energy technologies institute

An insights report by the
Energy Technologies Institute

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

Contents

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Key headlines

- » Biomass combined with Carbon Capture and Storage remains the only credible route to deliver negative emissions, necessary to meet the UK’s 2050 GHG emission reduction targets
- » Gasification technology is a key bioenergy enabler
- » Locational preferences for resource production are apparent
- » Hubs of bioenergy production with CCS appear to be efficient value chain options
- » UK land is finite and valuable – optimisation of land use, including for biomass production, will be important

Executive summary

The ETI's Bioenergy Value Chain Model (BVCM) is a comprehensive and flexible toolkit for the modelling and optimisation of full-system bioenergy value chains over the next five decades. It has been designed to answer variants of the question:

What is the most effective way of delivering a particular bioenergy outcome in the UK, taking into account the available biomass resources, the geography of the UK, time, technology options and logistics networks?

The toolkit supports analysis and decision-making around optimal land use, biomass utilisation and different pathways for bioenergy production. It does this by optimising on an economic, emissions or energy production basis, or with these objectives in combination. The ETI has undertaken a significant programme of work exploring a range of scenarios using the BVCM toolkit, to examine system sensitivities to parameters such as imports, land constraints, Greenhouse Gas (GHG) emissions, cost and technology assumptions, build constraints, and carbon pricing.

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Headline insights are shown below (and in the summary diagram overleaf):

- Biomass combined with Carbon Capture and Storage (CCS) remains the only credible route to deliver negative emissions, necessary to meet the UK's 2050 GHG emission reduction targets. Without targeted intervention and leadership, the opportunities to realise the full benefits of this negative emission potential could be missed
- Bio-hydrogen and bio-electricity are produced in preference to biofuels and bio-methane
- Bio-heat is deployed across the UK, especially in earlier decades
- Gasification technology is a key bioenergy enabler, producing both hydrogen and syngas, and is one of the most flexible, scalable, and cost-effective bioenergy technologies
- Locational preferences for resource production are apparent: with Short Rotation Coppice Willow (SRC-W) in the west / north-west of the UK and Miscanthus in the south and east of the UK. Short Rotation Forestry (SRF) when grown is preferred in the south and east of the country, along with the collection of waste for making Refuse Derived Fuel (RDF)
- Hubs of bioenergy production with CCS appear to be efficient value chain options: with gasification to hydrogen with CCS in the west of England (at Barrow) and Combined Cycle Gas Turbines (CCGT) running on syngas with CCS in the east of England (at Thames and Easington), based on key 'resource-conversion-CCS' pathway optimisation
- Imports (and port capacity) influences the location of key deployments of CCS technologies
- UK land is finite and valuable. With the right prioritisation we believe it could deliver sufficient sustainably-produced biomass feedstock to make a hugely important contribution to the delivery of the UK's overall GHG emission reduction targets

Executive summary

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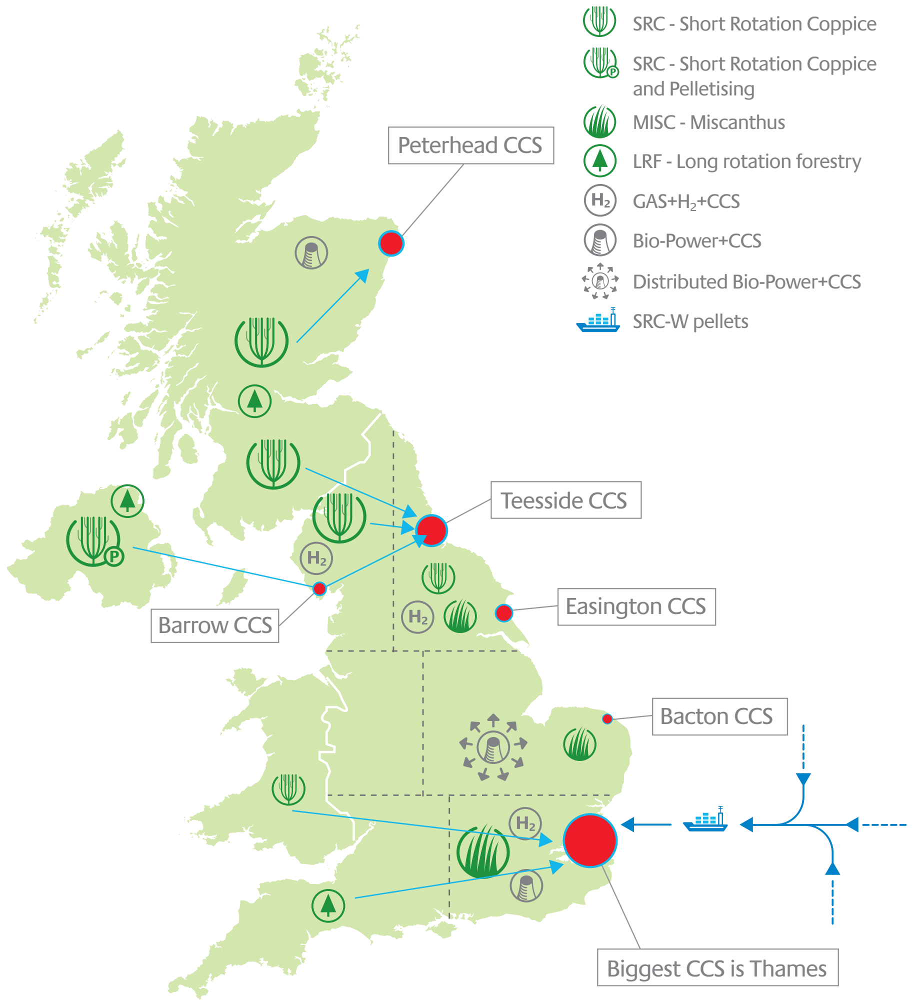
Scale indicator

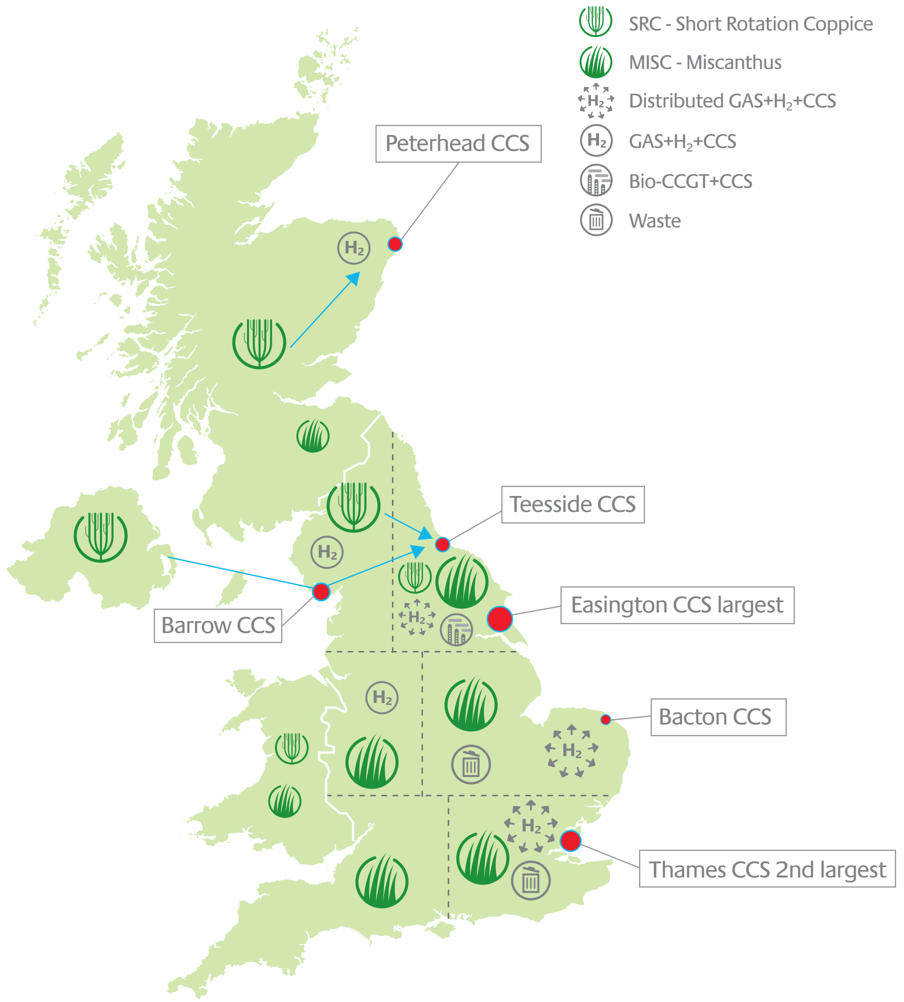
Major production

Minor production

Summary diagram of system differences between scenarios with imports



Summary diagram of system differences between scenarios without imports



Introduction

- Bioenergy sector is complex, yet immature
- Deployed properly, bioenergy has the potential to help secure energy supplies, mitigate climate change and create significant green growth opportunities

Assessments of the future UK energy system using a variety of tools, including ETI's ESME[1] model – an internationally peer-reviewed national energy system design and planning capability – and the UK TIMES / MARKAL models, indicate a prominent role for bioenergy in the coming decades as a means of meeting our GHG emission reduction targets by 2050, especially when combined with carbon capture and storage (CCS). The bioenergy sector is complex, yet immature, and the success of bioenergy's utilisation and growth will depend heavily on the route to deployment. Deployed properly, it has the potential to help secure energy supplies, mitigate climate change, and create significant green growth opportunities[2].

