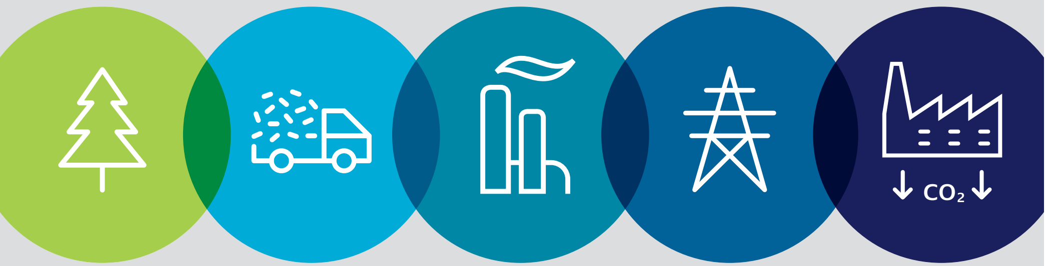
# Bioenergy

## Overview of the ETI's Bioenergy Value Chain Model (BVCM) capabilities

SOFTWARE MODEL GUIDE




In partnership with: E4tech (Strategic thinking in sustainable energy), Imperial College London Consultants

# Contents



## 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?

**BVCM**

**Bioenergy Value Chain Model**
Optimising Bioenergy

# Executive summary

The 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 purpose of this paper is to provide an overview of the BVCM toolkit, and is intended as background reading for those who are interested in knowing more about how the tool works, its architecture and functionalities.

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. A summary of the headline insights from this work can be found in the associated paper 'Insights into the future UK Bioenergy Sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)', available to download from our website.

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

## Introduction

Assessments of the future UK energy system using a variety of tools, including the ETI's ESME model and the UK TIMES / MARKAL models, indicate a prominent role for bioenergy in meeting our GHG emission reduction targets by 2050, especially when combined with carbon capture and storage (CCS). The bioenergy sector is complex, yet currently immature in the UK, 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[1].

It is therefore important to understand fully the end-to-end elements across the bioenergy value chain: from crops and land use, logistics, 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 Bioenergy Value Chain Model (BVCM). This model, together with the ETI's ESME[2] 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.

[1] LCICG 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

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

## Purpose and structure of this paper

The purpose of this paper is to provide an overview of the BVCM toolkit, and is intended as background reading for those who are interested in knowing more about how the tool works, its architecture and functionalities. It aims to set out the key properties of BVCM including the parameters that can be changed by the user, such as objectives, inputs and constraints; and the visualisation tools developed for reviewing the results. A summary of the headline insights from this work can be found in the associated paper 'Insights into the future UK Bioenergy Sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)', available to download from our website. It is the ETI's intention to publish further insights papers using the BVCM toolkit over the next 12 months. A more detailed paper on the mathematical formulation of the model can be found in Applied Energy (Samsatli et al. 2015)[27].

“The purpose of this paper is to provide an overview of the BVCM toolkit, and is intended as background reading for those who are interested in knowing more about how the tool works, its architecture and functionalities.”

## About the authors

The Energy Technologies Institute (ETI) is a public-private partnership between global energy and engineering companies BP, Caterpillar, EDF, Rolls-Royce and Shell and the UK Government. The ETI was established in 2007 to accelerate the development of new energy technologies for the UK's transition to a low carbon economy. It commissions engineering projects that accelerate the development of low-carbon technologies which help the UK address its long term GHG emissions reductions targets as well as meeting our future energy demands.

E4tech is an international strategic consulting firm, founded in 1997, working at the interface between energy technology, environmental needs and business opportunities, with a focus on innovative approaches to sustainable energy.

Imperial College Consultants (ICON) was founded in 1990 and is the UK's leading and largest university-owned consultancy company, providing practical and innovative solutions for external organisations by facilitating access to the expertise, facilities and equipment based at the College.

The ETI has worked with E4tech and ICON 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); ICON (model formulation and 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).

**"The ETI was established in 2007 to accelerate the development of new energy technologies for the UK's transition to a low carbon economy."**

## The Bioenergy Value Chain Model (BVCM) toolkit

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?**

BVCM is a spatial and temporal model of the UK, configured over 157 cells of 50km 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 optimise across 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[3], forestry, waste, biomass pre-processing & conversion technologies, transportation, storage, and the sale & disposal of resources. It also caters for international biomass imports, as well as $CO_2$ capture by CCS technologies and forestry.

The toolkit supports analysis and decision-making around optimal land use, biomass utilisation, different pathways for bioenergy production, and therefore opportunities for technology acceleration. It does this by optimising on an economic, emissions or energy production basis (or a combination of these) at the system level. Based on the optimal system deployed between the 2010s to the 2050s, an understanding can be gained around what crops to grow in each decade (and where to grow them), and what technologies to use (and where to build them), in order to convert resources to final energy vectors given any set of targets.

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 bioenergy supply chain model reported in the literature.

The BVCM toolkit comprises the following core components, and is illustrated in Figure 1:

- 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 optimisation scenarios, and visualising the results in the form of summary tables and network diagrams overlaid on a map of the UK;
- visualisation tools in Excel for the summary results and stochastic analyses.

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

# The Bioenergy Value Chain Model (BVCM) toolkit

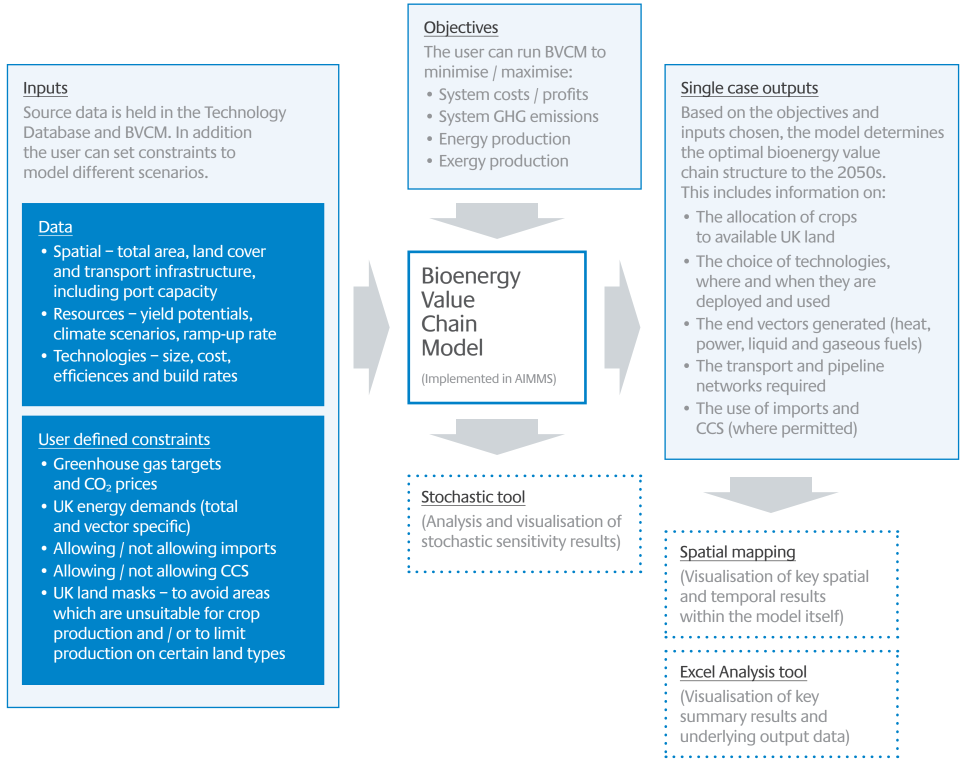
## Continued »

The ability to run different variants of similar versions of a problem is managed via the concept of cases. Once BVCM has solved, the solution can be analysed via the user interface and purpose-built visualisation tools described above. Different constraints and credits can be considered, including land suitability masks, carbon price scenarios, by-product and final product revenues and 'avoided' emissions, resource purchase and disposal, and CCS & forestry carbon sequestration.

The model 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 to the technology database) and made applicable over different spatial and temporal scales.

FIGURE 1

### Overview of the BVCM toolkit




A brief summary of the model's functionalities are provided in Table 1 below. The subsequent sections of this paper describe these BVCM elements in more detail: the objective function, temporal and spatial representation, land constraints, resources, technologies and infrastructure for transport of resources. The final section describes how BVCM is used. To illustrate the range of options considered by BVCM during an optimisation run, an example of the potential bioenergy value chains for Miscanthus is shown in Figure 2. Similar value chain options apply for the other biomass resource types, and these are optimised simultaneously by BVCM.

> "The data-driven nature of the BVCM toolkit enables it to be easily extended (e.g. by adding resources and technologies to the technology database) and made applicable over different spatial and temporal scales."

