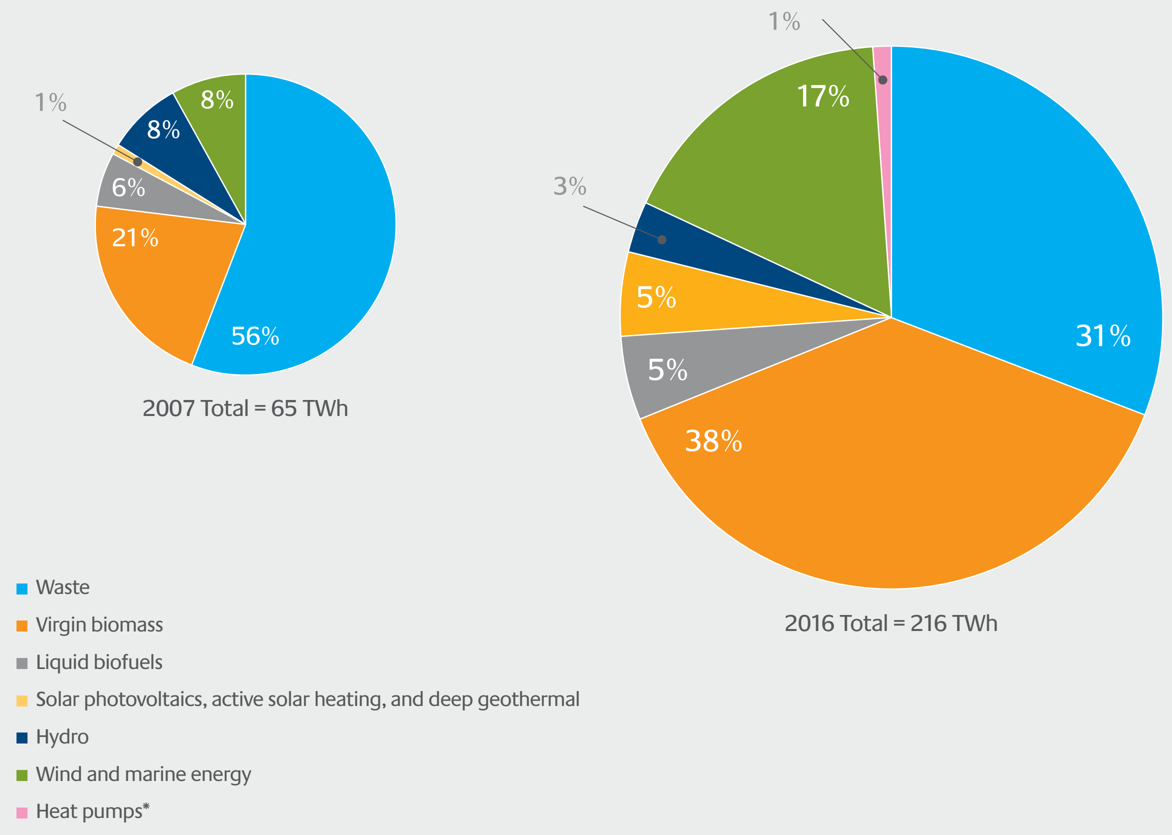
5 BEIS (2016). UK ratifies the Paris Agreement [online]. Available at: https://www.gov.uk/government/news/uk-ratifies-the-paris-agreement.
6 CCC (2016). UK Climate Action following the Paris Agreement [online]. Available at: https://www.theccc.org.uk/publication/uk-action-following-paris/
7 Oxburgh (2016). LOWEST COST DECARBONISATION FOR THE UK: THE CRITICAL ROLE OF CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage (CCS) [online]. Available at: http://www.ccsassociation.org/news-and-events/reports-and-publications/parliamentary-advisory-group-on-ccs-report/
8 There is currently one operational BECCS plant in Decatur, Illinois. Carbon dioxide is captured from a corn-to-ethanol plant and transported to a nearby injection well for dedicated geological storage. For more information visit: Global CCS Institute (2018). Illinois Industrial CCS: https://www.globalccsinstitute.com/projects/illinois-industrial-carbon-capture-and-storage-project
9 Including: CCC (2018). Reducing UK emissions – 2018 Progress Report to Parliament [online]. Available at: https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/

3. Trends and developments in UK bioenergy use

Between 2007 and 2016 (the latest year for which there is complete data), bioenergy – which includes heat, power and liquid transport fuels derived from biomass and waste – was consistently the largest source of renewable energy in the UK. As Figure 1 indicates, over that time the amount of renewables used has more than tripled in the UK and the bioenergy sector has changed from one dominated by waste feedstocks[10] to one where just over half the feedstock for the bioenergy sector is estimated to have come from imported and UK-grown plant biomass (on an energy input basis)[11]. Appendix 8.3 provides further discussion on UK biomass use and compares the data in Figure 2 with other data sources.

Figure 2

*Renewable and waste resources used for energy in 2007 and 2016. Figures represent energy used (TWh) on an input basis (using, where applicable, the Gross Calorific Value (GCV) of fuels)[12]. The data for this chart are provided in Appendix 8.3. *Heat pump data only includes the renewable fraction of heat generated*



10 Waste feedstocks includes: waste wood, animal biomass (poultry litter, meat and bone and farm waste), sewage gas, landfill gas, municipal solid waste, tyres, general industrial waste and hospital waste. It is important to note that some of these waste feedstocks will contain non-biogenic (i.e. fossil derived) waste. This portion of the waste is not renewable but is included in the overall DUKES data as it is part of a mixed waste feedstock. In 2016 of the 68 TWh of waste used, 15 TWh were non-biogenic. Source: BEIS (2017), Digest of UK Energy Statistics (DUKES) 2017, Chapter 6: Renewable sources of energy [online]. Available at: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes
11 BEIS (2017), Digest of UK Energy Statistics (DUKES), Renewables and Wastes: Commodity Balances, Tables 6.1-6.3 [online]. Available at: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes.
12 ibid

3. Trends and developments in UK bioenergy use

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Bioenergy is generated from a range of feedstocks

Of the plant biomass used in 2016, 44% (on an energy basis) was imported. The majority of this was wood pellets[13], with the main recipient being Drax power station, who have converted four of their six 645 MW units from coal to biomass[14]. In 2016, 63% of liquid biofuels used in the UK were imported – almost all was biodiesel and bioethanol.

UK-grown bioenergy feedstocks come from a wide range of sources, including:

- Woodfuel: low-value timber plus residues (chips and sawdust) from sawmills and round fence manufacturers predominantly used in heat and power production.
- Energy crops
  - o 1st generation (or conventional) crops. These include crops such as wheat, sugar beet, barley and oilseed rape which have all been grown in the UK at some point since 2008 to manufacture liquid biofuels for transport. In addition, maize is grown as a feedstock for anaerobic digestion, which can produce biomethane or power and heat.
  - o 2nd generation energy crops. These include perennial grasses such as Miscanthus, and short rotation coppice (SRC) willow or poplar (see Appendix 8.4 for a description of these crops). They are currently used to produce power and heat in power stations, combined heat and power (CHP) plants and in biomass boilers.
- Agricultural residues. This includes cereal and oilseed rape straw, predominantly used in dedicated power stations in the east of England.
- Waste feedstock covers a wide range of materials including waste wood, animal biomass, sewage and landfill gas, municipal solid waste, tyres, general industrial waste and hospital waste. It is important to note that some of these waste feedstocks contain non-biogenic (i.e. fossil derived) material[15]. A tax on landfilled waste and incentives for energy from waste technologies have both driven an increase in waste utilisation for energy since 2007. In 2016, 83% of waste feedstocks used for energy were used to produce electricity.

More information on the feedstocks used for bioenergy is provided in Appendix 8.4.

There are pre-existing policy support mechanisms for bio-electricity, bio-heat and biofuels

Since 2008, the UK Government has introduced support mechanisms for renewable heat and changed the way large-scale renewable electricity projects are supported (Table 2). Further details on each of the schemes in Table 2 are provided in Appendix 8.5.

Table 2

UK incentives for producing bio-electricity, bio-heat, or bio-transport fuels, 2008 and 2018.

	2008	2018
Electricity	Renewables Obligation (RO) Feed-in Tariff (FiT) – for anaerobic digestion only <5 MW	Contracts for Difference (CfD) Feed-in Tariff (FiT) – for anaerobic digestion only <5 MW – updated
Heat	–	Renewable Heat Incentive (RHI)
Transport	Renewable Transport Fuels Obligation (RTFO)	Renewable Transport Fuels Obligation (RTFO) – updated

Each scheme operates independently with separate budgets and mechanisms for setting the level of support provided. Most generators can only receive a subsidy under one scheme (there are some exceptions where combined heat and power (CHP) plants can claim both the RHI and either the RO or CfD). While some renewable technologies are only able to produce one end vector, most biomass and waste feedstocks can be used in more than one conversion process and there are several technologies which could claim support under more than one scheme, including:

- Gasification – the syngas produced from gasification can be combusted to produce electricity and/or heat, or upgraded to produce bio-synthetic natural gas (bioSNG), which could be used for heating or as a transport fuel. Syngas can also be upgraded to other fuels or chemicals for non-energy use.
- Anaerobic digestion – the raw biogas produced can be upgraded to biomethane or combusted directly to produce electricity and/or heat.

Supporting commercial deployment of bioenergy via a number of independent incentive schemes runs the risk that the most attractive scheme for a new generator may not be the one which supports the development of technologies and end vectors that deliver the most cost-effective emissions reductions today, or which deliver the greatest strategic value for the future (for example by encouraging the development of clean syngas production from gasification, or CCS-compatible technologies).

In 2018 the Energy Systems Catapult (ESC), with support from the ETI, is researching how the UK could improve incentives to cut emissions efficiently across the economy in their 'Rethinking Decarbonisation Incentives' project. A report from the first phase of the project, which is available from the ESC website, summarises the current pattern of economic signals in the UK for decarbonisation in different economic sectors and activities. The analysis shows that the effective carbon prices arising from current UK policies vary widely across different sectors and activities. This suggests that the UK may be over-rewarding some kinds of emissions-reducing activity, while under-rewarding emissions reductions in other activities or sectors[16].

13 DECC (2016). Woodfuel disclosure survey [online]. Available at: https://www.gov.uk/government/publications/woodfuel-disclosure-survey
14 Drax (2018). About Us – Our Businesses [online]. Available at: https://www.drax.com/about-us/
15 ibid

16 ESC (2018). Rethinking Decarbonisation Incentives [online]. Available at: https://es.catapult.org.uk/projects/rethinking-decarbonisation-incentives/

4. The future role of bioenergy in the UK energy system

The UK has a legally binding target to reduce GHG emissions by 80% from 1990 levels by 2050. No one technology will be able to meet this target in isolation. To help identify the technology combinations that can deliver the lowest-cost decarbonisation pathways for the UK energy system, the ETI developed its internationally peer-reviewed Energy System Modelling Environment (ESME). ESME is a least-cost optimisation, policy neutral tool which models carbon dioxide (CO_2) emissions for the whole UK energy system including the power, transport, buildings and industry sectors, and the infrastructure that underpins them, in five- or ten-year time-steps from 2010 to 2050[17].

By running several different scenarios in ESME – adding or removing certain technologies or resources and/or adjusting their cost and performance characteristics – we can build up a picture of which are the most valuable (combinations of) technologies for cost-effective CO_2 reduction under different conditions, which are the most resilient to different circumstances, and how the role of a particular technology varies with their cost and performance, and that of other technologies.

It is important to note that ESME doesn't consider non-CO_2 GHGs (such as methane) or particulate emissions. When calculating the 2050 CO_2 emissions limit in ESME, it is assumed that emissions of non-CO_2 GHGs will reduce by 70% by 2050 from 1990 levels through other activities. Achieving this reduction is highly uncertain, and means that even greater reductions in CO_2 may be needed by 2050 if reductions in non-CO_2 GHGs fail to materialise[18]. In addition, ESME is focused on delivering cost-effective GHGs reductions only. Incorporating other drivers, such as improving air quality, would have an impact on how the energy system evolved.

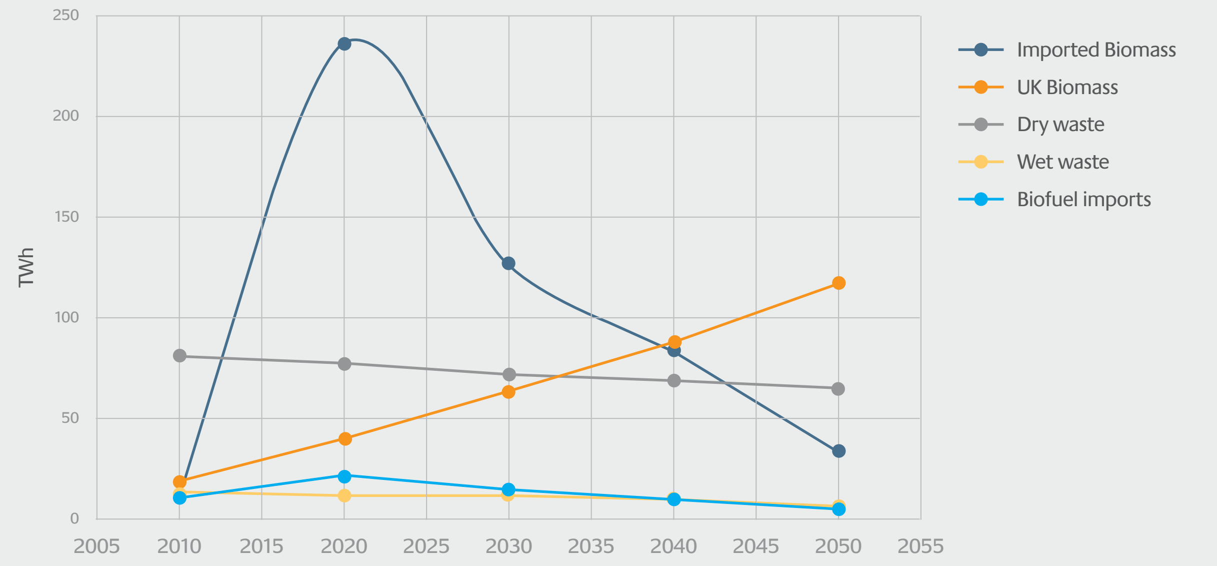
To highlight the impact wider energy system decisions have on the optimal role for biomass and wastes in the energy system, five scenarios have been analysed specifically for this report using the ESME model. The box below provides a summary of the biomass and waste resources and conversion pathways represented in ESME.

Biomass and waste resources and conversion routes in ESME

- **UK-grown biomass** and imported biomass can be converted directly to heat or power, or converted into an intermediate product such as a liquid biofuel, hydrogen or bioSNG for use in transport, industry, space heating and electricity generation
- **Imported liquid biofuels** are mixed with other liquid fuels for use in transport
- **Wet waste** can only be used in anaerobic digestion to produce either electricity or biomethane. The ESME resource assumptions do not include landfill or sewage gas
- **Dry waste** can be incinerated or gasified to produce heat and/or power

Resource availability assumptions and technology cost, performance and rate of deployment data are based on published literature and findings from ETI projects. Figure 3 shows the resource availability assumptions used in the base case (Scenario 1). These assumptions are also assumed in Scenarios 3, 4 and 5. Scenario 2 assumes that the resource availability for biomass and biofuel resources remains at 2010 levels.

Figure 3
Availability of biomass and waste resources in ESME (TWh, based on the GCV of resources), 2010-2050



Further details on how biomass and waste resources and technologies have been modelled in the ESME scenarios used in this paper are provided in Appendix 8.6.

17 A detailed overview of ESME covering the approach and the key technical features of the model is available in: ETI (2014). Modelling Low-carbon energy system designs with the ETI ESME model [online]. Available at: http://www.eti.co.uk/library/modelling-low-carbon-energy-system-designs-with-the-eti-esme-model
18 The ESME dataset and data references book are available to download from the ETI website.
Dataset: ETI (2018). Energy Strategy [online]. Available at: http://www.eti.co.uk/strategy
Data references book: ETI (2018). ESME [online]. Available at: http://www.eti.co.uk/programmes/strategy/esme

4. The future role of bioenergy in the UK energy system

Continued ›

The role of biomass and waste in the energy system

Table 3 and Figure 4 provide a description of each scenario and Table 4 provides a summary of their results. Figure 5 shows the additional cost of meeting the UK's 2050 emissions reduction target relative to meeting energy demand without an emissions target. More detailed results charts from each scenario can be downloaded alongside this report.

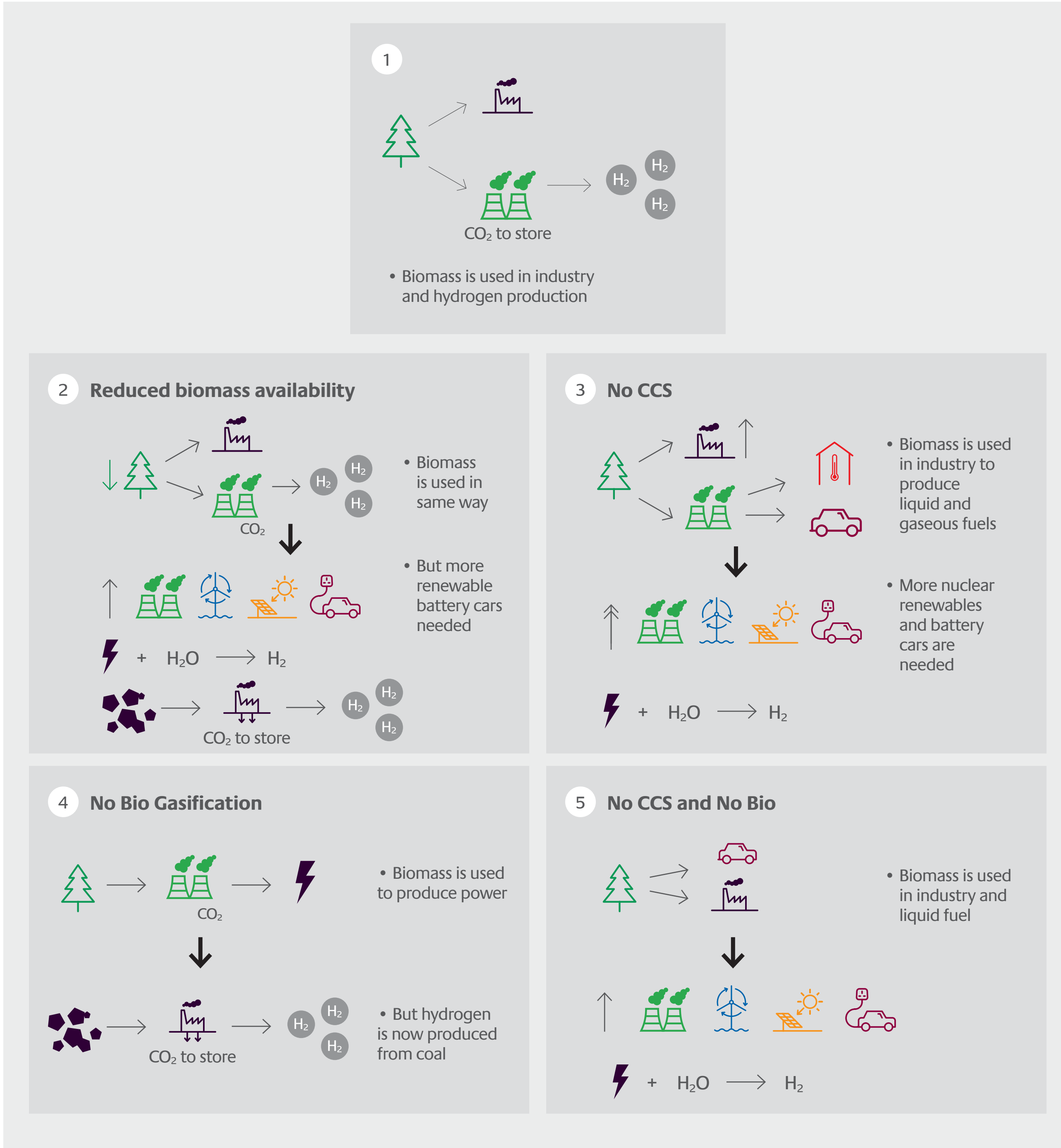
The results and following analysis focus on the dominant feedstocks and technologies deployed in the scenarios.

