Programme Area: Bioenergy

Project: Biomass Value Chain Modelling

Title: Model Formulation Report

Abstract:

This deliverable presents the specifications of the “optimisation” model structure (indices, sets, parameters, variables and constraints) and the form of the data that is provided to the model.

Context:

The development of the BVCM model has been ongoing since the project first started in 2011. The documents published here relate to the intial phases of model development. They do not included later developments and are therefore not representative of the current BVCM model, or in some cases, its findings. For a more recent overview of BVCM and the findings derived from it, readers are encouraged to look at the insights and reports published by the ETI, here: http://www.eti.co.uk/insights and here: http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities

BVCM is now managed by the Energy Systems Catapult (ESC). Any questions about the ESC should be directed to them at: info@es.catapult.org.uk

BI2002
Biomass System Value Chain Modelling

WP 2

Deliverable 2.2

Model formulation report

Version 2.0

The BVCM Consortium

For the Energy Technologies Institute
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Contents

1 Executive Summary

This document presents the specifications of the optimisation model structure (indices, sets, parameters, variables and constraints) and the form (not the content) of the data that is provided to the model via the neutral file format interface.

2 Model formulation

The mathematical model will be in the form of mixed integer linear programme (MILP). This will represent the best compromise between system representation and computational tractability. Such models are represented by:

- Sets and indices: the main system entities to be modelled
- Parameters: datasets which are usually defined on ranges associated with sets and indices; these are constants for the model
- Variables: these reflect the decisions available to the optimiser
- Constraints: these reflect the equations/rules which govern the system behaviour
- Objective function: the function to be maximised or minimised.

2.1 Model Indices and Sets

These are listed below

- [s] – scenario: sets some important global variables such as climate, learning rates, etc.
- [c] – cell: the basic element used to describe the region of interest. Square cells will be used in this project. Data associated with each cell will be the location (E,N) of the centroid, area, land cover information and grade (% arable, built up, forestry, NP, SSRI, etc.) and any allowable changes to land cover (e.g. arable to forestry)
- [b] – biomass type: this includes the name and compositional analysis (including any important minor constituents)
- [k] – species – the different constituents of arising and processed biomass (e.g. lignin, C6 polymers, C5 polymers, minor constituents, ...)
- [d] – decade (2010, 2020, ... , 2050)
- [t] – season (1, 2, 3, 4): the four quarters of the year
- [j] – technology: the equipment or processes that convert one or more input resources into one or more output resources. The same technology at different scales (e.g. small and large) is treated as different technologies (with potentially different efficiencies etc.).
- [r] – resource: all the resources which interact with the technologies will be listed
- [l] – transportation mode (link)
- [m] – processing mode: some conversion technologies will be able to operate in different modes (e.g. anaerobic digestion with different feedstocks) in which resource use will be different
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2.2 Parameters

These are in the form of multi-dimensional arrays:

- Y_{bdcs} = yield (odt/Ha) of biomass b in decade d, cell c, scenario s – this set of units applies to all arising biomass including agricultural residues and wastes. As data comes through from other projects these can be added.
- AA_{cd} = area available (Ha) for production of biomass resources in cell c.