TABLE 1

## Overview of the Bioenergy Value Chain Model's key parameters

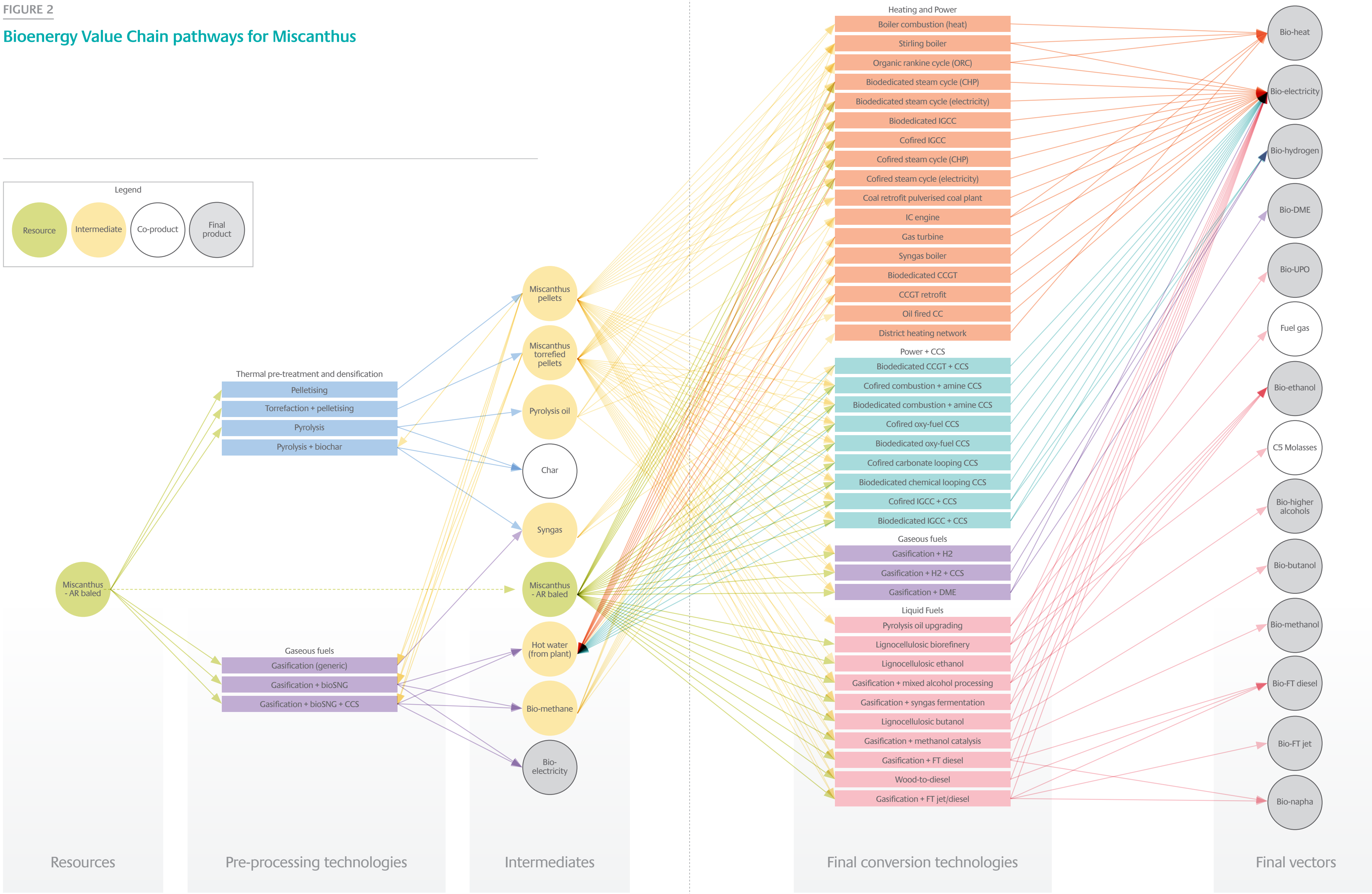
| | |
|---|---|
| Optimisation options and model constraints | The model can be configured to deliver each of the following optimisation options either in isolation or in combination:<br>» Minimise system level costs or maximise system level profit (these relate only to the bioenergy sector, not the wider UK)<br>» Minimise greenhouse gas emissions<br>» Maximise energy production<br>Each of these optimisation parameters can also be constrained in a number of ways. |
| Time | There are two important temporal elements<br>» Decadal – 2010s, 2020s, 2030s, 2040s, 2050s; and<br>» 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[4]. |
| 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[5] 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[5] 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.<br>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. |

[4] http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/

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

FIGURE 2

## Bioenergy Value Chain pathways for Miscanthus



## Objective function

All of the activities associated with the provision of energy through a bioenergy value chain give rise to a number of financial and environmental impacts. For example, planting, growing and harvesting of energy crops incur a cost, and the use of machinery results in $CO_2$ emissions. Similarly, building and operating technologies for converting resources also incur capital and operating costs, along with other environmental impacts. Whether the impacts are cost, GHG emissions, air quality indicators or anything else, they all arise in similar ways from the activities of the bioenergy value chain i.e. they are a function of one or more decision variables in the problem, such as the amount of capacity of a technology installed, the rate of operation of a technology, the rate of transport of a resource and so on.

Within BVCM, the user is able to set a combination of optimisation weightings and system targets as part of setting the objective function. System targets include setting a minimum or maximum level for energy production and / or maximum GHG emissions; and the system can be optimised to deliver minimum cost, maximum profit, minimum GHG emissions, or any combination of these.

Currently, there are three key impacts in BVCM: cost, $CO_2$ emissions and other GHG emissions[6]. Parameters then define how much each impact is increased (or decreased) by each activity in the value chain, and the value of each impact is calculated for each group of related activities: crop production, technology capex, technology opex, transport, storage capex, storage opex, grid purchase, imports, co-product revenue, end vector revenue, CCS, forest sequestration, wastes and disposal. The objective function is therefore the weighted sum over all impacts of the total value chain impact (capital + operating + transport + ... impacts). The values of the optimisation weightings are user defined and allow a variety of objective function scenarios to be considered. The weights can be calculated automatically using $CO_2$ prices (user-defined) to convert the environmental impacts into monetary impacts (cost). The objective function also includes other indicators of the value chain performance: total energy production and total exergy production, in terms of the user-defined final energy vectors, with appropriate user-specified weights. This then allows maximisation of total energy production as an objective function.

[6] Additional impacts such as non-GHG life-cycle assessment metrics, water use or air quality indicators could be added.

## Temporal and Spatial representation within BVCM

### Time

BVCM considers the strategic development of the bioenergy value chain from the 2010s to the 2050s. Time is represented on two levels: decadal and seasonal. Investment decisions, land-use changes, technology improvements and yield enhancements take place on a decadal basis. For example, the annual yields of any crop may be different from one decade to the next, but are assumed to be the same in each year within that decade.

The seasonal level accounts for the variation of biomass production throughout the year. The model may be run with only one season (i.e. the whole year), two seasons (winter/spring and summer/autumn) or all four seasons. When more than one season is considered, storage is modelled to account for the intermittent supply of crops (briefly described later).

Many of the properties that characterise the behaviour of the energy system are rates: e.g. a flow of resource from one cell to another (tonne per day, for example), the processing rate of a technology or its capacity (tonne per year), the growth of crops (odt/ha/yr) and so on. While the data for these properties can be stored in a variety of units, they are all converted to a common time basis, referred to as a 'rate basis'. This can be chosen (when the data are extracted) to be either hourly, daily or yearly.

### Space

In BVCM, the UK is divided into 157 square cells of length 50km. Each cell represents a geographical location and may have a dynamic demand for various resources. A cell may host different technologies for processing and converting resources. It may also contain infrastructure connections with other cells for transport of resources and external connections for import and export of resources. Examples of information that may vary with location include demand, resource availability, transport network distances, land cover and built environment. This spatial resolution is sufficiently high to account for regional variations in biomass yield, costs and GHG emissions; without being so high that the model becomes intractable. It also allows an appropriately detailed representation of transport networks (e.g. the trade-off between converting biomass to energy in-situ versus densifying the biomass and transporting it to a more centralised conversion plant).

**"BVCM considers the strategic development of the bioenergy value chain from the 2010s to the 2050s."**

# Land areas and constraints within BVCM

## Land area allocation

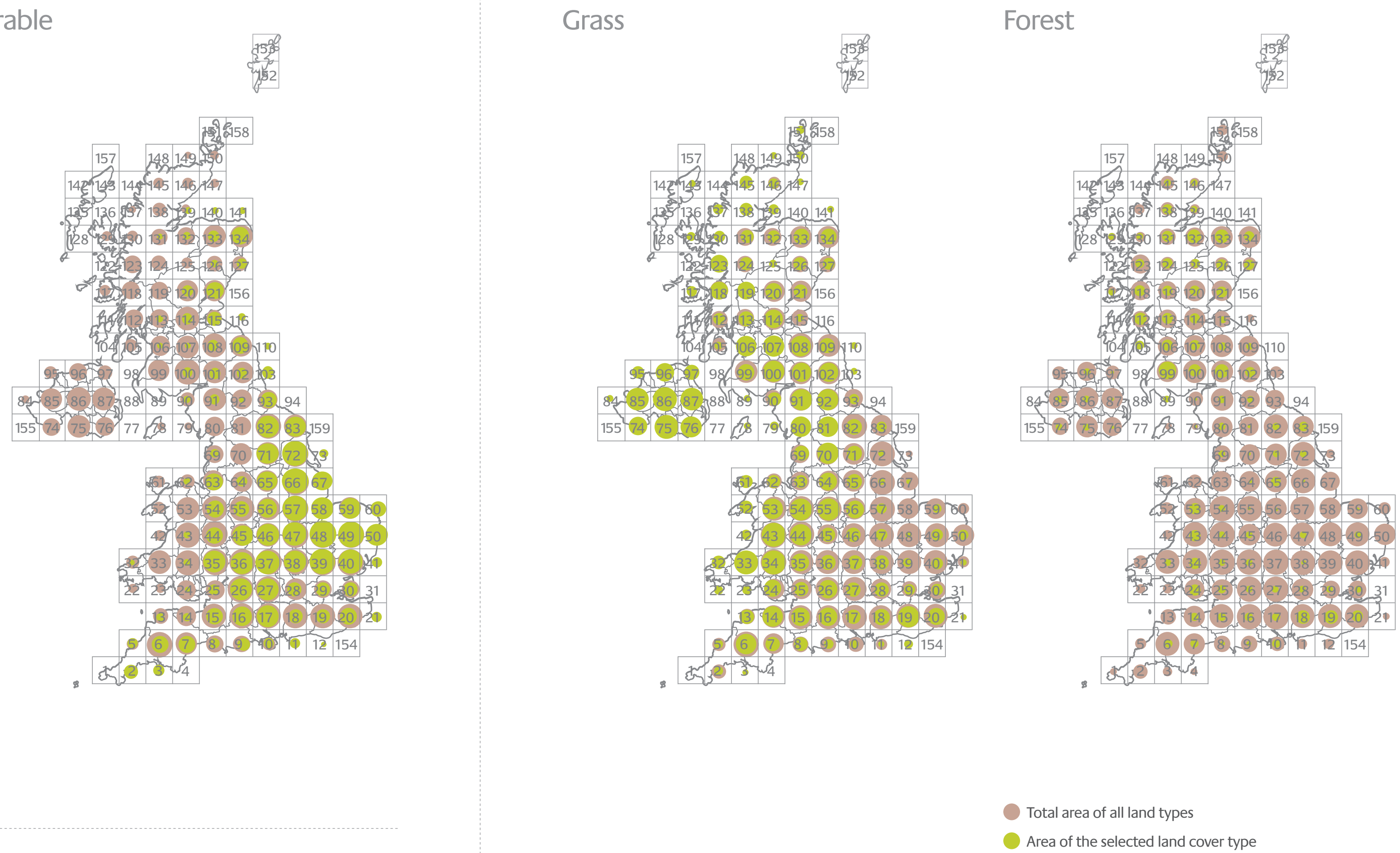
The model provides flexibility in defining different scenarios for the area of land available for biomass production. In BVCM, the user can either take the approach of categorising land use into four 'levels' of land available for biomass production, with increasing levels of 'aggression' in terms of land use change; or the approach of categorising land as one of three, mutually exclusive, land cover 'types': 'arable', 'grassland' or 'forest'. Both approaches are based on CORINE Land Cover (CLC) map[7] data (see Figure 3 and Table 2). For simplicity – only the latter approach (three land cover types) is described here. The user can vary the potential allocation of different existing land types to bioenergy feedstock production in two main ways:

1. The specification of the fraction of each land type that is available for bioenergy (e.g. the user could specify that only 10% of the available arable or grassland areas can be used).