ESME
Energy System
Modelling Environment

It is therefore important to understand fully the end-to-end elements across the bioenergy value chain: from crops and land use, conversion of biomass to useful energy vectors and the manner in which it is integrated into the rest of the UK energy system (e.g. into transport, heat or electricity). To this end, the ETI commissioned and funded the creation of the BVCM. This model, together with the ETI's ESME model, means the ETI is uniquely placed to assess the nature and potential scale of contribution that bioenergy could make to the future low-carbon UK energy system.

This paper aims to set out the key properties of the BVCM toolkit, and describe how it has been used, in conjunction with other ETI programme information, to draw out insights around the nature and scale of the future bioenergy sector which may develop in the UK over the next five decades. The following sections describe the model and work done to date; set out key background assumptions; and then illustrate some of the high level insights that have been identified.

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[1] http://www.eti.co.uk/project/esme/

[2] BioTINA: http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/bioenergy/ and NNFCC: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48341/5131-uk-jobs-in-the-bioenergy-sectors-by-2020.pdf

The Bioenergy Value Chain Model (BVCM)

- A comprehensive and flexible toolkit for the modelling and optimisation of full-system bioenergy value chains
- Models a large number of potential bioenergy system pathways, accounting for economic and environmental impacts
- Supports analysis and decision-making around optimal land use, biomass utilisation and different pathways for bioenergy production

BVCM is a comprehensive and flexible toolkit for the modelling and optimisation of full-system bioenergy value chains. It has been designed to answer variants of the question:

What is the most effective way of delivering a particular bioenergy outcome in the UK, taking into account the available biomass resources, the geography of the UK, time, technology options and logistics networks?

It models a large number of potential bioenergy system pathways, accounting for economic and environmental impacts associated with the end-to-end elements of a pathway. These include crop production, forestry, waste, biomass pre-processing & conversion technologies, transportation, storage, and the sale & disposal of resources. It also caters for biomass imports from outside the UK, as well as CO_2 capture by CCS technologies and forestry.

The toolkit supports analysis and decision-making around optimal land use, biomass utilisation and different pathways for bioenergy production. It does this by optimising on an economic, emissions or energy production basis, or with these objectives in combination. To date, and to the ETI's best knowledge, the BVCM toolkit can model more pathway options in a spatially and temporally explicit fashion than any other biomass supply chain model reported in the literature. Further details of the BVCM toolkit can be found in the Appendix and accompanying 'Overview of the BVCM toolkit capabilities', available on ETI's website[3].

> “The toolkit supports analysis and decision-making around optimal land use, biomass utilisation and different pathways for bioenergy production.”

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[3] www.eti.co.uk/project/biomass-systems-value-chain-modelling/

Background and work performed to date

The ETI has undertaken a significant programme of work exploring a range of scenarios using the BVCM toolkit, to examine system sensitivities to parameters such as imports, land constraints, GHG emissions, cost and technology assumptions, build constraints, and carbon pricing. The results gained have assisted us in developing insights around the future UK bioenergy sector – what it looks like, how big it may be, what resources and technologies are likely to be deployed, and ultimately, how big a role it could play in helping the UK meet its 2050 GHG emission reduction targets. In parallel with the scenarios work, the functionality and usability of the BVCM toolkit has also been progressively enhanced.

The scenario insights are not ‘forecasts’, as the complexity of the system means a multitude of actors will be involved across the chain. The realisation of the potential benefits of bioenergy, such as delivering substantial negative emissions when combined with CCS, will require significant interaction across these actors, facilitated by targeted interventions and leadership. Without this, these opportunities could be missed. Further work across the ETI’s Bioenergy programme, including further BVCM analyses, will be undertaken over the next year, to continue developing our understanding of this complex system.

High-level assumptions

- » BVCM is underpinned by a substantial technology database based on latest available information
- » The UK energy system is looking for around 130 TWh per year of energy delivered from bioenergy sources and GHG emissions of around negative 55 Mt of CO_2 per year in the 2050s

The BVCM toolkit is underpinned by a substantial technology database which contains data and assumptions around technology maturity, and the associated cost and performance improvements expected out to the 2050s, based on the latest robust available information. Technology scale-up risks may still challenge some of these assumptions, and will be updated over time. However, sensitivity analyses have been carried out in order to help understand the impact of cost and performance uncertainties on the likelihood of technology deployment.

Similarly, assumptions have been made around the nature, quantity and geographical distribution of available land in the UK for biomass production, and the potential future yields that could be achieved for different crops.

These assumptions have been based on the latest available data from our own projects, and external projects, in particular building on UKERC’s Spatial Mapping project[4], which identified different levels of ‘available land’ based on varying ‘land suitability’ scenarios.

The ETI’s ESME model has been used to inform the high-level bioenergy outcomes (or targets) that would be required to deliver the lowest-cost overall 2050 UK energy system blueprint. In broad terms this equates to around 130 TWh per year of energy being delivered from bioenergy sources (approximately 10% of total UK energy demand in 2050), and GHG emissions of around negative 55 Mt of CO_2 per year in the 2050s. This is against the national emissions target of 105 $MtCO_2$ per year in 2050. Figure 1.A illustrates an example pathway generated by ESME, that would meet future UK energy demands and emission reduction targets. BVCM has then been used to establish the most effective ways of delivering the bioenergy-specific target within defined resource, geographical, technological and logistical constraints.

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[4] UKERC Spatial Mapping Project – please refer to Global Change Biology Bioenergy 6 (2) (March 2014): Special Issue – Supply and Demand: Britain’s capacity to utilise home-grown bioenergy; and specifically Lovett, A. et. al. (2014) The availability of land for perennial energy crops in Great Britain. GCB Bioenergy 6, 99-107. Project lead: Professor Pete Smith, University of Aberdeen.

High-level assumptions
Continued »

FIGURE 1.A

Annual average energy flows in 2050 for an example pathway generated by ESME for meeting future UK energy demands

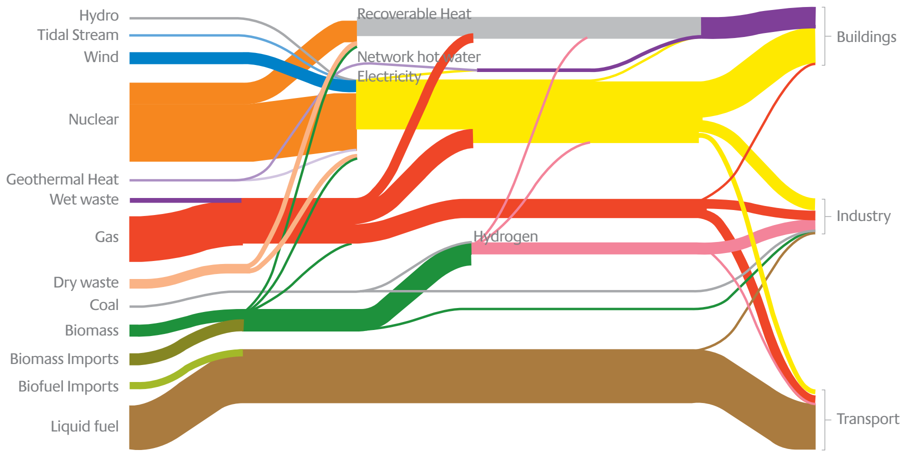
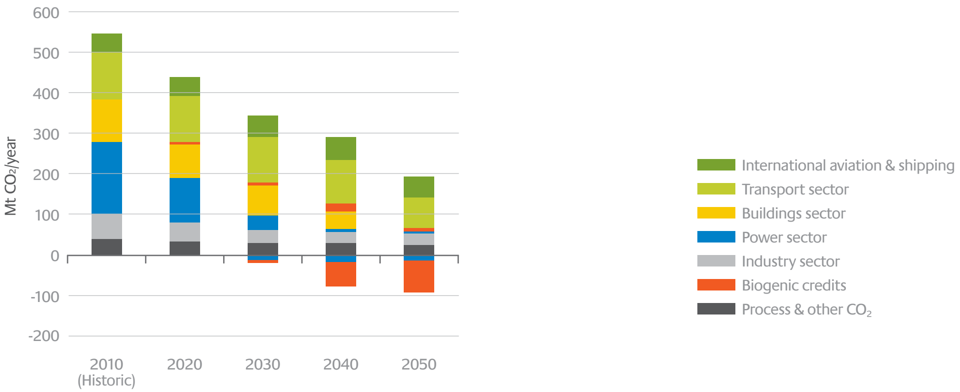


FIGURE 1.B

Emission reduction trajectory (2010–2050)

System CO_2 emissions



Emerging insights from the BVCM analysis

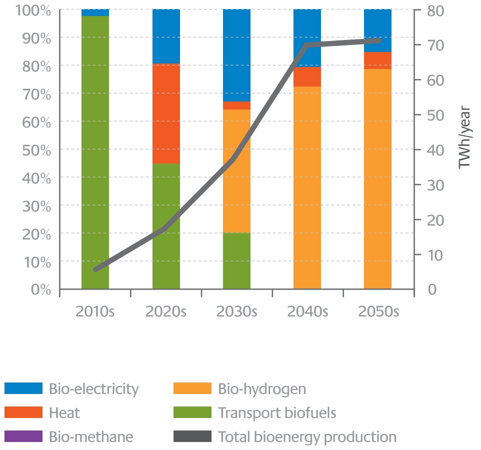
The role of hydrogen, power and CCS in meeting GHG emissions targets

- » Biomass combined with CCS remains the only credible route to deliver negative emissions, and is the dominant method adopted by BVCM to meet GHG emission reduction targets.
- » Using biomass in conversion plants with CCS to generate either hydrogen or electricity is preferred to using biomass for transport biofuels and bio-methane.