  CP_{bdcs} = production cost (£/odt) of biomass b in decade d, cell c, scenario s. This is the cost at farm-gate or roadside. Includes basic at-farm processing that is part of harvesting operations
- OP_{bdcs} = opportunity cost (£/odt) associated with biomass b in decade d, cell c, scenario s
- CE_{bdcs} = establishment cost (£/Ha) of biomass b in decade d, cell c, scenario s
- V_{bdcs} = Increase in land value (£/Ha) over a baseline land use associated with a switch to biomass type b in d, c, s – this may be very relevant to standing forest where production of biomass for energy use may not occur to any great extent during the time horizon
- F_{bt} = fraction of annual production of b arising in season t
- DG_{bdcs} = direct GHG emissions (tCO_2e/odt) associated with producing of biomass b in decade d, cell c, scenario s
- IG_{bdcs} = indirect GHG emissions (tCO_2e/odt) associated with producing of biomass b in decade d, cell c, scenario s (this will not have data at the moment but is a placeholder for values generated by other ETI projects)
- CO_{bk} = mass fraction of species k in biomass class b
- D_{rcdt} = demand of resource r in cell c, decade d, season t. This relates to end use resources (energy services) such as heat, power, transport fuel etc and is specified by scenarios. In some cases this can be a maximum value per cell and the amount actually satisfied will be determined by the model. Inputs to conversion technologies are determined by the model.
- DER_r = mass density ($kg.m^{-3}$) of resource r
- DEB_b = mass density ($kg.m^{-3}$) of biomass type b
- $LCB_{bcc'l}$ = cost per tonne to move biomass of type b from c to c' using mode l
- $LCR_{rcc'l}$ = cost per unit to move resource r from cell c to cell c' using mode l

  Both of the above are the average unit costs to move material between cells. The actual costs incurred will depend on the location (and therefore density) of different processing facilities at the regional level.

- $LGB_{bcc'l}$ = GHG emissions per tonne to move biomass of type b from cell c to cell c' using mode l
- $LGR_{rcc'l}$ = GHG emissions per unit to move resource r from c to c' using mode l
- CC_{jd} = (projected) capital cost (expressed in £ per relevant input/output unit, e.g. £/GW, £/ton of biodiesel) of technology j in decade d

- OC_{jd} = (projected) non-resource related operating cost of technology j in decade d (aligned with the ESME view of operating cost). This might include labour, maintenance etc. but not fuel/power, which are part of the resource-based costs.
- NC_j^{min}, NC_j^{max},= min and max nameplate capacity (in terms of major output, e.g. kWe) of technology j
- EL_j = economic lifetime of technology j
- TL_j = technical lifetime of technology j
- TD_j = allowable turndown (%) of technology j (the minimum operating capacity as a % of its nameplate capacity)
- PS_{jk} = maximum threshold of prohibited species k (minor constituents) associated with technology j
- PC_{jrmd} = unit/unit production/consumption (+ve or –ve coefficient) of resource r by technology j operating in mode m in decade d (note different decades may reflect improvements in efficiency); this will also capture indirect GHG emissions via the use of grid electricity etc. For example, this will capture the amount of biogas required to be combusted in an engine for a specific amount of electricity. The coefficient is always based on a unit amount of the main output resource; the coefficient of this main output resource will be +1. Input resources would be negative. So if the biogas engine had an electrical efficiency of 0.4, the coefficient for the biogas resource would be -2.5 and that for electricity would be +1. If heat is also produced, that might have a coefficient of, say, 1.1. Other by-products (e.g. DDGS) can also be captured by this.
- BR_{jd} = Build rates of (units of capacity per year) of technology j in decade d

All costs are expressed in 2010 GB pounds.

2.3 Model Variables

The model identifies an optimal solution by altering the values of the following decision variables:

- N_{jcd} number of technologies of type j available in cell c, decade d
- IT_{jcd} number of technologies of type j purchases in cell c, decade d
- RT_{jcd} number of technologies of type j retired in cell c, decade d
- $\mathcal{O}_{jmcdt}$ number of processes j operating in mode m in cell c, season t and decade d
- $\mathcal{P}_{\mathrm{jmcdt}}$ operating rate of process j in mode m, in cell c in season t and decade d
- P_{rcdt} production rate of resource r in cell c in season t and decade d
- $Q_{rcc'ldt}$ the flow of resource r from cell c to cell c' using transport mode l in season t and decade d
- I_{rcdt} and E_{rcdt} respective rates of import and export of resource r in cell c and decade d and season t
- S_{rcdt} the net consumption from storage of resource r cell c over season t of decade d

