Programme Area: Bioenergy

Project: Biomass Value Chain Modelling

Title: Opportunity Identification and Roadmapping

Abstract:

This deliverable presents technology opportunities and bioenergy roadmapping, based on the case study analysis carried out with the Biomass Value Chain Model (BVCM). The model has been used to investigate a series of case studies, designed to explore different scenarios in relation to resources, technologies, end uses, infrastructures and objective functions. For each case study a series of runs has been executed to explore trends and analyse the sensitivity and the resilience of the results. Based on these results, acceleration opportunities were identified for technologies in line with the ETI focus on the Technology Readiness Levels (TRL) 3 to 6. Roadmaps for the whole bioenergy sector are provided based on the results from the case study analysis.

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

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WP04.04

Opportunity Identification and Roadmapping Report

Version 2.0

The BVCM Consortium

For the Energy Technologies Institute
1 June 2012

Title	Opportunity Identification and Roadmapping Report	
Client	Energy Technologies Institute	
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Contents

1 Executive summary

This document presents technology opportunities and bioenergy roadmapping, based on the case study analysis carried out with the Biomass Value Chain Model (BVCM).

The Biomass Value Chain Model is a UK-wide spatially-explicit national optimisation model. It models pathway-based bioenergy systems over five decades (from 2010 to 2059). It currently includes seven bioresources (winter wheat, oilseed rape, sugar beet, Miscanthus, Short Rotation Coppice Willow, Short Rotation Forestry, and Long Rotation Forestry), and more than 50 distinct technologies for preatreatment and densification, gaseous and liquid fuel production, and power, heat, and combined heat and power generation (including carbon and capture technologies for power generation). The model either minimises a combined metric (referred to as objective function) which is a weighted sum of discounted whole system cost, CO_2 and non-CO_2 GHG emissions, or maximises energy production under a set of constraints, including cost, emissions, and minimum levels of demand of any energy vector (or total amounts of energy) to be met through bioenergy.

The model has been used to investigate a series of case studies, designed to explore different scenarios in relation to resources, technologies, end uses, infrastructures and objective functions. For each case study a series of runs has been executed to explore trends and analyse the sensitivity and the resilience of the results.

The main insights from the case study analysis are:

Demand, resources and land uses

- Bioenergy can meet 10% of estimated UK energy demand in 2050 by using about 11% to 15% of total UK land. As a theoretical upper limit, up to 32% of estimated UK energy demand in 2050 could be met by bioenergy, by using about 42% of total UK land.
- Different biomass types will be grown in different parts of the UK in order to meet the demand from bioenergy, with SRC-Willow and Miscanthus typically dominating the feedstock mix.
- Biomass resource choice, and their availability, is resilient to climate scenarios, at least till 2050.

Technologies

- Heat production – via large scale boilers and combined heat and power (CHP) plants with district heating networks - is a mature and relatively inexpensive route to bioenergy penetration, and low cost, low GHG emissions bioenergy systems are dominated by heat production especially till 2030s.
- Biogenic Synthetic Natural Gas (BioSNG) emerges as one of the dominant bioenergy vectors post 2040.
- Significant opportunity exists for negative emissions (in the range of 50 to 100 million tonnes of CO2 sequestered per year) via carbon capture and storage technologies in the power sector, with bio-dedicated chemical looping being the most promising one.

- Biomass to hydrogen routes, as well as other routes to fuels (e.g. aviation fuels) are relatively high cost, but may be important for the UK due to strategic and whole-energy system considerations.
- Biomass pyrolysis combined with pyrolysis oil upgrading is the preferred technology route for liquid transport fuels, except in the early years, when first generation ethanol may be used.
- First generation biodiesel (via oilseed rape) is likely to play a marginal role in the UK bioenergy system.

Logistics

- Limited transport of resources (both bioresources and intermediates) occurs. In particular, some transport of densified biomass takes place when land use is constrained and biomass must be grown sparsely over larger land areas. This may change further if imports are allowed, or if more stringent limits on the land locally available for bioenergy in given areas are applied.

Based on these insights, acceleration opportunities were identified for technologies in line with the ETI focus on the Technology Readiness Levels (TRL) 3 to 6. These are:

- Gasification coupled with synthesis of intermediates and fuels (bioSNG, FT fuels, and hydrogen)
- Pyrolysis oil upgrading
- Bio-dedicated chemical looping

Based on the results from the case study analysis, roadmaps for the whole bioenergy sector are provided.

2 Objectives

The main objective of this report is to identify the opportunities for the development and deployment of promising technologies based on the output of the optimisation runs of the Biomass Value Chain Model (BVCM).

2.1 Acceptance Criteria

As per contract, the acceptance criteria for the deliverable WP4-D4 are:

"The report will detail how opportunities have been identified and assessed [...]. The report will:

- *outline a set of recommendations of technology acceleration opportunities within technology readiness levels 3-6 in the bioenergy arena aligned with the ETI core focus of GHG reduction, energy security, and affordability, with an explanation of any gaps in development or information and appropriate justification*
- *outline development and deployment roadmaps, proposing how and when key targets and milestones should be met"*

2.2 Document structure

We have structured this document in the following parts:

- description of the Biomass Value Chain Model (Section 3)
- opportunity identification (Sections 4 to 5)
- roadmaps (Section 7
- next steps (Section 8)
- Appendices:
    - Case studies results: Section 9
    - Land cover categories: Section 10
    - Technology status and innovation needs for selected technologies: Section 11

3 The Biomass Value Chain Model

The Biomass Value Chain Model used for generating the results of this report is a fully-formed national optimisation model. It allows the development of pathway-based bioenergy systems over five decades (from 2010 to 2059). The model has been tested in a large number of configurations.

The various elements of model content are described below. An overview of model architecture and data flows is shown in Figure 3-1.

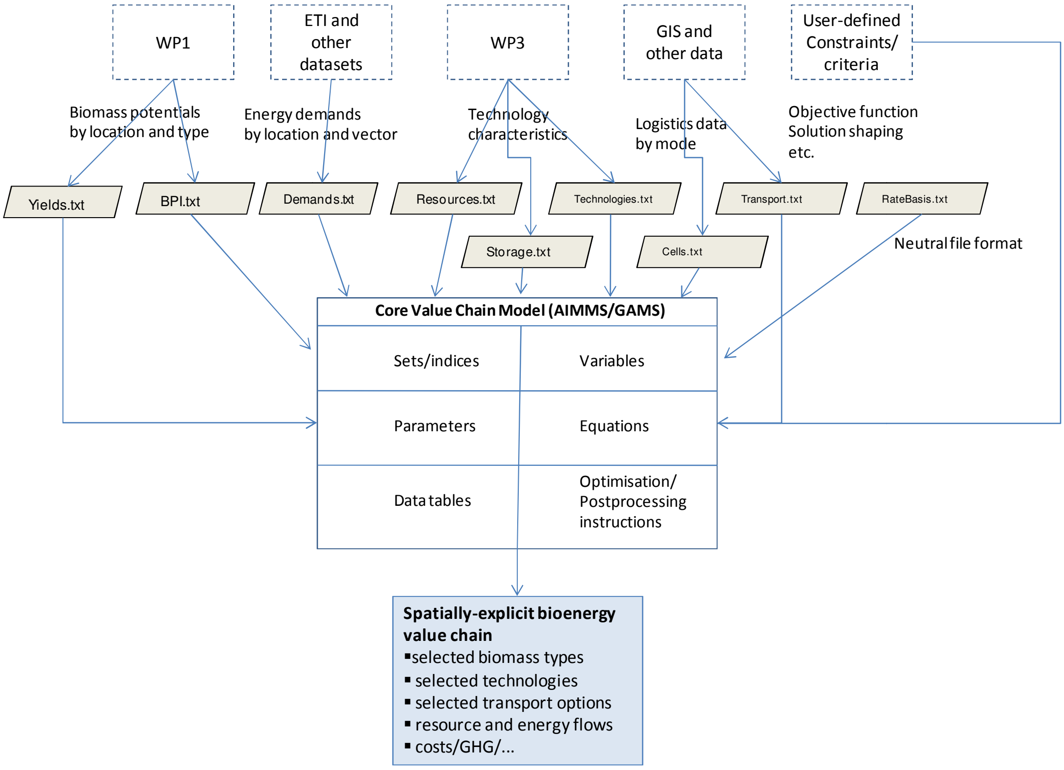

Figure 3-1. BVCM architecture and data flows

3.1 Time

The temporal elements of the model include:

- A maximum of 5 decades
- Up to 4 seasons per year[1]

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[1] Although the functionality to model seasonality exists in the model, a large number of tests and optimisation runs have shown that the key value chain results are not affected by seasonality at this stage. Running the value chain model without seasons results in a significant reduction of computational time. We have therefore switched off the seasonal temporal element of the model for generating the results for this report, in order to explore as many cases studies as possible. We will re-introduce the seasonal element in Phase 2, when other seasonality factors will be modelled as well.

3.2 Climate Scenario

The user has a choice of the “low” and “medium” climate scenarios. These essentially affect the biomass yields and, as consequence, biomass costs and emissions.

3.3 Area Level

This reflects the level of aggression in terms of how much land is potentially available for bioenergy. It has 4 values (1-4) which reflect increasing land area. The constraint masks associated with these levels are based on CORINE Land Cover classifications and are defined as follows:

- *Level 1*
  2.1 Arable land
  2.4 Heterogeneous agricultural areas
- *Level 2*
  As Level 1, plus
  3.2 Shrub and/or herbaceous vegetation association
  3.3 Open spaces with little or no vegetation
- *Level 3*
  As level 2, plus
  2.2 Permanent crops
  2.3 Pastures
- *Level 4*
  As level 3, plus
  3.1 Forests
  1.4 Artificial non-agricultural vegetated areas

Detailed definition of CORINE Land Cover classification is provided in Appendix (Section 10.1).

The philosophy behind these choices is reflected below:

- Level 1 as “easy, established technology”
- Level 2 as “pioneering plant establishment” – soil protection and improvement benefits
- Level 3 as “challenging techno-ecological and economic land use change”
- Level 4 as “last resort”

In addition, the user is able to allocate a certain amount of land under each level (either at aggregated level, e.g. a percentage of total Level 1 land, or at cell level) for purposes other than bioenergy, e.g. for food production.

3.4 Spatial Representation

The United Kingdom is divided into 157 square cells of length 50km. Each has a geographical reference and four sets of data, reflecting the total land cover according to the four classifications above. The representation is illustrated in Figure 3-2.

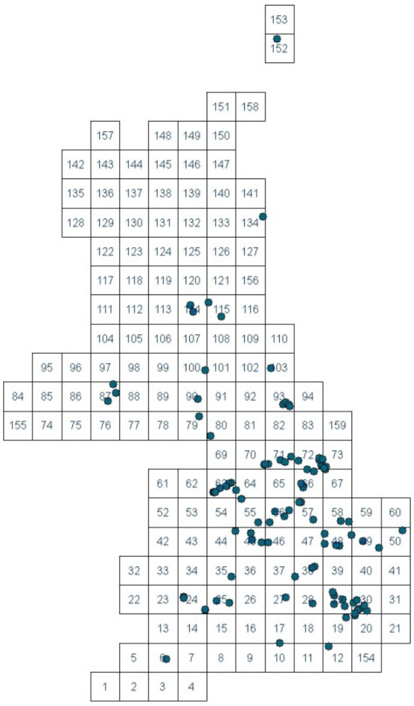

Figure 3-2. Spatial representation of the UK (in this case with power plant locations)

The user can choose which cells to include in a model run.

3.5 Resources

The model as currently implemented includes all the resources in the technology database (which include bioresources, intermediates, and final products). However, the user selects which resources to include in any particular run.

The model allows storage of resources between seasons (but not between years/decades). Maximum number of seasons, storage cost and storage efficiency (as mass loss) are specified. The user can select which resource is “storable”.

3.5.1 Bio-Resources

The bio-resources currently implemented in the BVCM toolkit are the following:

- Winter wheat, as:
    - Winter wheat whole crop
    - Winter wheat grain
    - Winter wheat straw
- Oilseed rape seed
- Sugar beet, as:
    - Sugar beet whole crop
    - Sugar beet root (as sugar)

- Miscanthus
- Short Rotation Coppice (SRC) – Willow
- Short Rotation Forestry (SRF)
- Long Rotation Forestry (LRF), both existing and newly planted.

For the resources above, spatially explicit, decade-dependent yields, costs and GHG emissions as derived in WP1 are used.

Also, no import of biomass feedstock is assumed in the current version of the model. Databases for key biomass imports will be developed and integrated in the BVCM in Phase 2.

3.6 Technologies

The model includes all technologies in the technology database, i.e. 45 distinct technologies, some with multiple scales. Again, the user can select which technologies to include in a run.

The technologies included in the current version of the BVCM toolkit are listed below[2]. Details on the technology models can be found directly in the Technology Database, a fully annotated Excel workbook, or in other WP3 deliverables (e.g. WP3-D3).

- pre-treatment and densification technologies, which include:
    - chipping
    - pelletising[3]
    - torrefaction
    - oil extraction
    - pyrolysis[4]
    - biomethane compression
- technologies for gaseous fuel production, which include:
    - anaerobic digestion
    - landfill gas[5]
    - biogas upgrading
    - stand-alone gasification module
    - gasification with catalytic methane synthesis
    - gasification with catalytic dimethyl ether synthesis
    - gasification with hydrogen production
- technologies for liquid fuel production, which include:

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[2] Technologies related to infrastructures, e.g. natural gas and hydrogen piping will be covered in the development of the optimisation model itself in WP2

[3] In general, if any drying requirements (which depend on the input) apply, those are included in the technology modelling

[4] In principle, pyrolysis oil could be also used for heat, power and combined heat and power generation

[5] Assumed to use MSW. This could be used if and when data on waste from other ETI projects become available.

  - first generation ethanol
  - first generation biodiesel
  - first generation butanol
  - lignocellulosic ethanol
  - lignocellulosic butanol
  - gasification with catalytic Fischer-Tropsch synthesis
  - gasification with catalytic methanol synthesis
  - gasification with catalytic mixed alcohol synthesis
  - gasification with syngas fermentation
  - pyrolysis oil upgrading
  - hydrotreatment[6]

- technologies for heat, power, and combined heat and power generation, which include:
  - boiler combustion (for heat application)
  - dedicated biomass steam cycle
  - biomass co-fired steam cycle
  - Stirling engine
  - organic Rankine cycle
  - internal combustion engine
  - syngas boiler
  - gas turbine
  - close-coupled gasification
  - biomass co-fired integrated gasification combined cycle
  - dedicated biomass integrated gasification combined cycle
  - gasification for power generation[7]

Where applicable, multiple scales of a given technology are considered, with performance parameters such as efficiency and costs depending on the scale. In the technology database scales are referred to "Small", "Medium", "Large". For example, a small 1G ethanol plant is referred to as "First gen ethanol – Small". If only one scale is considered, then the term "Unique" (U) is used.

In addition to the technologies listed above, the modelling of which has been carried out in the BVCM project, we have also included the eight carbon capture and storage (CCS) technologies from the ETI Biomass CCS project (also known as TESBIC).

3.7 Technology-Resources chains

Each technology at relevant scale can operate in several modes, whereby a mode is a combination of a given main input and a given main output. For example, for a biomass boiler, different feedstocks correspond to different modes. In general, efficiencies will vary depending on the mode.

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[6] For the production of Hydrotreated Vegetable Oil (HVO) and Hydrotreated Renewable Jet (HRJ).
[7] Via internal combustion engine or gas turbine

The rationale behind the introduction of technology modes in the modelling architecture is to allow for the functionality of representing technologies operating with multiple feedstocks. This functionality is important to allow for feedstock blending. The combinatorial nature of the links between resources, technologies and modes results in a large number of possible bioenergy chains. These are illustrated in the following Figures, one for each bio-resource.