In reality, there will be a broader mix of technologies and feedstocks used than indicated in the scenarios. Some technologies will continue to be used beyond the point at which our whole system analysis indicates that there are better alternative uses for their inputs. Subsidies and other market mechanisms (which are outside of the scope of ESME's analysis) mean that existing plants will continue to operate whilst it is still financially attractive at a company level to do so. There will also be examples of smaller-scale, local solutions, such as using anaerobic digestion to treat genuine wet wastes, which are not considered in detail in this paper.

Table 3
Description of ESME scenarios

	Name	Description	Purpose
1	Base case	Standard cost, performance and build-out rates for technologies and central resource availability[19]. CCS technologies are available for deployment from 2030.	A base case against which the other scenarios can be compared.
2	Reduced biomass and biofuel feedstock availability	Biomass and biofuel availability is limited to the amount used in 2010.	To examine whether feedstock availability changes the way biomass is used, and the wider impacts on energy system decarbonisation.
3	No CCS	CCS is not available for deployment.	To explore the role of biomass and waste in energy system decarbonisation without CCS, given the strategic value of BECCS as a route to delivering net negative emissions.
4	No biomass gasification	Biomass gasification technology is not available for deployment.	To explore alternative options if biomass gasification is not commercially deployed, given that wider ETI analysis has consistently highlighted the value of producing a clean syngas from biomass gasification.
5	No biomass gasification + No CCS	Combining Scenarios 3 and 4, neither biomass gasification technology nor CCS are available for deployment.	To explore the role for biomass without gasification and CCS deployment.

Figure 4
Infographic of ESME Bioenergy Scenarios – How is biomass used and consequences for the rest of the energy system



Whilst not considered in detail in this insight, previous ESME analysis has indicated that if the UK failed to deploy both CCS and any additional bioenergy (beyond the levels used in 2010) it would become very difficult to meet the UK's 2050 emissions reduction target at all and the additional cost of doing so would be significantly higher than the costs shown in Figure 4.

19 ibid

4. The future role of bioenergy in the UK energy system

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Table 4
Results from ESME Scenarios

	Description	Electricity sector	Transport sector	Heat sector	Industry sector	Biomass and waste	Hydrogen
2010 Baseline (all scenarios)							
1-5	2010 baseline	92 GW of capacity generating 371 TWh electricity. 76% of electricity generated is from gas or coal, with nuclear providing 17%.	32m vehicles, all assumed to have internal combustion engines (ICEs).	80% of space and hot water heating provided by gas. The remainder is a mixture of oil, solid fuel and resistive electric heating	Fuel use in industry is roughly evenly split between gas, electricity and liquid fuel, with a small contribution from biomass and coal.	Total of 83 TWh of biomass, biofuel and waste resource available. Biomass is used in industry, biofuel in transport, Dry waste is used to generate electricity via incineration and wet waste is used to produce a mixture of biogas and heat and power.	–
Scenario Results to 2050							
1	Base case – all feedstocks and technology options available	Generation capacity reaches 130 GW in 2050, producing 612 TWh. Nuclear generates 57% of electricity, Combined Cycle Gas Turbine (CCGT) with CCS 19%, with offshore renewables contributing most of the remainder.	By 2050, there are 52m vehicles (this is true in all scenarios). Very few vehicles use conventional ICEs. 41% of vehicles are hybrids with a further 26% being plug-in electric hybrids (PHEVs). 27% of vehicles are purely battery powered.	By the 2050s gas is no longer used to directly generate space and water heating. Instead this is provided through a mix of district heating, electric heating and heat pumps.	There is an 8% decline in industrial fuel use (this is true in all scenarios). By 2050, hydrogen is providing 17% of industrial fuel. This mostly offsets the use of liquid fuel, but there are also reductions in the use of gas, coal and electricity. Biomass makes a small contribution in each decade, peaking at 8% of fuel demand in the 2030s and 40s.	The majority of biomass, biofuel and waste feedstocks are used, hitting resource limits for all bio-feedstocks in the 2040s and 2050s. In the 2050s biomass, waste and imported biofuels make up 11% of primary resource consumption (228 TWh). Dry waste is used in waste gasification + CCS, while wet waste is used in anaerobic digestion to produce biogas. Some biomass is used in industry in all decades, peaking at 29 TWh of resource in 2030. Biomass for heating is only used until 2030 (26 TWh in 2030, 17% of biomass resource). From the 2030s onwards, the majority of biomass (59% in 2030 rising to 92% in 2050) is used to produce hydrogen via gasification with CCS.	69 TWh of hydrogen is produced in the 2050s, all from biomass gasification + CCS. 89% of hydrogen is used in industry in the 2050s. The remainder is used in hydrogen turbines (for peak-time electricity production) and hydrogen vehicles.
2	Reduced biomass and biofuel feedstock availability	Generation capacity reaches 170 GW in 2050, producing 680 TWh. Nuclear still provides 57% of electricity but a reduction in CCGT + CCS compared to the base case increases the reliance on intermittent renewables, particularly offshore wind.	By 2050, there are no conventional ICEs or standard hybrid cars. 69% of cars are battery powered, with a further 9% PHEVs. The remainder are hydrogen powered vehicles.	By the 2050s the fuel mix for water and space heating is similar to the base case. However, the use of gas for hot water heating ends a decade earlier (by 2040 rather than 2050).	The fuel mix in 2050 is similar to that seen in the base case.	Very similar use of wastes as in base case. Biomass resource limits are lower and are hit from 2030 onwards. Some biomass is used in industry in all decades peaking at 12 TWh (39% of biomass resource) in 2030. The remaining resource in the 2030s-2050s is used in technologies with CCS to produce hydrogen and power. Unlike the base case, up to 12 TWh (40% of biomass resource in 2040s) of this biomass is co-fired with coal (with CCS).	106 TWh of hydrogen is produced in the 2050s to meet increased demand from hydrogen vehicles. Half is produced via electrolysis, a quarter from Steam Methane Reforming (SMR) + CCS with the remainder from biomass and coal gasification + CCS. The increased demand for hydrogen relative to the base case is due to an increase in hydrogen vehicles.

4. The future role of bioenergy in the UK energy system
Continued ›

Table 4
Results from ESME Scenarios (Continued)

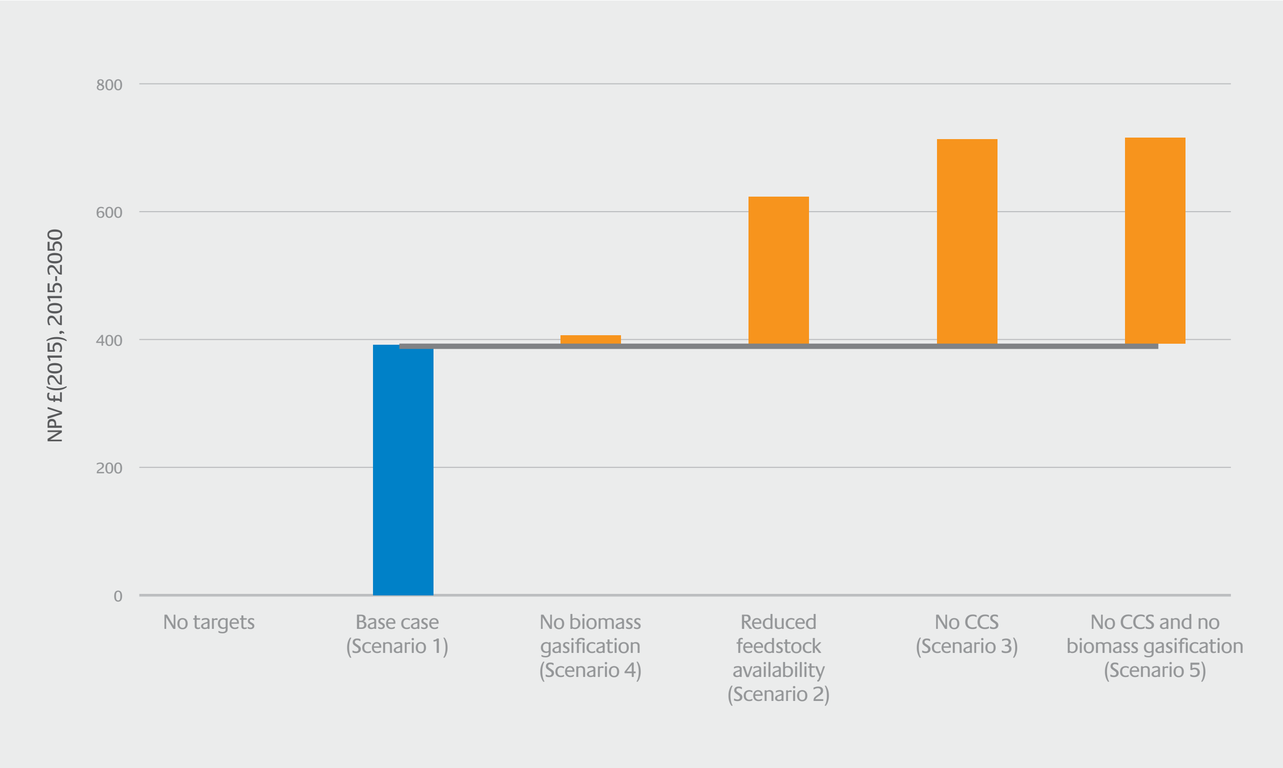
	Description	Electricity sector	Transport sector	Heat sector	Industry sector	Biomass and waste	Hydrogen
3	No CCS	Generation capacity reaches 231 GW in 2050, producing 776 TWh. The absence of CCS means almost all electricity is produced from nuclear or intermittent renewables, particularly offshore and onshore wind and solar.	By 2050, there are no cars with conventional ICEs. 69% of cars are battery powered, with a further 21% hydrogen powered. Only 9% of cars are PHEVs.	A similar fuel mix to the base case, but with much less gas used in the 2040s (both scenarios use no gas in the 2050s).	Greater use of hydrogen (21% of fuel in 2050) and biomass (11%) compared to the base case, to offset reductions in gas, liquid fuel and coal use.	Very similar use of wet waste compared to base case. Use of dry waste reduces to zero by 2040s. Biomass resources are fully exploited in 2040s and 2050s. Compared to the base case more biomass is used in industry in all decades (peaking at 52 TWh in 2040) and around 35 TWh biomass is used for heating in the 2030s and 2040s. The absence of CCS means that most biomass in the 40s and 50s is used to produce gaseous or liquid fuels – bioSNG or hydrogen via gasification in the 40s, liquid transport fuel in the 2050s.	121 TWh of hydrogen is produced in the 2050s, around 60% of which is used in industry. Most of the rest is used in transport with 6% used in hydrogen turbines. All hydrogen in the 2050s is produced via electrolysis. In the 2030s and 40s up to 18 TWh of hydrogen is produced using biomass gasification.
4	No biomass gasification	The 2050 generation capacity is 125 GW, producing 616 TWh. There is a similar fuel mix to the base case with 55% electricity from nuclear and 18% from CCGT+CCS. 5 GW of biomass generation + CCS are deployed, generating 41 TWh in 2050 (not seen in base case). Offshore renewables provide most remaining electricity.	Similar to the base case, in 2050 there are a mix of standard hybrids (37%), PHEVs (24%) and battery electric vehicles (33%). The remaining 6% of vehicles are mostly hydrogen fuelled with very few conventional ICEs.	A similar fuel mix and transition to the base case.	A similar fuel mix to the base case, with the contribution from biomass peaking in the 2040s at a slightly higher level than the base case (10%, 38 TWh).	The absence of biomass gasification means that the majority of biomass is used in biomass-fired generation with CCS from the 2030s.	65 TWh of hydrogen used in 2050s with the vast majority used in industry; a similar picture to the base case. However, this hydrogen is now produced from coal gasification + CCS rather than biomass.
5	No biomass gasification and no CCS	Generation capacity in 2050 is 231 GW, generating 776 TWh. The generation mix is very similar to Scenario 3 (No CCS).	A very similar mix of vehicles to Scenario 3 (No CCS).	A similar mix of fuels to Scenario 3 (No CCS).	A similar mix of fuels to Scenario 3 (No CCS).	Very similar use of wet waste compared to the base case. Use of dry waste reduces to zero by 2030s (similar to Scenario 3 (No CCS)). Biomass resources are fully exploited in 2040s and 2050s. Similar to Scenario 3, more biomass is used in industry compared to the base case (peaking at 52 TWh in 2040) and around 35 TWh of biomass for heat are used in the 2030s and 40s. The absence of both CCS and gasification routes means that most biomass in the 30s, 40s and 50s is used to produce liquid transport fuels – there is no route to produce bioSNG from biomass (via gasification).	121 TWh of hydrogen is produced in the 2050s, 62% of which is used in industry, with most of the rest used in transport and a small proportion used in hydrogen turbines. This is all produced via electrolysis in the 2050s. SMR's are used to produce hydrogen in the 2020s-2040s, peaking at 15 TWh in the 2040s. Electrolysis produces 51 TWh hydrogen in the 2040s.

4. The future role of bioenergy in the UK energy system

Continued ›

Figure 5

Additional cost of meeting UK 2050 emissions reduction target relative to meeting energy demand without an emissions target (Scenario 1). Additional cost of meeting UK 2050 emissions reduction target under Scenarios 2-5 relative to Scenario 1. (Net Present Value (NPV) 2015-2050, £bn (2015), Discount Rate 3.5%)



Additional cost (£(2015) bn NPV(2015-2050))	Scenario 1	Scenario 4	Scenario 2	Scenario 3	Scenario 5
relative to Scenario 1	–	16	235	323	326
relative to 'No targets'	390	406	625	713	716

Analysis consistently indicates that the successful deployment of bioenergy is critical to delivering a low carbon energy system transition in the UK

All scenarios make use of biomass and waste resources. Biomass and wet waste resources are fully exploited from the 2040s onwards in all scenarios, while dry waste resources are used in all scenarios where CCS is available. Prior to 2040, ESME does not make full use of all biomass resources and in the 2020s uses less biomass than the UK is likely to do based on current trends. This is because ESME's base data are based on the 2010 UK energy system and ESME's assessment of how this develops to 2020 to deliver cost-optimal emissions reductions may be different to what has actually happened in the UK.

Dry waste is not used beyond the 2030s in scenarios where CCS is not available (Scenarios 3 and 5). This is likely to be because dry waste has higher (non-biogenic) GHG emissions per unit of fuel used compared to biogenic biomass and wet waste feedstocks, because it is a mix of biogenic and non-biogenic (i.e. fossil-derived) waste.

In reality, the emissions associated with using waste and biomass feedstocks are variable and can have a material impact on whether bioenergy delivers genuine GHG emissions savings. The extent to which energy from waste (EfW) delivers emissions savings relative to disposal of waste in landfill, depends on several factors including the biogenic content of the waste, the efficiency of the EfW plant and whether the waste would otherwise be disposed of in a landfill which captures landfill gas[20]. Similarly, the emissions associated with the use of biomass for bioenergy are dependent on decisions made throughout the supply chain, which is why recipients of renewable energy subsidies must demonstrate that they meet GHG emissions thresholds.

The net GHG emissions associated with growing biomass or using waste to produce bioenergy can be calculated using a life cycle assessment (LCA), the scope of which can encompass indirect impacts such as indirect land use change, as well as the direct emissions associated with bioenergy production, such as transporting and processing the biomass or waste. The ETI's perspective, How can Life Cycle Assessment inform bioenergy choices?, provides further information on bioenergy LCAs[21].

Negative emissions from using biomass in conjunction with CCS enable more cost-effective decarbonisation across the energy system

Delivering negative emissions is the primary driver for deploying BECCS technologies. When considering the cost of energy generation alone, BECCS technologies are not, in themselves, the cheapest means of producing bioenergy, nor are they the cheapest means of producing renewable energy. However, their value in offsetting the need for more expensive decarbonisation measures elsewhere in the energy system, makes BECCS a hugely valuable part of a cost-effective system solution.

Figure 6 shows why negative emissions are so valuable. In Scenario 1 the use of biomass and waste delivers net negative emissions of 47 Mt CO_2 (carbon dioxide) in 2050[22]. The net emissions target in ESME for 2050 is 105 Mt CO_2, so negative emissions provide substantial additional 'headroom' for emissions in sectors which are more difficult and/or more expensive to decarbonise. The ETI's whole system analysis suggests that some transport emissions will be amongst the most expensive to mitigate, while others such as aviation emissions will be impossible to fully decarbonise within the 2050 timeframe. ESME analysis suggests that using biomass to deliver negative emissions to enable some emissions to continue in the transport sector, is a cheaper means of meeting the 2050 target than using the same biomass to decarbonise transport directly through liquid fuel production.

20 Defra (2014). Energy Recovery for residual waste – a carbon-based modelling approach [online]. Available at: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19019.

21 ETI (2018). How can Life Cycle Assessment (LCA) inform bioenergy choices? [online]. Available at: http://www.eti.co.uk/library/how-can-life-cycle-assessment-inform-bioenergy-choices

22 This is less than the biogenic credit shown below the x-axis in Figure 6. The biogenic credit is applied to all biogenic feedstocks used. When used there will be an emission associated with this in the relevant sector above the x-axis. The net negative emissions from bioenergy is the difference between the two. Further details on this calculation is provided in Appendix 8.6.