2. The user is able to limit transitions to particular land class types – for example, first generation energy crops such as sugar beet or oilseed rape can be limited to arable-only transitions, or the user may wish to limit existing forestry to only be used for short- or long-rotation forestry.

FIGURE 3

**Maximum area available on arable, grass and forest land cover (defined in Table 2) across the UK**




[7] CORINE Land Cover Map http://www.eionet.europa.eu/.

# Land areas and constraints within BVCM

Continued »

TABLE 2

## BVCM land types and the corresponding categories in CORINE Land Cover 2006 map

| BVCM land cover type | CORINE land cover map category | UK area available to BVCM, without any land constraint masks applied (%UK land shown) in hectares (ha) |
|---|---|---|
| Arable | 2.1.1 Arable land (non-irrigated) | 6,450,722 (26%) |
| Grassland | 3.2.1 Natural grasslands | 8,666,129 (35%) |
| | 2.3.1 Pastures | |
| Forest | 3.1 Forests | 1,987,704 (8%) |
| | Total | 17,104,555 (69%) |

### Land constraints

In addition to specifying the amount of each land cover type in BVCM, the user is able to apply additional 'constraint masks' for each analysis, such that further restrictions can be assumed in terms of the spatial availability of land for biomass feedstock production in the UK.

Different levels of constraints can be applied, as specified in Table 3 below, incorporating outputs from the UKERC 'Spatial Mapping' project led by the University of Aberdeen[8]. Figure 4 shows the breakdown of arable, grassland and forest areas available under these different constraint masks.

[8] UKERC Spatial Mapping Project – for an overview, 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.

TABLE 3

## Definition of the various constraint masks that can be applied in BVCM

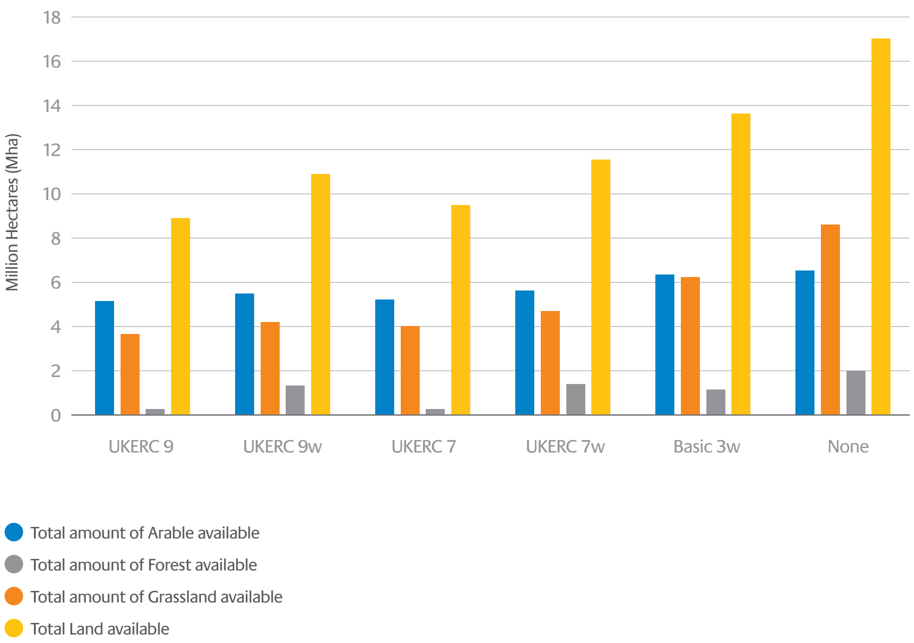
| Constraint Mask | Description | Area left after constraint mask applied (Mha) |
|---|---|---|
| None | All arable, grass and forest areas included (based on CORINE land categories) within the 157 BVCM cells | 17.10 |
| Basic-3w | Excludes land areas with elevation greater than 250m, slope greater than 15% and topsoil organic carbon greater than 10% | 13.69 |
| UKERC-7w | Basic 3w mask plus 7 further constraint masks to exclude urban areas, roads, rivers, parks, scheduled monuments, world heritage sites, designated areas, cultural heritage areas and natural and semi-natural habitats | 11.59 |
| UKERC-7 | UKERC 7w mask and also excluding existing woodland | 9.49 |
| UKERC-9w | UKERC 7w mask and also excluding areas with high naturalness score (>75% or >65% inside national parks and areas of outstanding natural beauty) | 10.95 |
| UKERC-9 | UKERC 9w mask and also excluding existing woodland | 8.90 |

# Land areas and constraints within BVCM

Continued »

FIGURE 4

**Breakdown of the amount of arable, grassland and forest areas available under different constraint masks applied across the UK**




# Resource parameters within BVCM

'Resources' refer to any distinct material or energy stream considered in the value chain: biomass feedstocks, intermediates, final products, co-products and wastes – and BVCM contains 82 different types of resource. A resource can be consumed or produced by a technology, transported from one cell to another, imported from abroad to specific locations (e.g. 'ports'), stored when seasonality is considered, and bought and sold.

Each resource is characterised by a set of properties (e.g. Lower Heating Value, density and composition). Although for biomass feedstocks these properties may depend on the location and decade in which they are grown, the properties of all resources are assumed to be independent of location and time. The user is able to specify the resources available in any specific scenario. The quantity of a resource is measured in a number of units: tonne, MWh or $m^3$, depending on the type of resource, with the exception of biomass yields, which are measured in oven-dry tonnes per hectare per year (odt/ha/yr).

Resources can be stored over a number of seasons (but never more than one year), and when BVCM is allowed to store resources the economics and environmental performance of the system is assessed, by taking in to account the unit cost and emissions due to moving, handling and settling the feedstocks in the storage location.

BVCM distinguishes between 'green' and 'brown' resources. 'Green' resources are biomass crops or output products from a bio-technology; if this output is an final energy vector (e.g. bio-electricity), it may have demands and its production contributes towards the bioenergy production target that the user can set. 'Brown' resources such as grid electricity or natural gas on the other hand, are produced by conventional (e.g. fossil) technologies outside of the BVCM system boundary; therefore within BVCM, they do not have demands and their production cannot count towards the bioenergy target. These 'brown' resources are present so that the model can choose to purchase them as an alternative to building technologies to produce them from biomass. This may be beneficial when they are needed in small amounts to operate the technologies, e.g. during the start-up phase of a gasifier for example. The unit purchase costs and emissions data were collected from ETI projects, the literature and existing models.

'Green' resources can be divided into two subsets: 'global demand resources' and 'local demand resources'. The former set represents resources such as bio-electricity and bio-methane, which can be transported easily and therefore it is only necessary to consider their 'global' demand (i.e. the total demand for the resource within the UK); the latter set represents resources that have 'local' spatially-dependent demands

# Resource parameters within BVCM
## Continued »

(currently only hot water used for space heating has been set up as a 'local demand resource', for which demands have been estimated from the DECC heat map)[9].

Resources can be sold, contributing to system revenues, if the user choses to allow this. Of the net production of a crop or intermediate resource, some will be used in downstream processes to produce bioenergy, some may be sold, and the rest may be disposed of (at a cost). The special case is hot water, since any production in excess of local demand cannot be sold, with the excess given zero disposal cost. Global demand resources always satisfy system demands, and cannot be wasted, but can also gain revenues if BVCM is run in profit maximisation mode.

In addition to receiving monetary credits for the sale of resources, GHG emissions credits may also be obtained if 'green' resources are assumed by the user to displace the consumption of an equivalent conventional (fossil) derived resource outside the BVCM system boundary. Prices for most of the bioenergy final energy vectors produced were obtained from the ETI's ESME model, whereas the prices of co-products (such as glycerine, rapeseed meal, Distiller's Dried Grains with Solubles (DDGS) and winter wheat straw) were obtained from current market trading data assuming that future prices stay constant (although the user can change all of these price assumptions). GHG emission 'credits' were parameterised in a similar way, with 'avoided' fossil emissions being calculated using data from ESME and, for some of the fossil carbon intensities and co-product emission credits, data were determined from the UK's carbon calculator for biofuels[10], and for solid & gaseous biomass[11]. To avoid the system being driven towards overproduction of certain resources with high values and to account for the limited market for these resources, a user-specified cap, expressed in terms of units of resource per year, can be used to limit the rate of sale of resources.

The resources are classified into a number of families with similar properties, or at similar stages of the supply chain. These are used to apply specific constraints to groups of resources that belong to the same family and also to perform sensitivity analyses at the family level (see list below).

The resource families are:

- Arable crops, i.e. winter wheat, oilseed rape, sugar beet
- Energy crops, e.g. Miscanthus, short rotation coppice (SRC) willow
- Forestry, e.g. short rotation forestry (SRF), long rotation forestry (LRF)
- Wastes, e.g. waste-wood, waste-bio (includes food wastes), waste-all (unseparated waste)
- Intermediates, e.g. chips, pellets, torrefied pellets, pyrolysis oil, syngas, Anaerobic Digestion (AD) biogas
- Co-products, e.g. DDGS, digestate, glycerine, sugar beet pulp
- Final energy vectors, e.g. bio-electricity, hot water, bio-methane, bio-ethanol, bio-hydrogen
- Miscellaneous, e.g. chemicals, such as hexane, urea and sulphuric acid, that are used as inputs to some technologies

The following sections describe the first four resource families in more detail.