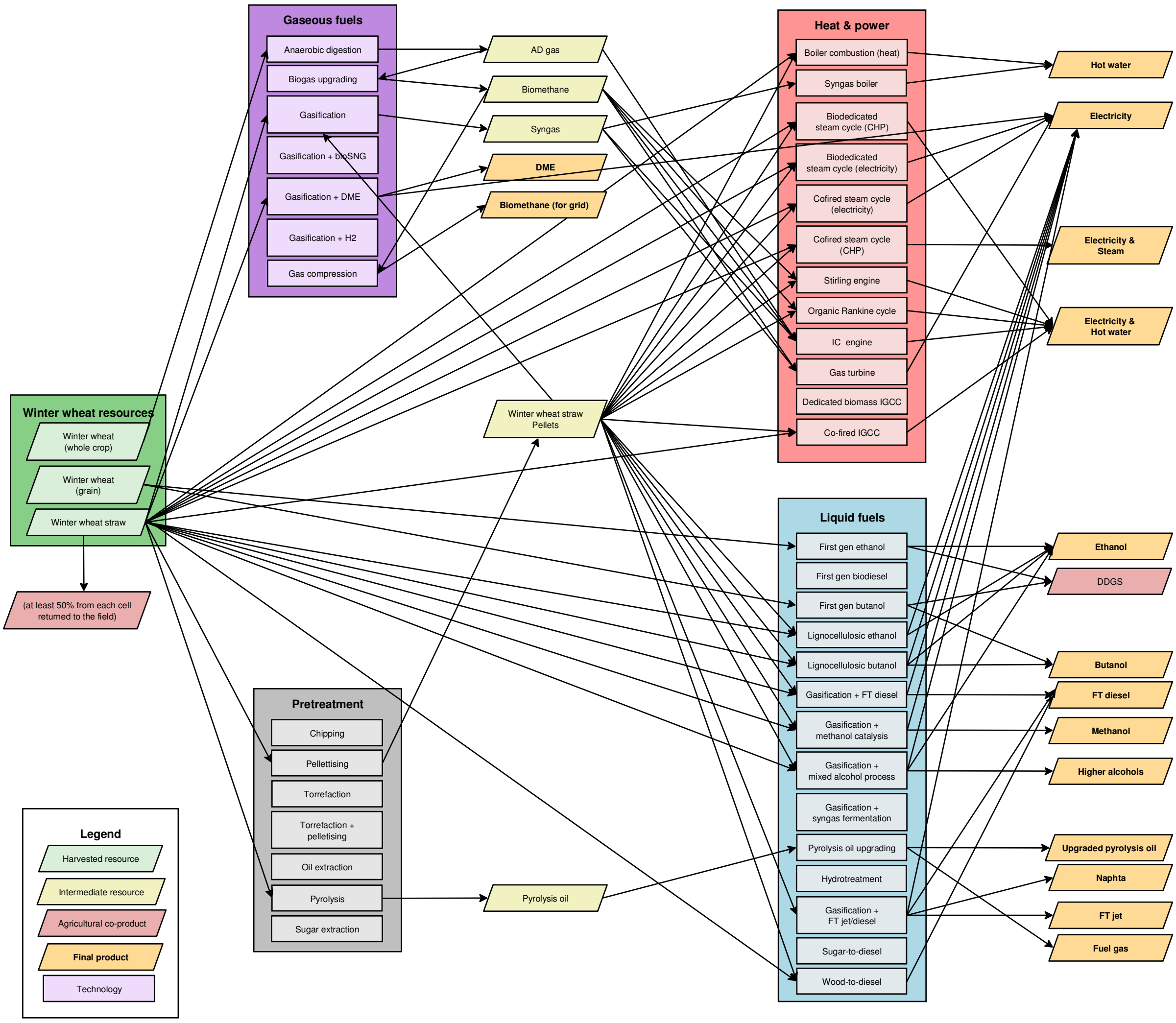

Figure 3-3 Winter wheat bioenergy chains

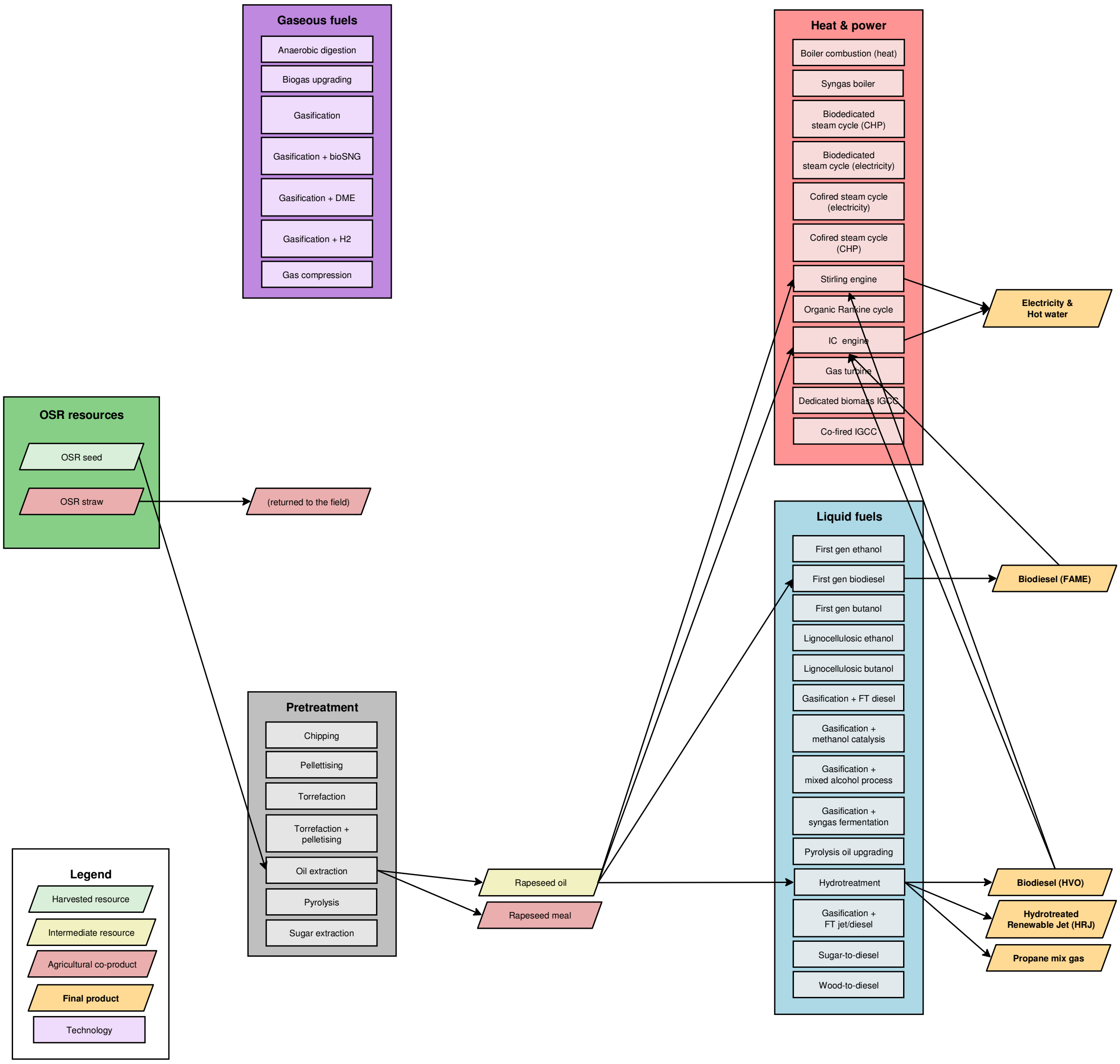

Figure 3-4 Oilseed rape bioenergy chains

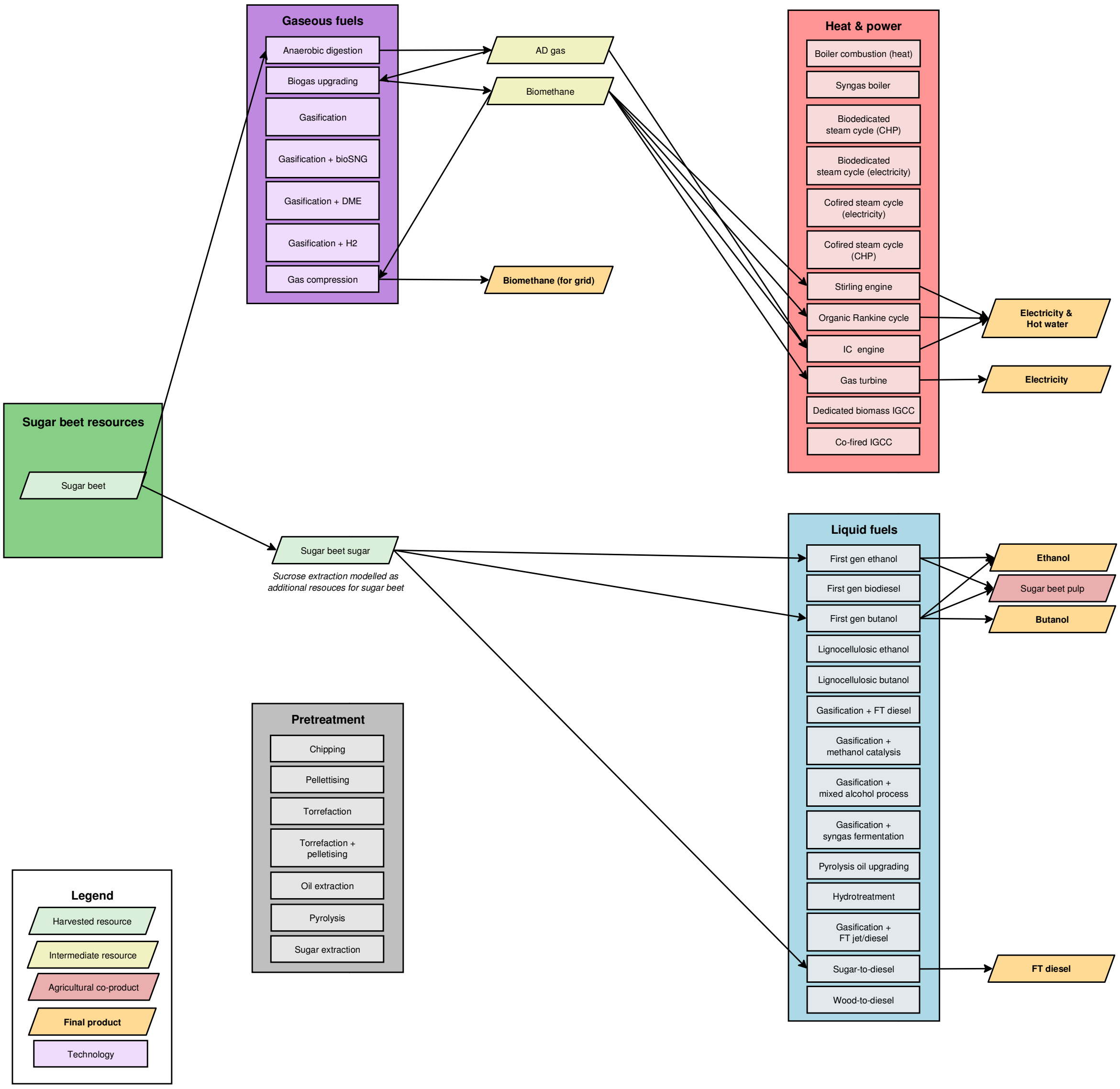

Figure 3-5 Sugar beet bioenergy chains

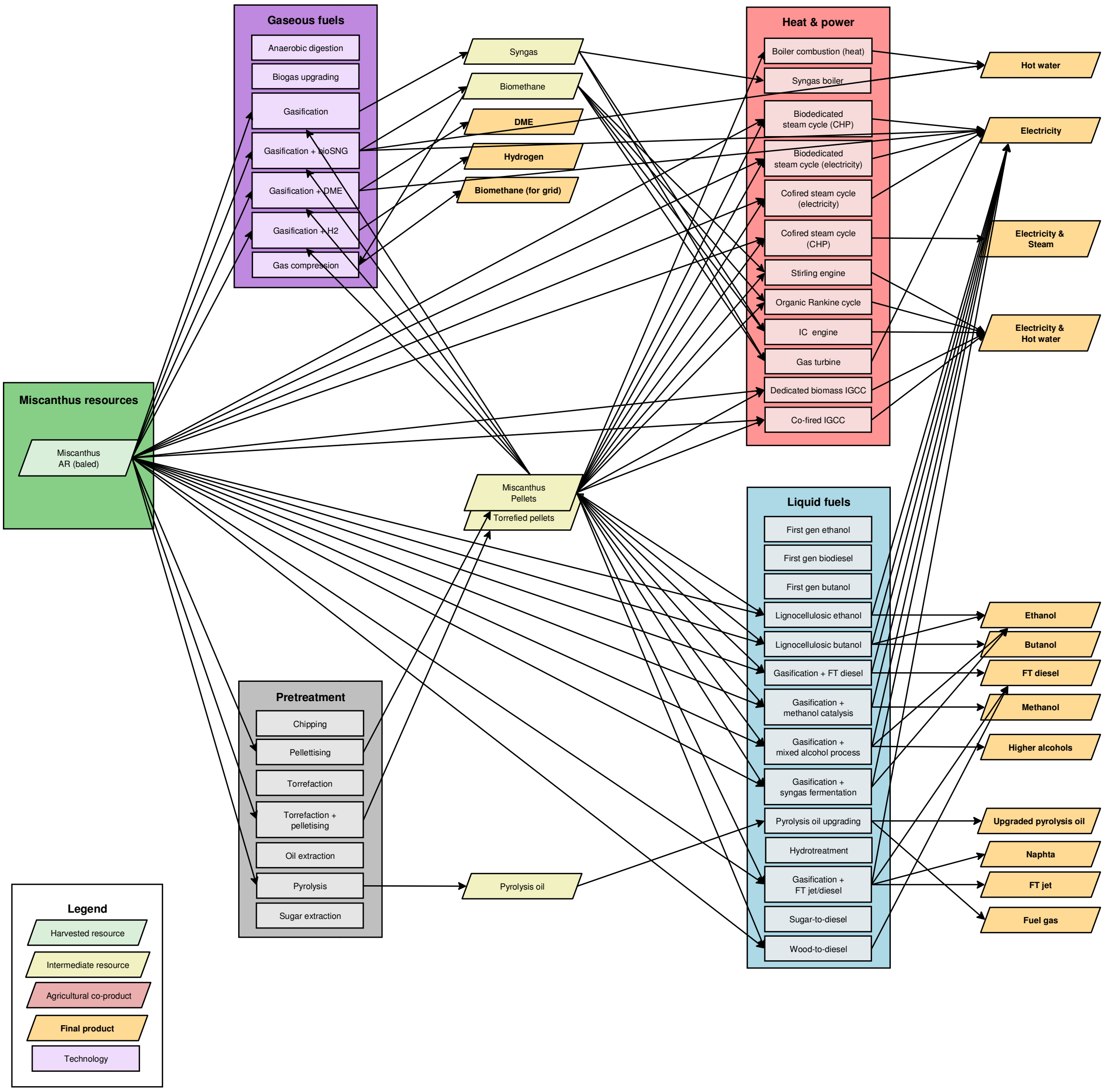

Figure 3-6 Miscanthus bioenergy chains

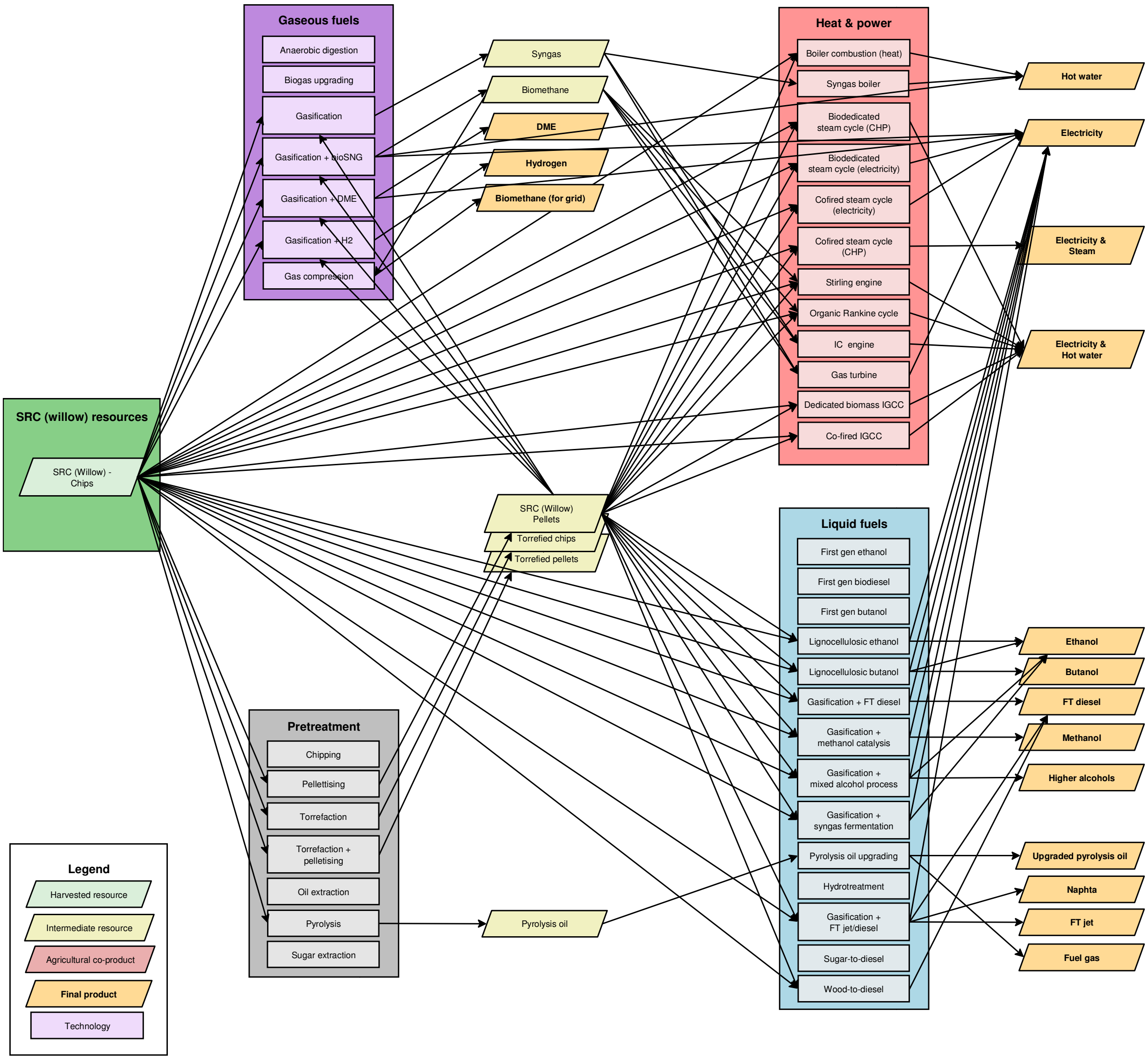

Figure 3-7 SRC Willow bioenergy chains

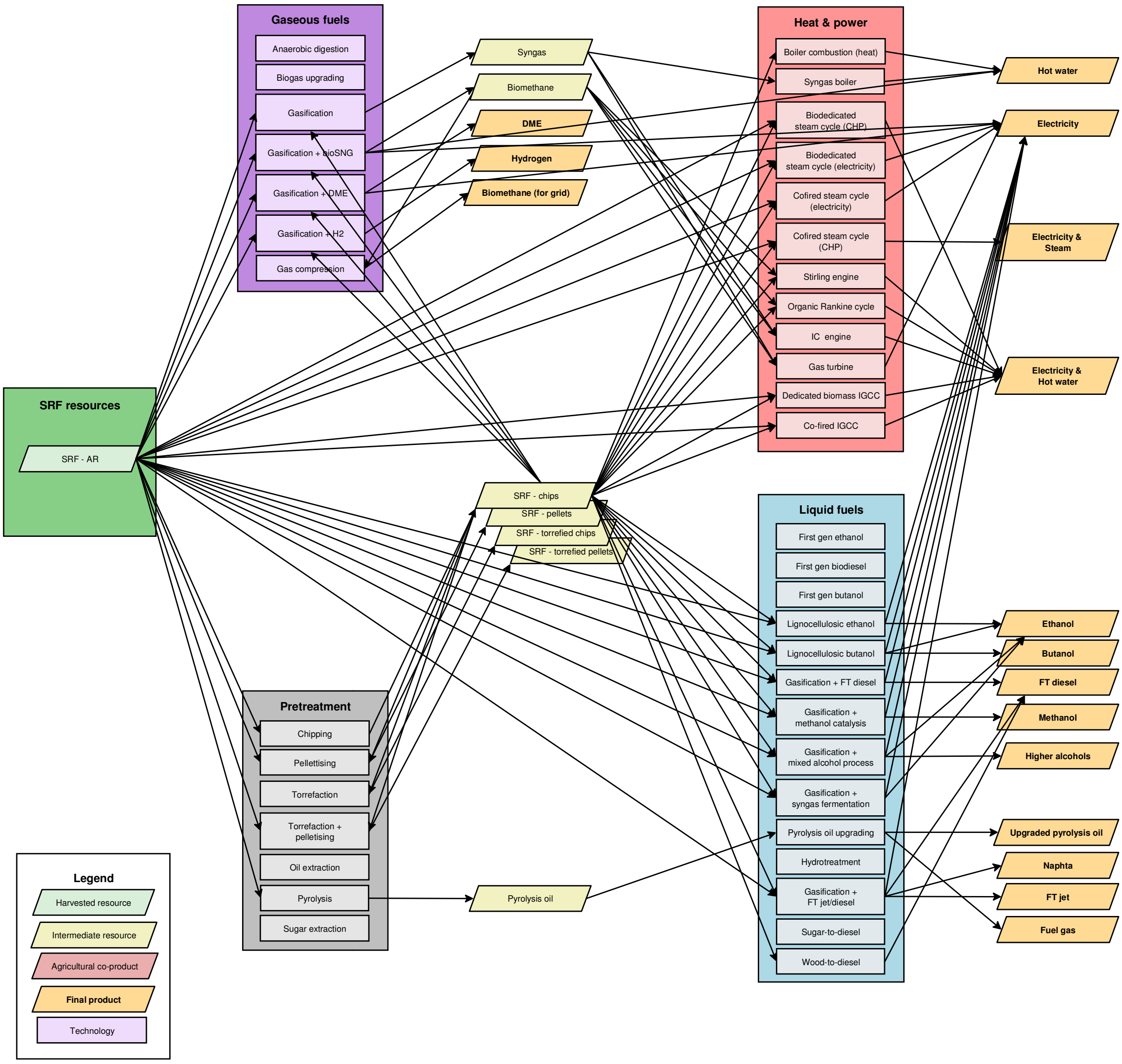

Figure 3-8 SRF bioenergy chains

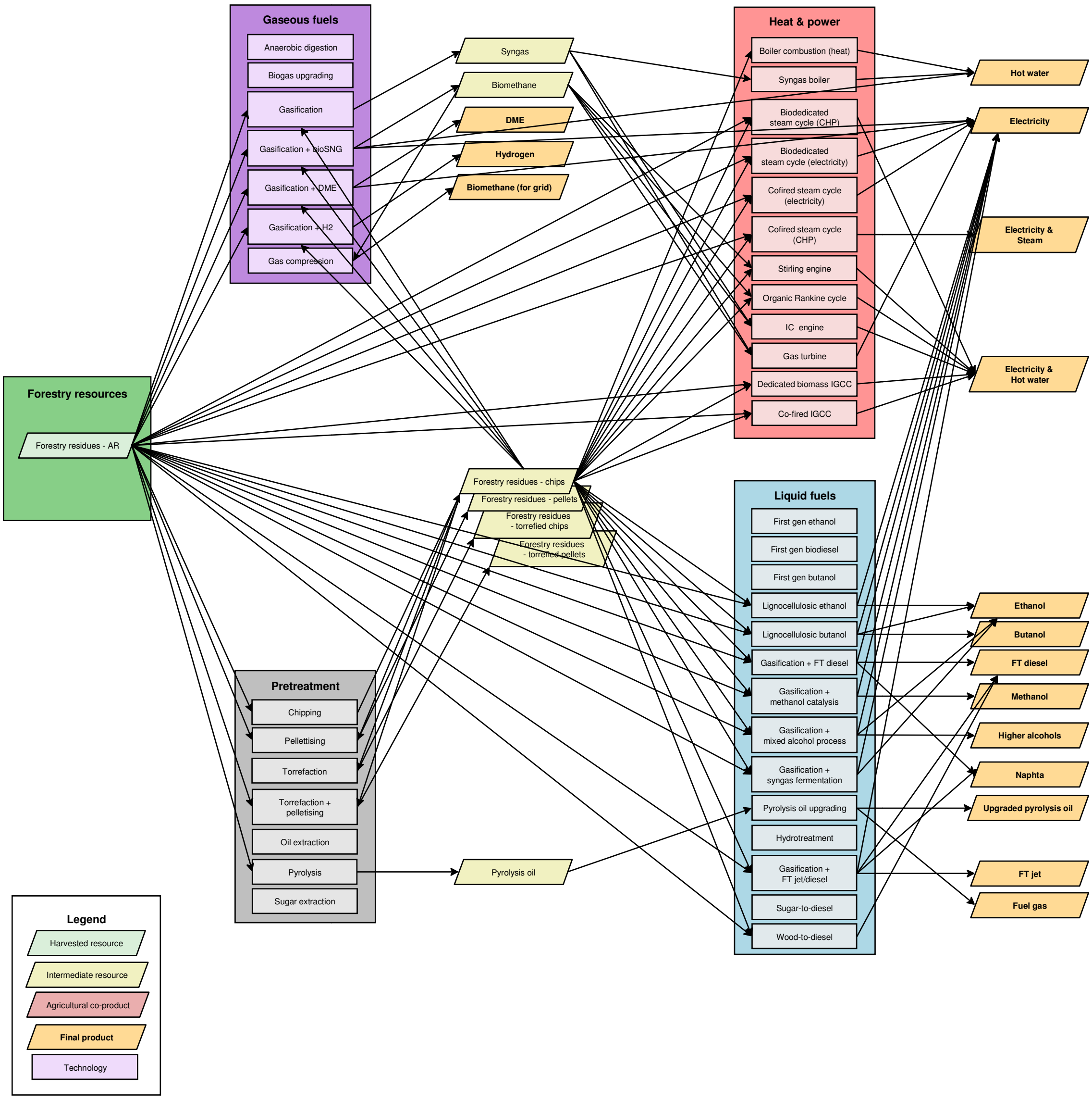

Figure 3-9 LRF bioenergy chain

3.8 Logistics

The model currently uses three logistics modes: road, rail and inland waterways[8]. These logistics modes apply to all resources modelled in the BVCM, i.e. both bioresources and intermediates.

The road network is modelled using average "tortuosity" per cell. A high road network density results in a low tortuosity and a low network in a high tortuosity. The road network tortuosities are illustrated in Figure 3-10 (left).

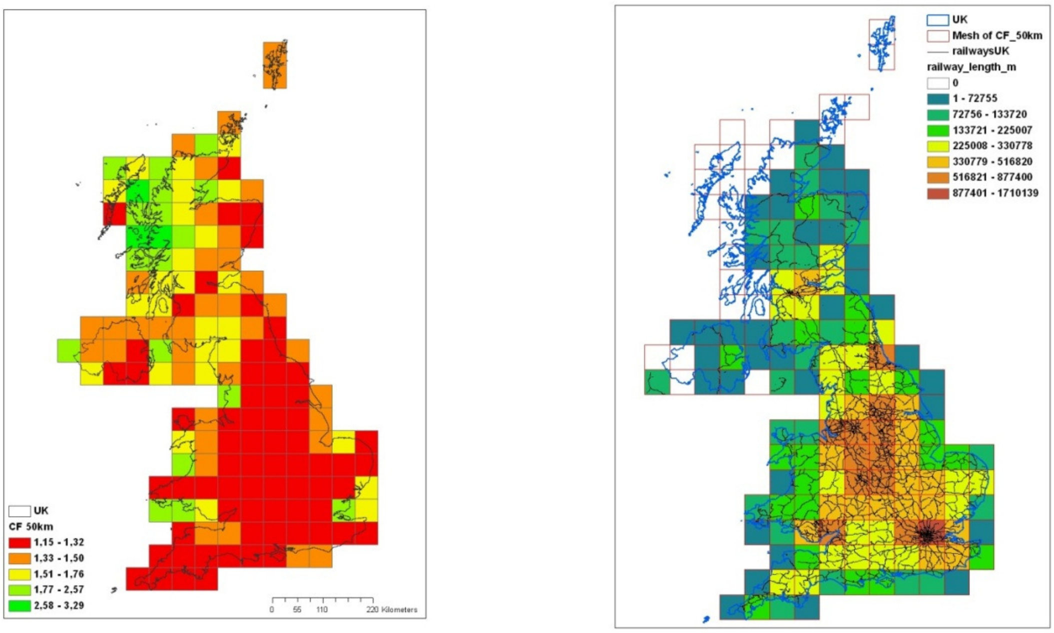

Figure 3-10. Road network tortuosities (left) and spatial distribution of railway lengths (right)

The road logistics costs are resource dependent and are based on a nominal cost per tonne-km adjusted by the volumetric density of each individual resource. Similarly, the GHG emissions are based on a standard emission per tonne-km and adjusted by resource density.

Similarly, the rail network is modelled as average tortuosity, based on spatial distribution of railway lengths as in Figure 3-10 (right).

The costs and GHG emissions of rail and waterway transport are treated in a similar fashion to those of road transport.

3.9 Demands

The user can specify demands for any resource (e.g. electricity, hot water, ethanol, etc.).

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[8] The model already includes data for port locations. We will use these in Phase 2, when feedstock import daya will be included in the mofel.

To ensure good computational performance, it was assumed that high energy density resources with existing and low cost distribution infrastructure (e.g. electricity and transport fuel) will not have spatially explicit demands, and there is no need to model the flow of these resources. Instead, the user can specify the UK wide demands for these resources and the fraction to be met by the overall bioenergy value chain in each decade.

On the other hand, heat is assumed to be difficult to transport over long distances and the model assumes that heat generated within a cell (50km x 50km) is consumed within that cell. The tool has a dataset of spatially-explicit annual heat demands. For heat, the user can specify the seasonal variation of annual demands, and the fraction of total heat to be met by the overall bioenergy value chain in each decade.

3.10 Objective function and solution control

The model either minimises a combined metric (the objective function) which is a weighted sum of:

- Discounted cost
- CO_2 emissions
- Non CO_2 GHG emissions

or maximises energy or exergy[9] production under a set of constraints, including:

- Whole bioenergy system cost
- Whole bioenergy system emissions
- Level of demand of any vector to be met

The minimisation or the maximisation is across the whole modelled periods (5 decades). So, for example, when energy is to maximise, the sum of the energy produced in each decade counts toward the objective function.

The problem can be solved in two modes:

- Relaxed Mixed Integer Programming (rMIP) mode; this gives “indicative” solutions where the technology investments are not restricted to be integer variables (e.g. 0.5 of a biorefinery can be installed, as per ESME). This mode is useful in that it will run about 10-100 times faster than the Mixed Integer Programming (MIP) mode (below).
- MIP mode; this gives a fully-feasible solution where discrete technology investments are to be made.

3.11 ESME–BVCM relationship and BVCM model boundaries

In the context of UK energy system analysis, the BVCM model uses a “partial equilibrium” approach, since minimum costs (minimum GHG, maximum energy) solutions from the BVCM do not necessarily corresponds to minimum costs (minimum GHG, maximum energy) solutions at whole UK energy system level. The latter should be determined using whole energy system models like the ETI ESME.