4. The future role of bioenergy in the UK energy system

Continued ›

Figure 6

Emissions by sector (plus biogenic credits) for Scenario 1, 2010-2050, million tonnes (Mt) CO_2 per year. Equivalent charts for Scenarios 2-5 are available to download alongside this report.

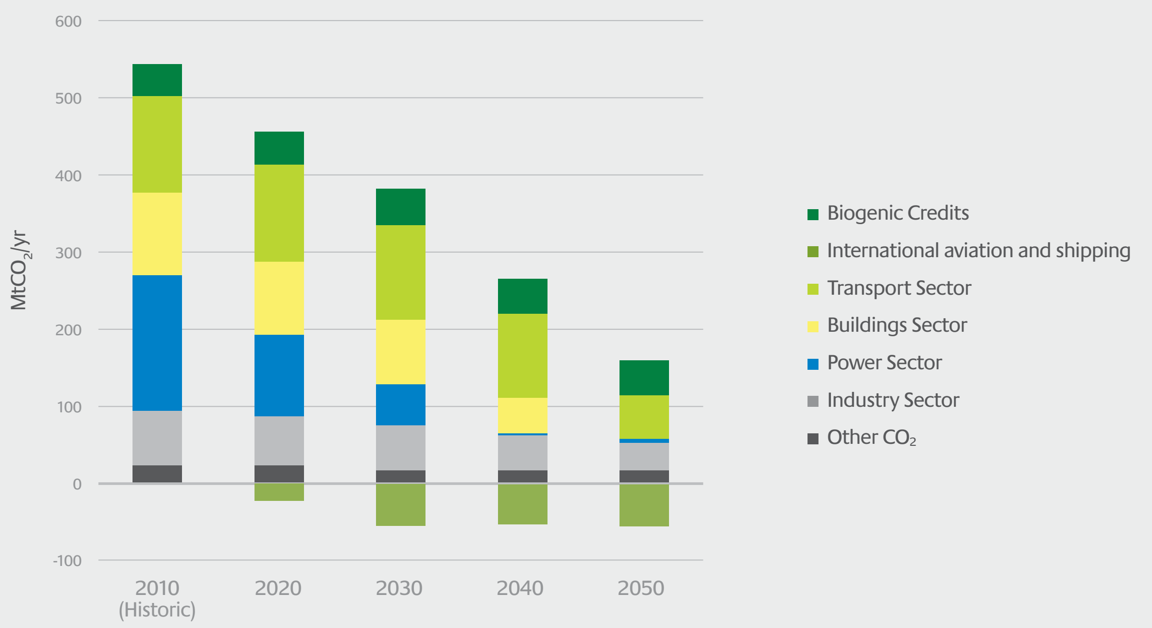


Figure 7

Transport fleet 2010-2050 (million vehicles); Scenario 1 (Base case, below), Scenario 2 (Low Feedstock Availability, bottom)

Lower bioenergy production as a result of reduced biomass resource availability means greater (and costlier) emissions savings will be required elsewhere in the energy system, particularly the transport sector

The ETI's assumptions on imported biomass and biofuel availability are towards the conservative end of recent estimates. However, the assumptions in ESME for UK-grown biomass are more ambitious and based on ETI-commissioned research on the potential for UK-grown energy crops in the UK. There is uncertainty associated with both figures, therefore it is useful to test how the energy system would respond to different levels of sustainable biomass availability.

Sensitivity analysis suggests that the way bioenergy is used in the energy system is unlikely to vary significantly with resource availability. By the 2050s, using the majority of available biomass in CCS applications to produce hydrogen or power is the most cost-effective route. However, a reduction in resource availability reduces the level of negative emissions that can be delivered. This has repercussions for the rest of the energy system as additional savings need to be made to meet the 2050 target.

The more significant changes are seen in the rest of the energy system, primarily as a result of the need to make greater savings in the transport sector. In order to meet the 2050 emissions target with fewer biomass resources, there must be a near-total transition away from fossil-fuel to fully electric or hydrogen-powered vehicles. This requires an increase in both electricity and hydrogen production capacity compared to Scenario 1 (Figure 7 and 8). In both Scenarios 1 and 2, Figure 7 shows a rapid transition from the 2040s to 50s – in reality, transitioning to the sector shown for the 2050s in either scenario will require planning and implementation over several decades. The UK is already seeing an increase in the take-up rate for hybrid and electric vehicles (collectively known as ultra-low emissions vehicles) – in 2017, they made up 1.7% of new vehicle registrations[23].

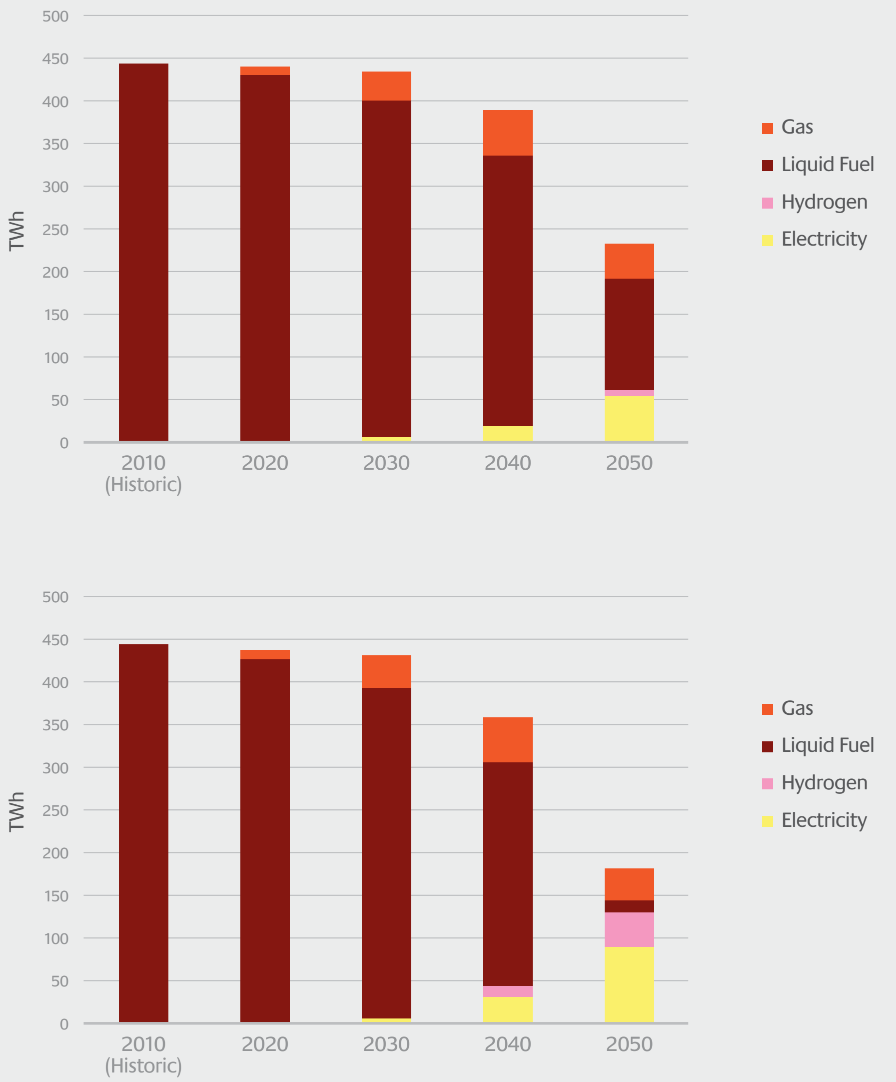
23 DfT and DVLA (2018). Vehicle Licensing Statistics: 2017 report [online]. Available at: https://www.gov.uk/government/statistics/vehicle-licensing-statistics-2017

4. The future role of bioenergy in the UK energy system

Continued ›

Figure 8

Road transport fuel consumption 2010-2050 (TWh based on the GCV of fuels); Scenario 1 (Base case, below), Scenario 2 (Low Feedstock Availability, bottom)



Without CCS, bioenergy is likely to provide the most value in low carbon fuels and heating applications

Failing to deploy CCS has wide-ranging impacts across the energy system. Without CCS, there must be a much steeper decline in the use of fossil fuels (in 2050 the quantity of fossil fuel used in Scenario 3 is less than half that used in Scenario 1), while the use of nuclear and renewable energy increases. In the 2050s, electricity consumption is 27% higher than in the base case, partly driven by an increase in electric vehicles. However, delivering this level of increase requires 78% more generation capacity compared to Scenario 1 due to the greater reliance on intermittent renewables.

In the absence of CCS, bioenergy without CCS is still important as a low carbon vector but can contribute to decarbonisation via several different pathways. In the 2040s there is significant production of bioSNG (via biomass gasification) whilst in the 2050s production switches to liquid fuels[24]. In reality, such a change in production is unlikely to take place over the course of a decade. The production of bioSNG could be used in both heating and transport applications or gasification could be deployed with Fischer-Tropsch or other technologies to develop liquid fuels for hard to decarbonise sectors such as aviation and shipping.

Gasification, to produce clean syngas, is a scenario resilient technology

Scenarios 1-3 highlight the ability of biomass and waste gasification technologies to produce electricity, hydrogen and bioSNG from clean syngas. Gasification is also one route to making liquid fuels from biomass or waste. This flexibility of gasification, both in terms of the feedstocks it can use, and the products it can make, means it is resilient to quite different future energy scenarios. Wider analysis using ESME and the ETI's Bioenergy Value Chain Model (BVCM) has reinforced this conclusion[25].

Gasification is the partial combustion of a material to produce syngas – a mixture of carbon monoxide, hydrogen, carbon dioxide and methane. If the syngas is not cleaned it will contain tars, particulates and other contaminants. This means it can only be combusted in a boiler to raise steam for power and/or heat generation. However, if sufficient tars, particulates and other contaminants are removed, clean syngas can be used to produce bioSNG, hydrogen or liquid biofuels, or can be combusted in an engine or turbine as a more efficient means of generating electricity than burning the syngas in a boiler. Clean syngas can also be upgraded to produce chemicals and other products for non-energy purposes.

While gasification has been deployed commercially, to date, plants have not included an effective syngas cleaning step, meaning that the full flexibility of gasification has yet to be realised. In the UK, two plants are currently under construction to demonstrate syngas cleaning technology at a commercial scale – the GoGreenGas demonstration plant will produce bioSNG, while the ETI and Kew Technology funded Sustainable Energy Centre (SEC) will generate electricity via syngas combustion in an engine[26].

While these two projects intend to demonstrate the commercial viability of gasification with syngas cleaning, there remains a risk as with all new technologies that they are not successful at commercial scale (either for technical or economic reasons) or that they cannot be deployed at a rate quick enough to make an effective contribution to the low carbon energy transition. Therefore, it is important to explore how the energy system might change if biomass and waste gasification technologies with syngas clean-up were not available.

24 In ESME V4.3 Biomass is converted to 'Liquid fuel' which is mixed with fossil derived fuel and can be used in any transport end use. In reality, biofuels are most valuable in the hard to decarbonise sectors such as aviation and shipping.
25 ETI (2015). Insights into the future UK Bioenergy Sector, gained using the ETI's Bioenergy Value Chain Model (BVCM) [online]. Available at: http://www.eti.co.uk/insights/bioenergy-insights-into-the-future-uk-bioenergy-sector-gained-using-the-etis-bioenergy-value-chain-model-bvcm
26 For more information on the demonstration projects visit: GoGreenGas (http://gogreengas.com/) and the ETI's waste gasification project page (http://www.eti.co.uk/programmes/bioenergy/waste-gasification-commercial-development-plant)

4. The future role of bioenergy in the UK energy system
Continued ›

Without biomass gasification (Scenarios 4 and 5), biomass is still heavily utilised. In both scenarios, some biomass is used in Industry, but the dominant conversion pathways are quite different:

- In Scenario 4 (where CCS is available), the value of delivering negative emissions results in the majority of biomass being used in biomass combustion + CCS technologies to produce power. Producing power from biomass combustion is already delivered at scale in the UK; coupling biomass combustion with CCS has not been demonstrated at a commercial scale, but Drax has recently announced a joint project with C-Capture to demonstrate commercial-scale post-combustion carbon capture using a solvent developed by C-Capture specifically designed to remove carbon dioxide from the biomass flue gases[27].
- In Scenario 5 (where CCS is not available), the production of liquid transport fuels is the dominant pathway. Biomass and waste can be converted to different liquid fuels through different processes, some of which (such as producing bioethanol from wheat or sugar beet) have been commercially deployed. However, concerns over extensive use of food crops for bioenergy, and the potential to deliver greater emissions savings, is driving research into new conversion routes using second generation energy crops, wood and wastes. While ETI's analysis suggests that converting biomass to liquid fuel should not be the dominant pathway for the bioenergy sector if CCS is available, the development of these alternative conversion pathways may be useful in other countries, such as New Zealand, where a review of bioenergy uses concluded that liquid biofuels are an important part of cost-effective emissions reductions[28].

Figure 4 suggests that the cost of meeting the UK's GHG emissions is not significantly more expensive without biomass gasification, as in both Scenarios 4 and 5 there are alternative conversion routes which the ESME technology data suggest could be deployed with a relatively small increase in cost compared to the scale of investment needed in the energy sector overall. However, it is important to note that many of these alternative conversion routes have themselves yet to be commercially demonstrated, therefore there is uncertainty surrounding the cost and rate at which these technologies could be deployed. Advantages of biomass gasification over alternative conversion routes are that it is both scenario and feedstock resilient (i.e. gasification can use different types of waste and biomass). In Scenarios 1 and 3 (base case and No CCS), biomass is used to produce different end products (hydrogen vs bioSNG/liquid fuels), but all can be produced from biomass gasification delivering a clean syngas. Removing this common intermediary (syngas) from Scenarios 4 and 5 means that the use of biomass in industry is the only overlap between the two pathways. In Scenario 4 most biomass is used in combustion with CCS to produce power, while in Scenario 5 most biomass is used to produce liquid fuels via non-gasification routes. Whilst there is uncertainty about the direction in which the energy system will develop, and limited time in which to demonstrate and deploy new technologies, focusing research and development efforts on 'low-regrets' technologies which can adapt to changes in the wider energy system. This is valuable in that it reduces the risk of investment in possibly sub-optimal technologies and increases the chance of bioenergy cost-effectively contributing to decarbonising the UK energy system. Investing in gasification today, buys flexibility for the future.

Summary

Using a whole energy system model such as ESME allows different energy futures to be explored and to identify where there are commonalities and where pathways diverge. While Scenarios 1-5 are a small snapshot of possible energy futures, they provide useful insights into the consequential impacts of certain choices.

All five scenarios make use of biomass resources, highlighting the value of biomass as part of a cost-effective, low-carbon energy system which is resilient to different futures. However, the way in which bioenergy is used varies depending on the extent to which CCS is deployed. Using biomass in industry and gasification with syngas clean-up are the main commonalities between these scenarios. Without gasification, there is greater divergence between a pathway for the bioenergy sector with CCS and one without. Investing in the development of gasification technology today retains options for the future.

The availability of sustainable biomass feedstock has consequences across the energy system. There is naturally uncertainty surrounding long-term predictions of sustainable imported biomass into the UK but the UK has the potential to develop a substantial biomass feedstock sector which could also deliver wider environmental benefits.

This section has provided an overview of the role of bioenergy out to 2050. The following sections examine the steps needed to achieve this and the challenges associated with their delivery.

27 Drax (2018). Drax to pilot Europe's first Carbon Capture Storage project [online]. Available at: https://www.drax.com/press_release/drax-to-pilot-europes-first-carbon-capture-storage-project-beccs/

28 Scion (2009). Bioenergy Options [online]. Available at: http://www.scionresearch.com/science/bioenergy/bioenergy-options and; Scion (2018). The New Zealand Biofuels Roadmap [online]. Available at: https://www.scionresearch.com/science/bioenergy/nz-biofuels-roadmap

5. Delivering bioenergy – opportunities and challenges

Section 4 has shown that there is a clear opportunity for biomass and waste resources to make a critical contribution to delivering lowest-cost energy system decarbonisation in the UK. However, delivering this in practice requires a strategy for biomass and waste resource use in the context of wider decarbonisation activities. Based on the ETI's whole energy system analysis a successful strategy would need to include steps to:

- Develop opportunities to deliver negative emissions by including BECCS as an integral part of UK CCS deployment
- Build flexibility into the bioenergy sector through deployment of clean syngas technologies (gasification)
- Develop capability in the supply chain to increase supplies of sustainable bioenergy feedstocks which are suitable for use in bioenergy conversion technologies
- Improve the consistency of biomass feedstocks and/or the ability of conversion technologies to manage variability in feedstock characteristics

This section looks at each of these areas in turn, summarising the status of the sector and identifying actions needed across academia, industry and government to deliver a bioenergy sector capable of making a significant contribution to UK decarbonisation.

UK CCS Strategy must include BECCS

Opportunity: Creating the right environment for BECCS in the UK, which through deployment can significantly reduce the cost of meeting the UK's 2050 emissions targets and increases the likelihood that the UK can deliver net-zero emissions (Table 5).

CCS is a proven process – there are 17 large-scale operational CCS plants globally, including one BECCS plant capturing the emissions from a corn-to-bioethanol process[29]. Despite the UK being well placed to exploit the benefits of CCS, including BECCS, CCS has not been deployed at a commercial scale in the UK.

The UK Government's Clean Growth Strategy published in October 2017, acknowledged the importance of CCS and BECCS in delivering deep decarbonisation. The government has invested over £130 million into research and development of more novel carbon capture technologies. However, it considers the current cost of CCS technology, and the cost and risk of sharing structures between the public and private sectors suggested by previous potential projects too high a price for consumers and taxpayers to pay. Therefore, it has yet to invest in a commercial-scale project[30]. This is despite the fact that the UK is exceptionally well-placed to exploit the benefits of BECCS, given the vast storage opportunities offshore around the UK; the UK's experience in bioenergy deployments; and our academic and industrial research and development strength across bioenergy and CCS. The ETI's Insight paper, The Evidence for Deploying BECCS in the UK[31], highlights the major advances that have been made in the fundamental science and technologies associated with BECCS, significantly de-risking this value chain in recent years.

Offshore storage appraisal work, in part funded by the ETI, has found that there is more than enough potential storage capacity to meet the UK's needs for carbon dioxide storage to 2050 and well beyond, even in high CCS deployment scenarios. Based on the appraisal work to date, there are no foreseen technical or economic barriers to the storage of carbon dioxide in offshore stores that could limit the CCS industry developing at scale in the UK[32].

In terms of reducing the costs of capture technology, the ETI's analysis strongly suggests that risk reduction through (at least three) sequential deployments of existing well-developed technologies (post-combustion amines and pre-combustion capture from gasification) in the UK can drive down output energy costs by as much as 45%, largely through a combination of increased scale, infrastructure sharing and reductions in financing costs[33]. This could then pave the way for the introduction of higher-risk emerging technologies once the overall CCS risk is reduced[34].