FIGURE 2

Typical BVCM transition pathway showing the end vectors produced by bioenergy

Bioenergy mix



The dominance of hydrogen and electricity as end vectors over time is illustrated in Figure 2. The fundamental reason for this is that electricity and hydrogen have no carbon content, and hence CCS can be used to capture the biomass carbon during conversion. By contrast, both bio-methane (bio-SNG) and liquid biofuels retain a significant proportion of the biomass carbon in the final product, which cannot be captured upon use. Whilst these routes can still deliver GHG emission savings compared with fossil-fuel equivalents, they are significantly less beneficial than those that deliver negative emissions.

The use of biomass for hydrogen production is generally much greater (typically 2-3 times) than its use for electricity generation in most scenarios involving no or limited imports, moderate UK biomass production, and moderate/high demand for GHG savings (through a direct negative emissions target or via medium/high CO_2 prices). This is due to biomass to hydrogen being one of the most feedstock-efficient conversion pathways with CCS, and is therefore capable of delivering greater GHG savings. It is important to note that when a CO_2 price is applied within the model, this would rely on a different carbon policy framework from today, where no revenue reward is available for net negative emissions delivered from bioenergy CCS plants.

The role of hydrogen, power and CCS in meeting GHG emissions targets

Continued »

Hydrogen production will generally dominate, apart from in the following scenarios where the mix of end vectors produced alters:

- Either when there is no value on CO_2 within BVCM (either no CO_2 price or no negative GHG emissions target – both of which would generally infer a world where less importance is attached to GHG reduction), or when CCS technology is not viable. In both these circumstances, use of biomass for heat production dominates, often accompanied by a slight increase in liquid transport fuel production. This is because without a CO_2 credit, these are the lowest-cost energy generation options.
- With a low CO_2 price (<£100/tCO_2 in 2010 terms[5]), parity between the amount of hydrogen and power production is often observed when feedstock is constrained (e.g. no imports).
- When feedstock is relatively unconstrained (e.g. high availability with imports), CO_2 prices are high (high system-wide value of CCS) and demand for bioenergy is capped, BVCM will prioritise the amount of CO_2 captured over the energy vector produced, and hence chooses power with CCS pathways. This enables the model to maximise CO_2 revenues whilst keeping under the bioenergy cap. Power with CCS technologies are typically slightly less feedstock efficient, and are expected to have equivalent or slightly higher carbon capture rates than gasification to hydrogen technologies, and hence deliver more (revenue from) GHG savings per unit of bioenergy output.

Although CCS remains the dominant method for BVCM to meet GHG emission targets, BVCM also illustrates that up to a third of the required emission savings could be derived from co-product and end-use energy vector credits. These credits refer to the amount of savings delivered through the displacement of fossil-fuel derived equivalents, or other material / products normally produced outside of the BVCM boundary. Examples include the displacement of oil-based transport fuels by biofuels; and the utilisation of Dried Distillers Grain with Solubles (a by-product from cereal distillation) for high-protein animal feed, displacing generally soya-based animal feed produced elsewhere. Both examples avoiding some of the associated costs and emission impacts from the production and transportation of the products they are displacing.

Modelling of the future UK energy system using ESME suggests a strong future demand for hydrogen within the UK energy system, as a low-carbon energy source, that is used predominantly for industrial processes (such as refining, chemicals, iron, steel, metals etc), or power generation via hydrogen turbines. Smaller amounts may also be used in the transport sector (see Figure 1).

> **“Although CCS remains the dominant method for BVCM to meet GHG emission targets, BVCM also illustrates that up to a third of the required emission savings could be derived from co-product and end-use energy vector credits.”**

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[5] ESME provides CO_2 prices, based on the marginal cost of abatement elsewhere in the UK energy system. The undiscounted low CO_2 price is £400/tCO_2. The discounted medium CO_2 price is £185/tCO_2 (undiscounted it would be ~£700/tCO_2). In BVCM emissions are an incurred cost penalty, and negative emissions are incentivised. Different CO_2 prices can be assumed within BVCM, enabling an assessment to be made of the effectiveness of different CO_2 prices in delivering negative emissions to the system.

The role of biomass for heating

Using biomass to produce heat is widely observed across the UK in most scenarios, initially involving significant deployment of biomass boilers (mostly between 3-10MW scale), or sometimes syngas boilers in the 2010s and 2020s. This deployment is important for strengthening the domestic market for biomass feedstock supply – vital for transitioning to the bio-CCS plant deployments in the 2030s to 2050s. Some of these will develop associated district heating schemes utilising the waste hot water from the bio-CCS plants, allowing bio-heat to play a role in a wider national district heating strategy.

Biomass heating is initially provided through local heating boilers (up to 10 MW scale), and normally in city locations where total heat demand is higher, including commercial, industrial and residential heat network demands[6]. A transition to a number of large-scale district heating schemes is observed in the 2040s and 2050s, driven primarily through the use of waste heat from the large CCS shoreline hubs at Easington and Thames. This would complement a wider national strategy of developing district heating schemes utilising heat from marine heat pumps and nuclear plants.

It is important to also note that bio-heat could play an important role in the required ‘scale up’ of the UK bioenergy sector, since the early deployment of bio-heat technologies encouraged by schemes like the Renewable Heat Incentive (RHI), is helping to strengthen the market for UK-produced biomass in the 2010s and 2020s. This is vital to ensure sufficient sustainable supply of biomass for future bio-CCS deployments from the 2030s onwards.

> “Using biomass to produce heat is widely observed across the UK in most scenarios, initially involving significant deployment of biomass boilers (mostly between 3-10MW scale).”

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[6] BVCM heat demands are based on DECC Heat Map (http://tools.decc.gov.uk/nationalheatmap/)

Biomass technology preferences

Gasification technology is a key bioenergy enabler and is resilient to a broad range of scenarios and sensitivities:

- For hydrogen production the preferred system approach is the gasification of biomass coupled with CCS
- For electricity production the preferred system approach is decentralised biomass gasification (into syngas), piped into centralised Combined Cycle Gas Turbine (CCGT) with CCS plants, particularly in scenarios with little or no imports. Where imports are permitted, gasification remains important, but tends to be less distributed. We do however still see strong deployment of biomass combustion to power with CCS in later decades.

Gasification technologies with CCS offer the best combinations of feedstock efficiency (input energy: output energy), carbon capture efficiency, and through-life costs. The prevalence in many scenarios of gasification technologies to produce both syngas and hydrogen is also in part due to its ability to handle a higher range of minor constituent[7] levels than direct combustion, especially in terms of the ash constraints associated with the combustion of Miscanthus and SRC-W, and the ability to utilise currently negative-cost waste RDF. The adoption of gasification technologies by BVCM remains high across a broad range of sensitivities (e.g. +/- 40% variation in technology cost and performance). This ‘scenario resilience’ provides confidence to move forward with flexible gasification technologies, whilst the relative scale of the emerging markets for hydrogen and electricity are clarified.

There are a variety of dedicated biomass to power with CCS technologies which could play a role in the future UK energy system, however it is important to note that there is currently insufficient operational evidence to confidently pick a specific ‘leading’ power with CCS technology[8].

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[7] Biomass resources often contain small amounts of substances such as potassium, chlorine and sodium for example, often collectively referred to as ‘minor constituents’. Technologies have operational limits to the levels of these minor constituents they can handle, before unacceptable issues of corrosion and fouling may arise. In BVCM it is possible to use set limits to these minor constituents in the input biomass resources, in order to optimise more realistic resource-technology pathways.

[8] The ETI’s Biomass to Power with CCS project assessed the cost and performance improvement trajectories anticipated for a variety of pre-, post and oxyfuel biomass with CCS technologies and concluded that current levels of uncertainties associated with each trajectory prevented a ‘single winner’ from being identified at this time. This is supported by broader conclusions from the ETI CCS Programme.

Locational preferences

The BVCM toolkit provides insights into which types of biomass resources should be grown, where, and over what time period, whilst at the same time identifying where particular gasification and conversion technologies should be located, and which CO_2 shoreline hubs (for carbon sequestration) should be utilised. The full-system nature of this analysis makes this approach extremely powerful in identifying bioenergy pathway options for the UK out to 2050.

Measuring Greenhouse Gas fluxes from cultivated land under ETI's ELUM project

Locational preferences for UK biomass resources

There are clear locational preferences for biomass resource production in the UK.

In general, the preferred resource production pattern follows a north-west / south-east trend, with more SRC-W being produced in the north and west including Northern Ireland, and more Miscanthus being produced in the south east and south of the UK.

SRF when produced, is generally preferred in the south and east. Winter wheat and sugar beet are often produced and used in the earlier decades when there is 'spare' arable land, maximising benefits accrued from co-product revenues. This production occured mostly in the east and south of the UK.