### Arable and energy crops
The user is able to vary several parameters that affect the amount of domestic biomass feedstock available over time, for a given cell. For biomass crops, these include yields, yield improvement scenarios (over time), climate scenarios, crop establishment factors, and crop ramp-up rates. Each of these are described below. A particular resource may be represented in distinct forms within BVCM, for example, winter wheat can be produced as 'whole crop'; 'grain' and/or as 'straw'. In BVCM it is assumed that arable crops can be rotated, and for each rotated set of crops , the ratio of areas planted each year is equal to the ratio of number of years that each crop is planted in the rotation.

### Yields
BVCM was populated with data for crop-specific resource yields – drawing on relevant process models for crops in the UK. Yields for winter wheat, oilseed rape, sugar beet and Miscanthus were provided by Rothamsted Research, based on empirical modelling[12]. Yields for SRC-Willow were provided by University of Southampton and Forest Research, based on the ForestGrowth SRC model; and yields for SRF and LRF were provided by Forest Research, based on their ESC-CARBINE models. The example in Figure 5 below shows the transition from SRC ForestGrowth yield outputs to the BVCM's 50km x 50km cell structure.

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

[10] The UK biofuel carbon calculator: https://www.gov.uk/government/publications/biofuels-carbon-calculator

[11] The UK solid and gaseous biomass carbon calculator: https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

[12] For Miscanthus, Rothamsted Research's predicted yields have been compared with Aberdeen University's MiscanFOR process model, such that potential regional sensitivities could be identified.

# Resource parameters within BVCM

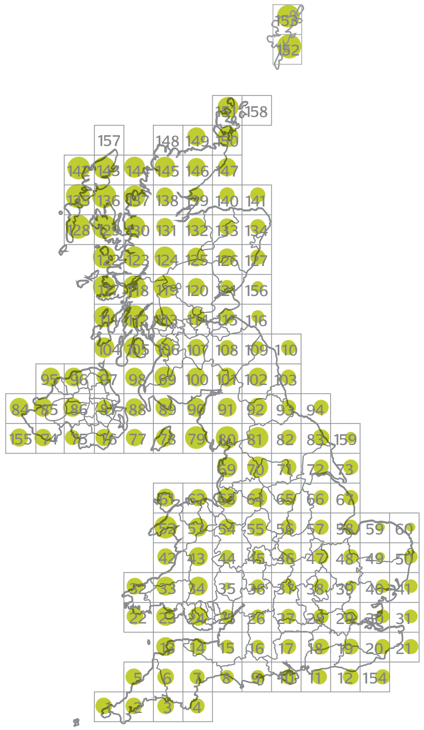
Continued »

FIGURE 5

## Translation of SRC-Willow yield maps based on the ForestGrowth SRC model to BVCM

Low yields SRC

High yields SRC



Circle size denotes yield potential – with larger circles in NW corresponding with higher yields

### Yield improvement scenarios

BVCM is pre-populated with three resource improvement pathways ('best', 'business as usual' and 'worst'), depending on a series of factors such as on-farm improvements, and how the gap between theoretical yields and on farm attainable yields evolves. These improvement factors have been estimated by Rothamsted Research using empirical modelling, and can be applied to wheat, sugar beet, oilseed rape and Miscanthus. In addition users are able to apply their own yield factors for any cell in the UK.

### Climate scenarios

The long-term strategic planning optimisation performed by BVCM needs to deal with climatic factors which could influence crop yield trends (predominantly by affecting temperature, precipitation and radiation; and increased atmospheric $CO_2$ concentration ($CO_2$ fertilisation effect)). In BVCM, the yield potentials of each biomass crop were calculated at a 1km x 1km level based on the 'low' and 'medium' scenarios from the UK Climate Projections 2009 (UKCP09)[13].

### Crop establishment ratios

For crops that require a period of establishment before their full yield potential is realised, the user can define a crop establishment factor between 0 and 1. For these crops, this fraction of the full yield potential is realised in the first decade of planting. For crops that do not require an establishment period, the full yield potential is achieved in the first decade of planting.

### Crop ramp-up rates

This refers to the rate at which the user believes UK production of biomass feedstocks can be scaled up within the UK, noting that Defra[14] estimate that approximately 51,000 hectares (kha) of agricultural land in the UK were being used for bioenergy (excluding AD) in 2013[15]. This parameter can be used to simulate constraints arising because of supply chain limitations, such as, limited specialist contractors, limited seedlings/propagative material available for planting, and/or limited specialist equipment for planting or harvesting.

The user can define their own ramp up rate but four default scenarios are included within the model:

- None: no constraint on scale-up is applied
- Low: 'conservative' scenario where, for example, the growth of the Miscanthus and SRC Willow industries are linear based on recent deployment trends seen in the dedicated energy crop sector (735 ha/yr and 135 ha/yr respectively) and no future acceleration is assumed

[13] Met Office UK Climate Projections: http://ukclimateprojections.metoffice.gov.uk/

[14] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/377944/nonfood-statsnotice2012-25nov14.pdf

[15] This equates to 0.8% of arable land in the UK, and was made up of approximately 8 kha oil seed rape, 8 kha sugar beet, 26 kha wheat, 7 kha Miscanthus and 3 kha SRC. Just over 80% (42 kha) of the land used for bioenergy in 2013 was for biofuel (biodiesel and bioethanol) crops for the UK road transport market.

# Resource parameters within BVCM

Continued »

- Medium: 'realistic' scenario where the planting rate for Miscanthus and SRC Willow increases by 30% per year, implying moderate scale-up of all supply-chain aspects
- High: 'stretch' scenario where the Miscanthus and SRC Willow planting rate increases by 50% per year, implying significant scale-up of all supply-chain aspects

### Crop uplift / downlift factors

Each biomass feedstock has scenario trajectories for how its production cost and yield will evolve over the five decades. However, in a similar way for BVCM technology costs and efficiencies, the user is able to specify factors to increase or decrease these costs and yields for each biomass feedstock, as a proxy for overall sector maturity expectations.

### Forestry

The BVCM forestry resources include short rotation forestry (SRF), long rotation forestry (LRF) and LRF for $CO_2$ sequestration. The first two are grown for energy production: nearly all of the trees are harvested and used as inputs to technologies. 'LRF for capture', on the other hand, is grown for $CO_2$ sequestration purposes (i.e. afforestation), and in this case none of the trees are harvested, hence the yields are zero but the $CO_2$ sequestration rate is high[16] (as the standing biomass stock acts as a carbon store). This is sometimes selected by the model as a pathway for delivering emission savings across the system, especially in scenarios where CCS is unavailable.

The SRF yield data are based on potential production from nine possible tree species: alder, ash, aspen, birch (downy and silver), beech (Nothofagus procera), poplar (cultivars), sitka spruce, and sycamore. The SRF yield data for an individual grid square were estimated based on the assumption that equal proportions of each species suitable to be grown in that cell are planted contributing towards the yield for that cell. This tends to result in 'conservative' yield estimates for SRF, but the user can alter the yields within the model.

Forestry yields cannot be represented on an annual basis. The yields for these resources are presented based on the relevant cycle of planting, thinning and harvesting activities associated with each forestry crop. Within BVCM, LRF is only planted and thinned over the timescales considered, whereas for SRF, the crop has time to go through the full management cycle, as shown in Table 4. This shows that the main yield of SRF forestry resources occurs 20 years after planting.

[16] Carbon accumulation rate was estimated based on those for Sitka Spruce – considered to have the greatest potential per hectare for long-term storage

TABLE 4

**SRF forestry resource sets representation in BVCM**
p = planting, He = early harvest, H = Harvest (main yield), Hl = late harvest (final removals)

| Planting period | 2010s | 2020s | 2030s | 2040s | 2050s |
|---|---|---|---|---|---|
| 2010s (set 1) | p | $H_e$ | H | $H_l$ | |
| 2020s (set 2) | | p | $H_e$ | H | $H_l$ |
| 2030s (set 3) | | | p | $H_e$ | H |

### Waste

In BVCM, the raw waste resources currently include:

- 'Waste-Bio': kitchen and green waste
- 'Waste-Wood': wood and furniture
- 'Waste-All': unseparated mixture of five waste resources: Bio, Wood, Paper/ Textiles, Plastics and Other

Intermediate waste resources, which are processed from the raw waste resources, are also considered. For example, 'Waste-RDF' is produced from 'Waste-All' by the Mechanical Biological Treatment (MBT) technology, 'Waste-Wood-Pellets' are produced from 'Waste-Wood' by pelletisation technology etc.

It is assumed that the generation of wastes is constant throughout the year and that transport of 'Waste-All' is not allowed across administrative borders. Therefore, 'Waste-All' cannot be transported between cells in BVCM. Default gate fee costs for waste have been included within BVCM, based on the latest WRAP Gate Fees report[17], although the user can specify custom values, enabling system sensitivities to future values to be assessed.