The cancellation of the government's CCS Commercialisation programme in 2015, following its decision to withdraw £1bn of capital funding for a commercial-scale project, was a setback to the development of a UK CCS industry. However, there are signs that industry is willing to start investing again in the development of new UK CCS projects:

- Drax Power and C-Capture have recently announced a project to test whether a solvent developed by C-Capture can remove carbon dioxide from the biomass flue gas at Drax Power Station. If successful it will be the first commercial-scale demonstration of carbon dioxide being captured, post-combustion, from a UK biomass power station[35].
- The Liverpool-Manchester Hydrogen Cluster project, led by Cadent and Progressive Energy, proposes converting natural gas into hydrogen using SMR, capturing the carbon dioxide and storing it in depleted gas reservoirs in the Irish Sea. The hydrogen would be used in industry and fed into the gas grid to partially decarbonise domestic use of gas[36]. The project is at an early stage of development but if successful, could be the start of a north-west (BE) CCS cluster as conceptualised in the ETI's 'start small and build' approach[37] and highlighted in the Carbon Capture, Usage and Storage (CCUS) Cost Challenge Taskforce report[38].
- OGCI has committed to developing a basic engineering design for a full-scale gas power plant with CCS in the UK, with a view to attracting the necessary government and private sector investment for further development[39].
- Related to CCS deployment, two projects are focusing on the practicalities of using hydrogen in the gas network – the HyDeploy project aims to determine the level of hydrogen which could be safely mixed into the gas grid[40], while the H21 City Gate project undertook a techno-economic assessment of converting the gas grid in Leeds to 100% hydrogen[41].

29 Large-scale integrated CCS facilities are defined as facilities involving the capture, transport, and storage of CO_2 at a scale of at least 800,000 tCO_2/yr for a coal–based power plant, or at least 400,000 tCO_2/yr for other facilities. For more information see: Global CCS Institute (2018). Large Scale CCS facilities [online]. Available at: https://www.globalccsinstitute.com/projects/large-scale-ccs-projects
30 BEIS (2017). Clean Growth Strategy [online]. Available at: https://www.gov.uk/government/publications/clean-growth-strategy
31 ETI (2018). The Evidence for deploying BECCS in the UK [online]. Available at: http://www.eti.co.uk/insights/the-evidence-for-deploying-bioenergy-with-ccs-beccs-in-the-uk
32 ETI (2017). Taking stock of UK CO_2 storage [online]. Available at: http://www.eti.co.uk/insights/taking-stock-of-uk-co2-storage
33 ETI (2016). Reducing the cost of CCS. Developments in Capture Plant Technology [online]. Available at: http://www.eti.co.uk/library/reducing-the-cost-of-ccs-developments-in-capture-plant-technology-2
34 ibid

35 Drax (2018). Drax to pilot Europe's first Carbon Capture Storage project [online]. Available at: https://www.drax.com/press_release/drax-to-pilot-europes-first-carbon-capture-storage-project-beccs/
36 Cadent (2018). Liverpool-Manchester hydrogen clusters project [online]. Available at: https://cadentgas.com/about-us/innovation/projects/liverpool-manchester-hydrogen-cluster
37 ETI (2017). Taking stock of UK CO_2 storage [online]. Available at: http://www.eti.co.uk/insights/taking-stock-of-uk-co2-storage
38 CCUS Cost Challenge Taskforce (2018). Delivering Clean Growth: CCUS Cost Challenge Taskforce [online]. Available at: https://www.gov.uk/government/publications/delivering-clean-growth-ccus-cost-challenge-taskforce-report
39 OGCI (2017). Catalyst for Change. Collaborating to realize the energy transition [online]. Available at: http://oilandgasclimateinitiative.com/wp-content/uploads/2017/10/OGCI-2017-Report.pdf
40 HyDeploy Project: https://hydeploy.co.uk/
41 H21 Leeds City Gate: https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

5. Delivering bioenergy – opportunities and challenges
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Table 5
Actions to deliver a UK BECCS sector

Recommendation 1: Create the right environment for BECCS in the UK, which through deployment can significantly reduce the cost of meeting the UK's 2050 emissions targets and increase the likelihood that the UK can deliver net-zero emissions.

	Recommended actions	Path forward
1.1	The UK Government commits to supporting the commercial-scale development of a UK CCS sector as soon as possible. This could take the form of a sector deal, similar to that agreed with other industries, bringing together expertise from a number of sectors.	A sector deal would require commitment from the Energy and Construction Industries, Investors, Academia and Local and National government.
1.2	Public and private sector investors collaborate to develop appropriate business models and risk-sharing mechanisms for Carbon Capture, Transport and Storage (separately or as a group). These should take into account the longer-term potential for individual CCS projects (both biomass- and fossil-fuelled) to develop into regional clusters using a 'start small and build' approach.	Negotiations will primarily be between UK Government (Treasury and Department(s) with responsibility for energy and climate change policy), and developers and investors associated with new UK (BE)CCS projects.
1.3	Ensure that incentives to capture and store carbon, distinguish between emissions from fossil fuels and those from systems delivering negative emissions (e.g. BECCS). This will need to align with other GHG reduction incentives to ensure there is no double counting of emissions.	An incentive will need to be implemented by government, but developed with views from industry, investors and specialists in carbon accounting and bioenergy life cycle assessments (LCAs).
1.4	Deliver initial cost-reductions through deploying, at a commercial scale, the most advanced carbon capture technologies (amines and pre-combustion). Sequential deployment of the same technology can drive cost reductions through risk-reduction and learning by doing.	The Liverpool-Manchester Hydrogen Cluster and the OGCI's CCS project are two examples of commercial scale projects under development. Delivering these (or similar) projects will require the previous three actions to be resolved and project-specific support from Industry, Investors, Government and Academia.
1.5	Demonstrate the technical and commercial viability of pre- and post-combustion carbon capture technologies using biomass and waste feedstocks. This would remove one of the few remaining technical uncertainties surrounding the application of CCS to bioenergy production.	Demonstration projects should be supported by dedicated Research and Development (R&D) funding from the public sector (such as the Department for Transport's (DfT's) Future Fuels for Freight and Flight competition (F4C)) and Industry (such as Drax's collaboration with C-Capture).

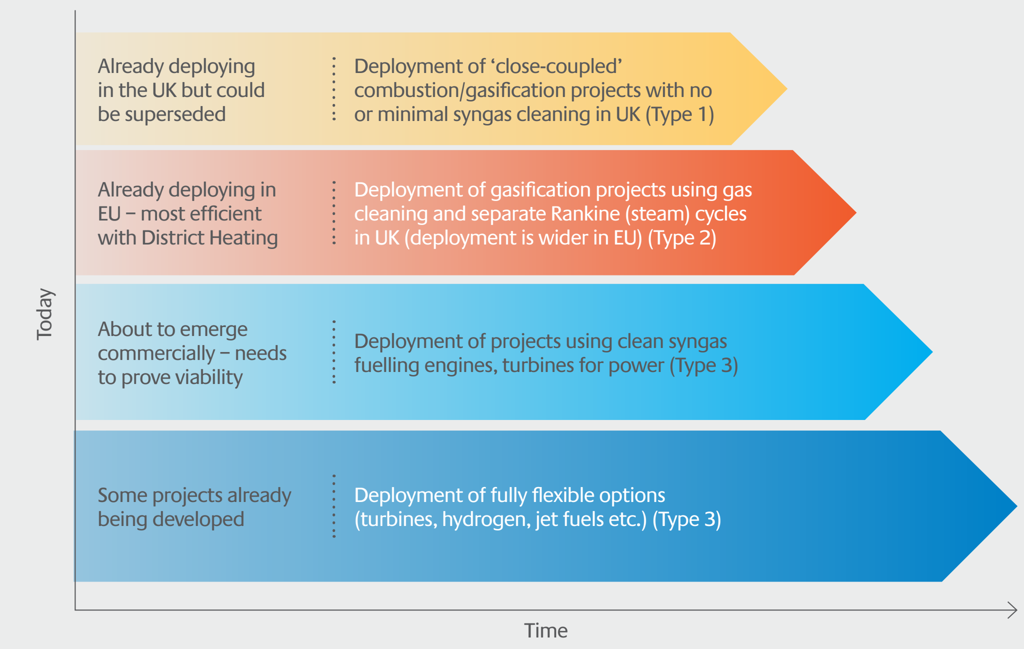
Invest in the development and commercial deployment of gasification-to-clean syngas

Opportunity: Developing gasification technology to produce clean syngas from biomass and wastes enabling bioenergy sector development to remain robust to changes elsewhere in the energy system (Table 6).

Gasification produces syngas which, if not cleaned, has limited uses – it can only be combusted in boilers to produce heat and/or power because it contains tars, particulates and other contaminants. Removing these contaminants to produce a 'clean' syngas creates a much more flexible product which can be upgraded to biomethane, hydrogen, liquid transport fuels and chemicals for non-energy use. It can also be used to generate power and/or heat through more efficient conversion routes.

The ETI's Insight paper, *Targeting new and cleaner uses for wastes and biomass using gasification*[42], provides an overview of current gasification technology and a direction of travel to develop and scale up gasification with syngas cleaning to enable a wider range of outputs to be produced. Figure 9 shows the different types of gasification and their current stage of development. Type 3 and 4 applications, in which the raw syngas is cleaned to a level at least the same as natural gas before utilisation, are the only ones which deliver the full flexibility benefits of producing a clean syngas.

Figure 9
Gasification status and programme approach to gasification progress[43]



42 ETI (2017). Targeting new and cleaner uses for wastes and biomass using gasification [online]. Available at: http://www.eti.co.uk/insights/targeting-new-and-cleaner-uses-for-wastes-and-biomass-using-gasification
43 ibid

5. Delivering bioenergy – opportunities and challenges

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Two commercial-scale Type 3 demonstration plants are currently under construction in the UK:

- The ETI commissioned Sustainable Energy Centre (SEC) in Wednesbury is a 1.5 MWe demonstration plant which will use clean syngas to generate electricity in an engine and demonstrate the production of advanced fuels from syngas
- The GoGreenGas project in Swindon will produce bioSNG via gasification for use as a transport fuel in heavy duty vehicles[44]

While these two sites are promising developments, the UK's recent experience with gasification has been one of mixed successes. The gasification industry needs to gain stronger experience in designing and using gasification equipment and systems while investors and policy makers need to gain confidence in gasification, in particular gasification with integral syngas cleaning. Small-scale commercial demonstrators can help with this. During their construction, commissioning and early operation they can highlight and address technical issues which may not have been identified through modelling and/or lab-scale work, thus preventing them becoming 'show-stopping' issues at a larger scale. Their successful long-term operation demonstrates the technical viability of gasification with syngas cleaning.

To help build confidence in financing and delivering successful gasification projects, UK gasification developments should be designed as an integrated programme of stages targeting the deployment of gasification projects which incorporate integrated gas cleaning steps which can provide the high efficiencies and flexibilities offered by gasification. Lessons should be learned from earlier projects and shared with the sector. A programme approach should drive a strong pace of innovation balanced with building confidence, and ensure that any publicly-funded support (which will still be needed in the early stages of commercialisation) is directed at the most strategically valuable types of gasification system.

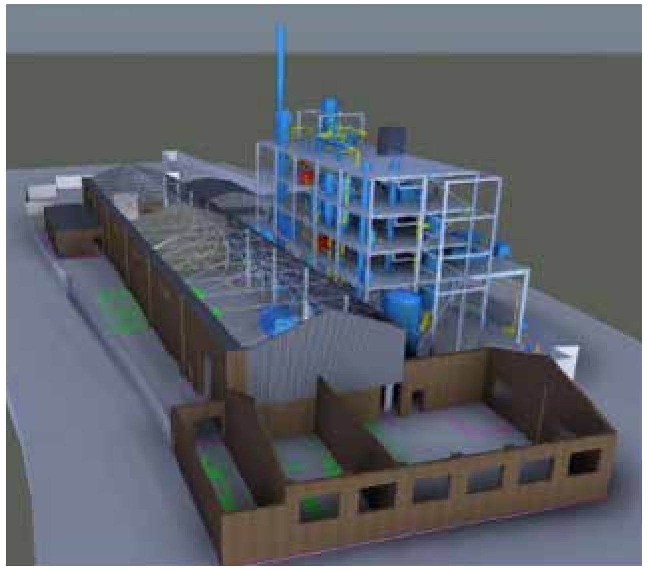

Table 6

Actions to commercialise biomass/waste gasification to produce clean syngas

Recommendation 2: Develop gasification for the production of clean syngas from biomass and wastes to enable the bioenergy sector to remain robust to changes elsewhere in the energy system.

	Recommended actions	Path forward
2.1	To fully realise the flexibility of gasification, R&D funding and support should continue to be provided to develop and commercialise new syngas upgrading technologies to produce, for example, hydrogen and liquid fuels.	A number of commercial demonstration projects are underway, including under the DfT's Advanced Biofuels Demonstration Competition (ABDC) and F4C which provide grant funding for the demonstration of new methods of producing low carbon transport fuels. R&D funding bodies should plan for future development support to capitalise on the learnings from current gasification projects and avoid development stalling.
2.2	Learn and share lessons from early commercial-scale projects to maximise the learning from R&D investments. Apply these in subsequent projects to drive efficiency improvements and cost reductions.	Knowledge exchange between Industry, Academia, and the public sector could be coordinated through networks such as the Knowledge Transfer Network (KTN) or SUPERGEN Research Hubs.
2.3	Ensure that the definition of Advanced Conversion Technology (ACT) used in government incentive schemes encourages the types of technology best able to deliver cost-effective emissions savings and flexibility to the bioenergy sector.	The definition was produced by BEIS, who consulted on the definition in 2018. Further consultation following this initial feedback is necessary to ensure the definition aligns with what is needed for incentives to be allocated effectively.
2.4	Gasification is supported under Contracts for Difference (CfD, electricity), Renewable Transport Fuels Obligation (RTFO, transport fuels) and Renewable Heat Incentive (RHI, heating, including bioSNG injection). This is not problematic while the sector is in its infancy but, as the use of gasification expands, it is important to ensure that incentives are directed towards end uses where it will deliver the greatest emissions savings.	Government (BEIS and DfT) and Industry, make use of findings from whole energy systems analysis to maintain up-to-date understanding of best uses of biomass.

44 For more information on the demonstration projects visit: GoGreenGas (http://gogreengas.com/) and the ETI's waste gasification project page (http://www.eti.co.uk/programmes/bioenergy/waste-gasification-commercial-development-plant)

5. Delivering bioenergy – opportunities and challenges
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Increase sustainable feedstock supply

As highlighted in the previous section, constraining biomass resource availability increases the total cost of decarbonisation as more expensive measures must be taken in other parts of the energy system to continue to meet UK emissions targets. Wider ESME analysis has also shown that biomass and waste continue to be heavily used as availability increases[45]. However, this assumes that the additional biomass can be sourced sustainably and deliver the same carbon benefits as the baseline availability assumptions. This section examines the opportunities and challenges associated with increasing availability of sustainable biomass feedstocks and appropriate waste resources for bioenergy.

Opportunity: Increasing biomass production and the supply of sustainable biomass for bioenergy in the UK, and maximising the use of appropriate residual waste resources for energy, to enable the delivery of greater emissions savings at a system level, through:

- Making greater use of residual waste resources in efficient EfW applications (see Table 7).
- Increasing the quantity of UK-grown second generation bioenergy crops, to deliver benefits to both the energy system and to the UK supply chain (see Table 8).
- Increasing resilience to changes in global biomass availability by exploring new supply chains for demonstrably sustainable imported biomass (Table 9).

Making greater use of residual waste resources in efficient energy from waste (EfW) applications

Energy recovery sits towards the bottom of the waste hierarchy, beneath waste reduction, reuse and recycling, and above disposal. The extent to which energy from waste reduces net GHG emissions depends, in large part, on the biogenic content of the waste. Generating energy from biogenic waste avoids the release of methane if that waste were left to decompose in landfill. On the other hand, energy from non-biogenic waste (e.g. plastic) releases CO_2 that would otherwise have been sequestered in landfill.

To invest in a new EfW plant, developers need to have sufficient confidence that there will be enough waste of the appropriate composition available over the lifetime of the plant, and that the balance of revenues from gate fees and the sale of energy will make the plant economically viable.

This requires a good understanding of current local resource availability, composition and gate fees[46] and how this may change over the lifetime of the EfW facility as a result of policy initiatives to reduce residual waste arisings, and changes in lifestyle and business practices which alter the types of waste produced.

In terms of long-term strategy, the government has set out its ambition to have zero avoidable waste by 2050 and will be publishing a new waste and resources strategy in late 2018[47]. This implies that there will be downward pressure on the quantity of waste available for energy recovery. This is likely to be countered to some extent by population increases, with recent assessments of long-term waste availability ranging from approximately 10% lower to 10% higher than current levels in 2050[48]. Within this long-term range, there is an assumption that residual waste from households and commercial and industrial (C&I) sites will fall, but there will be increases in the availability of (separated) food waste, sewage sludge and waste wood. For those plants using residual household or C&I waste, their business plan needs to account for the risk of gate fees falling as waste resources become scarcer, and potential changes in composition if a greater proportion of food waste is collected separately and recycling rates increase. Plants which aim to maximise efficiency rather than waste throughput will be more resilient to changing gate fees.

While long-term projections for household and C&I waste arisings anticipate a decline, in the near-term there are still significant opportunities for new energy recovery facilities to make use of these resources, particularly residual C&I waste (most household waste is already managed through long-term contracts between local authorities and waste management companies). Analysis by the Green Investment Bank[49] has suggested that a shortfall in energy recovery facilities in 2020 could see 8 Mt of waste being disposed of in landfill that could otherwise be used in EfW plants. This presents an opportunity for novel energy recovery technologies which can deliver greater efficiency and/or flexibility, such as gasification, to enter the market. However, there is little publicly available data on C&I waste arisings, and a lack of high-quality, up-to-date, detailed data on waste arisings has been identified as a barrier for new investment decisions[50].

Table 7
Actions to make greater use of residual waste resources in efficient EfW applications

Recommendation 3: Increase biomass production and the supply of sustainable biomass for bioenergy in the UK, and maximise the use of appropriate residual waste resources for energy, to enable the delivery of greater emissions savings at a system level, through:

Making greater use of residual waste resources in efficient energy from waste (EfW) applications.

	Recommended actions	Path forward
3.1	Increase the frequency and coverage of waste arisings data, with a particular focus on providing up-to-date data on the quantity, composition and location of commercial and industrial (C&I) wastes. This will lower one of the barriers to entry for new entrants who aren't able to access longer-term contracts and therefore need to assess the risk of feedstock shortages. The methodology for collecting this data needs to balance the potential gain from better utilisation of waste resources, with any additional burden placed on waste collectors to generate these data.	Develop robust waste data collection methods for C&I waste and update these data at least annually. These data should be publicly accessible (via Defra). The development of these statistics will require collaboration between Government (Defra), the waste management industry and academics working in waste management.
3.2	Encourage the development of EfW plants which are more economically and technically resilient to reductions in waste availability and changing composition by focusing on improving efficiency and processes which can manage feedstock variability.	Planning and permitting authorities and government departments in charge of EfW incentives ensure that their incentives, policies and procedures (including the procurement of waste management services) enable and incentivise the waste management industry to deliver best practice.