Waste arisings and the intermediate RDF are associated with large population centres, and therefore are highest around London & the south and east, and are fully utilised in all runs without imports.

These locational preferences reflect the optimisation between the highest yielding areas for each feedstock (and across feedstocks), the conversion technology demands, and the cost of transportation logistics across the bioenergy value chains.

The locational preferences for UK biomass resources showing some of the north-west and south-east patterns are demonstrated in Figures 3A, B and C.

> “The resource production pattern follows a north-west / south-east trend, with more SRC-W being produced in the north and west including Northern Ireland, and more Miscanthus being produced in the south east and south of the UK.”

Locational preferences for UK biomass resources

Continued »

FIGURE 3A

Locational map showing examples in the 2050s of regions producing SRC-Willow and Miscanthus

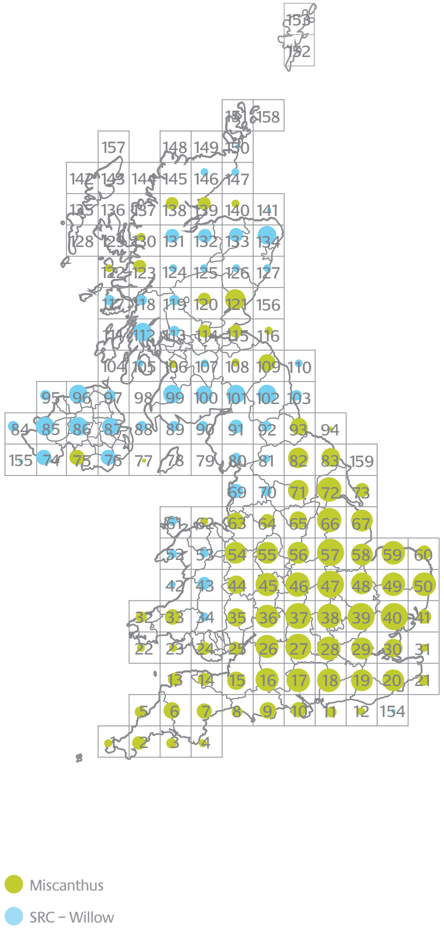


FIGURE 3B

Locational map showing examples in the 2050s of regions producing SRF

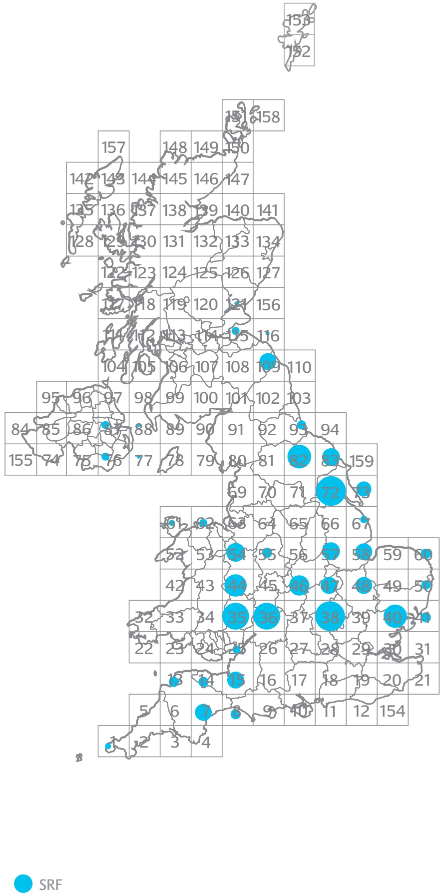
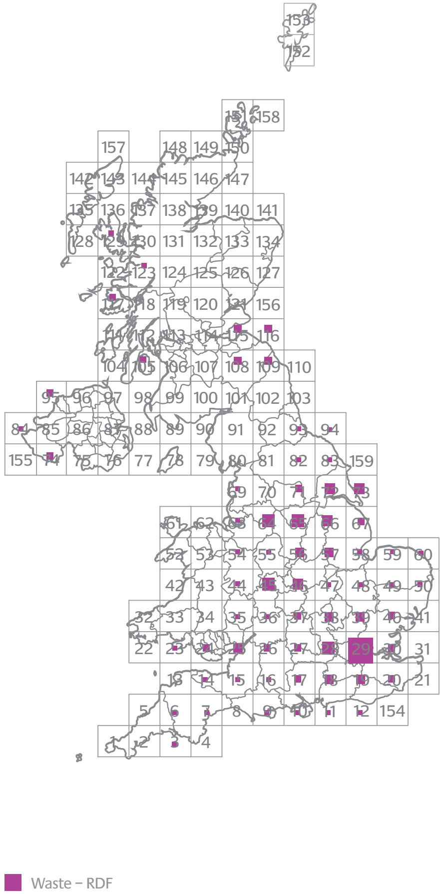


FIGURE 3C

Locational map showing examples in the 2050s of regions producing RDF from waste arisings



> “Waste arisings and the intermediate (RDF) are associated with large population centres, and therefore are highest around London & the south and east, and are fully utilised in all runs without imports.”

Each map has slightly different scale

Locational preferences for technology deployment

There are similar locational patterns of technology deployment observed across a range of scenarios, with the permitted CCS 'shoreline hub' sequestration points within the model having a significant influence on locational choices. These shoreline hubs are not the actual point of 'sequestration', but are the location on land from which CO_2 will be compressed and piped to offshore sequestration stores, that tend to be either saline aquifers or depleted oil and gas reservoirs[9]. It is the system-level balance between feedstock type & location, intermediates such as syngas, CO_2 transportation costs, and technology costs that determines the pathway choices made by the BVCM tool.

There are strong locational preferences for technology deployment in the UK, consistent with the locational resource preferences.

Gasification to hydrogen with CCS plants are located across a broad range of locations in the UK, but their feedstock inputs vary with location:

- In the west of England, large gasification to hydrogen with CCS plants are clustered around Barrow, which has both a large shoreline hub capacity and is an optimal location for the significant supplies of SRC-W (grown in the north, west and Northern Ireland) to be transported to
- In the south and east of England where Miscanthus predominates (in bales and pellets), a more distributed network of plants is preferred, requiring the captured CO_2 to be piped to the nearest shoreline hub

Bio-CCGT with CCS plant, and other forms of biomass combustion to power with CCS, tend to be deployed in the east and south:

- The former generally utilises syngas, produced locally from large-scale gasification plants or from a distributed gasification network across the south and east of the UK. Its main feedstock is negative cost waste RDF and waste wood. However, it also chooses Miscanthus in some areas
- The biomass to power combustion plants predominantly prefer Miscanthus as their main feedstock, when imports (SRC-W pellets) are not permitted, again dominant in the south and east where yields are generally highest

As an illustration, Figure 4 shows an example of resource consumption and production for two of the main technologies we believe could play a significant role in the future UK bioenergy system:

a) for large scale generic gasification plants[10], producing syngas which is piped to be utilised by centralised CCGT with CCS plants; and

b) for large scale gasification to hydrogen plants with CCS;

Figure 4 (c) and (d) then illustrate the potential spatial deployment of these technologies in the 2050s, along with the associated piping infrastructure that would be required to transport syngas to the centralised CCGT with CCS plants.

As can be seen in (cii) and (d) in this instance, two significant CO_2 shoreline hubs are built. The first at Easington is predominantly for CCGT with CCS plants (cii), and the second at Barrow is predominantly for gasification to hydrogen plants with CCS (d).

Due to the 'trade-offs' between transportation costs of feedstock, intermediates or CO_2 captured, there is often a case for moderate deployment of distributed gasification to hydrogen with CCS plants across the UK (closer to feedstock sources – assuming a distributed demand for hydrogen, e.g. for transport or power), when the cost of moving the captured CO_2 via pipelines to the nearest shoreline hub is more economic than significant movement of biomass feedstocks across the UK.

When this movement of captured CO_2 via onshore CO_2 piping is unfeasible or undesirable, or similarly, the movement of the intermediate syngas via pipeline networks; then the bioenergy system deployed is likely to involve more feedstock transportation, often following pre-processing densification steps.

> **“There are strong locational preferences for technology deployment in the UK, consistent with the locational resource preferences and proximity to CCS shoreline hubs.”**

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[9] These land locations from where CO_2 is piped to offshore storage sites, will be referred to as 'shoreline hubs' for the rest of the document.

[10] Generic gasification plants are plants that operate without CCS capability and often have greater feedstock flexibility. Their main output is syngas, which in BVCM is classed as an 'intermediate' product, which goes on to be converted to a different energy vector (electricity, heat, bio-methane, transport fuels).