[17] WRAP 2014 Gate Fee report: http://www.wrap.org.uk/content/wrap-gate-fees-report-detailed-2014

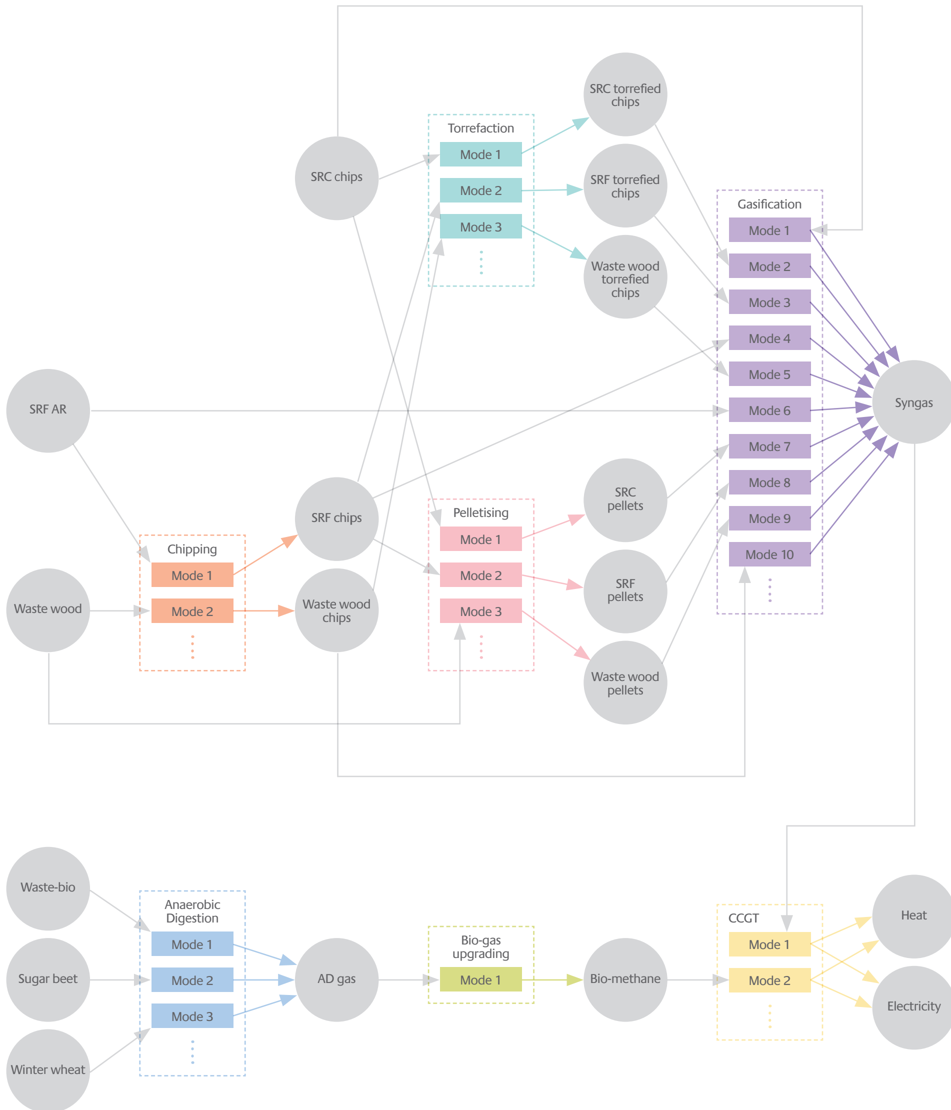
# Technologies within BVCM

A technology represents any process that converts a set of input resources to a set of output resources, and there are 61 distinct technologies included in the Technology Database (TdB) underlying BVCM, many available at multiple scales. These are listed in the Appendix. Most bioenergy technologies can process multiple feedstocks or produce multiple outputs: each distinct set of input resources that can be processed and set of output resources that can be produced by the same physical plant represents a mode of that technology. Some examples of technologies with multiple modes are shown below and in Figure 6:

- » the pelletising technology can process SRC Willow chips into SRC Willow pellets, winter wheat straw into winter wheat pellets and SRF into SRF pellets, among others
- » the boiler combustion technology can process a number of feedstocks, such as forestry biomass (as received, chips or pellets) and waste wood into heat
- » the sugar biorefinery technology can convert sugar beet into a number of final energy products and by-products: bio-ethanol, bio-electricity, sugar beet sugar and sugar beet pulp

FIGURE 6

**An example of technology mode pathways** (for illustration only – not an exact representation of the data in the TdB)




[7] CORINE Land Cover Map http://www.eionet.europa.eu/.

# Technologies within BVCM

## Continued »

Each technology is characterised by a number of properties, in each decade:

- Maximum and minimum capacity, measured in units of resource per rate basis
- Efficiency, represented by conversion factors for each mode and each resource
- Unit operating impact (cost and environmental impact), comprising fixed and variable elements. Fixed impacts are independent of the rate of operation of a technology (e.g. maintenance); variable impacts, on the other hand, depend on the rate of operation but do not include raw material impacts.
- Unit capital impact, which is the cost impact per unit capacity associated with the construction of a new facility
- Economic life: the duration of finance required to pay for the facility (i.e. the number of years over which the investment costs are annualised)
- Technical life: the number of years of operation (lifespan) of a facility
- Availability: the fraction of time available for operation
- Whether a technology is available for investment in a particular decade (to account for technologies that are not yet available/sufficiently developed or technologies that will be phased out in the future)
- Maximum build rate: the maximum number of facilities that can be built per year
- Existing stock: the location and capacity of any existing facilities

The technologies are grouped into 12 families in order to allow a batch of similar technologies to be conveniently included/excluded in a scenario and also to be able to apply constraints and perform sensitivity analysis at a family level rather than at an individual level. The technology families are:

- Densification, e.g. chipping, pelletising, oil extraction
- Thermal pre-treatment, e.g. torrefaction, pyrolysis, mechanical biological treatment (MBT)
- Anaerobic digestion, e.g. anaerobic digestion, biogas upgrading
- Gasification , e.g. gasification (generic), gasification (bioSNG), gasification ($H_2$)
- First generation (1G) biofuels, e.g. 1G bio-ethanol, 1G bio-diesel, 1G bio-butanol
- Second generation (2G) biofuels, e.g. lignocellulosic bio-ethanol, lignocellulosic bio-butanol, gasification (Fischer-Tropsch diesel), lignocellulosic biorefinery (e.g. Inbicon) based on woody/grassy crops
- Heating, e.g. boiler combustion, syngas boiler, district heating (DH) network
- Combined Heat and Power (CHP) onsite, e.g. Stirling engine, Organic Rankine Cycle, internal combustion engine
- CHP for district heating, e.g. gas turbine, steam cycle, integrated gasification combined cycle
- Power, e.g. combined cycle gas turbines, plasma gasification, incineration, pyro-liquid biorefinery (e.g. Ensyn)
- Power + CCS, e.g. oxyfuel, chemical looping, combustion + amine
- Gaseous + CCS, e.g. gasification (bioSNG) + CCS, gasification ($H_2$) + CCS

### Technology efficiency

A technology can operate in multiple modes using different inputs and often producing different outputs. The maximum capacity for the technology is independent of the mode, but the capacity units used generally refer to the main output of the first mode. For example, the maximum capacity of a combined cycle gas turbine (CCGT) plant would be in MWe, based on the main output, bio-electricity, while the main input of the two modes is syngas and bio-methane, respectively.

The efficiency of each mode of a technology is represented by specifying a coefficient for each resource associated with that technology mode. When a technology runs at a particular rate, the rate of production or consumption of a resource is the conversion factor multiplied by the rate of operation of the technology.

For co-fired technologies, the conversion factors represent only the biogenic output of a resource from the technology, e.g. the rate of bio-electricity production from a co-fired plant being fed with coal and biomass. The coal inputs and outputs are ignored in the mode data, as they are outside of the BVCM system boundary. Whilst the overall plant capacity remains unchanged, a smaller amount of biomass produces a commensurably smaller amount of main output – i.e. the co-firing factor is written into the mode input/output data. The co-firing fraction therefore represents the part of the plant production rate that is due to the biomass and therefore the actual rate of output produced from biomass is the conversion factor of the main biogenic output multiplied by the production rate of the technology.

### Carbon Capture and Storage (CCS) Technologies

Carbon capture and storage is modelled by allowing certain modes of technologies to capture $CO_2$ at a rate proportional to the operation of the technology (kg$CO_2$ per MWh of output). The captured $CO_2$ must then be transported via pipeline to a limited number of user-defined shoreline hubs (sequestration sites), where the amount sequestered gives rise to CCS credits, which are deducted from the total $CO_2$ emissions of the system. However, there are additional cost impacts associated with the transport of the captured $CO_2$ – the user can define the cost to transport one million kg of $CO_2$ from one cell to another (approximately 80km if taking typical tortuosity in to account).

# Transport logistics within BVCM

Five transport modes are considered in BVCM: road, rail, inland waterways, close coastal shipping; and piping (for intermediate gases). In BVCM, transport between cells is limited to adjacent cells, except in the case of shipping (see below) and inland waterways, where diagonals are allowed. Transport over longer distances on land is achieved by making several ‘neighbour-to-neighbour’ transfers along the route between the source and destination cell. The road and rail networks were obtained from OpenStreetMap[18] while the distribution of inland waterways (canals and navigable rivers) was taken from WaterWaysWorld[19]. The feasible transport connections were determined from these maps – an example of which is shown in Figure 7a for barge transport via inland waterways. The meshing of the road network with the BVCM cellular representation gives an average tortuosity per cell, which was then used to convert straight line distances to expected travel distances. For example, a high road network density has a low tortuosity (e.g. 1.15) and a low road network density has a high tortuosity (e.g. 2.5).

With respect to coastal shipping, only a single type of ship carrier is considered for simplicity, as ship emissions do not change significantly with scale (as evidenced by E4tech’s carbon calculators[20]), relative to the whole value chains. Unlike the inland transport modes, ship transport is not restricted to adjacent cells and instead transport from one port to any other port is allowed. The existing UK major ports were identified and pre-loaded in to BVCM, together with data from the Department for Transport on their maximum import and export capacities[21] (see Figure 7b).