Increasing the quantity of UK-grown second generation bioenergy crops, to deliver benefits to both the energy system and to the UK supply chain

The ETI's report, *Increasing UK biomass production through more productive use of land*[51], summarised the ETI's research on the GHG impacts of UK land use change to energy crops, and on the potential area of suitable land that could be made available for these crops. It concluded that between 1.0 and 1.8 Mha of land (6% to 10% of UK agricultural land) could be made available by the 2050s without impacting on current levels of food production, *if* improvements were made to agricultural land productivity. These productivity improvements included more effective management of livestock on grassland, and a reduction in food waste.

If 1.4 Mha were used to grow energy crops this area could provide feedstock with an energy content of between 70 and 105 TWh each year, the higher end of which would match the scale of UK biomass required needed to support base case energy transition scenarios when added to existing levels of biomass from other UK sources.

45 For example, see the 'Clockwork' scenario in: ETI (2015). Options, Choices, Actions. UK scenarios for a low carbon energy system transition [online]. Available at: http://www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system
46 The gate fee is the amount paid to a waste management company or energy from waste plant by the person disposing of the waste.
47 BEIS (2017). Clean Growth Strategy [online]. Available at: https://www.gov.uk/government/publications/clean-growth-strategy
48 Anthesis and E4tech (2017). Review of Bioenergy Potential: Technical Report [online]. Available at: https://cadentgas.com/about-us/the-future-role-of-gas/renewable-gas-potential
49 Green Investment Bank (2014). The UK residual waste market [online]. Available at: http://greeninvestmentgroup.com/media/25376/gib-residual-waste-report-july-2014-final.pdf
50 Ricardo Energy & Environment (2016). Waste Data in the UK [online]. Available at: https://ee.ricardo.com/downloads/waste/waste-data-in-the-uk

51 ETI (2017). Increasing UK biomass production through more productive use of land [online]. Available at: http://www.eti.co.uk/library/an-eti-perspective-increasing-uk-biomass-production-through-more-productive-use-of-land

5. Delivering bioenergy – opportunities and challenges

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The maximum GHG saving benefits from energy crops are delivered when land is planted with second generation energy crops such as Miscanthus, SRC willow and SRF, rather than conventional energy crops (food crops) as these can deliver higher yields with lower fertiliser inputs and less land disturbance. Soils are an important store of carbon, and increasing soil carbon would remove carbon dioxide from the atmosphere. The ETI-funded ELUM[52] (Ecosystem Land Use Modelling) project found that second-generation crops can, over time, increase the level of carbon sequestered in soils when planted on soils with lower levels of soil carbon (typically arable). Planting these crops on higher carbon soils (typically land such as permanent grassland) can lead to a reduction in soil carbon, but careful location, crop and end use selection can still deliver low carbon energy. Using these crops in CCS technologies will deliver net negative emissions and would increase the amount of feedstock/land able to deliver significant emissions reductions[53]. Further research into planting and management techniques could reduce the risk of soil carbon loss. Energy crop planting should avoid very high carbon soils such as peatland as the net GHG balance will be poor. Therefore peatland, along with other unsuitable land types, are excluded from the ETI's spatial modelling of UK biomass crop growth[54].

As well as excluding unsuitable land types, the ETI's spatial modelling of UK biomass crop growth, indicates that biomass yields could be maximised and GHG emissions minimised if SRC willow were grown in the North and West of the UK (including Northern Ireland), with Miscanthus more suited to the South and East[55].

As well as soil carbon sequestration, planting second generation energy crops can also deliver wider environmental benefits. There is evidence that energy crops can increase biodiversity if planted as part of a mixed landscape[56] and research is ongoing into the potential for energy crops to deliver other environmental benefits, including:

- SUPERGEN Bioenergy Hub are researching the extent to which energy crops can remediate contaminated land (or minimise the spread of contamination), and whether the crops are then still suitable for use as a fuel[57].
- AFBI (Agri-Food and Biosciences Institute) in Northern Ireland are conducting field trials assessing the potential for SRC willow to reduce nutrient levels in run-off from agricultural land, thereby reducing water pollution[58].
- In the north west of England, Iggesund are working with their growers and Rothamsted Research to understand the wider benefits SRC willow can bring to the environment, including increased biodiversity and flood impact mitigation by slowing the flow of water and trapping larger objects on flood plains[59].

Even though there is now a better understanding of the scope to expand second generation energy crop planting and the potential environmental benefits this could bring, the total area of Miscanthus and SRC willow in England is just 10 kha (0.1% of agricultural land in the UK) – a figure which has remained broadly stable over the past decade[60]. Increasing this area requires new technical and market solutions that can overcome current barriers.

Farmers need compelling business cases to plant second generation energy crops. ETI's case studies of farms growing energy crops show that planting Miscanthus and SRC willow on otherwise marginal land can be profitable. However, given the small scale of the current market all three case studies said access to long-term (5-23yr), index-linked contracts with buyers was an important factor in their decision making[61].

The buyers in question (Iggesund and Terravesta) have been able to establish their supply chains by avoiding the 'chicken and egg' problem that can hamper efforts to build dedicated energy crop conversion plants. Farmers need a reliable market to sell into before taking the decision to plant, whilst potential end users don't want to risk investment in feedstock supply chains 2-3 years in advance of operations, when there is still uncertainty over whether the end conversion technology will be built.

52 CEH (2018). Ecosystem Land Use Model [online]. Available at: https://www.ceh.ac.uk/services/elum-model
53 For further details of this analysis, see: ETI (2015), Delivering greenhouse gas emission savings through UK bioenergy value chains [online]. Available at: https://www.eti.co.uk/insights/delivering-greenhouse-gas-emission-savings-through-uk-bioenergy-value-chains
54 ETI (2016). Delivering greenhouse gas emission savings through UK bioenergy value chains [online]. Available at: http://www.eti.co.uk/library/an-eti-perspective-increasing-uk-biomass-production-through-more-productive-use-of-land
55 ETI (2015). Insights into the future UK bioenergy sector, gained using the ETI's Bioenergy Value Chain Model (BVCM) [online]. Available at: http://www.eti.co.uk/insights/bioenergy-insights-into-the-future-uk-bioenergy-sector-gained-using-the-etis-bioenergy-value-chain-model-bvcm
56 Including: Immerzeel, D. J., Verweij, P. A., van der Hilst, F. and Faaij, A. P. C. (2014), Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy, 6: 183–209. doi:10.1111/ gcbb.12067; and McCalmont, J. P., Hastings, A., McNamara, N. P., Richter, G. M., Robson, P., Donnison, I. S. and Clifton-Brown, J. (2017), Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. GCB Bioenergy, 9: 489–507. doi:10.1111/gcbb.12294
57 SUPERGEN Bioenergy Hub: http://www.supergen-bioenergy.net/
58 AFBI: https://www.afbini.gov.uk/
59 Iggesund (2016). Rothamsted Research shows growing SRC willow boosts biodiversity [online]. Available at: http://biofuel.iggesund.co.uk/rothamsted-research-shows-growing-src-willow-boosts-biodiversity/
60 Defra (2017). Area of crops grown for bioenergy in England and the UK: 2008-2016 [online]. Available at: https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2016.
61 ETI (2016). Bioenergy crops in the UK: Case studies on successful whole farm integration evidence pack [online]. Available at: http://www.eti.co.uk/library/bioenergy-crops-in-the-uk-case-studies-on-successful-whole-farm-integration-evidence-pack

Iggesund and Terravesta have avoided this problem by using energy crops alongside other feedstocks. Iggesund use a mixture of SRC willow and waste wood to power their CHP plant in Workington[62], enabling them to operate whilst building up their SRC willow supplier base, whilst Terravesta used to sell Miscanthus to Drax for use alongside wood pellets, but now supply the heating market and traditionally straw-fired power stations like Ely who have chosen to diversify their supply chain[63].

As well as looking at ways to increase market demand for biomass, there are also opportunities to value the wider environmental benefits second generation energy crops can bring. The government's Clean Growth Strategy[64], its 25 Year Environment Plan[65], and its more recent consultation on the future of farming after the UK leaves the European Union, all stated a desire to move towards an environmental land management scheme which supports the additional public goods land management can deliver, such as soil, air and water quality improvements[66].

As mentioned above, Miscanthus and willow have the potential to deliver a number of these benefits when planted in appropriate locations. An incentive which encouraged planting primarily as a way to improve the wider environment, rather than as an energy crop could encourage new areas of planting without the need for long-term contracts with buyers. To encourage planting in locations, and at a scale, which maximises the overall environmental benefit of second generation energy crops (both in terms of their contribution to cost-effective energy system decarbonisation and other environmental benefits), further work is needed to develop the right balance of incentives for energy crop planting and use.

Developing a robust business case for planting second generation energy crops will help set the UK on the pathway to delivering 1.4 Mha of Miscanthus and willow by 2050. However, it is vital to note that achieving the 1.4 Mha target would require an average planting rate of almost 44 kha per year, a rate which the Miscanthus and willow supply chains are not currently in a position to deliver. Research by ADAS highlighted the need for investment in the production of plant breeding materials, including research into new establishment techniques[67], specialist equipment for planting and harvesting, and training an expanding workforce if the UK is to substantially increase its planting rate. This is a substantial investment and one which will only be made if there is sufficient certainty that the increase in annual planting rate will be sustained.

62 Iggesund: http://biofuel.iggesund.co.uk/
63 Ely Power Station: http://www.mreuk.com/elyfuel
64 BEIS (2017). Clean Growth Strategy [online]. Available at: https://www.gov.uk/government/publications/clean-growth-strategy
65 Defra (2018). 25 Year Environment Plan [online]. Available at: https://www.gov.uk/government/publications/25-year-environment-plan
66 Defra (2018). The future for food, farming and the environment [online]. Available at: https://www.gov.uk/government/consultations/the-future-for-food-farming-and-the-environment
67 ETI (2017). Opportunities for rural job creation in the UK energy crops sector [online]. Available at: http://www.eti.co.uk/library/an-eti-perspective-opportunities-for-rural-job-creation-in-the-uk-energy-crops-sector

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Table 8
Actions to increase the quantity of UK-grown crops

Increasing the quantity of UK-grown second generation bioenergy crops, to deliver benefits to both the energy system and to the UK supply chain.		
	Recommended actions	**Path forward**
3.3	Continue to develop the knowledge base around the environmental impacts of energy crop planting and use this to inform best practice guidelines for energy crop planting and incentives for the delivery of public goods.	R&D funding bodies include energy crop research in their research programmes, and collaborate with Academia, Farmers and Foresters to prioritise research needs and establish/maintain long-term monitoring plots. Responsibility for incorporating findings into best practice updates should sit with the industry or a third party such as the Environment Agency or Government (Defra).
3.4	To encourage energy crop planting, develop a stable, spatially explicit financial incentive which values the public goods energy crops deliver.	Energy crop planting should be included in agricultural support mechanisms as a means of delivering wider public goods. This is an emerging area of policy – policy makers will need to work with the energy crops industry and academics to develop a mechanism to quantify the value of different environmental benefits. This should also highlight where there continue to be knowledge gaps and research needs.
3.5	Invest in research of new establishment and harvesting techniques to reduce the cost of biomass feedstock production. Encourage collaboration and learning between farmers and across disciplines.	R&D funding bodies work with Academia, Foresters and Farmers to identify research needs in the biomass supply chain.

UK-grown woodfuel

While the ETI's bioenergy research has largely focused on the potential for UK-grown energy crops such as Miscanthus and Willow, Section 2 showed that woodfuel is currently the largest source of UK-grown biomass used for energy purposes. Woodland is typically managed to deliver a range of products, from high-value timber to lower-value pulp and woodfuel, alongside meeting wider environmental objectives.

The UK has targets to increase forest cover – in England the target is 5,000 ha/yr, a rate it is not currently meeting. There are also targets to increase the proportion of forestry under active management[68]. While woodfuel is unlikely to be the primary driver in establishing a new long rotation (>25 yr) forest because it is of lower value than saw logs, demand from this secondary market can improve the economics of woodland management. In addition, the woodfuel industry can help bring neglected forests back into management by providing a market for the low-quality wood from the initial harvest. If managed well, future harvest rotation should be able to produce higher value timber for use in construction or manufacturing.

The Environment, Food and Rural Affairs Sub-Committee's 2017 inquiry into Forestry in England made several recommendations to increase woodland cover in England, chief amongst them delivering a well-functioning incentive scheme to encourage new woodland planting, providing clear and accessible data on woodland cover, and improving collaboration between government and the forestry industry[69].

Increasing resilience to changes in global biomass availability by exploring new supply chains for demonstrably sustainable imported biomass

The UK is currently the largest importer of wood pellets, importing 7.1 Mt in 2016. Most imports come from the USA, Canada and Latvia[70] with most used in Drax power station. Assessments of future availability of sustainable biomass imports are highly uncertain as the extent to which imports could meet an increase in UK demand for wood pellets is contingent on a number of variables, not least how demand for biomass changes in other countries and the impact this would have on the cost of imports relative to UK-grown feedstocks and other energy sources. The extent to which the UK can make use of additional imports is also dependent on port and rail capacity.

The extent to which those using imported biomass can insulate themselves from market pressures will be largely dependent on the way they structure their contracts with suppliers and/or whether they choose to invest directly in pelleting facilities. These users can retain a competitive advantage by exploring opportunities for new sustainable supply routes in other locations.

68 House of Commons Environment, Food and Rural Affairs Committee (2017). Forestry in England: Seeing the wood for the trees [online]. Available at: https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/environment-food-and-rural-affairs-sub-committee/inquiries/parliament-2015/forestry-inquiry-16-17/. Contains Parliamentary information licensed under the Open Parliament Licence v3.0 [online]. Available at: https://www.parliament.uk/site-information/copyright-parliament/open-parliament-licence/
69 ibid
70 BEIS (2017). Digest of UK Energy Statistics (DUKES): foreign trade statistics. Imports and Exports of wood pellets and other wood (DUKES G.6) [online]. Available at: https://www.gov.uk/government/statistics/dukes-foreign-trade-statistics

5. Delivering bioenergy – opportunities and challenges

Continued ›

Biomass Logistics

The current logistics network for biomass in the UK is a combination of bespoke supply chains for individual large end-users, and regional distribution networks for smaller scale users. There is little overlap between the two[71]. The ETI-funded project, Biomass Logistics in the UK, examined four different bioenergy sector pathways to 2050 and the logistics infrastructure demands each would create. All scenarios assumed the sector would grow but differed in their dependence on imported biomass and whether CCS would be available.

Across all scenarios there was an expansion in biomass import capacity (at ports and on railways). To date, biomass importers have been large-scale users with the ability to make investments in supply chain capacity at ports and railways. In the future, import demand and the need for import infrastructure expansion, may be driven by a number of smaller end users who don't, individually, have the capacity to make that investment decision.

Making the business case for investment in biomass infrastructure will require collaboration across end users, port authorities, planning authorities and public or private sector investors. Any expansion of biomass handling, storage and transportation facilities presents several health and safety risks. New developments need to apply the lessons learned from past projects.

The analysis in the Biomass Logistics in the UK project suggested that UK-grown biomass is likely to continue to be transported largely by road with little, if any overlap with import supply chains. The main infrastructure requirements will therefore be in expanding the road-fleet and storage facilities at regional distribution points and on site.

Table 9
Actions to increase resilience to changes in global biomass availability

To increase resilience to changes in global biomass availability by exploring new supply chains for demonstrably sustainable imported biomass.		
	Recommended actions	**Path forward**
3.6	Ensure lessons are learnt regarding biomass handling, storage and transport.	Industry and the Health & Safety Executive (HSE) should work together to identify lessons learnt from, for example, existing biomass import facilities and incorporate this into best practice guidance.
3.7	Continue to assess potential availability of sustainable biomass imports and collaborate across industry to ensure timely expansion of import infrastructure if needed.	Timely investment in import logistics infrastructure requires clarity on the future demand for imported biomass. Identifying and responding to future needs requires ongoing dialogue between the Biomass Industry, Port Authorities, Government, Academia and Investors.

71 Baringa (2018). Biomass Logistics Infrastructure Review [online]. Available at: http://www.eti.co.uk/programmes/bioenergy?size=10&from=0&_type=eti-document&publicOnly=false&query=&programmeName%5B0%5D=Bioenergy&projectName%5B0%5D=Biomass+Logistics+in+the+UK

Biomass Sustainability

To receive subsidies for biofuel or bioenergy production under the RTFO, RHI, RO or CfD the recipient must demonstrate compliance with the GHG criteria (emissions resulting from land use changes and supply chain activities must fall below the limit set in each scheme) and the land use criteria which prevent feedstocks being used if they were grown on land which was previously of high carbon stock. The methodology used to calculate emissions is set out in the Renewable Energy Directive (RED)[72].

The RED methodology accounts for emissions directly attributable to current production of bioenergy including land use *change*, but does not provide information on the indirect emissions associated with an increase or decrease in production of forest-derived feedstocks, such as those resulting from a change in forest management practices or displacement of other forestry products.

As set out in the ETI's perspective, *How can Life Cycle Assessment inform bioenergy choices?*[73], it is vital for policy makers to consider the causes of indirect emissions when analysing the impacts of an increase (or decrease) in bioenergy use, both domestically grown and imported. Indirect emissions, such as those resulting from a change in forest carbon stock, often have a large impact on overall LCA results, and can vary significantly depending on what is likely to have happened to the biomass otherwise. Ensuring bioenergy deployment delivers emissions savings at a global scale cannot be achieved through monitoring direct emissions alone. Additional measures are needed to encourage good land and forest management practices and prohibit high-risk practice which would lead to an increase in global carbon emissions. This should not only apply in relation to bioenergy feedstocks, but should take a holistic view across the production of all bio-based products.

Improve feedstock consistency and compatibility

Opportunities:

- Delivering more physically and chemically consistent feedstocks to end users, through improvement in plant breeding and pre-processing (see Table 10)
- Developing technologies more resilient to variations in feedstock composition (see Table 10)

The previous section focused on increasing availability of biomass feedstocks and highlighted examples where Miscanthus and willow are used alongside other feedstocks. For these feedstocks to be adopted more widely, their characteristics (both when blended or used in isolation) must be compatible with their end use application.

The ETI's *Characterisation of Feedstocks* project sampled UK-grown Miscanthus, willow and Forestry, grown in different locations, harvested at different times of year, and after different storage durations. While it found that some management practices can improve feedstock quality, such as harvesting later, removing problematic plant parts such as leaves, and leaving the crop to dry before use/baling, only stem wood samples from coniferous trees consistently met even the lowest quality standard currently used for wood pellets (Industrial, I3)[74].