Locational preferences for technology deployment

Continued »

FIGURE 4.A

Resource consumption and production (GWh/yr) for Gasification generic – Large

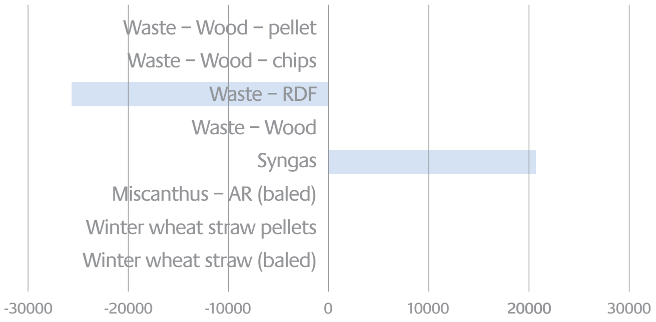


FIGURE 4.B

Resource consumption and production (GWh/yr) for Gasification + H_2 + CCS – Large

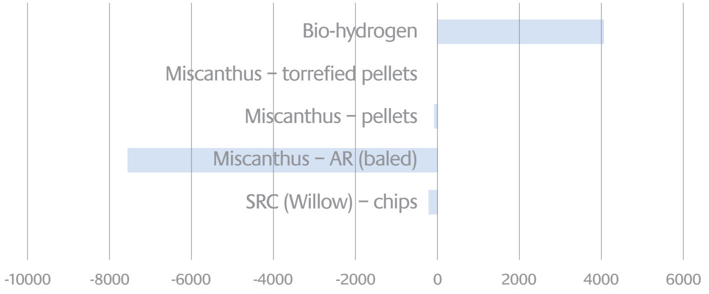
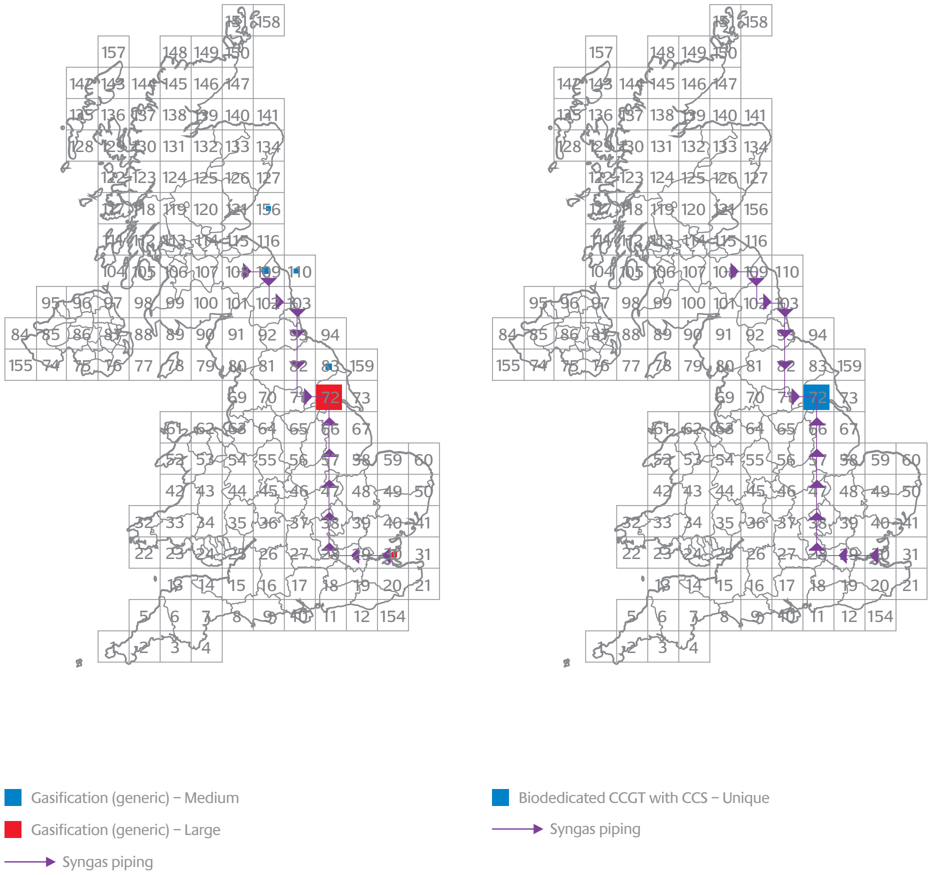


FIGURE 4.C / 4.CII

Example of resource consumption and production for three of the technologies deployed in the UK in the 2050s



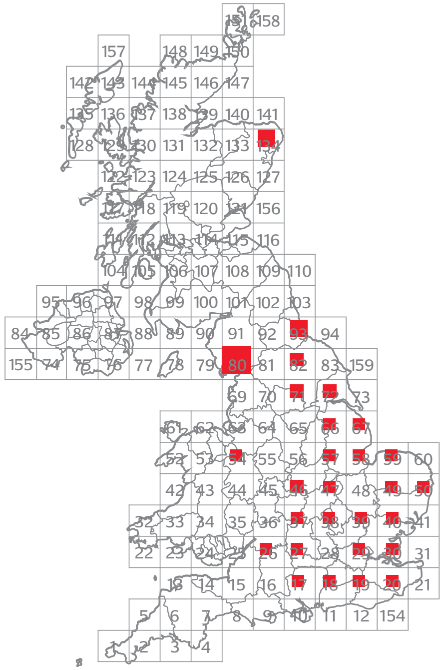
Each map has slightly different scale

Locational preferences for technology deployment

Continued »

FIGURE 4.D

Resource consumption and production for Gasification generic – Large



🟥 Gasification + H_2 + CCS – Large

Locational preferences for CO_2 shoreline hub development

The BVCM toolkit has been parameterised based on the optimised development plan of CCS capability across the UK, produced from a combination of ETI's ESME, and 'UK Storage Appraisal' work commissioned under the CCS Programme[11]. Details are shown in Table 1 below.

TABLE 1

Shoreline Hub capacities at sites identified as part of the suggested development plan of carbon sequestration infrastructure across the UK[11]

	Cumulative maximum sequestration rate (Mkg CO_2) at Hubs			
Shoreline Hub location within BVCM	2020s maximum capacity	2030s maximum capacity	2040s maximum capacity	2050s maximum capacity
Easington	125,000	275,000	300,000	300,000
Thames	50,000	225,000	250,000	250,000
Bacton	0	150,000	200,000	200,000
Peterhead	75,000	150,000	150,000	150,000
Barrow	25,000	100,000	100,000	100,000
Teesside	0	25,000	50,000	50,000

Numerous scenarios have been run to assess the influence of available CCS shoreline hubs on the spatial bioenergy sector deployment seen in BVCM. An example of the results of this analysis is shown in Table 2.

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[11] http://www.eti.co.uk/wp-content/uploads/2014/03/A_Picture_of_Carbon_Dioxide_Storage_in_the_UKUPDATED.pdf

Locational preferences for CO_2 shoreline hub development

Continued »

In the case where biomass imports ARE NOT permitted:

- There is a strong preference to build large, highly-efficient biomass-CCS plants at three shoreline hub locations – Thames, Barrow and Easington. These locations align most favourably with the dominant growing regions and waste arisings
- Outside of these dominant areas, biomass may be converted locally via a more distributed network of gasification to syngas, or to hydrogen with CCS, with CO_2 piping carrying the captured CO_2 from the latter to the nearest shoreline hubs
- If this onshore piping of syngas or CO_2 is not feasible or desirable, feedstock can still be transported to these CCS shoreline hubs, but this comes with cost and emission penalties

In the case where biomass imports ARE permitted:

- The Thames shoreline hub is the strongly preferred CCS location due to its proximity to ports with significant biomass feedstock import capacity
- Very little transport of CO_2 within the UK is observed – most of it being captured near to the CCS shoreline hubs

Under the general scenarios with no biomass imports and all six CCS shoreline hub locations available, BVCM prefers to build large, highly-efficient CCS plants (either biomass gasification into hydrogen or electricity) at three main shoreline hubs: Easington, Thames and Barrow. These locations offer the most economically optimal balance between access to biomass and waste feedstocks and CO_2 capture and transportation costs within the UK. The shoreline hubs at Teesside, Peterhead and Bacton play much less significant roles in the majority of 'no-import' scenarios.

When biomass imports are permitted, the Thames hub becomes the clearly-preferred shoreline hub location[12]. This is in part due to its proximity to ports with significant biomass import capacity, and its sizeable CO_2 storage capacity. The shoreline hub at Teesside also plays a larger role in the 'import' scenarios. There is very limited transport of CO_2 within the UK associated with scenarios permitting imports, as most is captured near to one of the main CCS shoreline hubs (due to the more centralised nature of the bioenergy system deployed). When imports are not permitted, the carbon capture part of the system becomes more decentralised, with an increase in CO_2 being transported to the shoreline hubs, as shown in the table below. This reflects the economic trade-offs made between feedstock transportation and CO_2 transportation via pipelines.

TABLE 2

Carbon capture and transportation preferences in the 2050s (with and without biomass imports permitted), at each of the six CCS shoreline hubs

Mkg CO_2/yr	Thames	Barrow	Easington	Teesside	Peterhead	Bacton
Captured at site	77,994 1,032	3,141 4,711	2,339 9,280	13,923 1,570	3,524 1,570	561 208
Transported in to site	3,557 10,263	0 1,341	2,489 6,181	281 1,178	1,296 563	1,534 3,791
Total sequestered	81,552 11,295	3,141 6,052	4,828 15,461	14,204 2,748	4,820 2,133	2,095 4,000

Whilst there might be a slight difference in the pathways of CCS development when imports are, and are not permitted, the dominance of Thames and Easington CCS shoreline hubs is apparent in both scenarios. This 'scenario resilience' suggests there is a robust pathway forward today without waiting for certainty about the role of imports in the future UK bioenergy sector.