- $\mathbb{S}_{rcd}^{\max}$ Maximum storage capacity for resource r in cell c in decade d
- $\mathbb{S}_{\mathrm{rcdt}}$ Amount of resource r in storage in cell c at the end of season t in decade d
- Z the objective function, which is a weighted sum of metrics (e.g. cost, GHG emissions and other environmental impacts) associated with the costs of resources, equipment and operations

2.4 Model Equations

2.4.1 Resource balance

The resource balance is written for each resource, r, in each cell, c, during each decade, d, and season, t. The net production, P, plus the inflow from other cells, less the outflow to other cells, plus the rate of import (from other countries) plus the net rate of resource consumption from storage must balance the demand for that resource plus the rate of export. The ability to store material between seasons together with the breakdown of yield by season enables good utilisation of process technologies.

$$P_{rcdt} + \sum_{c',l} Q_{rc'cldt} - \sum_{c',l} Q_{rcc'ldt} + I_{rcdt} + S_{rcdt} = D_{rcdt} + E_{rcdt}$$

For biomass resources, the amount produced is dependent on the potential yield and area available in the cell:

$$\sum_{bt} P_{bcdt} \;/\; Y_{bcds} \leq AA_{cdt}$$

2.4.2 Imports and exports

For generality, imports and exports can be subject to minimum and maximum rates (which may be a function of time), when a transaction takes place. When there are physical or contractual limitations on the rates of import or export, these can be set by specifying the variable bounds $I_{rdt}^{\min}$, I_{rdt}^{max}, $E_{rdt}^{\min}$ or E_{rdt}^{max}; otherwise suitable numbers can be used to ensure the rates are effectively unconstrained. These can be used to explore different supply options, including the case with no biomass or process biomass imports.

2.4.3 Resource conversion technologies

The net production of (non-biomass) resource r in each cell is P_{rcdt}. It is calculated by taking the total production rate of each technology (for each mode, m) $\mathcal{P}_{jmcdt}$ and multiplying by the conversion factor (*PC*) for resource r:

$$P_{rcdt} = \sum_{jm} PC_{jmrd} \mathcal{P}_{jmcdt}$$

The total production rate of each technology is limited by the number of technologies operating in mode *m* multiplied by the maximum production rate for that technology/scale/mode combination. $\mathcal{O}_{jmcdt}$ is the number of technologies (on average) operating in mode m and $\mathcal{P}_{jm}^{\max}$ is the maximum production rate of that technology in mode m.

$$\mathcal{P}_{jmcdt} \leq \mathcal{O}_{jmcdt} \mathcal{P}_{jm}^{\max}$$

The total number of technologies operating in all modes must be less than or equal to the total number of installed technologies, N_{jcd} (this allows some technologies to be idle).

$$\sum_{m} \mathcal{O}_{jmcdt} \leq N_{jcd}$$

Finally, a technology balance tracks how many technologies are available in each decade, N_{jcd}. IT_{jcd} and RT_{jcd} are respectively the number of new investments and retirements of technology j in cell c during decade d.

$$N_{jcd} = N_{jcd-1} + IT_{jcd} - RT_{jcd}$$

2.4.4 Resource transportation

Resource transportation is modelled using transport modes, l. The modes include road, rail, canal, sea, pipeline etc. Not all modes may be available between cells. This information is recorded as part of the input data. Similarly, for all modes, the straight line distance is modified by a tortuosity factor which depends on the actual transportation infrastructure available. Each mode has a per unit cost (£ per tonne▪km) and GHG emissions (kgCO2e per tonne▪km), as defined in the parameters section.

The key variable, *Q*, is then constrained as follows:

$$Q_{rcc'ldt} \leq QMAX_{cc'l}$$

Where $QMAX_{cc'l}$ is the maximum flow possible (set to zero if mode l is not available between cells c and c').