Widely recognised and rigorously enforced biomass standards help the development of the bioenergy sector enabling biomass to become a more widely traded commodity, and reassuring buyers that biomass from different sources which meet a given standard are fungible products of the right quality for their application. Variability in feedstock quality and the higher levels of some chemicals seen in Miscanthus and willow when compared to wood pellets makes it difficult to apply common standards and may deter end users from using energy crops. To make energy crops more attractive relative to more consistent and well-understood wood-derived feedstocks, investment either needs to be made in pre-processing technologies which can remove problematic contaminants and improve feedstock consistency, and/or in conversion technologies which are better able to deal with a wider range of physical and chemical characteristics.

72 Further information on the development of sustainability criteria in the RO can be found in: Ofgem (2016). Renewables Obligation: Sustainability Criteria [online]. Available at: https://www.ofgem.gov.uk/publications-and-updates/renewables-obligation-sustainability-criteria.
All information from Ofgem contains public sector information licensed under the Open Government Licence v3.0 [online]. Available at: https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/

73 ETI (2018). How can Life Cycle Assessment (LCA) inform bioenergy choices? [online]. Available at: http://www.eti.co.uk/library/how-can-life-cycle-assessment-inform-bioenergy-choices

74 ETI (2018). Understanding Variability in Biomass Feedstocks and the Opportunities for Pre-Processing [online]. Available at: http://www.eti.co.uk/insights/understanding-variability-in-biomass-feedstocks-and-the-opportunities-for-pre-processing

5. Delivering bioenergy – opportunities and challenges

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The ETI-funded Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project, assessed the circumstances under which the additional cost of adding a pre-processing step into the supply chain could be offset by reductions in transport cost and/or improvements in conversion efficiency. Pre-processing technologies can be used to change the physical and/or chemical properties of biomass. The TEABPP project found that, for UK feedstocks, the cost of densifying biomass is unlikely to pay off in reduced transport costs because of the relatively short distances travelled. However, it may be considered worthwhile if it improves biomass handling and/or storage properties.

TEABPP found that improving the chemical characteristics of the biomass may be worthwhile, particularly where it can consistently bring feedstock characteristics within the range required to retain boiler performance or lifetime guarantees. The project found that water washing could cost-effectively improve biomass characteristics and consistency by removing surface contamination and encouraging problematic compounds to leech from the biomass. This technology has not been commercially deployed but has demonstrated promise in academic research[75].

While the TEABPP project's main focus was on pre-processing technologies, it did highlight that some combustion and gasification technologies are not currently optimised to handle a wide variety of biomass feedstocks, potentially causing issues with biomass handling as well as corrosion, fouling or slagging in the equipment[76]. Technology developments which focus on optimising equipment for other feedstock types or to handle a wider range of feedstock characteristics broadens the feedstock base available to biomass users and could potentially be more cost-effective than some pre-processing steps.

Table 10
Actions to improve feedstock consistency and conversion technology resilience

Recommendation 4: Deliver more physically and chemically consistent feedstocks to end users, through improvements in plant breeding and pre-processing, and/or develop conversion technologies more resilient to variations in feedstock composition.

	Recommended actions	Path forward
4.1	Invest in demonstrating new pre-processing technologies (e.g. water washing) at a commercial scale to understand whether the improvements they deliver in feedstock quality outweigh the additional cost of the pre-processing step.	R&D funding bodies should include pre-processing technologies within their energy crop research programmes and collaborate with the biomass supply industry and academia to support commercial-scale demonstration projects.
4.2	Continue research in plant breeding, focused on developing characteristics suited to energy end use applications.	R&D research programmes on plant breeding should continue to work with biomass growers, users and the wider academic community to prioritise and fund research needs.
4.3	Invest in developing conversion technologies which can be optimised for different feedstock types or which can accept a wider change of chemical characteristics.	R&D funding bodies should include conversion technologies within their energy crop research programmes and collaborate with the biomass industry and academia to prioritise research needs and fund demonstration projects.

75 Including: Gudka B, Jones JM, Lea-Langton AR, Williams A, Saddawi A (2016), A review of the mitigation of deposition and emission problems during biomass combustion through washing pre-treatment. Journal of the Energy Institute, 89 (2), pp. 159-171. https://doi.org/10.1016/j.joei.2015.02.007

76 For more detail on the chemicals which cause this issue see the ETI's Insight paper – *Understanding Variability in Biomass Feedstocks and the Opportunities for Pre-Processing* Available at: http://www.eti.co.uk/insights/understanding-variability-in-biomass-feedstocks-and-the-opportunities-for-pre-processing

Conclusion

Bioenergy is, and should continue to be, an important part of the UK's energy system mix. With the UK's commitment to reduce emissions, the greatest strategic value of bioenergy will be in encouraging the growth of sustainable biomass and delivering net negative emissions through deployment of BECCS technologies. These negative emissions enable the UK to meet its 2050 emissions targets (an 80% reduction in GHGs relative to 1990 levels) more cost-effectively, by offsetting the need for more expensive decarbonisation interventions in other sectors. Delivering negative emissions through BECCS will become increasingly important beyond 2050 as the world works towards becoming net-zero between 2060 and 2080. Reaching net-zero will require GGR techniques such as BECCS to offset any remaining emissions from fossil fuel sources.

The bioenergy sector has more than doubled in size over the last decade and has consistently been the largest source of renewable energy in the UK. To further expand the bioenergy sector sustainably and in a way which is strategically valuable to the UK's decarbonisation efforts, action must be taken to develop sustainable feedstocks supplies and demonstrate the technical and commercial viability of key technologies. The actions set out in this report will help the UK capitalise on key opportunities to develop the bioenergy sector.

- **Recommendation 1:** Create the right environment for BECCS in the UK, which through deployment can significantly reduce the cost of meeting the UK's 2050 emissions targets and increase the likelihood that the UK can deliver net-zero emissions.
- **Recommendation 2:** Develop gasification for the production of clean syngas from biomass and wastes to enable the bioenergy sector to remain robust to changes elsewhere in the energy system.
- **Recommendation 3:** Increase biomass production and the supply of sustainable biomass for bioenergy in the UK, and maximise the use of appropriate residual waste resources for energy, to enable the delivery of greater emissions savings at a system level, through:
  - o Making greater use of residual waste resources in efficient EfW applications.
  - o Increasing the quantity of UK-grown second generation bioenergy crops, to deliver benefits to both the energy system and to the UK supply chain.
  - o Increasing resilience to changes in global biomass availability by exploring new supply chains for demonstrably sustainable imported biomass.
- **Recommendation 4:** Deliver more physically and chemically consistent feedstocks to end users, through improvements in plant breeding and pre-processing, and/or develop conversion technologies more resilient to variations in feedstock composition.

Further reading

Other sources of information on bioenergy use in the UK include:

- **Energy Systems Catapult (ESC)** – Together with certain outputs from the ETI Bioenergy programme, the ESC continues to highlight the value of bioenergy as part of its whole systems analysis. https://es.catapult.org.uk/
- **SUPERGEN Bioenergy Hub** – The SUPERGEN Bioenergy Hub aims to bring together industry, academia and other stakeholders to focus on the research and knowledge challenges associated with increasing the contribution of UK bioenergy to meet strategic environmental targets in a coherent, sustainable and cost-effective manner. http://www.supergen-bioenergy.net/
- **IEA Bioenergy** – An international collaboration with the aim of improving cooperation and information exchange between countries that have national programmes in bioenergy research, development and deployment. http://www.ieabioenergy.com/
- **Committee on Climate Change (CCC)** – The CCC's update to their Bioenergy Review is due to be published in late 2018, along with a review of the importance of hydrogen in meeting the UK's 2050 emissions targets and a report on the role of land use in climate mitigation and adaptation. https://www.theccc.org.uk/

The role of the ETI

The Energy Technologies Institute (ETI) was established in 2007 to identify and accelerate the development of low carbon technologies to help the UK address its long-term GHG emissions reduction targets, as well as delivering nearer-term benefits. The ETI's Bioenergy Programme was established to deliver research, technology development and deployment projects which would fill knowledge gaps within the sector and assess and understand the potential for different bioenergy value chains in the UK.

The ETI was established as a 10-year partnership between the UK Government and industry and will cease to operate at the end of 2019.

The role of the ESC

Energy Systems Catapult (ESC) was established by the UK Government in 2015 as part of a network of world-leading centres to transform the UK's capability for innovation. The ESC has a mission to unleash innovation and open new markets that help transform the energy system and capture the growth opportunity recognised in the UK Industrial Strategy. Working with government, industry, academia and consumers, the ESC vision for the UK energy sector will see it overcoming systemic barriers and delivering the innovation, products, services and value chains required to accelerate the decarbonisation of the energy system at least cost and deliver the UK's economic ambitions.

The ETI's Whole System Analysis Function transferred to the ESC in September 2017. The ESC now manages the system modelling suite developed by the ETI as well as providing consultancy services to the ETI as it completes its portfolio of energy innovation projects and analysis.

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8. Appendices

8.1. List of abbreviations

ABDC	Advanced Biofuels Demonstration Competition
ACT	Advanced Conversion Technology
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy and Industrial Strategy
BioSNG	Bio-Synthetic Natural Gas
BVCM	Bioenergy Value Chain Model
C&I	Commercial and Industrial (waste)
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DUKES	Digest of United Kingdom Energy Statistics
EfW	Energy from Waste
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute
F4C	Future Fuels for Freight and Flight
FID	Financial Investment Decision
FiT	Feed-in Tariff
GCV	Gross Calorific Value
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
HSE	Health and Safety Executive
ICE	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
KTN	Knowledge Transfer Network
LCA	Life Cycle Assessment
NPV	Net Present Value
OGCI	Oil and Gas Climate Initiative

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PHEV	Plug-in Hybrid Electric Vehicle
R&D	Research and Development
RED	Renewable Energy Directive
RHI	Renewable Heat Incentive
RO	Renewables Obligation
RTFO	Renewable Transport Fuels Obligation
SEC	Sustainable Energy Centre
SMR	Steam Methane Reforming
SRC	Short Rotation Coppice
SRF	Short Rotation Forestry
TEABPP	Techno-Economic Assessment of Biomass Pre-Processing

8.2. Units and conversion factors

Units

Kilo (k)	1, 000 =	10^3
Mega (M)	1,000,000 =	10^6
Giga (G)	1,000,000,000 =	10^9
Tera (T)	1,000,000,000,000 =	10^{12}
Peta (P)	1,000,000,000,000,000 =	10^{15}

Conversion factors

Energy

1 Kilowatt hour (kWh)	=	3,600	Kilojoules (kJ)
1 Kilowatt hour (kWh)	=	0.000086	Tonnes of oil equivalent (toe)

Area

1 Hectare (ha)	=	2.47	Acres (ac)
1 Hectare (ha)	=	10,000	Square metres (m^2)

8.3. Additional information on trends and developments in UK bioenergy use

The role of bioenergy within the renewable energy sector

Table 11 contains the data used in Figure 2. It shows that, in 2007, bioenergy accounted for 83% of renewable energy used in the UK on an input basis. This was dominated by waste feedstocks, with only a third of the primary bioenergy resource coming from virgin biomass or in the form of biofuels. By 2016, renewable energy production had more than tripled in size (on an energy input basis), and while the bioenergy sector had grown at a slower rate than the wind and solar sectors, biomass, biofuel and waste feedstocks still made up 74% of renewable energy inputs.

Between 2007 and 2016 there was been a shift within the bioenergy sector from a sector dominated by waste feedstocks to one where just over half the feedstock was biomass (on an energy basis)[77]. The use of waste feedstocks increased by 89% between 2007 and 2016, but biofuels saw a 179% increase and plant biomass saw a 499% increase over the same period through a combination of increased imports (predominantly wood pellets) and use of domestic forestry (woodfuel) and energy crops[78].

The following sections provide more information on the available data detailing the use of woodfuel, energy crops and wastes for bioenergy in the UK.

77 In 2016, DUKES (2017) showed that 51% of bioenergy inputs were from biomass feedstocks, with 7% coming from biofuels and 42% from waste.
78 BEIS (2017), Digest of UK Energy Statistics (DUKES), Chapter 6 and Renewables and Wastes: Commodity Balances, Tables 6.1-6.3 [online]. Available at: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes.

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Table 11
UK Renewable Energy Inputs, 2007 and 2016 (using, where applicable, the Gross Calorific Value (GCV) of fuels)[79]

High Level Category	Detailed Category	2007			
		Net Production	Imports	Sub-Total	Total
		(UK Production – Exports), TWh	*TWh*	*TWh*	*TWh*
Wastes	Waste wood	1.2	–	1.2	**35.9**
	Animal biomass and anaerobic digestion	3.1	–	3.1	
	Sewage gas	2.5	–	2.5	
	Landfill gas	18.0	–	18.0	
	Waste[80]	11.1	–	11.1	
Virgin Biomass	Wood (for heating)	3.9	–	3.9	**13.5**
	Plant biomass (includes, for example, wood pellets, energy crops)	5.2	4.4	9.6	
Liquid biofuels		3.3	0.9	4.2	**4.2**
Solar photovoltaics, active solar heating, and deep geothermal		0.5	–	0.5	**0.5**
Hydro		5.1	–	5.1	**5.1**
Wind and marine energy		5.3	–	5.3	**5.3**
Heat pumps		–	–	–	–
Total renewables		**60.5**	**4.0**	**64.5**	**64.5**

High Level Category	Detailed Category	2016			
		Net Production	Imports	Sub-Total	Total
		(UK Production – Exports), TWh	*TWh*	*TWh*	*TWh*
Wastes	Waste wood	3.3	0.4	3.7	**67.7**
	Animal biomass and anaerobic digestion	12.9	–	12.9	
	Sewage gas	4.5	–	4.5	
	Landfill gas	18.1	–	18.1	
	Waste[80]	28.5	–	28.5	
Virgin Biomass	Wood (for heating)	22.2	0.5	22.7	**80.8**
	Plant biomass (includes, for example, wood pellets, energy crops)	22.9	35.3	58.1	
Liquid biofuels		4.4	7.3	11.7	**11.7**
Solar photovoltaics, active solar heating, and deep geothermal		11.0	–	11.0	**11.0**
Hydro		5.4	–	5.4	**5.4**
Wind and marine energy		37.4	–	37.4	**37.4**
Heat pumps		2.1	–	2.1	**2.1**
Total renewables		**176.6**	**39.6**	**216.2**	**216.2**

79 Ibid. 'Waste' includes municipal solid waste, tyres, general industrial waste and hospital waste. It is important to note that some of these waste feedstocks will contain non-biogenic (i.e. fossil derived) waste. This portion of the waste is not renewable but is included in the overall DUKES data as it is part of a mixed waste feedstock. In 2016 of the 67.7 TWh of waste used, 15.0 TWh was non-biogenic.

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Woodfuel

Table 11, which is derived from the government's Digest of UK Energy Statistics (DUKES), shows that UK-grown wood is a significant source of bioenergy feedstock. In 2016, DUKES estimated 22.2 TWh of wood was used by domestic end users based on results from a survey of domestic wood users[80].

Other sources of information on UK-grown woodfuel, such as the Forestry Commission's Forestry Statistics, are based on data gathered through their surveys of sawmills, round fence manufacturers and other wood suppliers, plus input from their expert group on timber and trade statistics. These data show that there has been an increase in the supply of woodfuel from both managed hardwood (broadleaf) and softwood (coniferous) forests over the last 10 years.

In 2016, 2.68 million green tonnes of UK-grown wood were used for energy purposes. Most came from softwood forests (1.55 million green tonnes), but woodfuel from hardwood forests (0.4 million green tonnes) makes up a greater proportion of the smaller hardwood market (Figure 10 and Figure 11). A further 0.73 million green tonnes were residues (chips and sawdust) supplied by sawmills and round fencing manufacturers[81]. However, this total is likely to only represent between a third to a half of the quantity shown in DUKES[82]. Some of the discrepancy is due to the uncertainties associated with the methodologies used in both datasets but another significant source of difference is the fact that not all wood is sourced from managed forests – the domestic wood use survey estimates that 31% of wood used in domestic heating is gathered by end users from their own land or local environment.

Figure 10
Deliveries of UK-grown softwood (million green tonnes), 1994-2016[83]

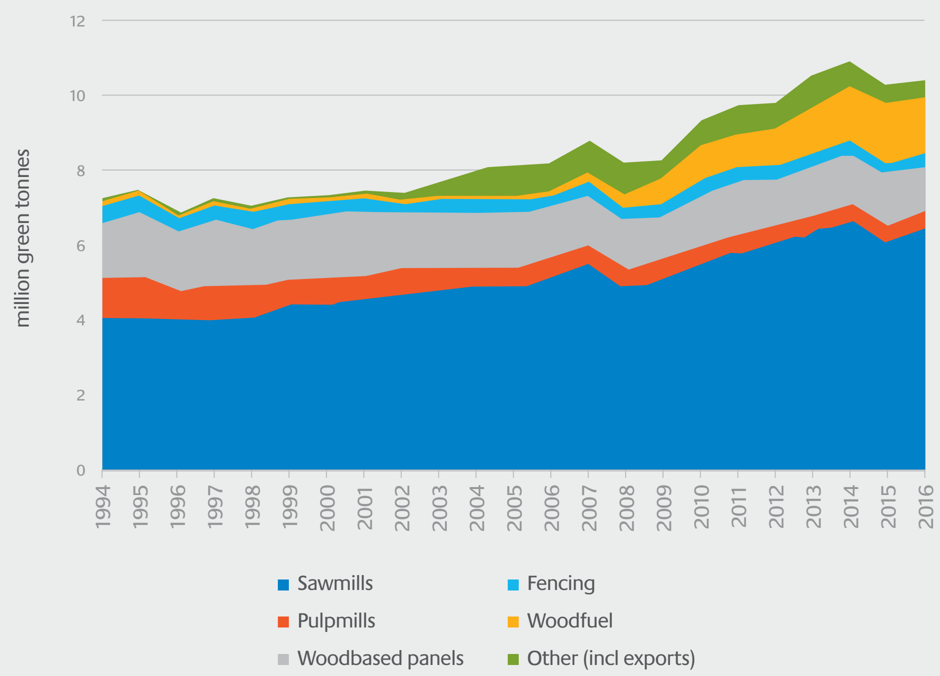
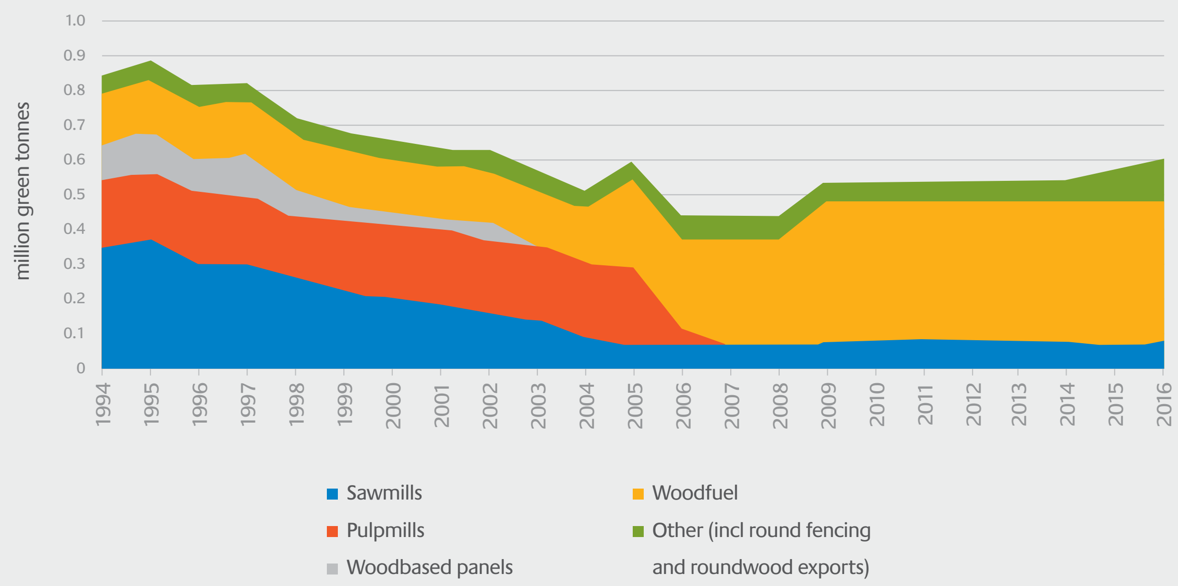


Figure 11
Deliveries of UK-grown hardwood (million green tonnes), 1994-2016[84]



Energy crops

132 kha of land was used to grow crops for bioenergy in the UK in 2016[85]. This represents 2.2% of the UK's arable area. The majority of this (70 kha) was used to grow wheat and sugar beet for bioethanol production. A further 52 kha was used to produce maize as a feedstock for anaerobic digestion. Only 10 kha was used to grow lignocellulosic crops such as Miscanthus and SRC willow (which, along with Short Rotation Forestry (SRF), are also known as second generation crops) for use in heat and power production. This figure has remained broadly stable since 2008.