[18] OpenStreetMap http://www.openstreetmap.org

[19] WaterWaysWorld, Widebeam map: http://www.waterwaysworld.com/images/widebeam_map.png

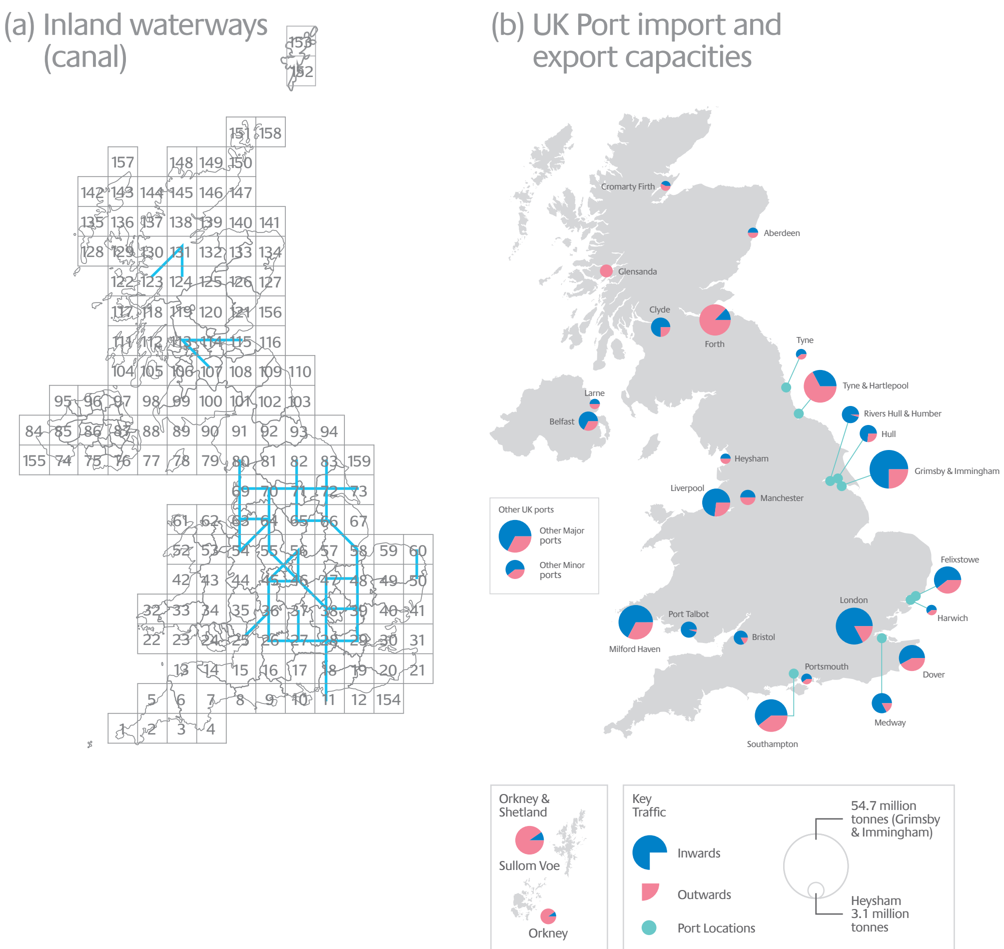
[20] The UK biofuel carbon calculator: https://www.gov.uk/government/publications/biofuels-carbon-calculator; and the UK solid and gaseous biomass carbon calculator: https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

[21] UK ports and traffic (PORT01): https://www.gov.uk/government/statistical-data-sets/port01-uk-ports-and-traffic#table-port0102

FIGURE 7

**(a) Representation of feasible inland waterways transport connections for barges in BVCM**

**(b) Shipping traffic into/out of through UK ports**



# Transport logistics within BVCM

## Continued »

The resource transport 'impact' is expressed in terms of £ per tonne-km and in $kgCO_2e$ per tonne-km. The cost component comprises a fixed cost for loading and unloading; charter cost including hire, labour and overheads; and a fuel cost. GHG emissions are based on the Biograce[22] efficiencies multiplied by the carbon intensity of the fuel.

Gaseous resources are assumed to be transported only by pipeline, and hence include the levelised capital costs of building dedicated pipeline infrastructure (assuming an 8 inch diameter), plus the operational costs of maintenance and compression. These costs were derived for natural gas and hydrogen and scaled for the other resources by their density. Pipeline costs in BVCM were aligned with data from the ETI's 2050 infrastructure project[23].

### Imports

Although in general any resources can be imported, BVCM is currently configured for the import of biomass feedstock resources only. This allows the user to analyse the role of biomass imports as part of the future UK energy mix. Four import scenarios are pre-defined:

- None: no import of resources
- Low: low availability, high price
- Medium: medium availability, medium price
- High: high availability, low price

These scenarios were derived from global supply-cost curves for a number of generic groups of biomass (e.g. energy crops, forestry and sawmill residues, small roundwood, agricultural residues). In any given year, each port can only receive and send a certain total amount of resource (tonnes per year). The cost and emissions of imports will vary depending on the actual country of origin of the feedstock. However, in BVCM the origin of the import was not taken into account, instead the data were based on typical exporting countries, such as North America and Canada. The price paid for biomass landed at a UK port typically consists of biomass production cost (raw unprocessed biomass) in the country of origin, processing cost, transport cost (usually by road/rail and sea) and profit margins with respect to the international supply chains. The GHG emissions for imported resources, include carbon dioxide, methane and nitrous oxide emissions (calculated in $kgCO_2$ equivalent) due to cultivation, harvesting, drying, processing and transport of resources[24].

[22] Biograce: http://www.biograce.net/

[23] http:/www.eti.co.uk/project/2050-energy-infrastructure-outlook/

[24] The UK solid and gaseous biomass carbon calculator: https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

# BVCM architecture

As described earlier, the BVCM toolkit comprises the following:

- a mixed-integer linear programming (MILP) model implemented in the AIMMS modelling platform[25] and solved using the CPLEX MIP solver[26];
- databases, provided as a series of Excel workbooks, that are used to store all of the data concerning technologies, resources, yield potentials, waste potentials etc. along with a data extraction tool;
- graphical user interface (GUI), also implemented in AIMMS (version 3.12), for configuring and performing optimisations and visualising the results; and
- tools implemented in Excel for further analysis of the results.

In the GUI the user starts at the home page, shown in Figure 8, from which they may navigate to a number of input data pages and output (results) pages. The top left hand part of the screen allows the user to select a case (a saved set of input parameters and results of an optimisation) and quickly view a summary of the results; it also allows the user to load the built-in reference case.

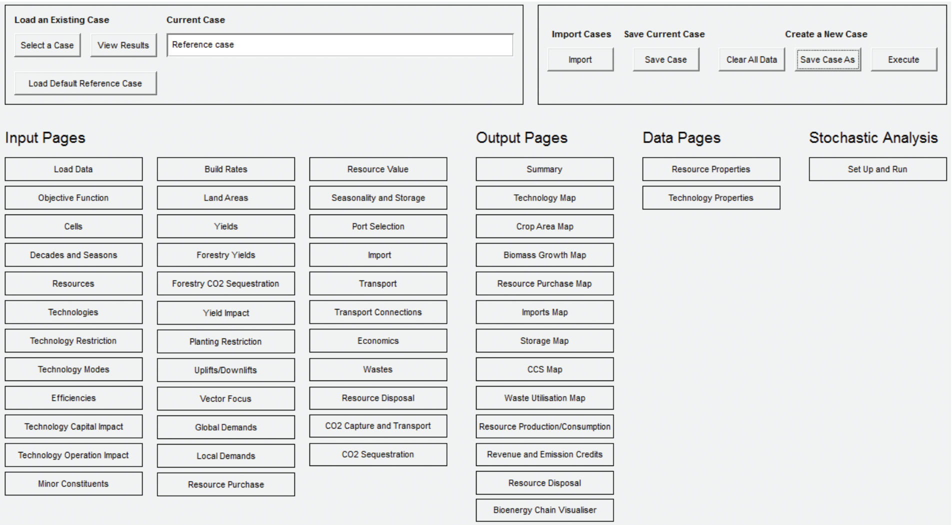
[25] http://www.aimms.com/aimms/overview/

[26] http://www.aimms.com/aimms/solvers/cplex/

# BVCM architecture
## Continued »

FIGURE 8

### Home page of BVCM




The BVCM home page is organised into four sections: input pages (which users will use to adjust the data for the problem definition), output pages, data pages (which show properties of the resources and technologies that have been imported from the Technology Database) and finally stochastic analysis where multiple optimisations are performed with some of the parameters being randomly sampled from distributions and the results are collated in the Stochastic Analysis Tool. Stochastic Analysis is used to assess the impact of the uncertainties associated with biomass yields and costs, and conversion technology capital costs and efficiencies.

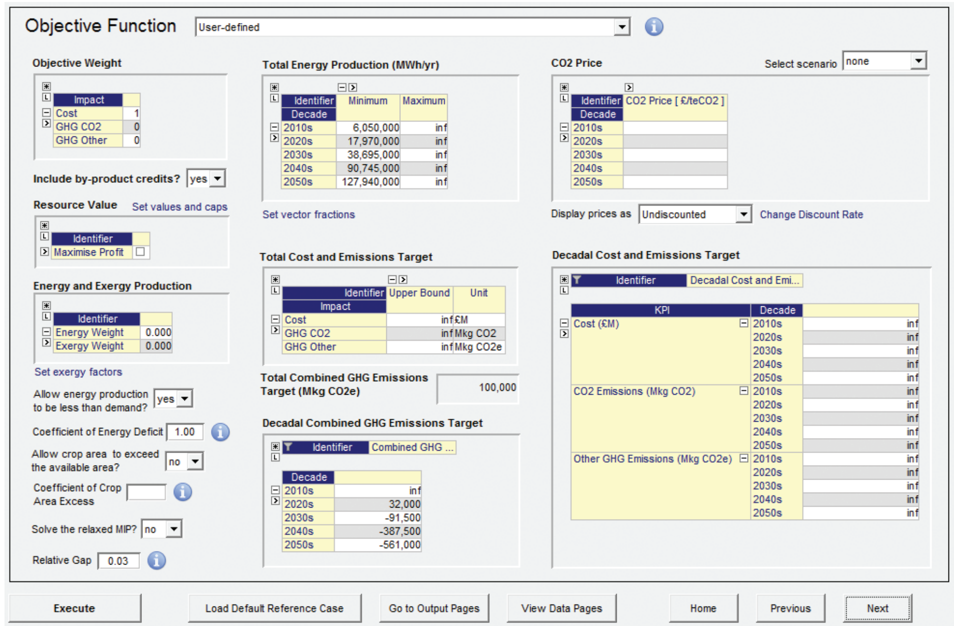
The input pages typically contain check-boxes, data tables and maps. Check-boxes are used to enable certain features of an optimisation run or to select which technologies, cells etc. are included in the optimisation. Data tables typically have two purposes:

1. To allow the user to specify parameters that quantify certain aspects of the optimisation run, such as constraints on energy or GHG emissions, costs, prices, caps etc.
2. To display spatially distributed data, such as yields and waste potentials. These data are also typically displayed graphically in a map of the UK on the same page.

Figure 9 shows the Objective Function page, where the type of optimisation can be defined, along with values for various constraints; some solver settings can be applied here too. The drop-down menu at the top allows a number of pre-configured objectives to be selected. The left-hand column defines the type of objective function; the middle column defines the constraints used in the optimisation; and the right-hand column defines the $CO_2$ price scenario and further impact constraints.