2.4.5 Storage constraints

The amount of resource *r* in storage at the end of season *t* in decade *d* is: $\mathbb{S}_{rcdt}$. The storage balance, below, states that the amount of resource in storage at the end of season t is equal to the amount at the end of the previous season (*t* – 1) less the net amount consumed in season *t* (as defined by the equation in 2.4.1. Note that the net amount consumed could be negative, i.e. there is a nett production of the resource over season *t* – 1.

$$\mathbb{S}_{rcdt} = \mathbb{S}_{rcdt-1} - S_{rcdt}$$

In order to ensure that there is no net accumulation of resource from year to year in the same decade, the amount of resource being stored at the beginning of the year ($\mathbb{S}_{rcd0}$) must be equal to the amount in storage at the end of the year ($\mathbb{S}_{rcd4}$).

$$\mathbb{S}_{rcd0} = \mathbb{S}_{rcd4}$$

This seasonal storage enables the balancing of resource supply and demand over the year. This allows us to model resources that arise at different times of the year, and seasonally-varying demands (especially heat). Each season lasts 3 months; we believe that this reflects a good balance between accuracy and tractability.

Finally, the amount of resource that can be stored is limited by the maximum storage capacity available:

$$\mathbb{S}_{rcdt} \leq \mathbb{S}_{rcd}^{\max}$$

2.4.6 Objective function and model drivers

A number of objective functions can be developed. These are driven by the use cases for the studies. They include:

- Minimise total annual system cost for a certain amount of bioenergy penetration
- Maximise bioenergy penetration for a given capital and operating cost budget
- As above but with environmental impact constraints (e.g. overall GHG emissions)
- Minimise an environmental impact (e.g. overall GHG emissions) subject to cost constraints and a minimum amount of bioenergy penetration]

We expect the key model drivers to be the potential yields, the costs and, especially, the demands for different bioenergy end-uses (heat, power, biodiesel, bioethanol, biogas, etc.). Each of these can be specified spatially or in aggregate by decade to generate alternative scenarios. This is achieved via the specification of the parameters D_{rcdt}. We anticipate that a major use of the tool is to explore the impacts of different penetration levels of bioenergy vectors.

2.5 Model outputs

The key model outputs will be the optimal values of the following variables:

- Total system cost
- Total system bioenergy production (primary and end-use)
- Total system greenhouse gas emissions
- PB_{bcd} = production of biomass b (t) in cell c, decade d
- IT_{jcd} = number of technologies of type j invested in in decade d and cell c
- RT_{jcd} = number of technologies of type j retired in decade d and cell c
- N_{jcd} = number of technologies of type j available in decade d and cell c
- O_{jmcdt} = number of technologies of type j operating in mode m cell c in decade d and season t
- $\mathbb{S}_{rcd}^{\max}$ = maximum level of storage for resource r in decade d and cell c
- PT_{jdtc} = average production rate of technology of type j in decade d, season t and cell c
- PR_{rtdc} = amount of resource r produced/consumed over season t of decade d in cell c
- $\mathbb{s}_{rcdt}$ = amount of resource r stored at the end of season t of decade d in cell c
- $Q_{rcc'ldt}$ = amount of resource r moved from c to c' during season t of decade d using link type l

These will be post processed and stored as comma-separated (.csv) files as well as input shape files for ArcGIS™. They will also be aggregated regionally for compatibility with ESME.

3 Data interface

The data/parameters to be exchanged between WP2 and WP1 (bioresource yield potentials) and WP3 (equipment data) have been specified in the report D2.1.

To make data interchange as easy as possible, we recommend that data be exchanged between models in comma separated file formats.

For simplicity, these will organise the data using a dense notation for the multi-dimensional arrays, whereby the first 7 columns (INTEGER) will be reserved for index values and the 8th column for the content (REAL).

There will be a degree of iteration in finalising the data import interface (not the data specification which is as laid out in D2.1) as data is exchanged between work packages.