When CCS as a technology is not permitted within the model, BVCM is unable to generate the same level of GHG savings. Significant benefit can still be derived from utilising biomass to generate energy that displaces fossil-fuel-derived equivalents, e.g. heat and liquid transport fuels. The only alternative, scalable option for delivering emissions savings is through the deployment of long rotation forestry for carbon capture purposes (utilising significant land for afforestation, e.g. 0.5-1 million hectares (Mha)) – i.e. the biomass standing stock acts as a longer-term carbon store. BVCM will often deploy a combination of these routes in 'non-CCS' scenarios to deliver around 50% of the CCS-scenario GHG emission savings, although there are associated cost and land-use impacts of not utilising CCS.

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[12] When imports are permitted and a medium or high CO_2 price is used, the system will often over-generate GHG savings. In this example, the import scenario generates nearly twice as many savings as the non-import scenario, however, the example is being used to illustrate the relative importance of different CCS locations and CO_2 piping within each scenario.

Implications for UK biomass potential

The potential scale of UK biomass production could be very substantial, but optimisation of land use is key.

- BVCM has affirmed there are plausible routes for bioenergy to deliver significant negative emissions into the future UK energy system – hugely important for ensuring the UK meets its GHG emission reduction target in an affordable way. In addition to the negative emissions, 10% of the UK final energy demand could also be met. Our analyses shows that around two-thirds of this could be delivered by UK-sourced biomass feedstocks; reducing reliance on imported feedstocks in the longer-term
- UK land is finite and valuable. With the right prioritisation, taking in to account other key uses such as food and feed production, conservation and wider ecosystem services; we believe it could deliver sufficient sustainably-produced biomass feedstock in later decades to make a hugely important contribution to the delivery of the UK's overall GHG emission reduction targets without the need for potentially unacceptable levels of land-use change having to be implemented

A significant focus for the ETI in using the BVCM tool has been on assessing the potential scale of UK biomass production, and quantifying how much bioenergy this could deliver. The granular spatial approach offered in the BVCM toolkit enables us to test the system sensitivities to different assumptions around available land, and consider national versus local land use constraints. These assumptions can yield significantly different outcomes, both in terms of volumes and the spatial distribution of feedstock production. Applying constraints at the local level (50km x 50km cell in BVCM) can be a proxy for locally-applied land use policies (e.g. no more than 15% of any arable farm could be converted, or no more than 15% of the arable portion of a mixed farm). Applying constraints at the national level can reflect national land use policies which favour (for example) optimisation of land across the UK, or adherence to national land use restrictions, but without determining what each farm or region does (e.g. some farms located in optimal areas could switch to growing 100% biomass feedstocks if appropriate and sustainable[13]).

When identical conservative constraints on land class types are applied locally and nationally, with all other parameters remaining constant, national optimisation could lead to a decrease in the amount of land required to produce the same amount of biomass feedstock. By contrast, constraining each cell (locally) forces bioenergy to be grown in increasingly sub-optimal areas. This is potentially very significant in terms of energy production, emissions reduction and amount of land required. To illustrate this concept, under the 'national' scenario above, ~135 TWh/yr of UK biomass could be produced from 1.28 Mha of land; whereas 2.3 Mha is needed to produce a similar level of feedstock under local land constraint scenarios. This more concentrated production scene, requiring less land use change, could reduce competition between other land uses at the national level, and may present less overall risk of displacing other key agricultural land uses such as for food and feed production. Opportunities for wider land use optimisation across the entire agricultural system should be considered (sometimes referred to as 'sustainable intensification'). To reiterate, the example shown on the following pages is used to illustrate the potential reduction in land use change required to deliver a set amount of biomass. It is not at this stage, a comprehensive assessment of the 'preferred' locations for more intense biomass feedstock production. This assessment would need to take account of much wider considerations such as ecosystem services, other agricultural activities including food and feed production, and public acceptability. To facilitate an initial assessment of this the ETI has granted a licence for BVCM to be used in a Supergen Bioenergy project, led by Imperial College London, looking at optimisation of land for food, feed and bioenergy biomass production, and wider ecosystem services[14].

Land use optimisation could also have an impact on the location of technologies deployed across the UK. As an example, Figures 5 and 6 below illustrate the difference between the two scenarios for Miscanthus and SRC-W production (assuming no imports), and the impact it has on the spatial aspects of technology deployment. It could also have significant implications for the scale of associated infrastructure, for example CO_2 piping networks required, as shown in Figure 7. Again, in the absence of certainty today, in terms of how land use constraints (policy) may apply, the resilient locations that occur in both scenarios are likely to offer lower risk options for developing resource and technology deployments in the near term.

One of the issues for the bioenergy sector is that decisions around the size and location of resource and technology investments are made by many, different organisations and actors. This makes a coordinated approach to land use optimisation, with sustainability and delivery of genuine carbon savings at its core, more challenging. This highlights the need for a more strategic and systematic national plan to guide more local initiatives seeking to incentivise either biomass production, or bioenergy technology deployment.

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[13] Noting that planting a mix of cultivars (genotypes) and species (crops) at the farm level may remain important for pest and disease resilience, and optimising wider biodiversity and ecosystem service benefits.

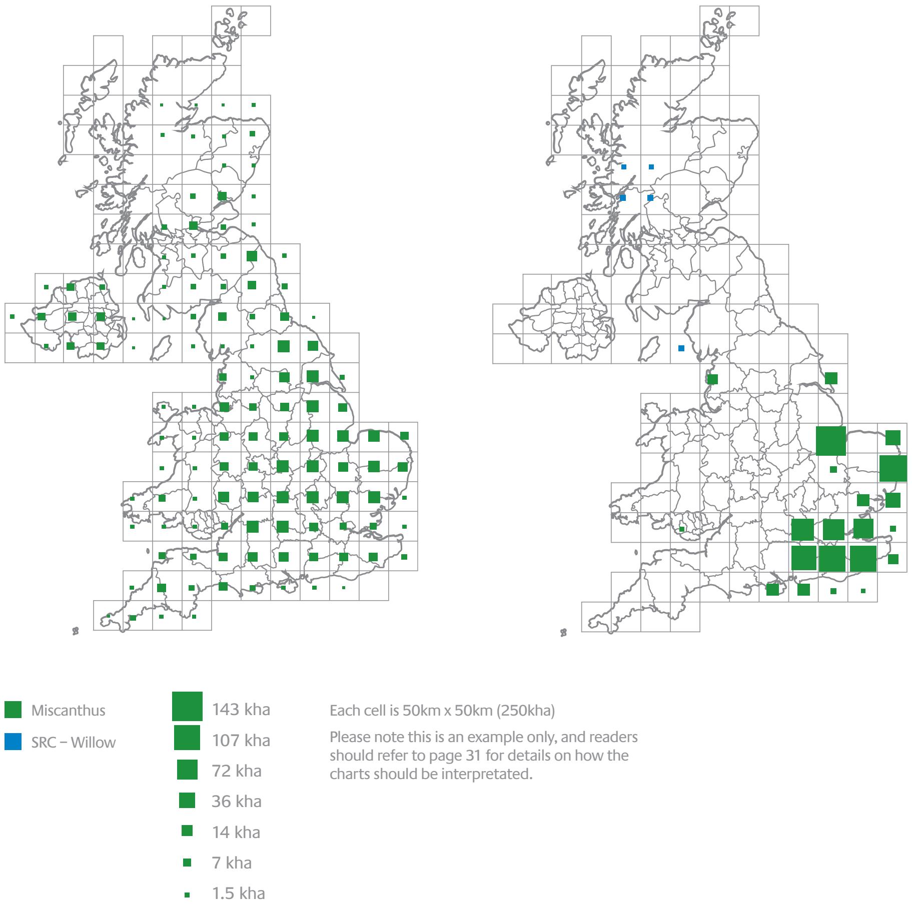
[14] EPSRC SUPERGEN Bioenergy Challenge Project EP/K036734/1: http://www.supergen-bioenergy.net/research-projects/bioenergy-value-chains--whole-systems-analysis-and-optimisation/

Implications for UK biomass potential

Continued »

FIGURE 5

Example to illustrate the reduction in land use change required for UK biomass production when land class constraints are applied (a) locally, and (b) nationally, in the 2050s decade, with moderate yield assumption and land constraints applied



A. Local land use optimisation (cell level)

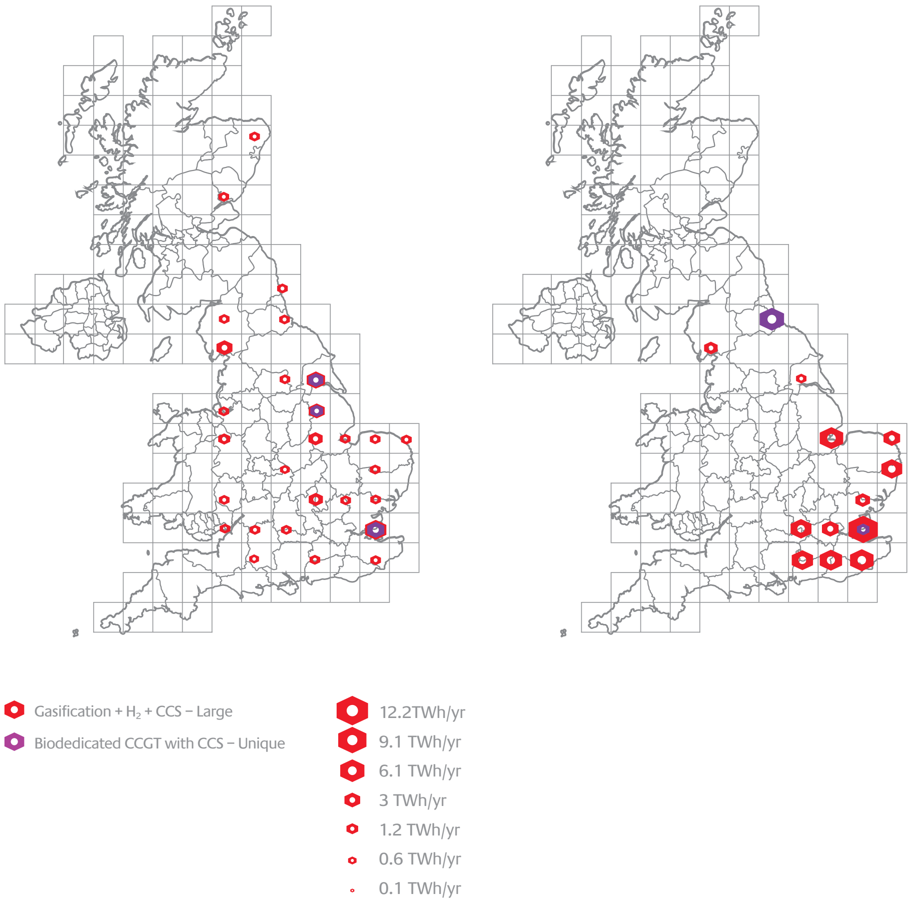
B. National land use optimisation (UK level)