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[9] Exergy is a thermodynamic property of a system which measures the maximum work that can be extracted from the system. It is therefore a measure of the “quality” of energy.

Indeed, the BVCM should be considered as a much more detailed modelling representation of the bioenergy sector under the ESME, and the BVCM results should be aggregated at a suitable level and fed back into ESME for an improved representation of the bioenergy sector.

From a process point of view, the interaction between ESME and BVCM consists in the following steps:

1. ESME determines the contribution of bioenergy to the optimal whole energy system (which in ESME is a least cost system). The contribution of bioenergy can be expressed at different level of disaggregation in terms of energy vectors and geography. For example, a total requirement of energy from biomass can be used. Alternatively, the total energy requirement can be broken down into relevant energy vectors (e.g. electricity, heat, fuels)

2. The requirements on the bioenergy system are used as constraints on the BVCM. In turn, the BVCM provides solutions for the optimal bioenergy system, under the requirements from ESME.

3. The optimal solutions from BVCM should be then aggregated at a suitable level (in terms of technologies and their locations, costs, emissions, etc.), so that they can be fed back into ESME.

4. Theoretically, step 1 to 3 above should be iterated until full alignment between ESME and BVCM occurs. Based on our experience with the two models, we would expect that one or two iterations should suffice.

The relationship between ESME and BVCM explained has important consequences on the technologies and energy vectors chosen to be included in the BVCM.

It is our understanding that ESME defines requirements on the bioenergy system in terms of:

- Electricity
- Heat
- Gas
- Transport fuels
- Hydrogen

This implies that end-use technologies that use the vectors above are by definition out of scope from the BVCM, as they are already modelled within ESME. For example, cars (using transport fuels), fuel cells (using hydrogen or biomethane), heat pumps (using electricity), etc. do not need to be included in the BVCM model.

In the BVCM we have considered the following vectors for matching with the requirements from ESME:

ESME requirements on bioenergy	**Corresponding BVCM energy vectors**
Electricity	Electricity
Heat	Hot water
Gas	Biomethane (both from thermochemical and anaerobic digestion[10] routes)
Transport fuels	Ethanol, Fatty Acid Methyl Esters (FAME), Hydrotreated Vegetable Oil (HVO), Butanol, Fischer-Tropsch (FT) diesel, FT jet, Hydrotreated Renewable Jet (HRJ), Methanol, Dimethyl Esters (DME), Upgraded Pyrolysis oil (UPO), and Hydrogen[11]
Hydrogen	Hydrogen

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[10] Note that no anaerobic digestion technologies are in Phase 1 of the model, but will be included in Phase 2.
[11] Hydrogen is considered as a transport fuel, unless a specific requirement on hydrogen demand exists.

4 Methodology for opportunity identification

4.1 Case studies

In WP4-D2 and WP4-D3 we have identified a series of case studies[12], and provided the rationale for their choice. The purpose of case studies in the BVCM project is threefold:

1. to identify optimal biomass supply chains at UK and regional level while exploring different scenarios in relation to:
    a. resources
    b. technologies
    c. infrastructures
    d. objective functions
    e. solution drivers
2. to identify acceleration opportunities (at regional level), based on the optimal biomass supply chains identified above
3. to generate broader insights into UK bioenergy options, by using the BVCM model as a toolkit to assess robustness and sensitivities with respect to assumptions and uncertainties

Case studies are defined as a combination of scenarios (or options) concerning:

- Resources
- Technologies
- Infrastructures
- Objective functions
- Solution Drivers

Details on different scenarios can be found in previous deliverables (WP4-D2 and WP4-D3).