In addition to the 132 kha used to produce purpose grown crops, around 5% of cereal and oilseed rape straw produced in 2016 (560 thousand tonnes, equivalent to straw production across 166 kha) was used in power stations. Total UK straw production in 2016 was 10.4 million tonnes, 75% of which was used for animal bedding or feed[86].

Figure 12 shows how the quantity and type of crops grown in the UK for energy has changed since 2008 (figures for maize used in anaerobic digestion have only been published since 2014).

Wheat has been the main crop used in biofuel production since 2010 when the Ensus bioethanol plant was opened in Teesside. This was followed by the Vivergo plant which opened in 2012 (reaching full production capacity in 2014). However, both plants have experienced difficult economic conditions[87]. Both plants have experienced long shutdown periods and Vivergo recently announced the closure of their Hull plant from 30th September 2018 onwards (Figure 12).

80 DECC (2016). Energy Trends. Summary results of the domestic wood use survey [online].
Available at: https://www.gov.uk/government/publications/energy-trends-march-2016-special-feature-article-summary-results-of-the-domestic-wood-use-survey
81 Forestry Commission (2017). Forestry Statistics 2017 (Chapter 2 – Timber, and Background Information) [online]. Available at: https://www.forestry.gov.uk/forestry/infd-7aqdgc.
All information from Forestry Commission is Crown Copyright, courtesy Forestry Commission (2017), licensed under the Open Government Licence [online].
Available at: https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/
82 Assuming a GCV of 16.3 GJ/tonne and 20% moisture content (the assumptions made for Domestic wood in DUKES), 2.68 million tonnes is equal to 12.1 TWh (half the figure shown in DUKES). However, the majority of the Forestry Statistics data are provided in green tonnes which are likely to have a higher moisture content. Assuming a GCV of 9.7 GJ/tonne and 52% moisture content (based on samples taken for the ETI's Characterisation of Feedstocks project), 2.68 million tonnes is equal to 7.2 TWh (just under a third (31%) of the figure shown in DUKES).
83 Forestry Commission (2017). Forestry Statistics 2017, Chapter 2 – Timber, Figure 2.1 [online].
Available at: https://www.forestry.gov.uk/forestry/infd-7aqdgc.
84 Ibid – Chapter 2 - Timber, Figure 2.2.
85 This does not include the area of crops converted to biofuels for use abroad.
86 Defra (2017). Area of crops grown for bioenergy in England and the UK: 2008 – 2016 [online].
Available at: https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2016.
87 BBC (2017). Biofuels plant in Hull stops production and may not reopen [online]. Available at: http://www.bbc.co.uk/news/business-42226808 and;
Financial Times (2017). Producers say plan for biofuels cap puts plant at risk [online]. Available at: https://www.ft.com/content/188ac0fe-f76d-11e6-9516-2d969e0d3b65 [Paywall].
BBC (2018). Vivergo: Biofuels plant in Hull to stop production. https://www.bbc.co.uk/news/uk-england-humber-45435022

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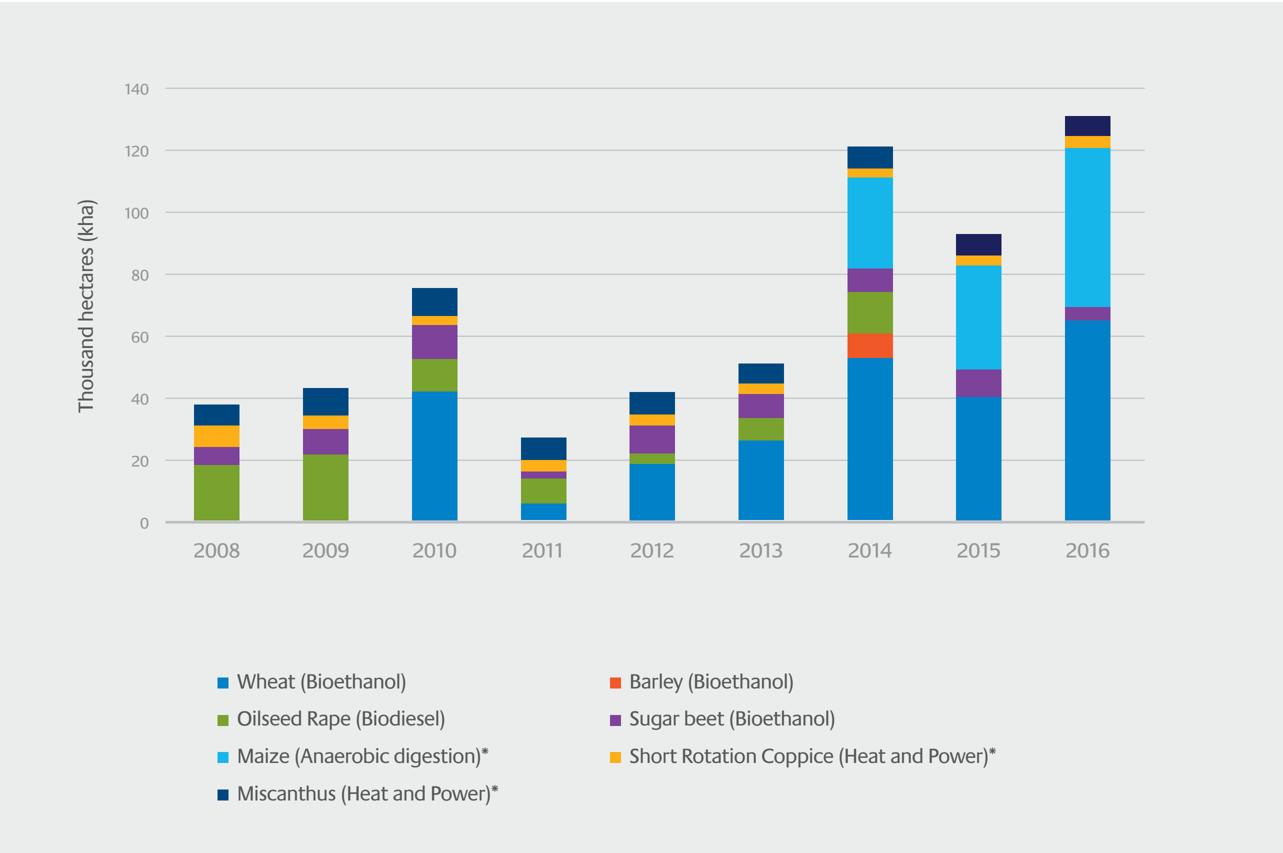
Figure 12
*Area used for energy crops in the UK 2008-2016 (*England only), thousand hectares (kha)[88]*



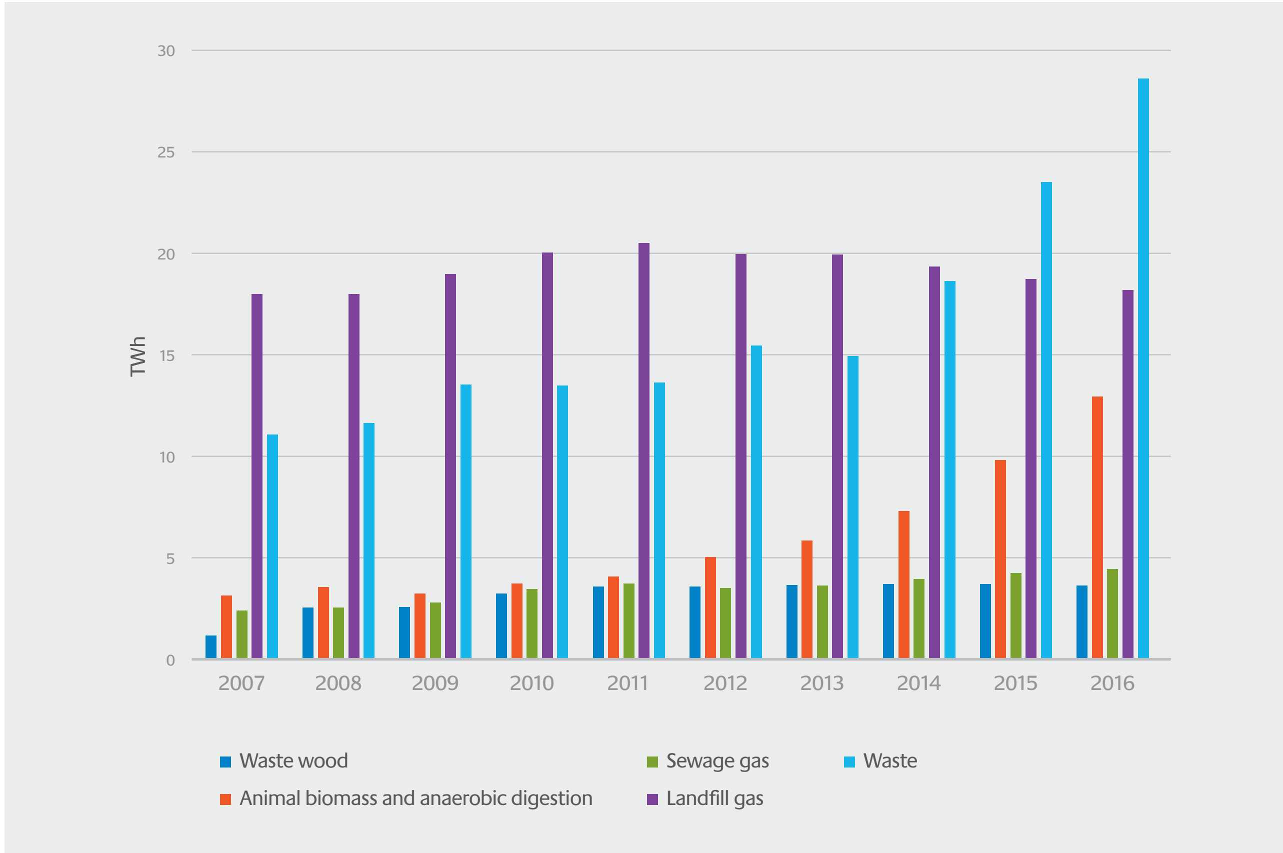
It should be noted that the data in Figure 12 do not cover any crops grown in the UK which are subsequently exported for processing into biofuels, or which are converted to biofuels in the UK and then exported. DUKES reports that 219 million litres of UK produced bioethanol were exported in 2016. In 2016, this was equivalent to around a further 76 kha of wheat used for bioethanol[89]. In addition, an average of 20% of the UK's oilseed rape crop between 2012-2016 was exported to the European Union, much of it destined for conversion to biodiesel. On average this equates to around 142 kha of production[90].

Wastes

The use of wastes for energy increased by 89% between 2007 and 2016. Figure 13 shows that this was driven by an increase in the use of municipal solid waste, tyres, general industrial waste and hospital waste (together categorised as 'waste' in Figure 13), and an increase in the use of 'animal biomass and anaerobic digestion' which includes the use of poultry litter, meat and bone and farm waste. In 2016, 83% of waste feedstocks were primarily used to produce electricity.

88 ibid
89 Based on 1 tonne wheat grain producing 367 litres bioethanol (Defra) (2017). Area of crops grown for bioenergy in the UK: 2008-2016 [online]. Available at: https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2016) and the 2016 UK average wheat yield being 7.9 tonnes/hectare (Defra (2017). Agriculture in the UK Datasets. Chapter 7 – crops [online]. Available from: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom)
90 Derived from: Defra (2017). Agriculture in the UK Datasets. Chapter 7 – crops [online]. Available from: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom

Figure 13
Waste resources used for bioenergy, 2007-2016 (TWh, based on the GCV of resources)[91]



8.4. Second generation energy crops

Miscanthus is a perennial energy crop that can grow to heights of 2.5-3.5m. Rhizomes (an underground stem/bulb) are planted in the spring at a density of 10,000-15,000 per hectare. After its first year of growth, it can be harvested annually for biomass for 20 years or more. New shoots emerge around March each year, growing rapidly in June-July, producing bamboo-like canes. The Miscanthus dies back in the Autumn/Winter, when the leaves fall off, providing nutrients for the soil, and the dry canes are harvested in winter or early spring. It can be grown successfully on marginal land in all soil types, in both wet and dry conditions. The highest yields are typically seen in the west of the UK.

Short Rotation Coppice (SRC) willow is planted as rods or cuttings in spring using specialist equipment at a density of around 15,000 per hectare. The willow stools readily develop multiple shoots when coppiced and several varieties have been bred specifically with characteristics well suited for use as energy crops. During the first year it can grow up to 4m in height, and is then cut back to ground level in its first winter to encourage it to grow multiple stems. The first crop is harvested every three years subsequently, giving a total of seven harvests over a typical 23-year crop life[92].

Short Rotation Forestry (SRF) – poplar or conifer – is planted as a single stem species with a harvest rotation of 12-25 years. An SRF plantation – as of 2018 there are none in the UK – could be planted for predominantly bioenergy purposes, meaning the whole tree (stem/trunk and tops) could be available for bioenergy. More commonly, forestry is planted on a longer rotation to manufacture products for a variety of end uses. The wood used for bioenergy is generally taken from parts of the tree unsuitable for higher value purposes such as sawn logs, or from thinnings which are smaller trees removed part way through the harvest cycle to provide space for the remaining trees to grow.

91 BEIS (2017), Digest of UK Energy Statistics (DUKES), Renewables and Wastes: Commodity Balances, Tables 6.1-6.3 [online]. Available at: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes.
92 Forest Research (2018). Energy Crops [online]. Available at: https://www.forestry.gov.uk/fr/beeh-9uhpxh

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8.5. Additional information on incentives for UK bioenergy production

Table 12
UK incentives for producing bio-electricity, bio-heat, or bio-transport fuels, 2008 and 2018.

	2008	2018
Electricity	Renewables Obligation (RO) Feed-in Tariff (FiT) – for anaerobic digestion only <5 MW	Contracts for Difference (CfD) Feed-in Tariff (FiT) – for anaerobic digestion only <5 MW – updated
Heat	–	Renewable Heat Incentive (RHI)
Transport	Renewable Transport Fuels Obligation (RTFO)	Renewable Transport Fuels Obligation (RTFO) – updated

Each scheme operates independently with separate budgets and mechanisms for setting the level of support provided. Most recipients can only receive a subsidy under one scheme although there are some exceptions where CHP plants can claim both the RHI and either the RO or CfD.

Electricity

Renewables Obligation (RO) and Contracts for Difference (CfD)

A number of biomass-to-power technologies were eligible for the RO until it closed to new entrants in March 2017. Under the scheme, eligible generators receive a fixed number of certificates for every MWh of electricity generated over a 20-year period. These are then sold to electricity suppliers as evidence that suppliers are meeting their annual obligation to source a certain percentage of their electricity from renewable sources[93].

The CfD scheme is the replacement for the RO. It held its first auction in 2015 and is now the only policy support mechanism for new biomass to power technologies. Contracts are awarded through periodic auctions with successful bidders receiving a 15-year contract for a guaranteed, index-linked price for each MWh of electricity sold.

The value of the contracts available in each auction is currently split between three groups of technologies:

- Established technologies (Pot 1). This includes EfW with CHP, Landfill Gas and Sewage Gas, alongside Onshore wind (>5 MW), Solar Photovoltaic (>5 MW) and Hydro (>5 MW and <50 MW)
- Less established technologies (Pot 2). This includes Advanced Conversion Technologies (ACT)[94] (with or without CHP), Anaerobic Digestion (with or without CHP) and Dedicated Biomass with CHP, alongside Offshore Wind, Wave, Tidal Stream and Geothermal (with or without CHP)
- Conversion of fossil fuel power stations to biomass (Pot 3)

The first CfD auction set separate budgets for Pot 1 and Pot 2 technologies. The second CfD auction in 2017 only supported Pot 2 technologies. Neither auction supported biomass conversions (Pot 3). A further £557m of funding has been allocated to future CfD auctions. The next auction, to be held in May 2019, is expected to support Pot 2 technologies plus onshore wind on Scottish Islands. Beyond 2019, auctions are expected to take place every two years[95].

93 Ofgem (2018). About the RO [online]. Available at: https://www.ofgem.gov.uk/environmental-programmes/ro/about-ro.
94 Advanced Conversion Technologies (ACT) include gasification and pyrolysis.
95 Reuters (23 July 2018). Britain to hand out 557 million pounds of renewables funding via auction [online]. Available at: https://uk.reuters.com/article/uk-britain-renewables/britain-to-hand-out-557-million-pounds-of-renewables-funding-via-auctions-idUKKBN1KD0NJ

For successful bidders, a CfD contract provides greater revenue certainty as generators do not have to bear the risk of changes in the price of a RO certificate. However, the auction process means that eligible biomass technologies must compete for funding and are not guaranteed support.