Each cell is 50km x 50km (250kha)

Please note this is an example only, and readers should refer to page 31 for details on how the charts should be interpreted.

FIGURE 6

Example to illustrate the difference in locational deployment of key technologies, based on location of biomass production when land class constraints are applied (a) locally, and (b) nationally, in the 2050s decade



A. Local land use optimisation (cell level)

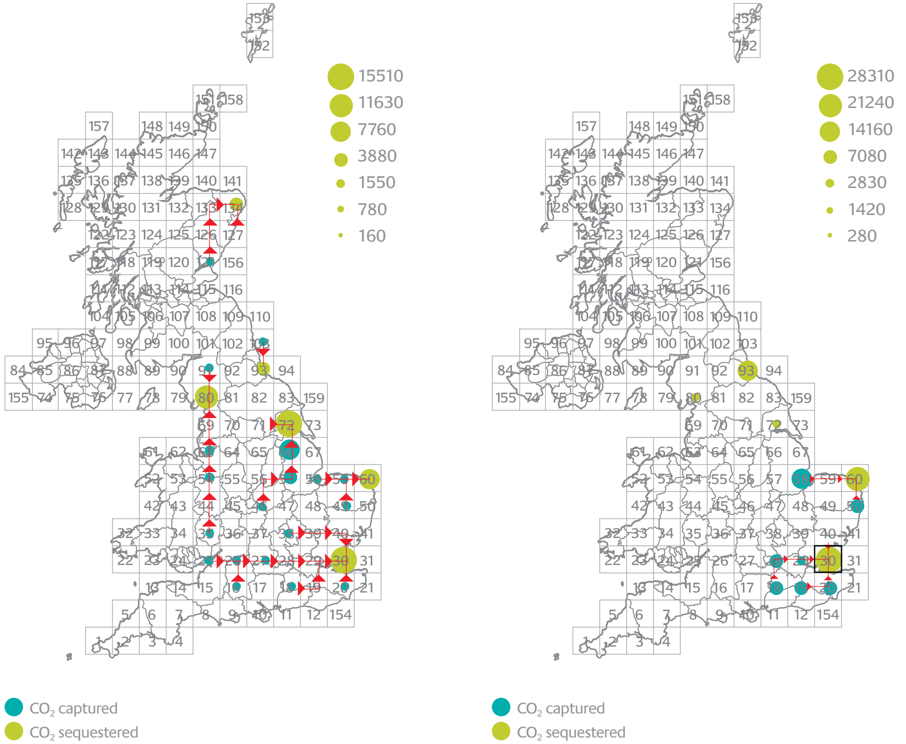
B. National land use optimisation (UK level)

Implications for UK biomass potential

Continued »

FIGURE 7

Example to illustrate the change in scale of CO_2 piping infrastructure required, based on location of technology deployments when land class constraints are applied (a) locally, and (b) nationally, in the 2050s decade (see each scale; units are $MkgCO_2$)


A. Local land use optimisation (cell level)

B. National land use optimisation (UK level)

CO_2 values for cell 30 (Mkg CO_2)

Captured	6,680
Transported in	8,815
Transported out	0
Sequestered	15,495

CO_2 values for cell 30 (Mkg CO_2)

Captured	9,363
Transported in	18,950
Transported out	0
Sequestered	28,314

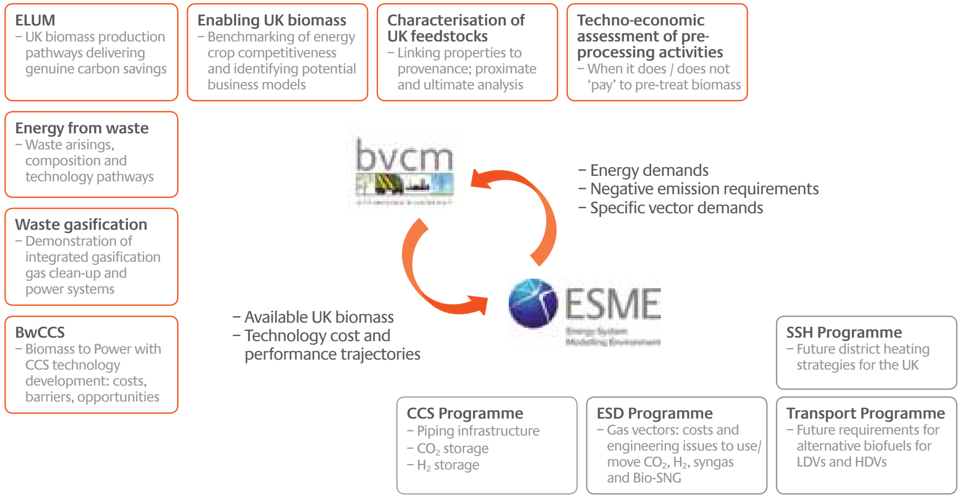
Summary and next steps

Clear locational and deployment preferences for resources, technologies and CO_2 shoreline hubs that may play a significant role in a future UK bioenergy sector have been identified. The BVCM toolkit enables us to assess the sensitivities of the system to different parameters, drawing on the best available data. The ETI is uniquely placed to assess the impact of different pathways for the whole energy system, and determine the level of integration needed across different sectors to successfully transition to the future low carbon economy required to meet our 2050 GHG emission reduction targets. This is illustrated in Figure 8 below. Further work across the programme and using BVCM will be undertaken by the ETI over the next 12 months to continue developing our understanding of system sensitivities, and identify resources and technologies resilient to different drivers and constraints. This will enable us to develop further insights on the potential nature and scale of the future UK bioenergy sector, and the types of policy and wider sector support required to deliver the benefits identified.

FIGURE 8

Illustration of the integrated analysis undertaken by the ETI, of the role of bioenergy within the wider UK energy system, drawing on work which is planned, underway or completed.

Integrated analysis of the role of bioenergy within the wider UK energy system



Orange boxes denote data and information flowing from ETI Bioenergy projects, and grey boxes denote data used from other ETI projects.

Acknowledgements

The ETI has worked with E4tech and Imperial College Consultants to enhance the functionality of the BVCM toolkit over the last 12 months, building on the outputs from the original BVCM project which was delivered by: E4tech (project management and technical oversight); Imperial College London (model formulation and Advanced Interactive Multidimensional Modelling System (AIMMS) implementation); Forest Research (ESC-CARBINE yield data), Rothamsted Research (first generation crops and Miscanthus yield data), EDF (EIFER) (Land Cover mapping), University of Southampton (ForestGrowth SRC yield data), Agra-CEAS (opportunity cost data) and Black & Veatch (technology performance data).

Appendix

Description of the BVCM toolkit

BVCM is a spatial and temporal model of the UK, configured over 157 cells of 50 x 50km size, with a planning horizon of five decades from the 2010s to the 2050s. As a pathway optimisation model, it is able to determine the optimal combination of crops[15] to be grown and the optimal allocations of land production over each decade, to deliver a particular bioenergy outcome. Similarly, the optimal combinations of biomass pre-processing, conversion technologies and the transport networks required to satisfy particular production targets[16] can be assessed. All of these aspects are considered simultaneously to determine optimal outcomes at a system level.

The model is able to assess the relative benefits of immediate bioenergy value chains, as well as the longer-term transition pathways over the next five decades, as the bioenergy sector develops. The optimal energy systems and pathways between them are determined in order to minimise a combination of whole-system cost and environmental impacts.

Different constraints and credits can be considered, including land suitability masks, carbon price scenarios, by-product and end-product revenues and 'avoided' emissions, resource purchase and disposal, and CCS & forestry carbon sequestration. Being a combined spatial and temporal model, the BVCM considers the dynamics and spatial inter-dependence of system properties such as the allocation of crops to available land based on optimal yields and centres of demand. It also identifies the optimal location and type of conversion technologies based on feedstock quality & availability and logistical interconnections. In addition to the analysis of the optimal feedstock and technology pathway, it also provides an analysis of the staging of investment and operational strategies.