It is important to note that the case study analysis undertaken for this report is of an illustrative nature, examining the impacts, challenges and opportunities of possible ways of developing the bioenergy system in the UK from 2010 till 2050. They are meant neither to be predictive scenarios not mutually exclusive options for the future, but are developed around the most important current and emerging elements and uncertainties around bioenergy.

In general, for each case study we will perform a series of optimisation runs to explore sensitivities to different objective functions. These will normally include:

- Maximise energy production (on all available land)
- Minimise system costs, given constraint on total energy provision from biomass (this will typically include three scenarios: 10% and 20% of UK 2050 energy to be met by biomass, and demand for energy vectors from ESME model)
- Minimise GHG emissions, given constraint on total energy provision from biomass (constraint as above)

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[12] Some case studies, e.g. Imports, will be covered in Phase 2 of the project, when dedicated databases will either become available from other ETI projects or be generated by the BVCM consortium.

In the appendix we have provided the detailed parameterisation of the case studies (e.g. what climate scenario is used, what constraints on demand to be met by bioenergy are assumed, what the objective function is, etc.), and their results. Key insights and messages from the case studies are presented in Section 5.

4.2 Key modelling limitations and caveats

It is important to flag the key limitations and caveats to bear in mind when interpreting the results. The severity of the implications is ranked from Low to High based on the impact they may have on the emerging technologies from the model.

Limitations and caveats	**Implications**	**Severity**
The model does not include any biomass imports (yet).	Availability of imports at port locations may have an impact on the supply chain, especially in terms of where plants will be installed and resources and intermediates logistics. The impact on technology choice is expected to be limited, since the model has shown that a high level of flexibility exists, in terms of which resource can be used by the dominant technologies. This will be explored in Phase 2.	<u>Medium</u>
The model does not include any waste resources (yet).	This may have impact on the emerging technologies, depending on the amount the biogenic waste resources. However, target of energy from biomass are typically intended excluding waste resources.	<u>Low</u>
The model does not optimise on value generation (i.e. profit)	Rather, the model either minimises on system costs or GHG emissions, or maximises on energy (or exergy) production, so the market value of different final energy vectors is not reflected in the results.	<u>Low</u>, in the whole ESME context (Potentially) <u>Medium</u> from a single ETI member's perspective[13]

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[13] It should be noted that exergy can be used as a proxy for value.

The model includes only cultivation emissions and co-product credits, but no land use change (both direct and indirect) emissions	The life cycle emissions of bioenergy crops are not fully taken into account. Results from the ETI ELUM project may be fed back into the BVCM to improve the GHG modelling. However, for the time being, it is fair to say that a large error bar exists for emission estimates, especially when large demand are assumed to be met by bioenergy (i.e. when large areas are used).	High (when using the BVCM with minimum emissions objective function)
The model does not include any planting rate constraints	One of the main constraints on the penetration of bioenergy is planting rate, i.e. the maximum rate at which land can be converted into cultivation. Typically, bioenergy targets imply plant rates that exceed historical planting rate, so uncertainties exist on whether planting rates can be stepped up to meet bioenergy targets. However, it is the consortium's view that build rate constraints (which are modelled in BVCM) are usually more stringent that plant rate constraints	Low It is unlikely that planting rates constraints will affect technology acceleration insights.
Levelised cost of energy (LCOE)	This should be seen as indicative – the model does not include inflation, debt/equity, operators' margins, considerations etc. It is useful to rank solutions but should be viewed with caution.	n/a (this is a caveat rather than a limitation)

5 Case studies analysis

In this section we first present and comment on the insights from the case study analysis. We then summarise the insights into key messages and identify technologies emerging from the model and to be considered for acceleration. Last we comment on possible model improvements based on the lessons learnt from the case study analysis.

5.1 Insights from the case studies

Insights from case studies are discussed below. Reference to the case study/ies (detailed case study results are in the Appendix) they have been derived from also is provided. Insights are qualified with Low, Medium and High based on the level of confidence and their resilience. The level of confidence is based on the quantity (e.g. how many studies are the data based on) and quality (e.g. how recent are those studies) of the data in the model. The resilience is based on the frequency a given result emerges when exploring the envelope of scenarios as defined by the case studies.

5.1.1 Demand, resources and land uses

Result	Discussion	Case study reference	Level of confidence	Resilience
Bioenergy can meet 10% of UK energy demand in 2050 by using about 12% to 15% of total UK land.	Meeting 10% of UK energy demand in 2050 (as projected by in Pathway Alpha in the 2050 DECC Calculator) implies using a share of land that typically ranges from 12% to 15% of total UK land (c. 3-3.5 Mha), depending on the energy mix to produce.	All (where 10% of UK demand is to be met).	**High** This corresponds to an average efficiency of 3 MWh of energy (in the relevant energy vectors in the BVCM) per hectare, which is a sensible number.	**High** This level of land use occurs under several scenarios.
Using all available suitable land in the UK, with the exception of current total arable land used for food production (about 4.6 million hectares) could theoretically	This is an extreme case, and should be interpreted as a theoretical (i.e. not achievable) upper limit. The amount of energy that can be provided is limited by land availability and by technology build rates.	Base (Max energy run).	**High** The land use, its efficiency (~3 MWh/hectare) and the mix of energy vectors produced in this run indicates that is a	**N/A** This is an extreme, unique run.

Result	Discussion	Case study reference	Level of confidence	Resilience
provide up to 32% of total UK 2050 energy demand.	A combination of Miscanthus, SRC willow and wheat are used to meet such demand. Also, due to technology build rates, a very wide portfolio of technologies (and resulting products) would emerge as result, including hydrogen, upgraded pyrolysis oil, DME, and bioSNG.		sensible upper limit.	
Providing 20% of 2050 UK energy demand via biomass would require about 25% to 30% of total UK land.	Land use scales almost linearly with the level of demand to be met by bioenergy.	All (where 20% of UK demand is to be met).	**High** Same consideration as in the 10% UK energy demand case	**High** This level of land use occurs under several assumptions.
SRC-Willow and Miscanthus are the dominant bioresources.	SRC-Willow and Miscanthus dominate the bioresources mix, the former mostly on low emissions merits, the latter on low costs merits.	All	**High** Detailed process models and meta-models have been used for generating potential yield data, which have been then filtered based on considerations including altitude, slope and soil carbon, to derive attainable yields. Also, the North/South split has been already highlighted in previous works (e.g. TSEC[14] project).	**Medium** If emissions are to be minimised, short rotation forestry plays an important role as well. Also, if biofuels are to be produced, then winter wheat enters the feedstock mix as well.
Different biomass types are better suited for different	There appears to be a north/south split in biomass type, typically with	All		**High**

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[14] http://www.tsec-biosys.ac.uk/

Result	Discussion	Case study reference	Level of confidence	Resilience
parts of the UK	Miscanthus grown towards the South and SRC Willow in the North of the UK			This feedstock mix and geographical split occur in a very large number of runs, unless high levels of demand for specific vectors (e.g. ethanol) are imposed on the system.
Biomass resource choice is resilient to climate scenarios	Results obtained using the two different climate scenarios in the model ("UKCP09-SCP Low emissions" and "UKCP09-SCP Medium emissions") show negligible differences in terms of technology and bioresources choices.	Base Low Carbon Climate	**Medium** Detailed models have been used to generate yields under different climate scenarios. Also, the difference in atmospheric CO_2 under the different climate scenarios is limited with the 2050s timeframe, and becomes significant only towards year 2100. However, the BVCM does not include extreme weather and climate related events (e.g. droughts) that may disrupt the production of biomass in a short time frame.	**High** No significant difference in results occurs for both 10% and 20% UK 2050 energy demand)

5.1.2 Technologies

Insight	Discussion	Case study reference	Level of confidence	Resilience
Heat production is a mature and relatively inexpensive route to bioenergy penetration.	This makes sense from first principles. Dominant heat technology is biomass boiler at medium and large scale, first. Cofired combined heat and power steam cycles emerge post 2030s. Heat share in the energy mix is typically very high in the first decades.	All, particularly the base case (min cost, 10% and 20% UK 2050 energy demand runs)	**Medium** Biomass boiler and steam cycle costs are relatively well known. However, a large deployment of district heating networks underpins the production of heat, and considerations on its feasibility are not included in the model.	**High** All cases, except when energy system constraints are imposed (e.g. ESME)
Biomethane (bioSNG) emerges as one of the dominant bioenergy vector post 2040	Thermochemical routes are efficient way of converting biomass into energy vectors. In particular, gasification and methanation to obtain bioSNG is the least expensive thermochemical routes (cheaper than routes to hydrogen, DME, etc.), and it also produced heat, being an exothermic process.	All	**High** A detailed techno-economic study has been used for cost estimates More realistic data (i.e. more expensive, less efficient) than those used for the Technology Innovation Needs Assessment (TINA) Bioenergy have been used, which is a conservative approach. Also, BioSNG as a critical vector in bioenergy has been identified in other modelling exercises in the past (e.g. ETI	**High** BioSNG emerges under a very large number of runs, for different energy demand levels, and under different crop availability assumptions. In some cases it emerges also earlier than 2040.

			ESME).	
Significant opportunity exists for negative emissions via CCS technologies.	Biodedicated chemical looping combustion is a promising negative emissions technology, followed by co-firing oxycombustion and co-fired combustion with amine CCS. Carbon sequestration in the range of 50 to 100 million tonnes of CO_2 sequestered per year is a realistic opportunity by 2050.	CCS	**Medium** These are based on data from the TESBIC project, which although as accurate as possible, are based on technologies that have not been scaled up yet.	**High** These technologies appear across a large number of CCS scenarios
Biomass to hydrogen route does incur additional costs, but may be important for the UK.	Same thermodynamic considerations as regards bioSNG apply to H_2.	Base (min cost, 20% UK 2050 energy demand) ESME	**Medium** Lower than bioSNG, as based on older techno-economic studies	**Medium** Hydrogen is the “second-best” high energy vector after bioSNG, so it emerges only with high penetration targets, or if imposed by ESME.
Pyrolysis fuels could contribute to transport fuel demands from biomass.	Biomass pyrolysis combined with pyrolysis oil upgrading is the preferred technology for transport fuels, except in the first years, when first generation ethanol may be used.	ESME Vector focus: biofuels	**Medium** Detailed techno-economic study has been used for cost estimates. We have no validation from technology developer yet.	**Low** Pyrolysis fuels appear only when a transport fuel demand is imposed on the solution.

5.1.3 Logistics

Insight	Discussion	Case study reference	Level of confidence	Resilience
Limited transport of resources (both bioresources and intermediates) occurs	There are several reasons that justify this: 1. The amount of demand for energy (especially for heat) is very large in any given 50x50 km cell. In particular, it is typically much larger than the amount of energy that can be produced locally, hence it is cost and GHG-optimal to use resources locally without transport beyond 50km. 2. The amount of feedstock that can be generated in a 50x50 km cell is potentially very large in comparison to the size of large scale bioenergy plants (without applying constraints on the amount of biomass that could be produced in each cell). For example, assuming a notional 10 odt per hectare per year of SRC-Willow (at 10 GJ/odt), and that 50% of a cell area (50% of 2,500 km2 = 1,250 km2 = 25,000 ha) is used for SRC-Willow, this corresponds to about 430MW (thermal input) plant.[15]. This means that, unless the amount of available land is further constrained (which would be sensible, e.g. from an amenability point of view), there is typically sufficient feedstock available in a cell to achieve economies of	Base Low Carbon Climate Syngas/H2 economy	**Medium** High level of confidence in transport data and transport modelling, since: 1. Good references for transport costs and emissions have been used in modelling logistics. 2. Sensitivity analysis has been carried out to verify if and when transport is used. Lower level of confidence on the amount of land that is reasonable to consider as available in each cell.	**Medium** It will have to be understood (in Phase 2) how large amounts of feedstock available in few locations (i.e. imports) will affect logistic needs. Also, more transport may be needed in reality, if more stringent constraints apply to how much land in each cell can be used for bioenergy.

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[15] Assuming 8000 hours/year of operation.

	scale in that cell (i.e. without transport). *6 However, if tight land constraints are used so that biomass is grown sparsely, then densification of biomass combined with longer-range transport does become important.*			

6.1 Summary of key messages

Bioenergy can meet 10% UK energy demand in 2050 by using 12% to 15% of total UK land

Up to 32% of UK energy demand in 2050 can be met from bioenergy under an extreme (theoretical) case of land use. However a share around 10% of UK energy could be realistic, putting the use of land for bioenergy at a level similar in magnitude to current arable land, and with enough high grade land set aside for food production.

Different biomass types for different parts of the UK

There appears to be a North/South split in biomass type, typically with Miscanthus grown towards the South and SRC Willow in the North.

Heat is low cost but liquid fuels may have additional value

Heat production is a mature and relatively inexpensive route to bioenergy penetration. However, fuel and electricity from biomass may be required in the context of a whole energy system optimisation, and may also command higher value. Of course, this comes at extra costs and might be a good reason to explore technology acceleration and cost reduction.

Gasification to fuels is an effective pathway

Gasification and subsequent conversion to hydrogen and particularly synthetic natural gas are cost-effective and resource-efficient pathways. Other products such as FT jet do incur significant additional costs, but may be important for the UK.

Limited opportunities exists for first generation biodiesel (via oilseed rape)

Our runs have shown that, unless a given quota is mandated, first generation biodiesel (as FAME, Fatty Acid Methyl Esters) seldom appears as a transport fuel, under all optimisation scenarios.

Significant opportunity exists for negative emissions

Figures in the range of 30-100M tonnes per year of CO_2 can be sequestered via BioCCS. This is in line with other estimates (e.g. AVOID project). A range of BioCCS technologies are available, with amine based processes used early on and oxy-combustion and looping combustion later on.

Feedstock supply chains are important and ensure flexibility.

Dedicated bioenergy crops are developed in all solutions; what is interesting is the fact that their conversion and utilisation transitions over time from applications such as co-firing and CHP to more sophisticated ones such as gasification. This finding corroborates many others which indicate that mature bioenergy technologies are important to give growers confidence in a long-term market for their crops, given the longevity of most bioenergy crop investments.

6.2 Predominant value chains

The following technologies appear to be predominant in the results from the case studies (in bold those with high level of resilience):

	TRL 3-6	TRL > 6
Pre-treatment and densification technologies	• Pelletising if there are tight land constraints	• Pyrolysis
Technologies for gaseous fuel production	• **Gasification + bioSNG** • Gasification + H_2	
Technologies for liquid fuel production	• Pyrolysis oil upgrading	
Technologies for heat, power, and combined heat and power generation	• **Dedicated chemical looping CCS** • Co-fired and dedicated oxy-fuel CCS • Cofired combustion + amine CCS	• **Biomass co-fired steam cycle (CHP)** • **District heating network** • **Boiler combustion (for heat)**

A technology overview, including current development status and innovation needs for the technologies above in the TRL 3 to 6 space[16] is given in the Appendix.

6.3 Possible further model developments

Based on our judgement and on the experience gained from the runs and sensitivity analysis runs so far, some further developments in the model can be envisaged. Some of these developments have been already identified in the course of the project and will be covered in Phase 2:

- Seasonality effects. Improvement of the model functionalities by taking into account seasonal effects on biomass characteristics and availability.

- Value of strategic transport fuels. At the moment, when optimising on costs and/or energy, the model typically chooses road transport fuels over jet fuel. This is mainly due to the extra costs and emissions associated with the hydrogenation required for achieving jet fuel specifications. However, from a UK-wide strategic point of view, it may make more sense to generate jet fuel, as this may have more economic value. A possible model development is therefore to implement an objective function that maximises the value of the biogenic energy vectors.

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[16] Excluding CCS technologies, which are covered in the ETI BioCCS project.

- Value of carbon sequestration of long rotation forestry. The current model does not take into account the potential benefit of storing carbon stocks by means of long term forestry, and additional functionality in this regard can be added.
- Improved modelling of credits (economic and GHG) from co-products, e.g. by modelling how credits will vary in the future, and including possible saturation effects.
- Improved modelling of land constraints, i.e. limiting the area in each cell than can be realistically used to produce biomass for bioenergy.
- Constrain the location of CCS technologies to areas where it is expected that CCS infrastructure will be located (e.g. Thames Estuary, Humberside).
- Further alignment between the BVCM and the ESME model, i.e. aggregating and feeding back BVCM technology and resource data to ESME.