The RO accredited 5,867 MW of fuelled (biomass and waste) capacity while open to new entrants between 2002 and 2017[96]. CfD contracts have so far been awarded to 1,671 MW of biomass and waste technologies. Three projects, totalling 1,364 MW, were awarded contracts prior to the first auction as part of a Financial Investment Decision (FID) enabling process. The three plants were Drax Unit 1, Lynemouth (both coal-to-biomass conversions), and MGT Teesside, a dedicated biomass CHP plant[97]. The first and second CfD auctions awarded contracts to, respectively, 157 MW[98] and 150 MW of bioenergy plants (all of which are expected to be operational by 2022/23)[99].

Feed-in tariff (FiT)

The FiT covers small-scale renewable electricity production from anaerobic digestion, solar photovoltaics, CHP, hydro-electric schemes and wind turbines. It provides a pence per kilowatt hour (p/kWh) tariff to all successful applicants. For the majority of installations, the subsidy is paid for 20 years. In July 2018, the government proposed closing the scheme to new entrants at the end of March 2019[100].

Up to March 2017, the FiT has supported 366 anaerobic digestion installations with a total installed capacity of 250 MW. This is 4.4% of the total capacity installed under the scheme, which is dominated by solar photovoltaic installations[101].

Heat – Renewable Heat Incentive (RHI)

The RHI covers domestic and non-domestic properties and provides a p/kWh tariff for renewable heat produced via biomass boilers, heat pumps and solar thermal installations. The non-domestic scheme also supports biogas combustion, deep geothermal, biomass CHP and biomethane/bioSNG injection into the gas grid. Eligible applicants receive the tariff for 7 years (on the domestic scheme) or 20 years (on the non-domestic scheme). The non-domestic scheme was launched in November 2011, followed by the domestic scheme in April 2014. Funding for new applications under both schemes is in place until April 2021.

As of April 2018, the 16,788 accredited installations of biomass boilers, biogas combustion, biomethane/bioSNG injection, and biomass CHP plants made up 97% of installed capacity under the non-domestic renewable heating incentive (3,916 MW of 4,025 MW). Under the domestic RHI, 20% of applications (12,559 of 62,239 applications) have been for biomass boilers, with a mean capacity of 26.6 kW[102].

Transport – Renewable Transport Fuels Obligation (RTFO)

The RTFO is an obligation on transport fuel suppliers to source a certain percentage of their fuel from renewable and sustainable sources. Producers of sustainable liquid or gaseous biofuels receive certificates for every litre of fuel produced. These certificates are sold to suppliers in order for them to meet their obligation. If a supplier does not meet their obligation in any given year, they must pay a fixed price for each missing certificate[103].

Updates to the scheme in 2018 have set the targets for the RTFO until 2032 when the scheme aims for biofuels to make up 12.4% of the liquid fuel mix, with an increasing proportion derived from wastes and limits on the amount of biofuel that can be derived from crops. Recent changes to the scheme also mean that it now includes sustainable aviation fuels as well as road transport fuels[104]. In 2016/17, 1,541 million litres of renewable transport fuel were supplied into the UK market; 3% of total road and non-road machinery fuel[105].

96 Ofgem (2018). Renewables Obligation (RO) Annual Report 2016-17 [online]. Available at: https://www.ofgem.gov.uk/publications-and-updates/renewables-obligation-ro-annual-report-2016-17.
97 DECC (2014). Final Investment Decision Enabling for Renewables [online]. Available at: https://www.gov.uk/government/publications/increasing-certainty-for-investors-in-renewable-electricity-final-investment-decision-enabling-for-renewables
98 BEIS (2015). Contracts for Difference (CFD) Allocation Round One Outcome [online]. Available at: https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-one-outcome
99 BEIS (2017). Contracts for Difference (CFD) Second Allocation Round Results [online]. Available at: https://www.gov.uk/government/publications/contracts-for-difference-cfd-second-allocation-round-results
100 BEIS (2018). Feed in Tariffs scheme [online]. Available at: https://www.gov.uk/government/consultations/feed-in-tariffs-scheme
101 Ofgem (2017). Feed-in Tariff (FIT): Annual Report 2016-17 [online]. Available at: https://www.ofgem.gov.uk/publications-and-updates/feed-tariff-fit-annual-report-2016-17
102 BEIS (2018). RHI Deployment Data (April 2018) [online]. Available at: https://www.gov.uk/government/statistics/rhi-deployment-data-april-2018
103 DfT (2018). RTFO guidance Year 10 [online]. Available at: https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-guidance-year-10
104 DfT (2018). New regulations to double the use of sustainable renewable fuels by 2020 [online]. Available at: https://www.gov.uk/government/news/new-regulations-to-double-the-use-of-sustainable-renewable-fuels-by-2020
105 DfT (2018). Renewable Transport Fuel Obligation statistics: period 9 2016/17, report 6 [online]. Available at: https://www.gov.uk/government/statistics/biofuel-statistics-year-9-2016-to-2017-report-6

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8.6. Modelling bioenergy in ESME

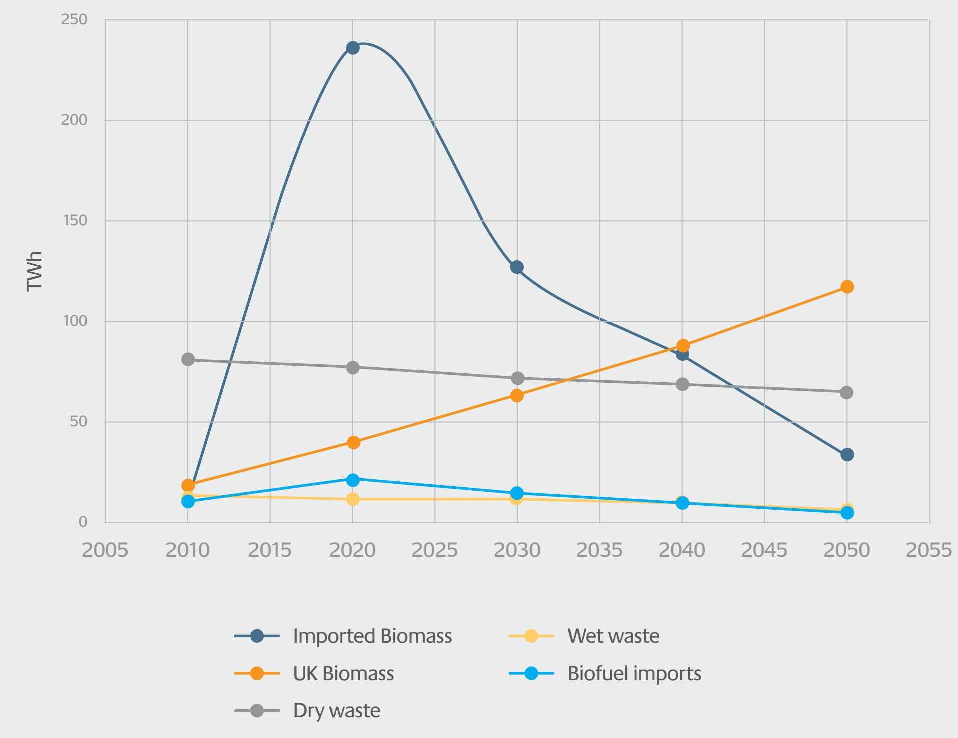
This Appendix introduces the biomass and waste resources and bioenergy technologies used in ESME. Version 4.3 of ESME was used to model the scenarios used in this report. More detail on model assumptions and data can be downloaded from the ETI website[106].

Resources

There are five biomass and waste resources in ESME. The availability of each resource over time is based on the literature and findings from ETI projects. Resource availability for a base case scenario is shown in Figure 3 (repeated here as Figure 14).

- UK biomass – this resource represents energy crops, forestry and agricultural residues. The availability of biomass increases in each decade as the area planted with energy crops is assumed to grow. By the 2050s there is around 1.4 Mha of energy crops grown in the UK. This land area is in line with the findings from the ETI's Refining Estimates of Land for Biomass project and yield maps used in BVCM[107]. The cost of the biomass resource is based on the central price scenario in the UK and Global Bioenergy Resource Model analysis[108].
- Imported Biomass is assumed to be wood pellets. The resource limit is based on the most conservative scenario in the UK and Global Bioenergy Resource Model. It reflects a scenario where there is limited global biomass available, coupled with high demand for biomass imports in other countries. Consequently, the UK is assumed to have access to a declining share of the global market. The price of imported biomass is taken from the central estimate in the same model.
- Imported biofuels – liquid transport fuels which can be mixed with fossil-derived fuels. In a similar pattern to imported biomass, availability peaks in the 2020s and then declines. This is also based on a conservative scenario in the UK and Global Bioenergy Resource Model. The cost of biofuel imports is set relative to future fossil fuel prices in ESME, the cost premium being 30%, an ETI assumption.
- Wet waste – food waste plus agricultural and sewage slurries. This is assumed to decline gradually as a result of efforts to minimise waste. The gate fee paid for wet waste is based on an ETI review of gate fees for waste, including the 2016 WRAP Gate Fees Report[109].
- Dry waste – residual (post-recycling) municipal and C&I waste. Measures to reduce, reuse and recycle waste are assumed to drive a reduction in residual waste arisings over time. Residual waste is assumed to be 45% biogenic. The gate fee paid for wet waste is based on an ETI review of gate fees for waste, including the 2016 WRAP Gate Fees Report.

Figure 14
Availability of biomass and waste resources in ESME (TWh, based on the GCV of resources), 2010-2050



Emissions calculations

Table 14 provides the consumption and emissions factors used in ESME for UK and imported biomass, imported biofuel and dry waste (wet waste is assumed to be carbon neutral as it is biogenic waste which would otherwise have decomposed on land or in landfill). Biofuel imports just have an emissions factor.

106 The ESME data references book and further reading on the ESME model and its outputs is available at: http://www.eti.co.uk/programmes/strategy/esme. The ESME dataset can be downloaded from: http://www.eti.co.uk/strategy
107 ETI (2017). Increasing UK biomass through more productive use of land [online]. Available at: http://www.eti.co.uk/library/an-eti-perspective-increasing-uk-biomass-production-through-more-productive-use-of-land
108 BEIS (2017). The UK and Global Resource Model [online]. Available at: https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model
109 WRAP (2016). Gate Fees Report 2016 [online]. Available at: http://www.wrap.org.uk/content/gate-fees-report-2016

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Table 13
Consumption and emissions factors (tCO_2/kWh, calculated based on GCV of resource) for bio-resources in ESME v4.3[110]

Resource	Consumption (tCO_2/kWh)	Emission (tCO_2/kWh)
UK Biomass	0.0002920	0.0003318
Imported Biomass	0.0002678	0.0003318
Imported Biofuel	–	0.0001000
Dry Waste (45% biogenic)	0.0001674	0.0003435

Emission Factor: This represents the tonnes carbon dioxide (CO_2) released if 1kWh (GCV) of biomass is fully combusted (i.e. the embodied carbon in the biomass).

Consumption Factor: This is in effect a carbon credit which offsets some of the carbon dioxide released when 1 kWh biomass is used. The % of the embodied carbon offset depends on the source of the feedstock (UK biomass, imported biomass or UK waste).

For a bioenergy generated without CCS:

Net carbon dioxide emissions associated with using 1kWh biomass in bioenergy production = *Emission Factor – Consumption Factor*

The net emissions calculation includes supply chain emissions but does not include direct land use change or consequential impacts such as indirect land use change or changes in forest carbon stock as a result of changes in harvesting or management practice.

The emissions factor for Imported Biofuels has effectively already carried out this calculation (i.e. the net emissions are 0.0001 tCO_2/kWh). This happens outside the model because liquid biofuels are effectively an end product, rather than a feedstock which is converted to another energy vector.

For bioenergy generated with CCS:

Net carbon dioxide emissions from bioenergy production = *Emission Factor – Consumption Factor – Sequestered Carbon*

where 'Sequestered Carbon' = *Carbon Capture Rate x Emission Factor*

The Carbon Capture Rate represents the % of carbon dioxide captured in a BECCS plant and is technology specific.

Technology assumptions

Figure 15 and Figure 16 show the conversion pathways for biomass and waste in ESME (Version 4.3).

110 ETI (2018). ESME data set [online]. Available to download from: http://www.eti.co.uk/strategy

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Figure 15
Conversion pathways for biomass and biofuels in ESME (V4.3)

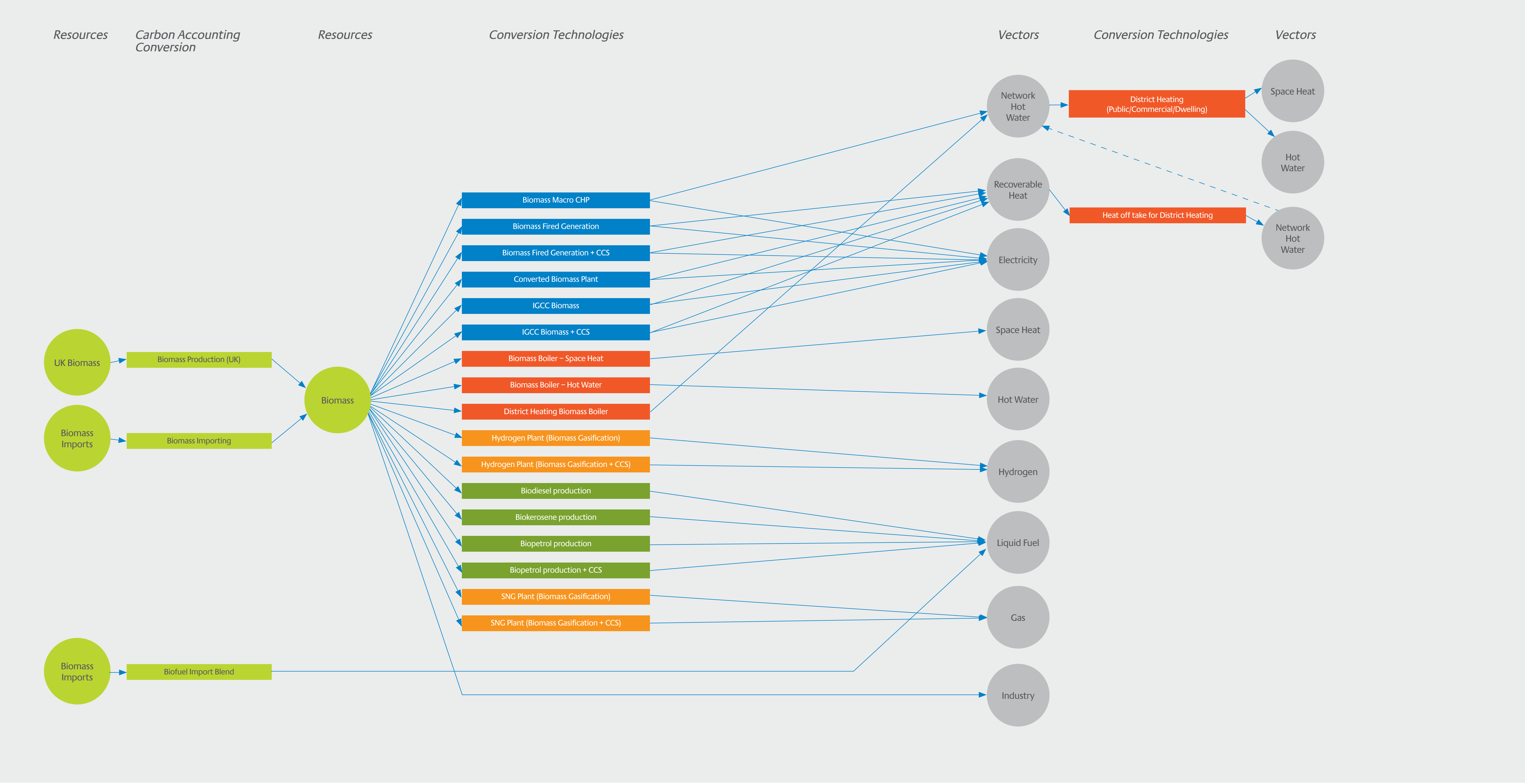

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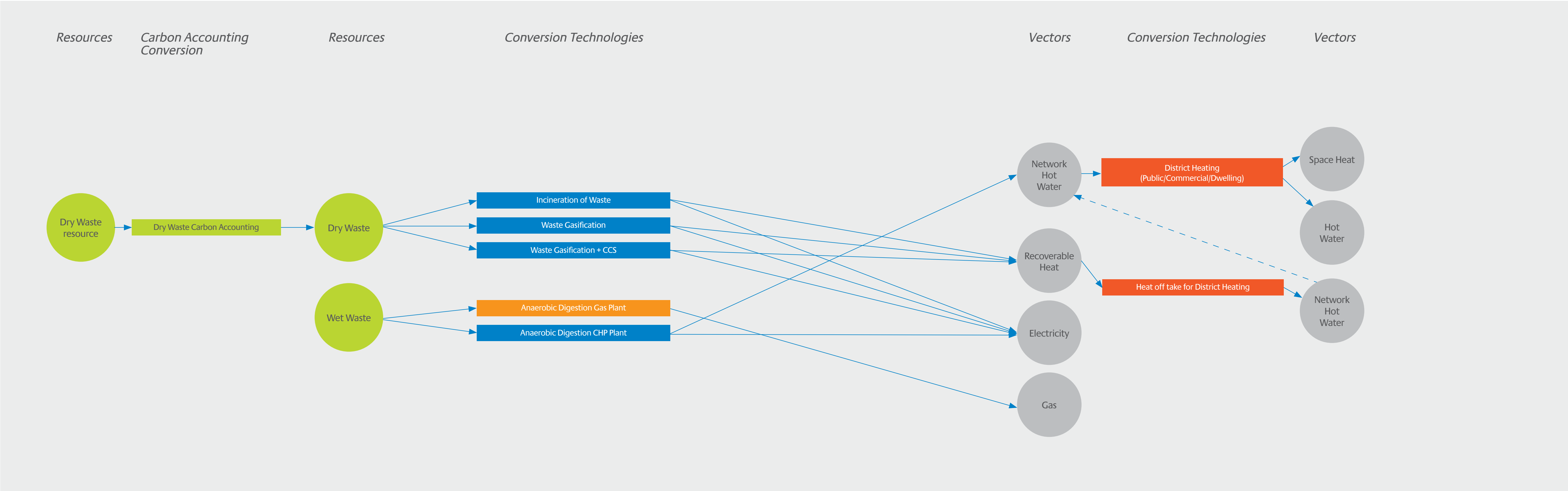
Figure 16
Conversion pathways for wet and dry waste in ESME (V4.3)



8.7. Data charts from ESME

Charts from the ESME scenarios described in Section 4 are available to download alongside this document.

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