The BVCM toolkit comprises the following core components

- a mixed-integer linear programming (MILP) model implemented in the AIMMS modelling platform and solved using the CPLEX MIP solver
- databases, in a series of Excel workbooks and text files, that are used to store all of the data concerning technologies, resources, yield potentials, waste arisings, etc
- a user-friendly interface in AIMMS for configuring and performing the 'what-if' optimisation scenarios, and visualising the spatial results (see below)
- visualisation tools in Excel for the summary results and stochastic analyses

The toolkit also includes a stochastic analysis module whereby uncertainties in key parameters (e.g. biomass yields and costs, and technology costs and efficiencies) can be specified as distributions. This allows the identification of key sensitivities and the more robust solutions, i.e. those resources and technologies that appear across a large number of different scenarios. The data-driven nature of the BVCM toolkit enables it to be easily extended (e.g. by adding resources and technologies) and made applicable over different spatial and temporal scales.

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[15] The crops considered by the model include a variety of first and second generation biomass feedstock, e.g. winter wheat, sugar beet, oil seed rape, Miscanthus, short rotation coppice willow, short rotation forestry and long rotation forestry.

[16] Production targets in this context can be whole-system energy targets, targets for each specific energy vector, or even targets at the regional level

Table 3

Summary of BVCM functionality

A brief summary of the model's functionalities are provided below. More details on the model functionality, architecture and mathematical formulation can be found in Samsatli et al. (2014)[17].

Optimisation options and model constraints	The model can be configured to deliver each of the following optimisation options either in isolation or in combination: » Minimise system level costs or maximise system level profit (these relate only to the bioenergy sector, not the wider UK) » Minimise greenhouse gas emissions » Maximise energy production Each of these optimisation parameters can also be constrained in a number of ways.
Time	There are two important temporal elements » Decadal – 2010s, 2020s, 2030s, 2040s, 2050s; and » Seasonal – there is a division of a typical year of each decade into a maximum of four seasons to reflect the fact that biomass production is seasonal in nature
Climate	The biomass yields within BVCM are climate-dependent. The user can choose one of two pre-defined climate scenarios based on the UK's climate projection scenarios from 2009 – the UKCP09 datasets.
Spatial	Biomass production, logistics and technology location within BVCM are defined within 'cells'. The UK is divided into 157 square cells of length 50km.
Energy resources	These include biomass feedstocks, intermediates[18] and end-use energy vectors. BVCM does not prescribe a fixed pathway to the value chain and resources may undergo a number of transformations from harvested biomass to finished products. The toolkit is populated with 82 different energy resources, and the user can add new ones via a database. Biomass feedstock resources have yields specific to each cell, decade and climate scenario. All resources have a fixed set of properties (e.g. Lower Heating Value, composition) independent of location or decade.
Conversion technologies	These convert input resources into output resources: either intermediates[18] or end-use energy vectors. The toolkit is populated with 61 distinct conversion technologies (some of which are the same technology at different scales). Again the user can add new ones via the database.
Transportation logistics	The model allows resources to be moved from one cell to another by five different means: road, rail, inland waterway, close coastal shipping and pipelines (for certain gaseous intermediates). Viable routes and their associated tortuosity have been mapped and used to determine the relative costs of different routes.
Biomass imports	The user can choose to allow or prohibit imports of biomass feedstocks to the UK. The tool is configured with some pre-defined import scenarios (cost, availability and GHG impacts) based on previous studies; the user is free to modify these. The likely import and export capacities of all the UK's ports are embedded within the model.
Stochastic analysis	The model can run in stochastic mode to assess the impact of the uncertainties associated biomass yields and costs, and conversion technology capital costs and efficiencies. These uncertainties are specified as ranges, and a set of results is generated by sampling from these ranges. This allows the identification of more robust solutions, i.e. those resources and technologies that appear across a large number of scenarios.
Land use and biomass production	The user has the ability to constrain the BVCM model based on existing land use, and preferred land use transitions. Yield maps for all crop options underpin the model, and variations of the yields expected in each cell are characterised (high, medium, low) under different climate scenarios and different yield scenarios using assumptions around crop breeding and management improvements. It is also possible to take account of diminished yields in the establishment phases of second generation crops, and to assess the impact of constraining crop production ramp-up rates e.g. if planting were limited by a finite supply of contractors, equipment or rhizomes etc.
CCS	CO_2 can be captured anywhere in the UK (once a CCS plant has been built) but CO_2 can only be sequestered via 'shoreline hubs' to be permanently stored underground at certain offshore locations, e.g. saline aquifers or depleted oil and gas reservoirs. The model allows CO_2 to be transported from the point of capture to the permitted shoreline hubs via pipelines at a defined cost. This means that BVCM can make siting and transportation trade-offs, e.g. transporting feedstocks to a conversion plant near a shoreline hub, versus more local conversion coupled with CO_2 transportation, versus converting feedstock to an intermediate product (such as syngas) and then piping that to a conversion plant close to a shoreline hub. Full value-chain optimisation is only possible by optimising the combination of feedstock, pre-processing and transportation mode, conversion technology, energy vector and carbon capture & sequestration.

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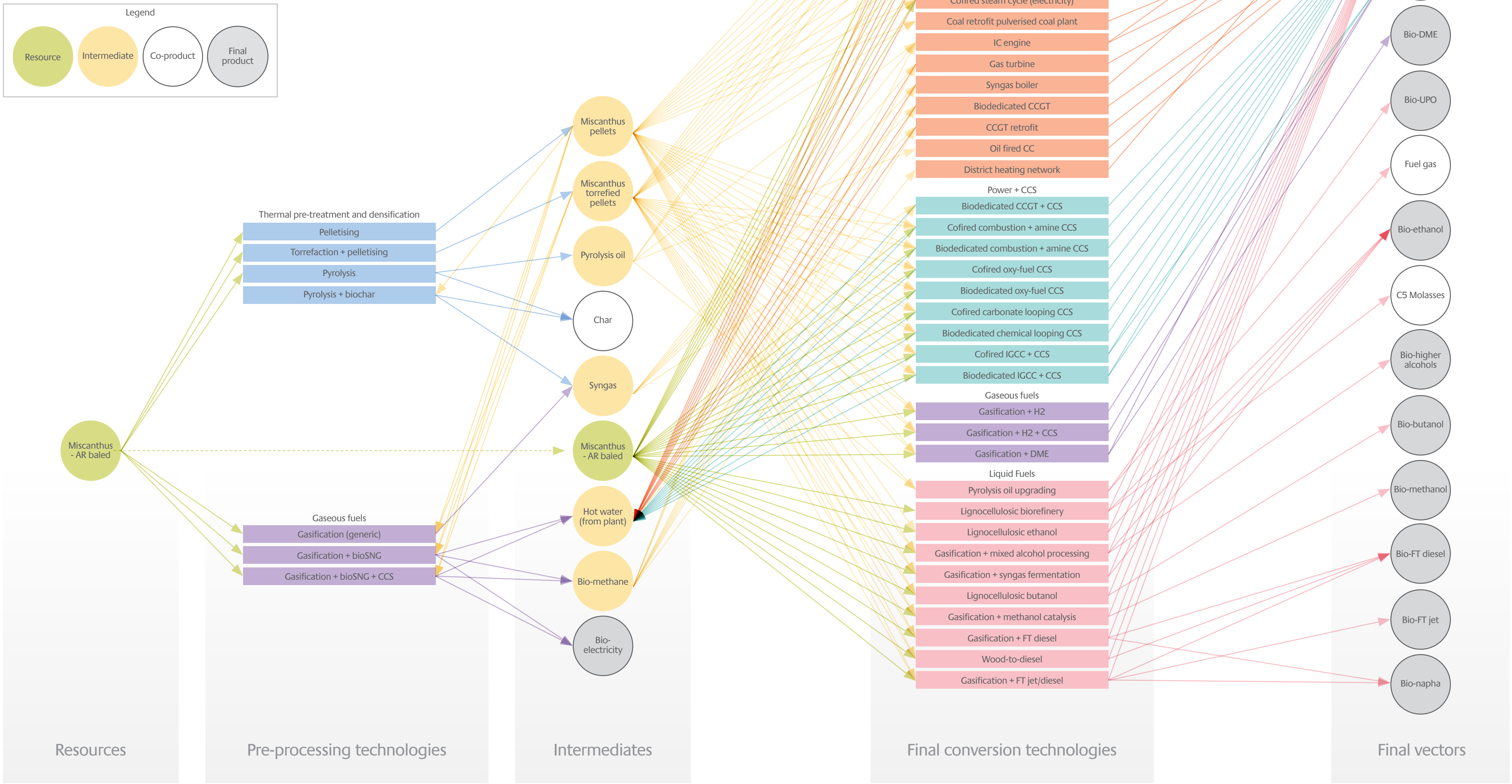
[17] Samsatli, S., Samsatli, N., and Shah, N. (2014) BVCM: a comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – mathematical formulation – submitted for publication (Elsevier, 2014).

[18] Intermediates are defined as raw feedstocks that have been processed in some way, but not yet been converted in to an end-use energy vector.

FIGURE 9

An example of resource-technology chains for Miscanthus

To illustrate the range of options considered by BVCM during an optimisation run, an example of the potential bioenergy value chains for just Miscanthus (as received in bales) is shown in Figure 9. Similar value chain options apply for the other biomass resource types, and these are optimised collectively by BVCM.



Biomass Gasification Plant

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