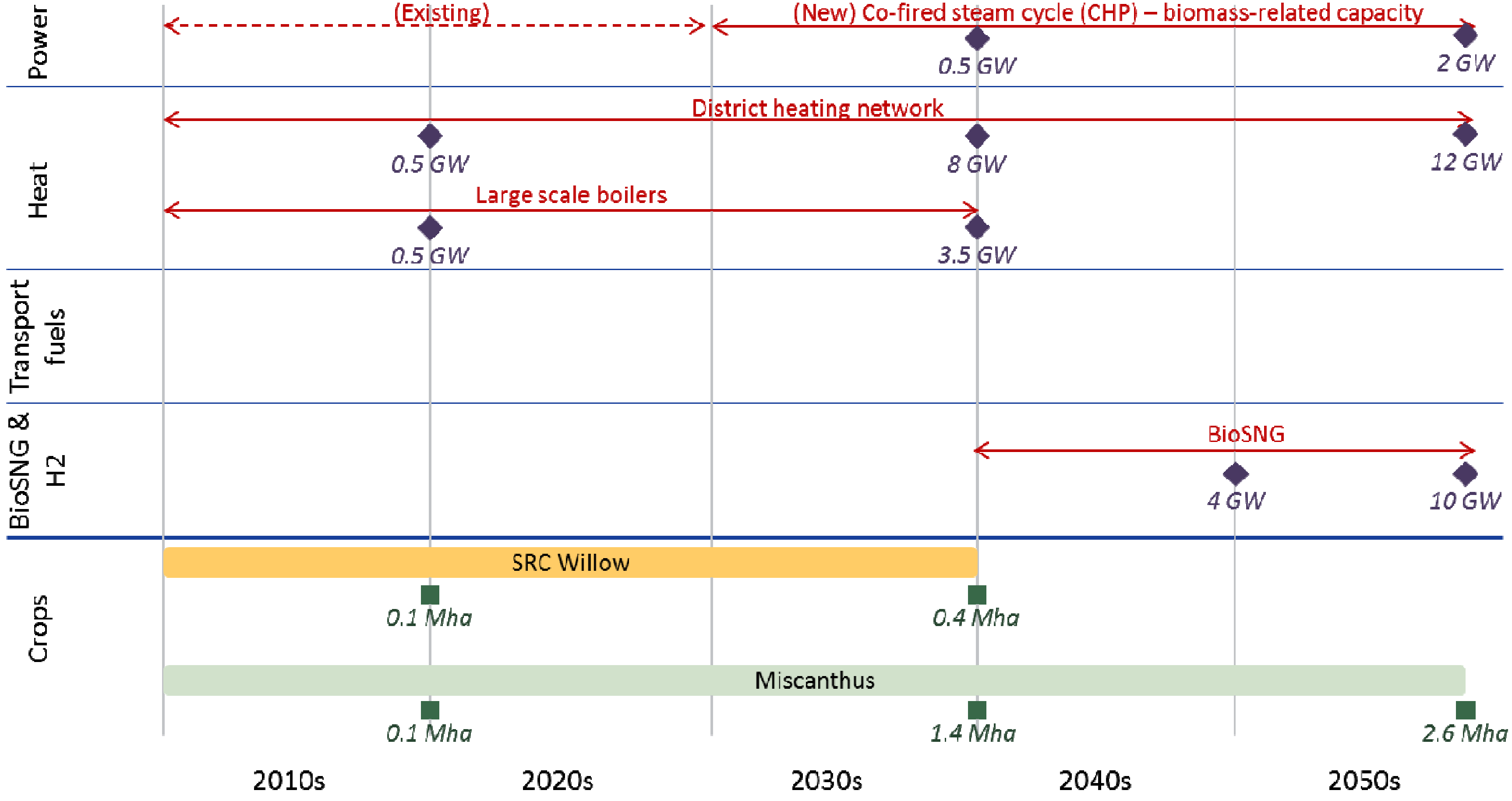
7 Overall bioenergy roadmaps

In this section, two possible whole bioenergy system roadmaps are provided. The first is based on the Base case run, where 10% of UK 2050 energy demand is met by biomass at minimum cost, the second is based on the ESME case, in which ESME demand for energy vectors from bioenergy is to be met at minimum cost, and CCS technologies are included[17].

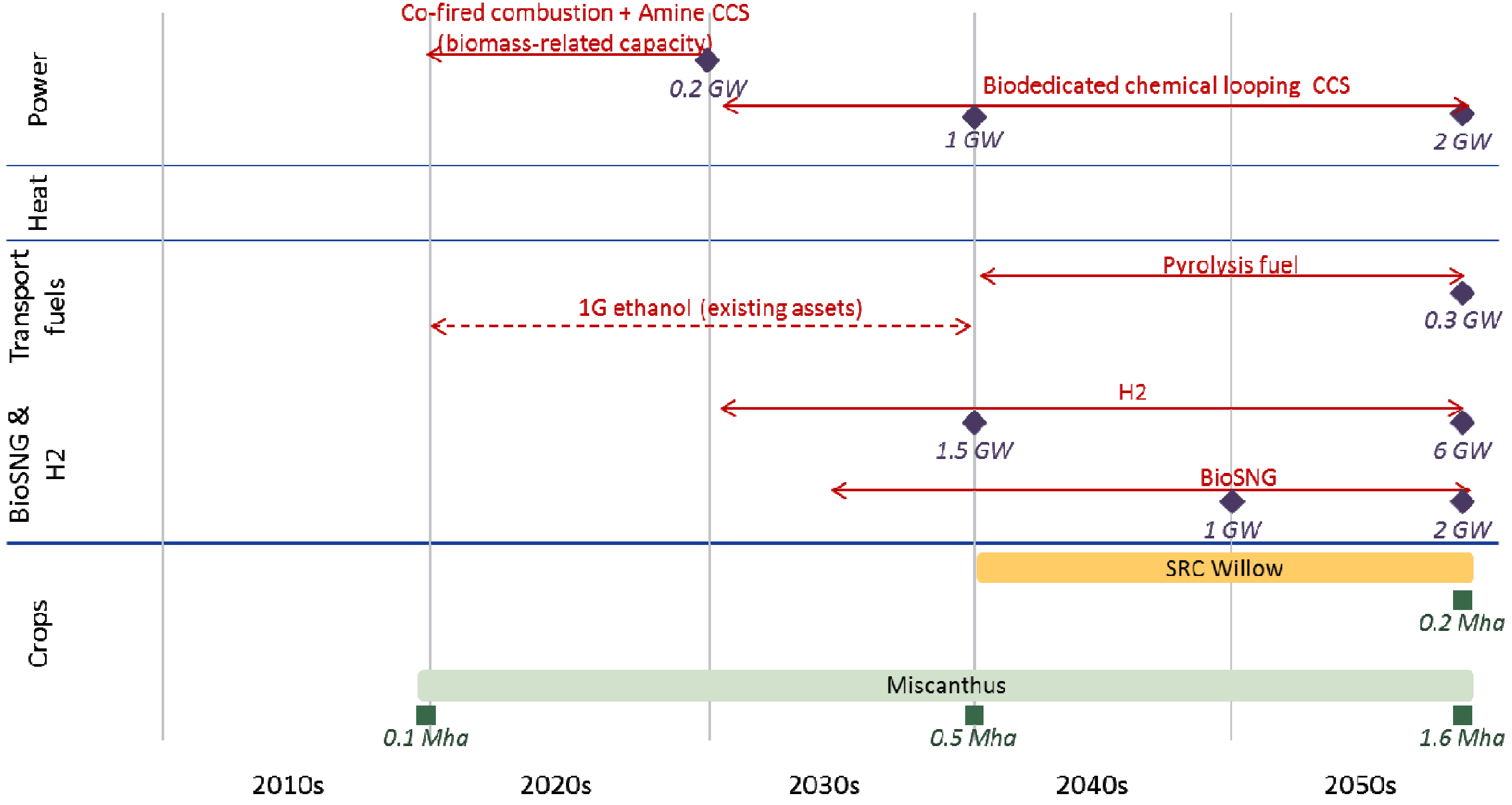
In the roadmaps, the size of technologies at a given point in time refers to the cumulative technology investment to that point; for crops, the amount of land refers to the amount used at a given time.

[1717] For this run, a 0.01 weight is applied to the GHG objective function as well, which translate into an average carbon price of 10£/tonne of CO_2.

7.1 Roadmap 1: 10% of UK 2050 energy demand at minimum cost



7.2 Roadmap 2: ESME case, minimum cost, with CCS



8 Next steps

The next steps after this deliverable will be:

- To re-submit the Benefit assessment report (WP4-D5), the last formal deliverable of Phase 1 of the BVCM project, where we will provide the benefit case, in line with ETI objectives of secure, sustainable, and affordable energy, for development and deployment of the technologies identified for acceleration
- To progress with Phase 2 of the BVCM project, where a series of additional or improved model functionalities and data inputs will be implemented.

9 Appendix 1: Case study runs

9.1 Note on results

The followings apply to all results presented in this report:

- "Share of UK land" refers to the ratio of land used for bioenergy purposes over total UK land (about 24.3 million hectares)
- Values on energy provision, bioenergy mix, land use etc. for each decade (e.g. 2010s) should be interpreted as "typical" values in that decade
- "Share of UK energy consumption" refers to the ratio of energy produced from biomass (as in the vectors included in the Bioenergy mix) over a notional UK final energy consumption, based on Pathway Alpha of the DECC 2050 Calculator. In particular:
    - "10% of UK 2050 energy consumption" to be provided by biomass corresponds to the following energy provision requirements on bioenergy:
        - 2010s: 7 TWh/year
        - 2020s: 35 TWh/year
        - 2030s: 86 TWh/year
        - 2040s: 144 TWh/year
        - 2050s: 180 TWh/year[18]
    - "20% of UK 2050 energy consumption" to be provided by biomass corresponds to the following energy provision requirements on bioenergy:
        - 2010s: 14 TWh/year
        - 2020s: 70 TWh/year
        - 2030s: 172 TWh/year
        - 2040s: 288 TWh/year
        - 2050s: 360 TWh/year
- When a budget constraint is imposed, this is set to £40Bn/decade, unless specified. £40Bn/decade corresponds approximately to 10% of current (2010) investments in the UK in the electricity and gas sectors.
- When a run is said to be "infeasible", this means that no combination of land use, resources, technologies and vectors exist to satisfy the constraints imposed by the model. This typically means that the level of demand for total energy and/or energy vector(s) is too large given the amount of land available and the technology build rate.

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[18] 180 TWh is equal to 10% of the final energy consumption in Pathway Alpha of the DECC 2050 Calculator. Progression to 180 TWh in the previous decades assumed by the BVCM consortium.

9.2 Case study "Base"

9.2.1 Description of case study

This is the initial case study chosen for the investigation. As already explained elsewhere (e.g. see "Case studies definition report" WP4-D2), the base case study is not meant to represent a "balanced" or "most probable" case, but a set of scenarios and assumptions which can be varied to generate all other case studies.

9.2.2 Case study parameterisation

The following assumptions apply for this case study:

- **Resources:**
    - Climate: UKCP09-SCP – Medium emissions scenario
    - Resource costs:
        - Biomass production costs as calculated in the cost model developed in WP1 (no uplift or downlift factors)
        - No biomass production opportunity costs included
        - Costs for fossil resources (e.g. natural gas) as in ESME (central values)
        - No credit from co-products, unless specified otherwise
    - Emissions:
        - Biomass cultivation emissions as calculated in the GHG model developed in WP1
        - No land use (both direct and indirect) emissions
        - Emissions for fossil resources (e.g. natural gas) as in ESME (central values)
        - No emission credit from co-products, unless specified otherwise
    - Land constraints
        - Level 4 of land aggression, i.e. all types (1 to 4) of land included
        - 4.6 million hectares of Type 1 land set aside for purposes other than bioenergy (i.e. food production) for the whole period covered by the model[19]. This corresponds to the current amount of arable land in the UK.
    - Imports: not allowed
- **Technologies:**
    - Efficiency: medium scenario for all technology (as defined in the technology database developed in WP3)
    - Capital costs: medium scenario for all technology (as defined in the technology database developed in WP3)
    - No carbon capture technology available
- **Infrastructure:**
    - No hydrogen or syngas grid available

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[19] We are assuming that factors that may cause larger amount of land for domestic food production in the UK (e.g. increase in population, increase in food security, etc.) are balanced by factors that imply use of less land (e.g. dietary changes, technology and yield improvements, etc.)

This being the base case, a very large number of runs were undertaken to generate insights into promising value chains. Results of the most interesting runs are provided below.

9.2.3 Run 1: Maximise energy production, no budget constraint

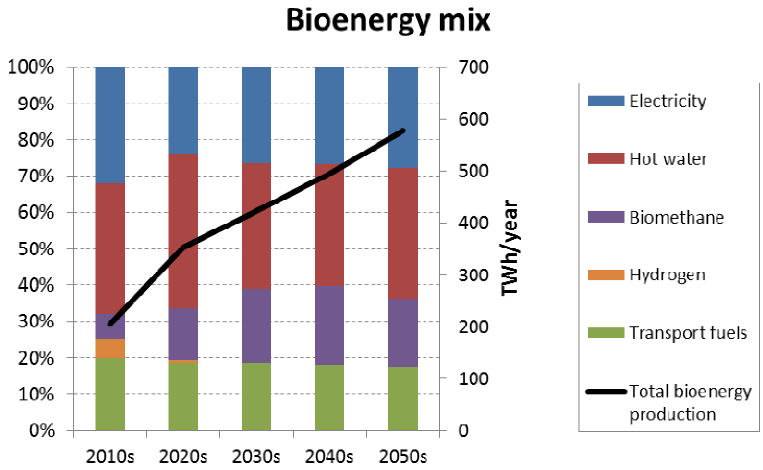
Constraints

- None, except land allocated to food production as above

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	205	354	423	495	577	TWh/year
	Power	66	85	112	132	160	TWh/year
	Heat	74	150	146	166	208	TWh/year
	Biomethane	14	50	85	107	108	TWh/year
	Hydrogen	11	3	0	0	0	TWh/year
	Transport fuels	5	7	9	10	11	MLge[20]/year

Item		2010-2059	Unit
Costs	System total	94.569	£Bn/decade
	Average	55.4	£/MWh
Emissions	System total	11.0506	Mt CO_2/year
	Average	26.90	kgCO_2/MWh



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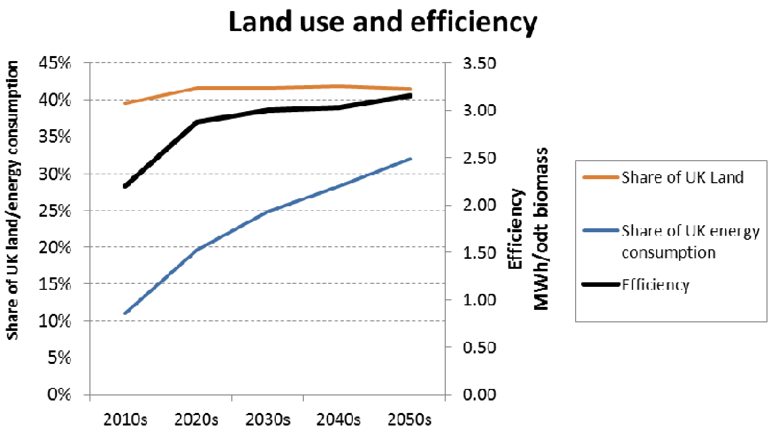
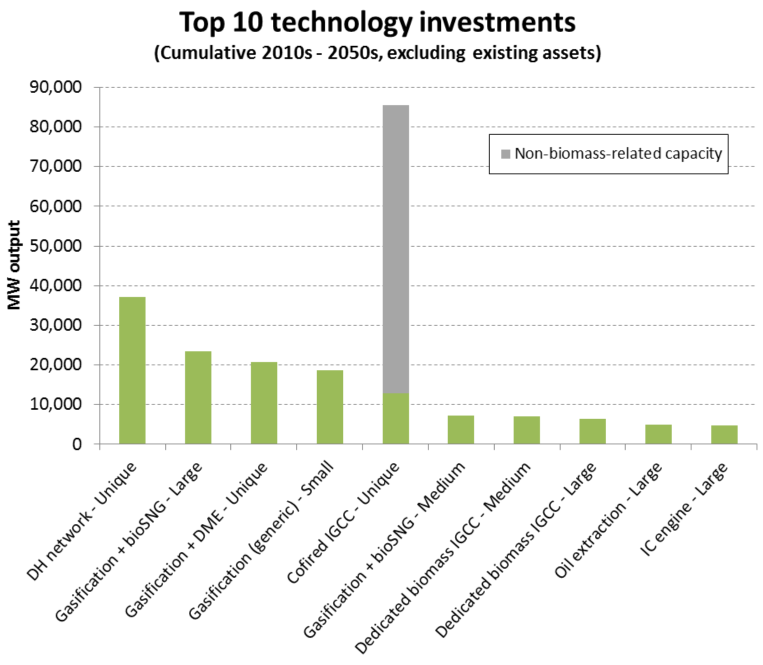
[20] 1 MLge corresponds to 8.94 TWh.



This is a very extreme case, using all possible land other than that which is unsuitable or reserved for food production. Under these extreme conditions, up to 32% of total UK energy can be provided by bioenergy. This is limited by the amount of available land and the technology build rates.

Emerging Technologies and Insights from the Run

- Heat is important (including district heating network)
- Gasification, on its own and coupled with SNG, DME, is important
- Cofired and dedicated IGCC are important
- There is a north/south split in biomass type with Miscanthus towards the south and SRC Willow in Scotland, but post 2030 Miscanthus becomes the preferred crop in more than 90% of the land used for bioenergy.