FIGURE 9

### Objective function page of BVCM



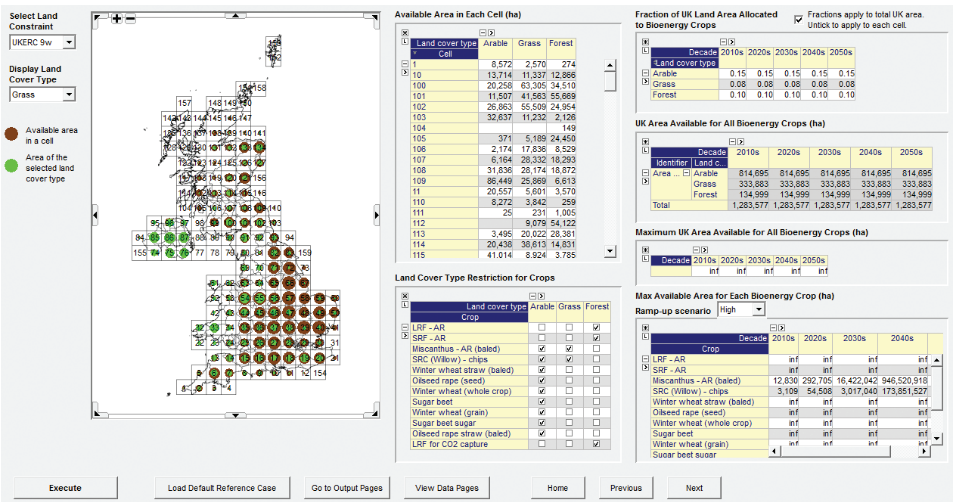
# BVCM architecture

## Continued »

Figure 10 shows an example of an input data page with a map: here, the user can select which land constraint mask to apply (top left drop-down menu) and what fraction (top right table) of the available area under each land cover type (arable, grass, forest) can be used for growing energy crops. Given these settings, the total available area in each cell is shown as brown circles on the map, with the maximum allowed area as green circles on top, the size of the circles indicating the available/allowable area. Further constraints can be added in the form of ramp-up rates for specific crops (bottom right table), and restrictions on what land cover types the energy crops can be grown (bottom middle table).

FIGURE 10

### Example of one of the 'Land Areas' pages of BVCM (where Land Cover Type approach is being used)

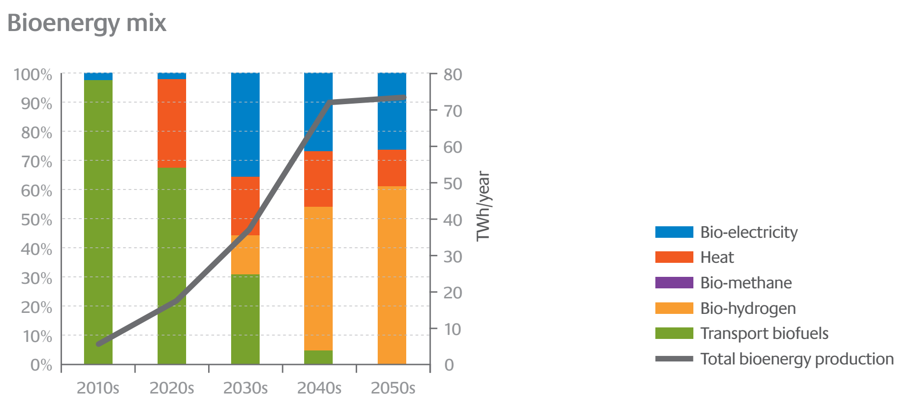



The results of any optimisation can be viewed in BVCM itself, and in the Excel analysis tool, examples of which are shown in Figure 11. The user can view the location and size of various properties of the value chain (e.g. area planted for each crop, amount of each crop grown, capacity of each technology installed etc.), along with transport flows, represented by arrows on the map. Some of the most important data can be combined on a single map, using the bioenergy value chain visualiser (see Figure 11): biomass growth, imports, technologies present and resource transport, allowing the key pathways to be followed and understood.

FIGURE 11

### Examples of result outputs available in both the Excel analysis tool, and from the model itself using the Bioenergy Chain Visualiser

Note that the images shown are for illustrative purposes only.



# BVCM architecture

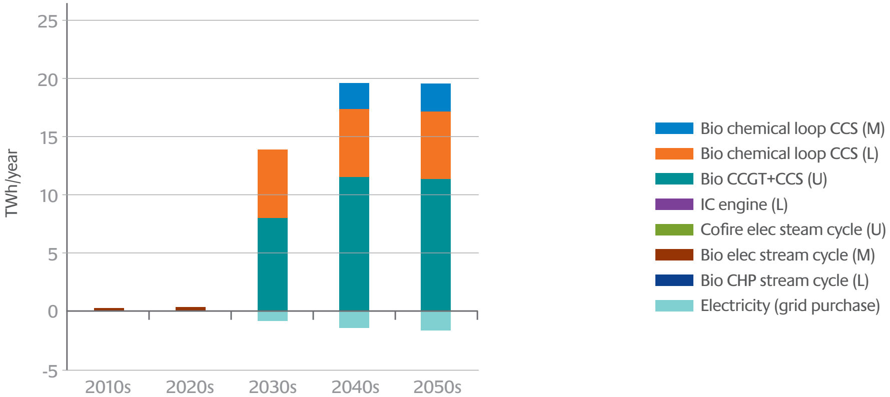
Continued »

FIGURE 11

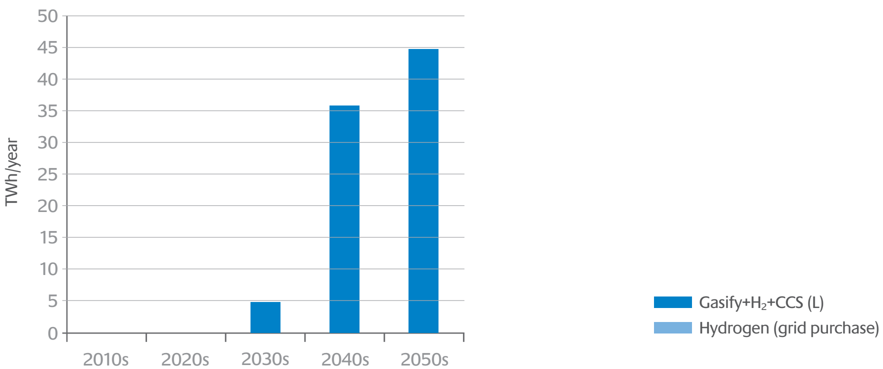
## Examples of result outputs available in both the Excel analysis tool, and from the model itself using the Bioenergy Chain Visualiser

Note that the images shown are for illustrative purposes only.

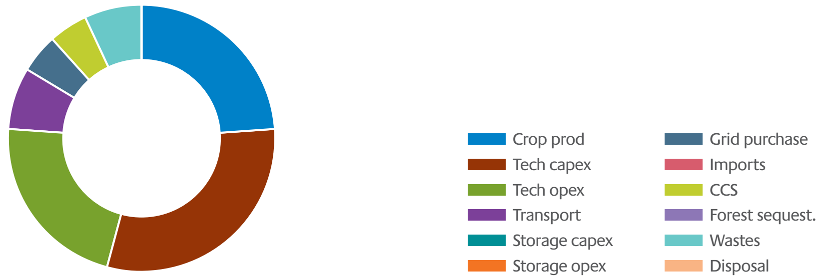
### Bio-electricity production



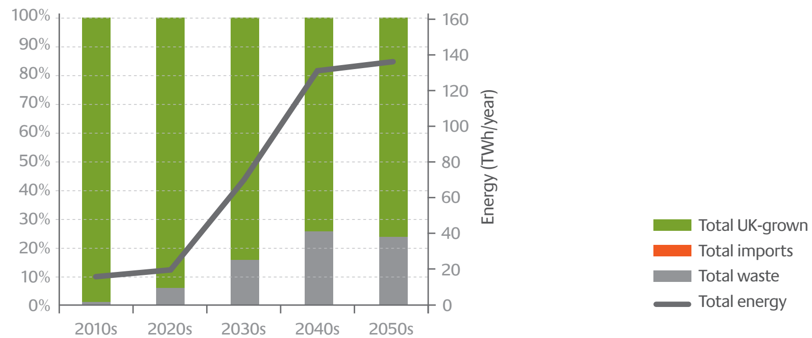

### Bio-hydrogen production




### Bioenergy system base costs, excluding revenues




### Feedstock energy mix (Total)



# BVCM architecture

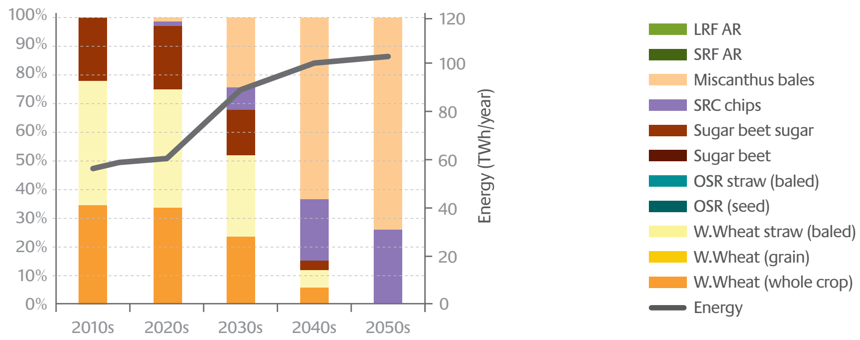
## Continued »