This is a rather extreme case; two other cases involving maximisation of production were also run to give further insights:

i. Maximise total energy production subject to a total budget of £200bn (discounted to 2010)
ii. Maximise total exergy production subject to a total budget of £200bn (discounted to 2010)

9.2.4 Run 2: Maximise energy production, £200bn budget constraint

Constraints

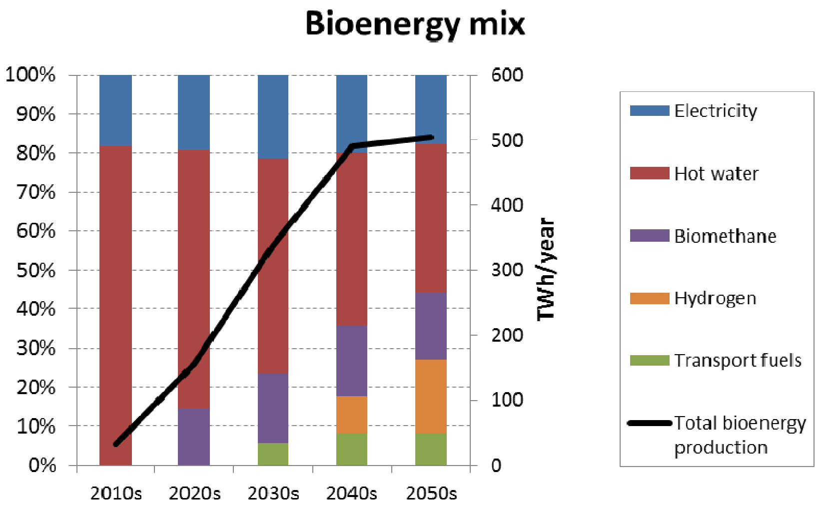
- This was the same as above, but with total system cost constrained. £200Bn (£40Bn/decade) corresponds approximately to 10% of current (2010) investments in the UK in the electricity and gas sectors

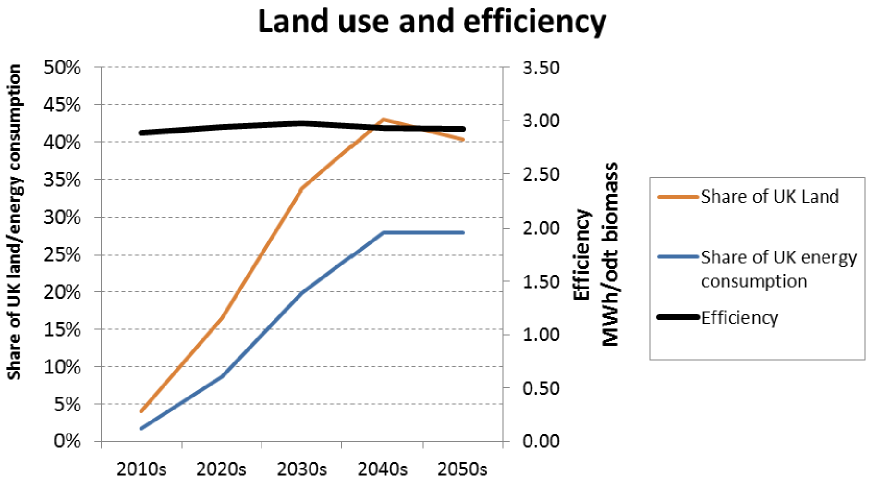
The main results are highlighted below.

Main results

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	32	155	338	490	504	TWh/year
	Power	6	30	72	97	90	TWh/year
	Heat	26	103	185	216	191	TWh/year
	Biomethane	0	23	61	90	87	TWh/year
	Hydrogen	0	0	0	45	95	TWh/year
	Transport fuels	0	0	2	5	5	MLge/year

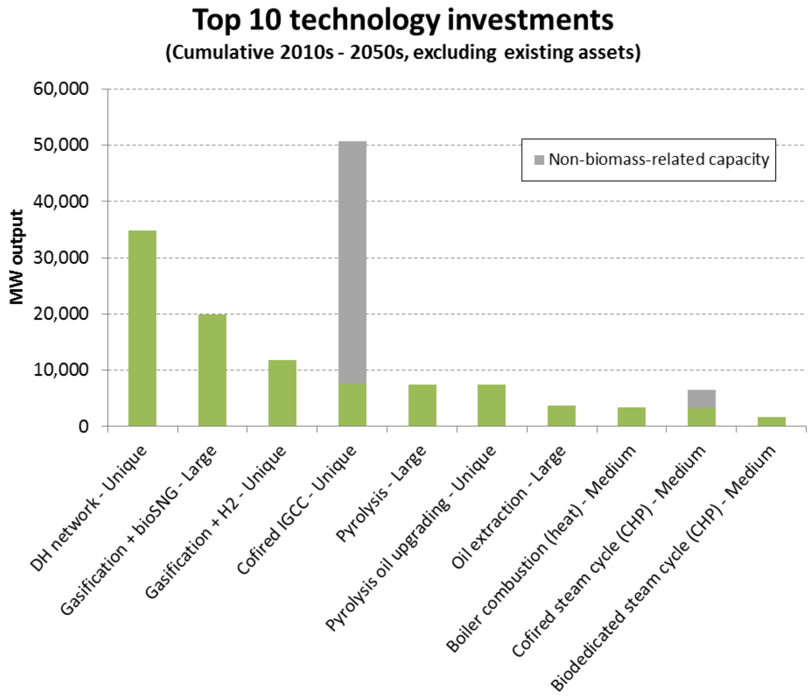
Item		**2010-2059**	**Unit**
Costs	System total	40.000	£Bn/decade
	Average	37.9	£/MWh
Emissions	System total	8.8965	Mt CO_2/year
	Average	29.29	kgCO_2/MWh





Emerging Technologies and Insights from the Run

- Heat has the largest share in the energy mix
- Gasification, in its own right and coupled with power production, SNG, methanol and H_2 production, is important
- Pyrolysis technologies become important
- Amount of UK land used for bioenergy is still considerable



9.2.5 Run 3: Maximise exergy production, £200bn budget constraint

Constraints

- As above
- In all the runs where energy is maximised or overall energy penetration is set as a target and cost is minimised, a large amount of heat demand is typically met by bioenergy. To explore alternative, potentially higher added value configurations, each vector other than heat was given an exergy coefficient of 1 and heat was given an exergy coefficient of 0.28 (approx. 90℃[21]).

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	10	100	285	434	471	TWh/year
	Power	3	18	39	40	37	TWh/year
	Heat	2	22	47	48	45	TWh/year
	Biomethane	0	41	85	97	98	TWh/year
	Hydrogen	0	0	50	157	213	TWh/year
	Transport fuels	1	2	7	10	9	MLge/year

It is worth noticing that the sum of the exergy produced across the five decades will be by definition less than the sum of energy produced in the same run. This is because the exergy factors in the model are less or equal that unity. However, the exergy produced in a given decade (e.g. 2050s) can be higher that the energy produced in the same decade, when optimising for energy rather than exergy. This is because the model maximises energy or exergy across the five decades.

Item		2010-2059	Unit
Costs	System total	40.000	£Bn/decade
	Average	46.7	£/MWh
Emissions	System total	9.3140	Mt CO_2/year
	Average	35.83	kgCO_2/MWh

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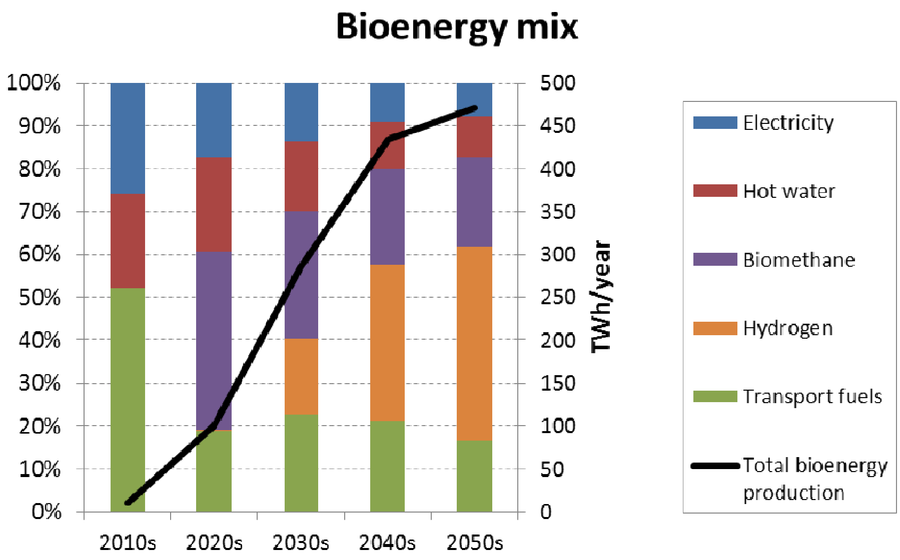
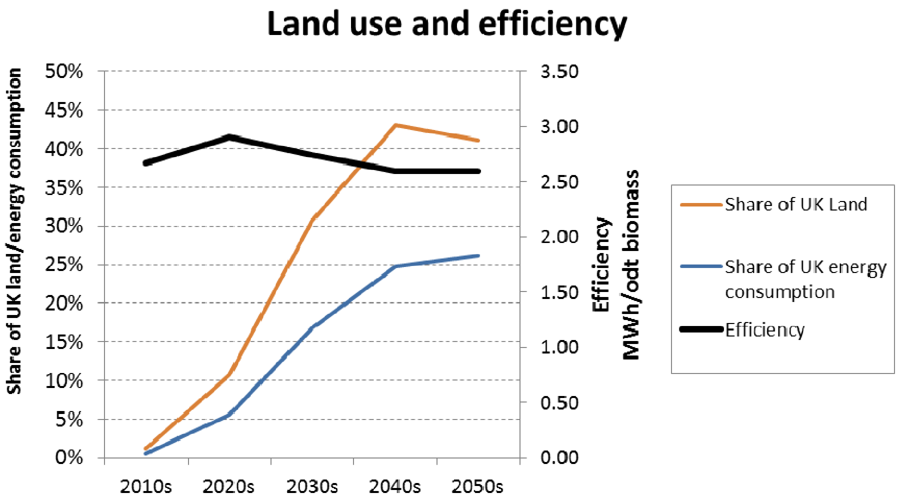
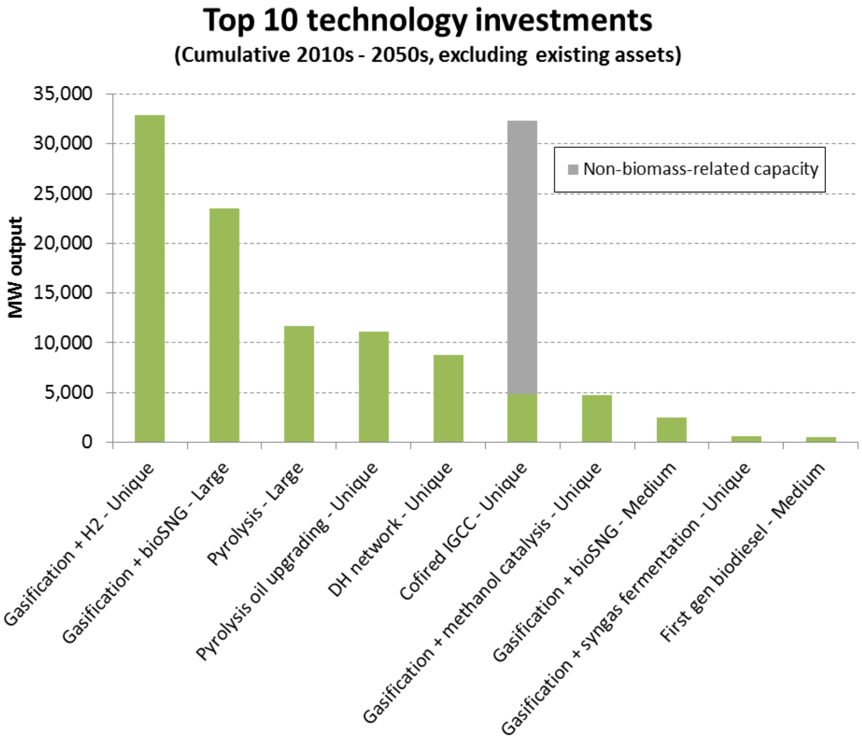
[21] In general, exergy is a function of material properties (internal energy, volume, entropy, and number of moles) and properties of the environment (pressure, temperature, and chemical potential). The exergy factor is the ratio between exergy and energy. For water at 90℃ and environment at 25℃ this is approximately equal to 0.28.





Emerging Technologies and Insights from Run

- The fuel based pathways (gasification into hydrogen, methanol, and BioSNG, as well as pyrolysis fuels) are emphasised in this case; exergy is a good proxy for value-added.



The cases run below are for more realistic energy levels, with cost and GHG minimisation.

9.2.6 Run 4: Minimise Cost, 10% UK 2050 energy demand

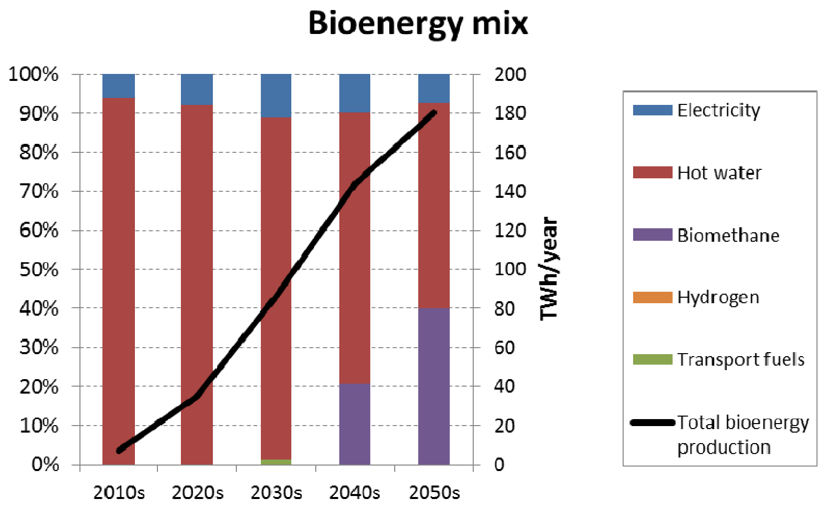
Constraints:

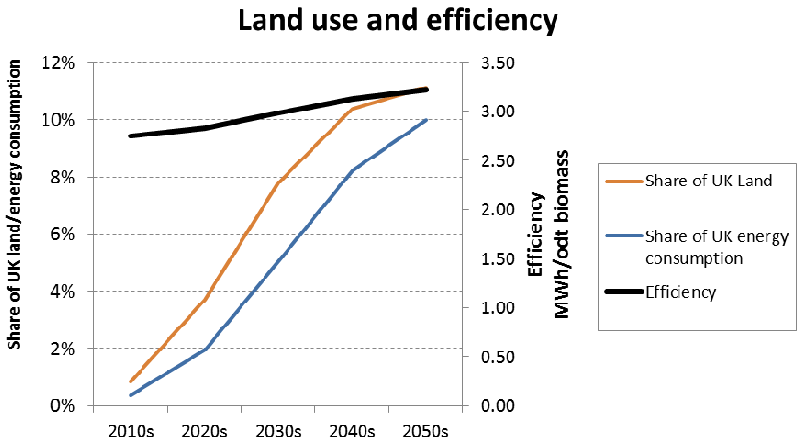
- None, except land allocated to food production as above

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	9	14	13	TWh/year
	Heat	7	32	75	100	95	TWh/year
	Biomethane	0	0	0	30	72	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

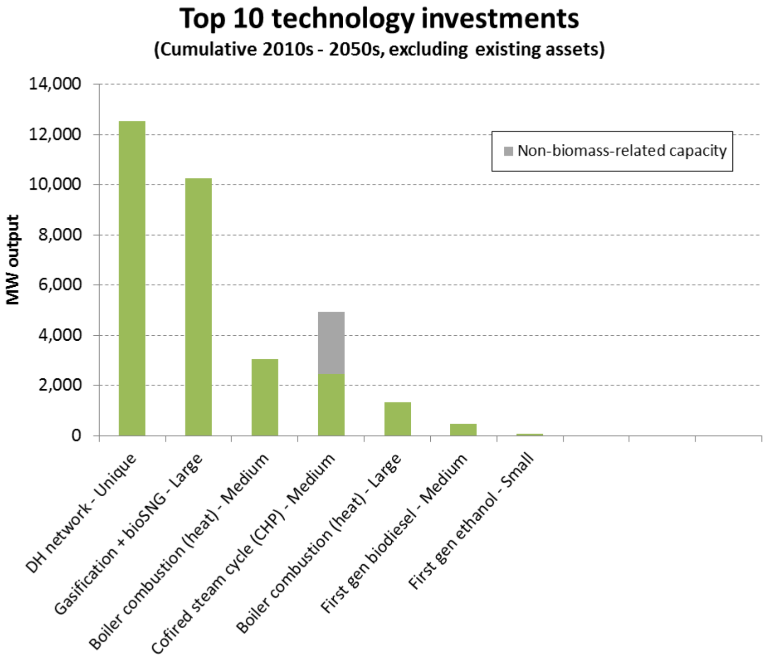
Item		2010-2059	Unit
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh
Emissions	System total	1.8394	Mt CO_2/year
	Average	20.35	kgCO_2/MWh





Emerging Technologies and Insights from the Run

- Heat production dominates the energy mix and is a relatively cheap way to achieve overall targets[22]. Investments in boilers for heat generation occur in the first three decades, while CHP co-fired steam cycles emerge in the last three. Large amount of district heating networks are functional to the delivery of heat from CHP plants and BioSNG plants.
- BioSNG is critical in the last two decades, covering up to 40% of the energy provided by biomass in 2050s.
- Electricity, produced by co-fired CHP steam cycle plants contributes to less than 10% of the total energy from biomass.
- There is no production of high level of value-added energy vectors such as hydrogen and aviation fuels.



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[22] This is in line with the findings of the "Biomass sector review for the Carbon Trust", 2005.

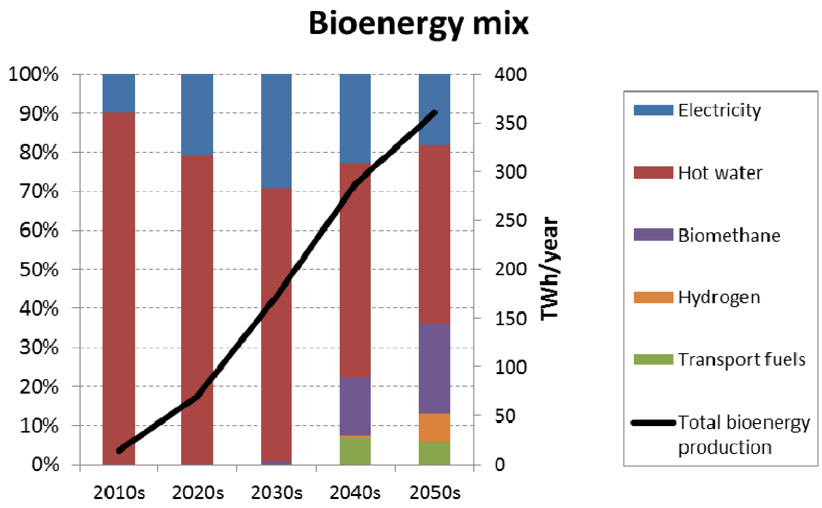
9.2.7 Run 5: Minimise Cost, 20% of UK 2050 energy demand

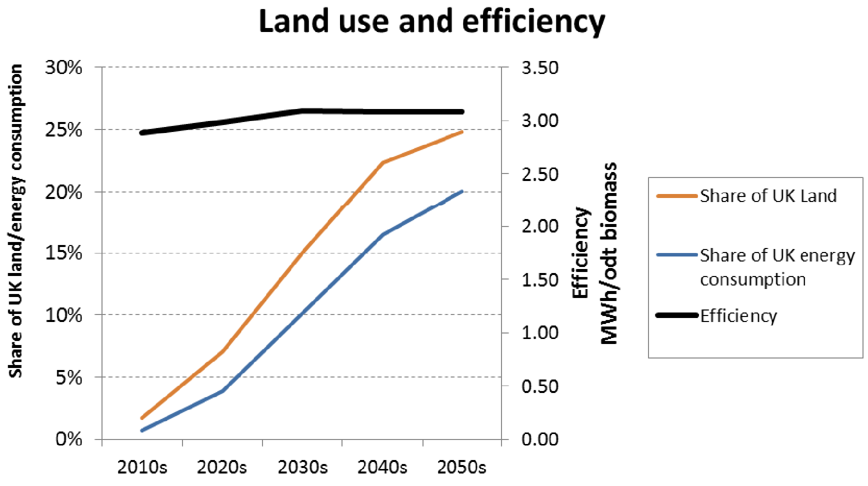
Constraints:

- As above, with double energy production by decade

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	1	15	50	66	66	TWh/year
	Power	13	55	120	158	163	TWh/year
	Heat	0	0	1	43	84	TWh/year
	Biomethane	0	0	0	1	26	TWh/year
	Hydrogen	1	15	50	66	66	TWh/year
	Transport fuels	0	0	0	2	2	MLge/year

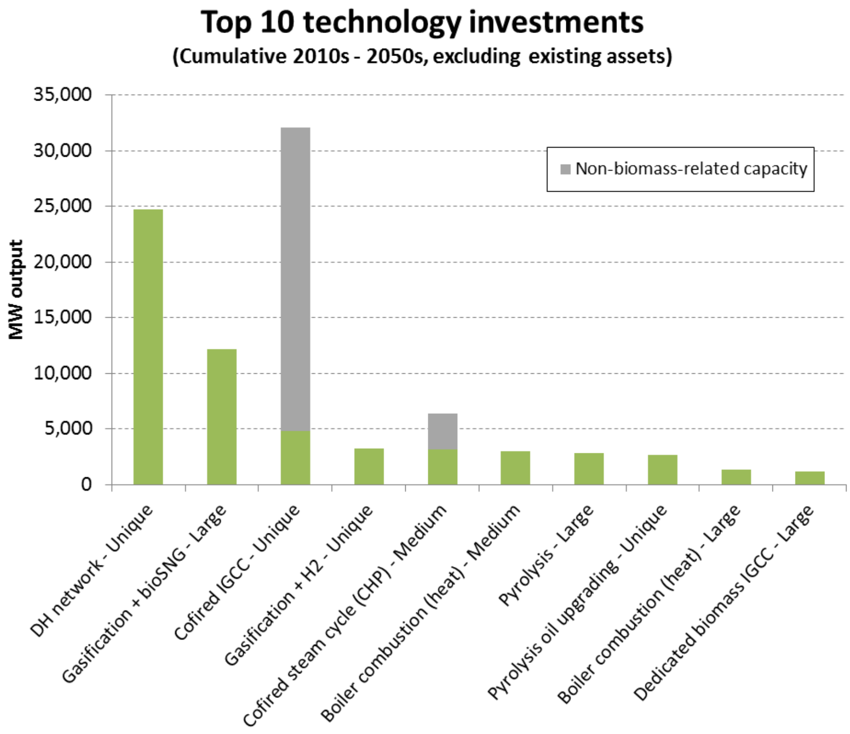
Item		2010-2059	Unit
Costs	System total	21.45	£Bn/decade
	Average	36.3	£/MWh
Emissions	System total	4.3773	Mt CO_2/year
	Average	24.21	kgCO_2/MWh





Emerging Technologies and Insights from the Run

- When the decadal energy demands are doubled, there are some subtle shifts, with more power and hydrogen production in particular:
- Note that the average costs and emissions increase when the energy to be met by biomass in 2050s goes from 10% of UK energy demand to 20%:
    - Cost: from 32.9 £/MWh to 36.3 £/MWh
    - Emissions: from 20.3 to 24.2 kgCO_2/MWh



9.2.8 Run 6-7: Minimise GHG, 10% UK 2050 energy demand

Constraints:

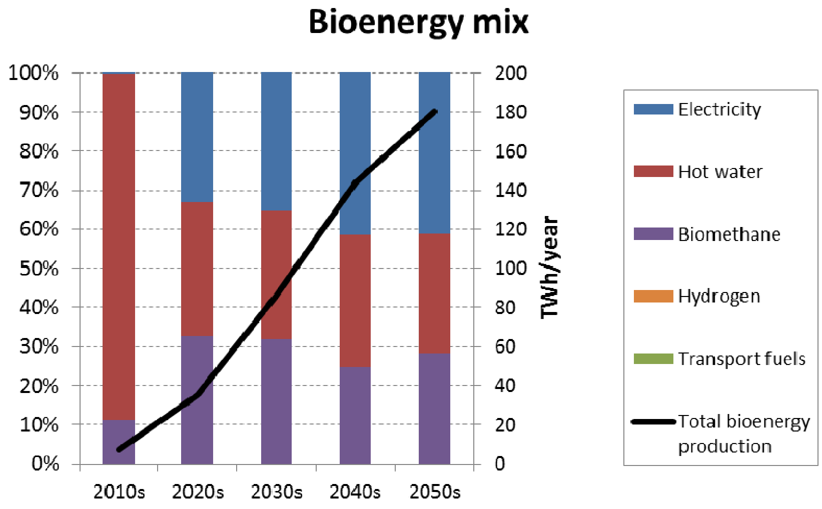
Two different runs were undertaken for the minimum GHG case. These were all based on the requirement of meeting 10% UK 2050 energy demand:

i. Minimise total GHG emissions including co-product credits.
ii. Minimise total GHG emissions excluding co-product credits

Main results

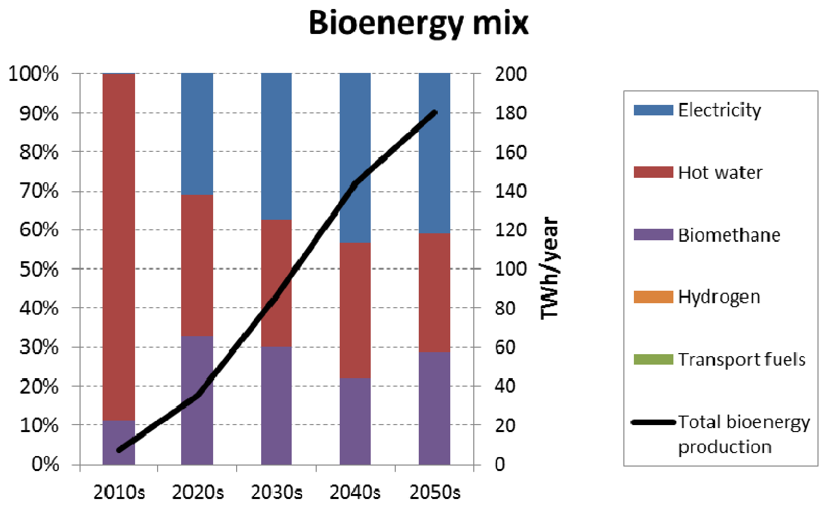
Case (i)

Item		2010-2059	Unit
Costs	System total	20.88	£Bn/decade
	Average	70.60	£/MWh
Emissions	System total	0.32	Mt CO_2/year
	Average	3.50	kgCO_2/MWh



Case (ii)

Item		2010-2059	Unit
Costs	System total	21.40	£Bn/decade
	Average	72.35	£/MWh
Emissions	System total	0.32	Mt CO_2/year
	Average	3.50	kgCO_2/MWh



Emerging Technologies and Insights from the Run

- Co-products credits do not have any appreciable impact on the system costs, emissions, and emerging value chains
- Gasification into BioSNG and both-cofired and dedicated IGCC technologies play a crucial role
- Heat production in boiler combustions is an important technologies in the earlier decades
- The feedstock mix is largely dominated by SRC-Willow, with SRF contributing in the later decades as well
- No transport fuels (both 1G and 2G) are produced.

9.2.9 Overall insights from case study

- Up to 32% of the UK energy demand can be met from bioenergy under an extreme case. Besides efficiency, land availability and technology build rates are the limiting factors.
- Heat production is a straightforward and relatively inexpensive route to bioenergy penetration
- Gasification and subsequent conversion to heat, hydrogen, and particularly synthetic natural gas, is a cost-effective and resource-efficient pathway.
- Pyrolysis fuels emerge as the most cost effective transport fuels in the long term.
- Production of biodiesel and ethanol do not emerge in the base case.
- Co-firing is exploited in many of the scenarios

9.3 Case study "ESME"

9.3.1 Description of case study

In this case study, we impose the requirements on the bioenergy system as imposed by the cost optimal energy system wide solution (central case) as calculated in the ETI ESME model.

9.3.2 Case study parameterisation

The only difference with the base case study is that the following constraints on the total energy production and on energy vectors are imposed as constraints onto the BVCM[23]:

Item		2010s	2020s	2030s	2040s	2050s	Unit
Minimum total energy		0%	3.59	16.04	41.96	86.60	TWh/year
Minimum fractions	Power	0%	53%	60%	29%	19%	-
	Heat	0%	22%	3%	0%	0%	-
	Biomethane[24]	0%	25%	15%	16%	24%	-
	Hydrogen	0%	0%	20%	51%	53%	-
	Transport fuels	0%	0%	3%	4%	5%	-

9.3.3 Run 1: ESME demand, minimum cost

Constraints

- None, except land allocated to food production as in the base case

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	0	4	16	42	87	TWh/year
	Power	0	2	10	12	16	TWh/year
	Heat	0	1	0	0	0	TWh/year
	Biomethane	0	1	2	7	21	TWh/year
	Hydrogen	0	0	3	21	46	TWh/year
	Transport fuels	0.0	0.0	0.1	0.2	0.5	MLge/year

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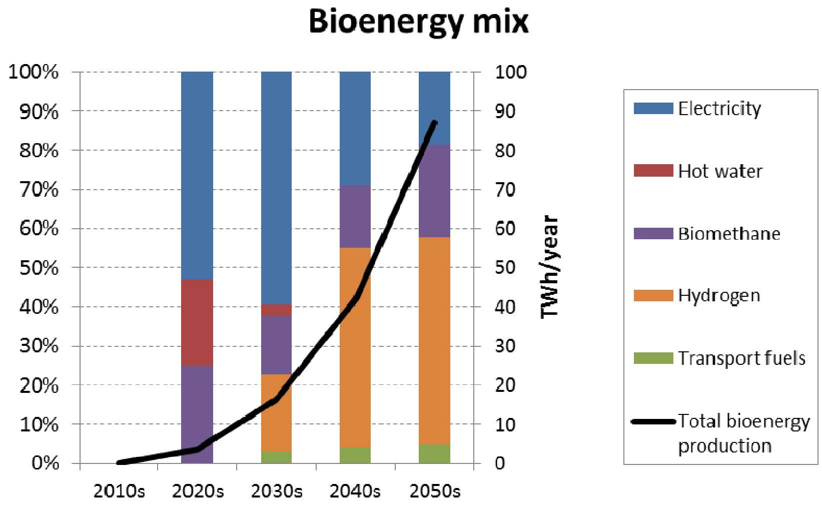
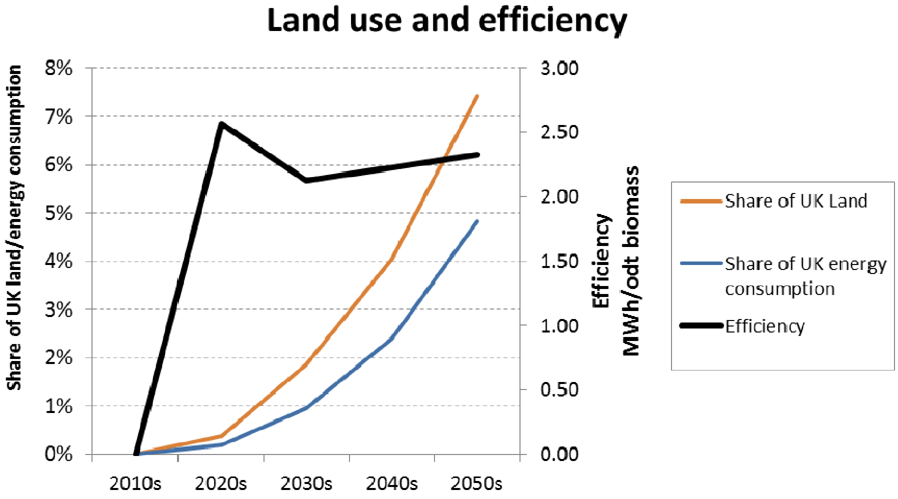
[23] Personal communication with Chris Heaton, April 2012.

[24] In ESME this includes both biomethane from anaerobic digestion (AD) as well as BioSNG. As AD technologies are not included in the current version of the BVCM (will be included in Phase 2), we assume that the whole biomethane to be produced in ESME is from BioSNG.