FIGURE 11

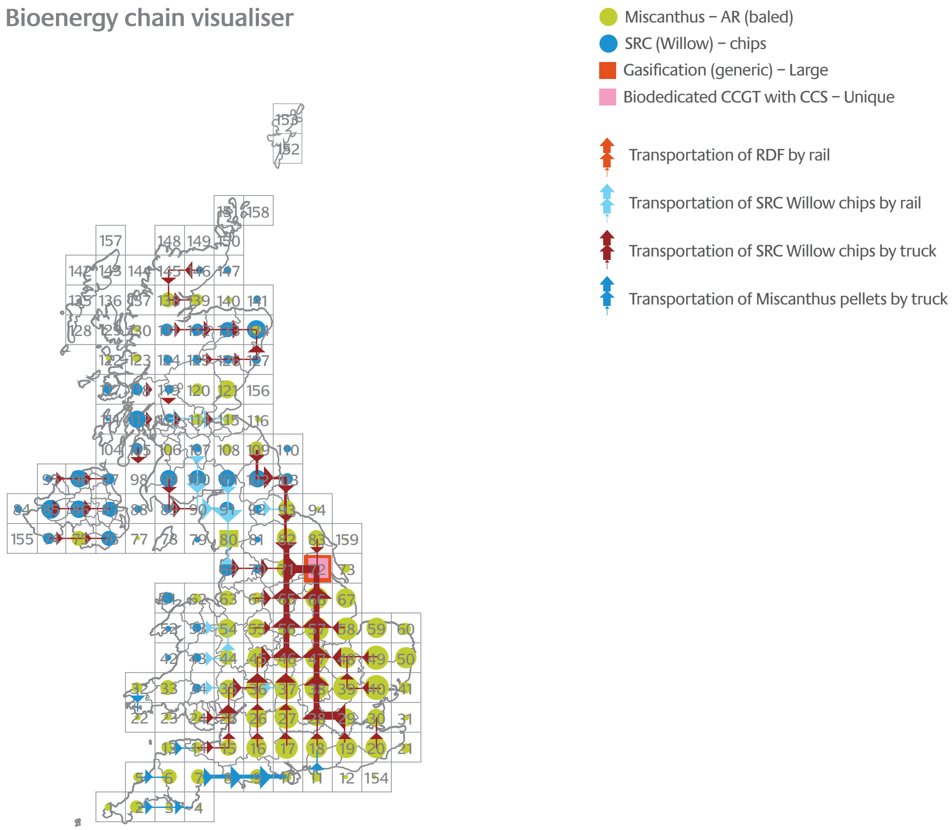
### Examples of result outputs available in both the Excel analysis tool, and from the model itself using the Bioenergy Chain Visualiser

Note that the images shown are for illustrative purposes only.

#### Feedstock mix (UK-grown)




#### Bioenergy chain visualiser



# Summary

Biomass must play a significant role in the future energy mix if the UK is to meet its GHG emissions targets cost-effectively. BVCM is a comprehensive and flexible toolkit used to understand the most effective routes from biomass to energy accounting for all end-to-end elements in the pathways: land use, biomass production (including arable crops, energy crops and forestry); imports, conversion, transport, storage, purchase, sale and disposal of resources; CCS technologies and utilisation of waste resources. The most effective route depends on the resource and technology data, combined with the objective function chosen and the constraints imposed on the system.

To the ETI's knowledge, BVCM is the most comprehensive and flexible model for whole system optimisation of bioenergy value chains to be produced to date. It currently contains 82 different resources comprising bio-resources, wastes, intermediates, final energy vectors and co-products. There are 61 distinct technologies, at different scales with multiple modes (more than 1200 combinations in total), including: pretreatment and densification; gaseous fuel production; liquid fuel production; heat, power and combined heat and power generation; waste-to-energy; and carbon capture technologies.

The UK is represented by 157 50km square cells and the time horizon is over five decades, from the 2010s to the 2050s; seasonality can also be considered, with up to four seasons being modelled per year. Restrictions on the amount of existing land use available for conversion to biomass production can be modelled using the CORINE Land Cover 2006 map. Resources can be transported by road, rail, pipeline, inland waterways and close-costal shipping and can be imported into major UK ports with three import scenarios relating to the impacts and availability of the resources. More information on the mathematical formulation and model functionality can be found in Samsatli et al. (2015)[27].

Since BVCM is data-driven, it can easily be extended to include other resources or technologies by adding to the database, or modified to analyse alternative assumptions. It could also be applied to other countries simply by providing different data sets for the available land areas, yield potentials (and impacts), waste potentials and so on.

The BVCM toolkit enables us to assess the sensitivities of the system to different parameters, drawing on the best available data. The ETI is using the BVCM toolkit to help determine the role that biomass should play in achieving the UK's energy and GHG emissions targets in 2050. The ETI does not currently have plans to release the BVCM toolkit publicly in the near future, but has so far provided a licence for its use in two Supergen projects[28].

“To the ETI's knowledge, BVCM is the most comprehensive and flexible model for whole system optimisation of bioenergy value chains to be produced to date.”

[27] Samsatli, S, Samsatli, N. J. and Shah, N. (2015). BVCM: a comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – mathematical formulation. Applied Energy. doi:10.1016/j.apenergy.2015.01.078

[28] EPSRC SUPERGEN Bioenergy Challenge Project EP/K036734/1:
http://www.supergen-bioenergy.net/research-projects/bioenergy-value-chains--whole-systems-analysis-and-optimisation/
;and the recently-funded MAGLUE project: http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/M013200/1.

## **Appendix:** Resources and Technologies in BVCM
### Table A1: Resources in BVCM

| Family | Resource |
|---|---|
| Food crops (1st generation energy crops) | Winter wheat (whole crop) |
| | Winter wheat (grain) |
| | Oilseed rape (seed) |
| | Sugar beet |
| | Rapeseed oil |
| Energy crops (2nd generation) | SRC (Willow) – chips |
| | SRC (Willow) – torrefied chips |
| | SRC (Willow) – pellets |
| | SRC (Willow) – torrefied pellets |
| | Miscanthus – As Received (AR) (baled) |
| | Miscanthus – pellets |
| | Miscanthus – torrefied pellets |
| Forestry | SRF – As Received (AR) |
| | SRF – chips |
| | SRF – torrefied chips |
| | SRF – pellets |
| | SRF – torrefied pellets |
| | LRF – As Received (AR) |
| | LRF for $CO_2$ capture |
| | LRF – chip |
| | LRF – torrefied chips |
| | LRF – pellets |
| | LRF – torrefied pellets |
| Wastes | Animal slurry |
| | Waste – All |
| | Waste – Bio |
| | Waste – Wood |
| | Waste – Plastics |
| | Waste – Paper/textile |
| | Waste – Other |
| Intermediate | Winter wheat straw pellets |
| | Pyrolysis oil |
| | Syngas |
| | Anaerobic digestion (AD) gas |
| | Methane (vented) |
| | Hot water (from plant) |
| | Waste – RDF |
| | Waste – Wood – chips |
| | Waste – Wood – pellet |
| | Waste – Wood – torrefied chips |
| Final energy vectors | Bio-diesel (FAME) |
| | Bio-diesel (HVO) |
| | Bio-hydrotreated jet (HRJ) |
| | Bio-methanol |
| | Bio-ethanol |
| | Bio-butanol |
| | Bio-higher alcohols |
| | Bio-FT diesel |
| | Bio-FT jet |
| | Bio-naphtha |
| | Bio-DME |
| | Bio-UPO |
| | Bio-hydrogen |
| | Bio-methane |
| | Hot water |
| | Bio-electricity |
| Co-product | Distiller's Dried Grains with Solubles (DDGS) |
| | Winter wheat straw (baled) |
| | Oilseed rape straw (baled) |
| | Rapeseed meal |
| | Sugar beet sugar |
| | Sugar beet pulp |
| | C5 Molasses |
| | Char |
| | Glycerine – crude |
| | Propane mix gas |
| | Fuel gas |
| | Digestate |
| Other | Heavy fuel oil |
| | Methanol |
| | Diesel |
| | Hydrogen |
| | Natural gas |
| | Electricity |
| | Hexane |
| | Sodium methoxide |
| | HCl |
| | $H_3PO_4$ |
| | Caustic soda |
| | Sulphuric acid |
| | Urea |
| | Gasoline |

## **Appendix:** Resources and Technologies in BVCM
### Table A2: Technologies in BVCM

| Family | Technology |
|---|---|
| 1G biofuels | First generation biodiesel |
| | First generation butanol |
| | First generation ethanol |
| | Hydrotreatment |
| | Sugar Biorefinery |
| 2G biofuels | Gasification + FT diesel |
| | Gasification + FT jet/diesel |
| | Gasification + methanol catalysis |
| | Gasification + mixed alcohol processing |
| | Gasification + syngas fermentation |
| | Lignocellulosic Biorefinery (e.g. Inbicon) |
| | Lignocellulosic butanol |
| | Lignocellulosic ethanol |
| | Pyrolysis oil upgrading |
| | Sugar-to-diesel |
| | Wood-to-diesel |
| Anaerobic Digestion | Anaerobic Digestion |
| | Biogas upgrading |
| CHP for district heating | Biodedicated IGCC |
| | Biodedicated steam cycle (CHP) |
| | Cofired IGCC |
| | Cofired steam cycle (CHP) |
| | Gas turbine |
| CHP onsite | IC engine |
| | Organic Rankine Cycle |
| | Stirling engine |
| Heating | Boiler combustion (heat) |
| | District Heating (DH) network |
| | Syngas boiler |
| Power | Biodedicated CCGT |
| | Biodedicated steam cycle (electricity) |
| | CCGT retrofit |
| | Coal Retrofit Pulverised Coal Plant |
| | Cofired steam cycle (electricity) |
| | Incineration |
| | Oil-fired CC |
| | Plasma gasification |
| | Pyroliquid Biorefinery (e.g. Ensyn) |
| Power + CCS | Biodedicated CCGT + CCS |
| | Biodedicated chemical looping CCS |
| | Biodedicated combustion + amine CCS |
| | Biodedicated IGCC + CCS |
| | Biodedicated oxy-fuel CCS |
| | Cofired carbonate looping CCS |
| | Cofired combustion + amine CCS |
| | Cofired IGCC + CCS |
| | Cofired oxy-fuel CCS |
| Thermal pre-treatment | Mechanical Biological Treatment (MBT) |
| | Pyrolysis |
| | Pyrolysis-biochar |
| | Torrefaction |
| | Torrefaction + pelletising |
| Densification | Chipping |
| | Oil extraction |
| | Pelletising |
| Gasification to gaseous | Gasification (generic) |
| | Gasification + bioSNG |
| | Gasification + DME |
| | Gasification + $H_2$ |
| Gaseous + CCS | Gasification + bioSNG + CCS |
| | Gasification + $H_2$ + CCS |

## Biomass Gasification Plant

energy technologies institute

Energy Technologies Institute
Holywell Building
Holywell Way
Loughborough LE11 3UZ

www.eti.co.uk