Item		2010-2059	Unit
Costs	System total	5.51	£Bn/decade
	Average	67.27	£/MWh
Emissions	System total	0.93	Mt CO_2/year
	Average	31.42	$kgCO_2$/MWh



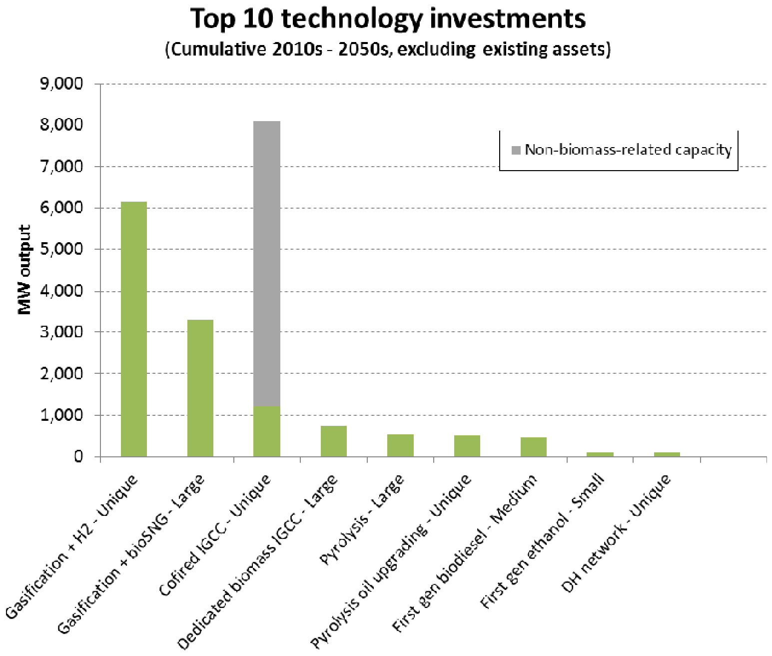


Emerging Technologies and Insights from the Run

- The technology choice is heavily driven by the vector requirements as imposed by ESME:
    - Gasification into BioSNG and hydrogen are important
    - Co-fired and dedicated IGCC are the technology of choice for electricity production
    - Pyrolysis fuel is the dominant technology for transport fuel production

- When imposing vector requirements as in ESME, both average costs and emissions increase compared to those in the base case (e.g. minimum cost, 10% UK 2050 demand):
    - Cost: from 32.9 £/MWh to 67.2 £/MWh
    - Emissions: from 20.3 $kgCO_2$/MWh to 31.42 $kgCO_2$/MWh

This increase is explained by the fact that under the ESME case, much larger quantities of high value energy vectors (e.g. H_2, BioSNG, and electricity) are produced than in the Base Case, where mostly heat is produced.



9.4 Case study “Yield acceleration”

9.4.1 Description of case study

This is the same as the base case, but with yield “uplift” and “downlift” factors applied to resources, in order to understand the impact of accelerating yield improvements on the shape and value of bioenergy value chains, as well the resilience of the value chain results on missing yield targets.

9.4.2 Case study parameterisation

The uplift and downlift factors shown below were explored with respect to minimising cost and GHG emissions.

		Uplift Factor				
Decade	**Resources**	**2010s**	**2020s**	**2030s**	**2040s**	**2050s**
1	Wheat (W)	1	1.1	1.15	1.2	1.25
2	Sugar beet (SB)	1	1.1	1.15	1.2	1.25
3	Oilseed Rape (OSR)	1	1.1	1.15	1.2	1.25
4	Miscanthus (M)	1	1.1	1.15	1.2	1.25
5	SRC-Willow (SRC)	1	1.1	1.15	1.2	1.25
6	SRF	1	1.1	1.15	1.2	1.25
7	Forestry Residue (ForRes)	1	1.1	1.15	1.2	1.25

		Downlift Factor				
Decade	**Resources**	**2010s**	**2020s**	**2030s**	**2040s**	**2050s**
1	Wheat (W)	1	0.9	0.85	0.8	0.75
2	Sugar beet (SB)	1	0.9	0.85	0.8	0.75
3	Oilseed Rape (OSR)	1	0.9	0.85	0.8	0.75
4	Miscanthus (M)	1	0.9	0.85	0.8	0.75
5	SRC-Willow (SRC)	1	0.9	0.85	0.8	0.75
6	SRF	1	0.9	0.85	0.8	0.75
7	Forestry Residue (ForRes)	1	0.9	0.85	0.8	0.75

9.4.3 Run series 1: Minimise GHG, 10% UK 2050 energy demand, £200bn budget constraint

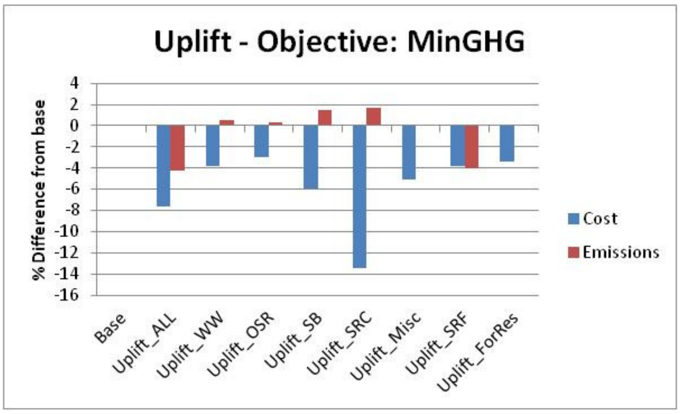
Constraints:

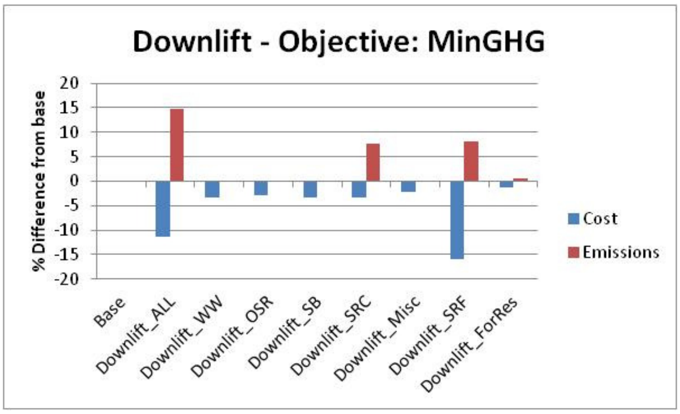
- No other than those imposed in the base case.
- Overall budget constraints of £200Bn

Main results

Results presented are outcomes from minimising overall GHG emissions.

Results are expressed as variation w.r.t. results obtained without uplift/downlift factors.





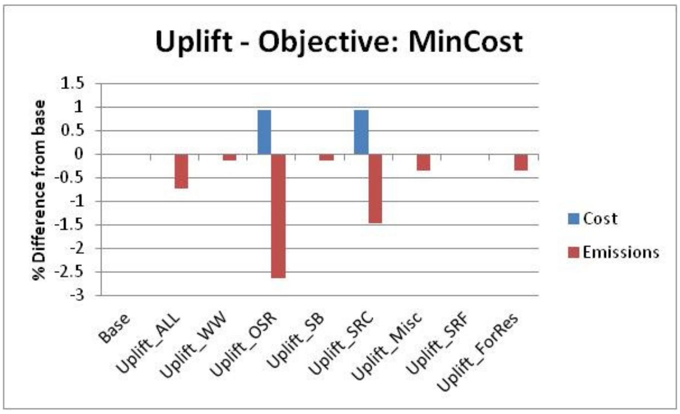
9.4.4 Run series 2: Minimise cost, 10% UK 2050 energy demand

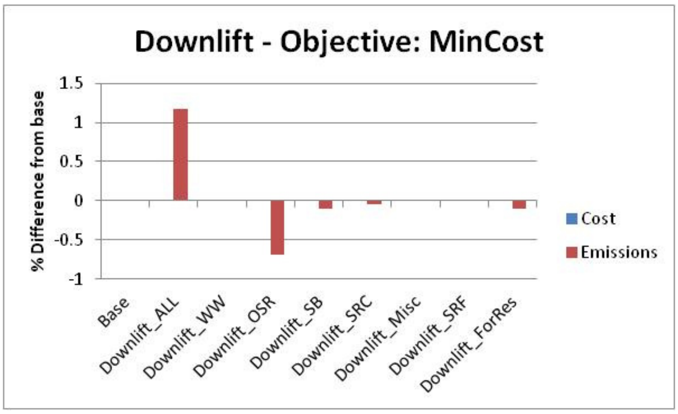
Constraints:

- No other than those imposed in the base case.

Main results

Results are expressed as variation w.r.t. results obtained without uplift/downlift factors.





9.4.5 Overall insights from case study

- System emissions and costs are robust to yield up and down lifts, with variation in emissions and costs within +/- 15% from the base case[25]
- Decadal technology options and corresponding capacities are consistent and robust to variations in yield.
- Share of UK energy demand can be met with different combinations of various crops, depending on the expected crop yields
- Feedstock mix is robust to variations and mainly dependant on a mix of SRC-willow and Miscanthus whilst minimising for cost and a mix of SRC willow and SRF whilst minimising for GHG emissions.
- DH network, gasification and boiler combustion technologies are a continuous feature in the top ten technologies for investment, with cofired IGCC technology emerging more when higher SRC yield are assumed.

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[25] In general, uplift (downlift) factors for yield result in lower levelised costs and emissions (£ and $kgCO_2e$ per MWh of energy produced, respectively). However, since the resulting final energy vector mix is not imposed on the solution, it may happen that – in case of yield uplift, for example - the additional yield is used by a more expensive technology, thus resulting in a higher cost.

Also, it should be noted that the margin of optimality in the model (i.e. the gap between the optimal energy solution as found by the optimisation and the theoretical one) is set at 3%, so any difference between levelised costs and emissions below 3% should be considered within the "noise" of the solution.

9.5 Case study "Low Carbon Climate Scenario"

9.5.1 Description of case study

This case study is the same as the Base Case, but the yield data for all resources are those based on the UKCP09-SCP Low scenario. These yield data also feed through to costs and GHG emissions; hence a coherent data set is used.

9.5.2 Case study parameterisation

In this case, the two cost minimisation runs of the Base Case (10% and 20% of UK 2050 demand) were run with the Low Climate Scenario.

9.5.3 Run 1: Minimise Cost, 10% of UK 2050 energy demand

Constraints:

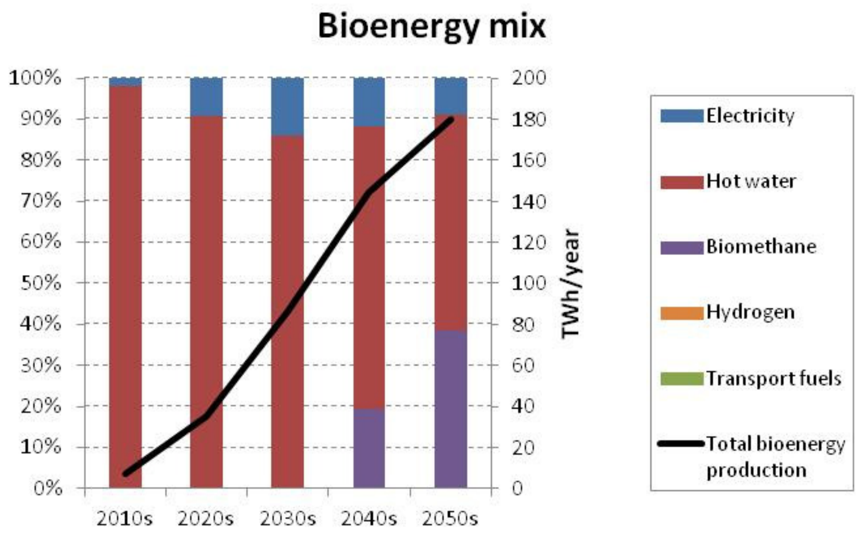
- No other than those imposed in the base case.

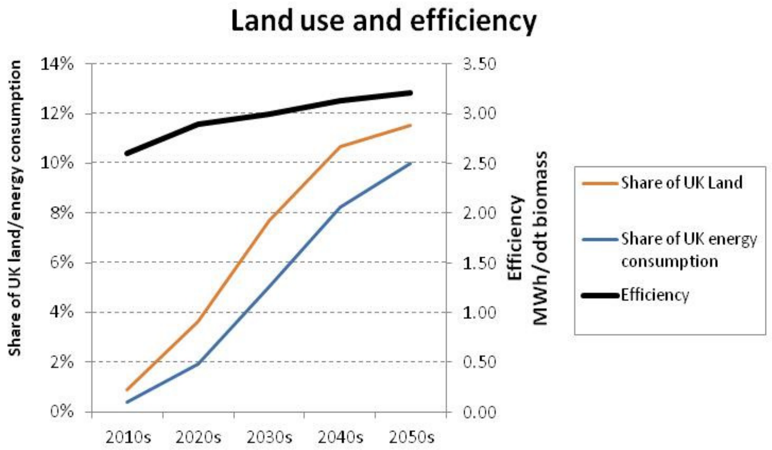
Main results

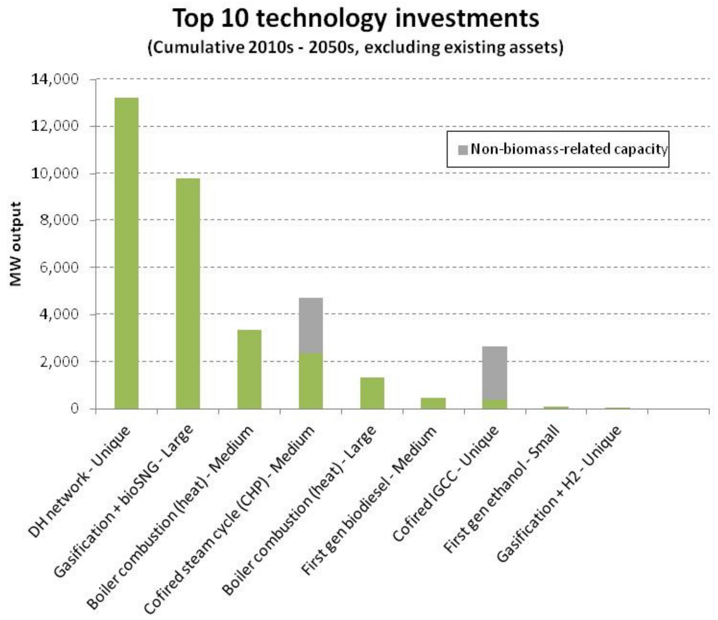
Results presented are outcomes from minimising overall costs.

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	12	17	16	TWh/year
	Heat	7	32	74	99	95	TWh/year
	Biomethane	0	0	0	28	68	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	9.802	£Bn/decade
	Average	10.8	£/MWh
Emissions	System total	1.8328	Mt CO_2/year
	Average	20.27	kgCO_2/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production


Land use and efficiency
Share of UK land/energy consumption
14%
12%
10%
8%
6%
4%
2%
0%
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency


Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
MW output
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Non-biomass-related capacity
DH network - Unique
Gasification + bioSNG - Large
Boiler combustion (heat) - Medium
Cofired steam cycle (CHP) - Medium
Boiler combustion (heat) - Large
First gen biodiesel - Medium
Cofired IGCC - Unique
First gen ethanol - Small
Gasification + H2 - Unique

The results are very similar to those in the base case (i.e. with Medium climate scenario). Both the resource mix and the technology choice have a high degree of resilience to climate scenarios. This is also the case when demand is doubled (below).

9.5.4 Run 2: Minimise Cost, 20% of UK 2050 energy demand

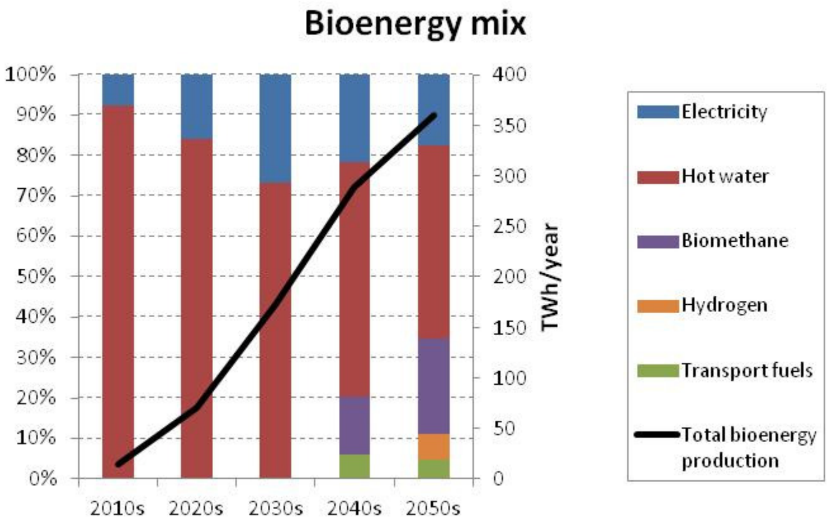
Constraints:

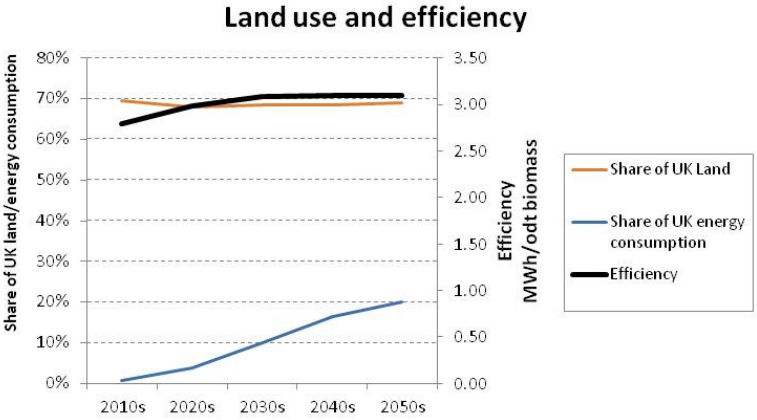
- As in equivalent run in Base Case.

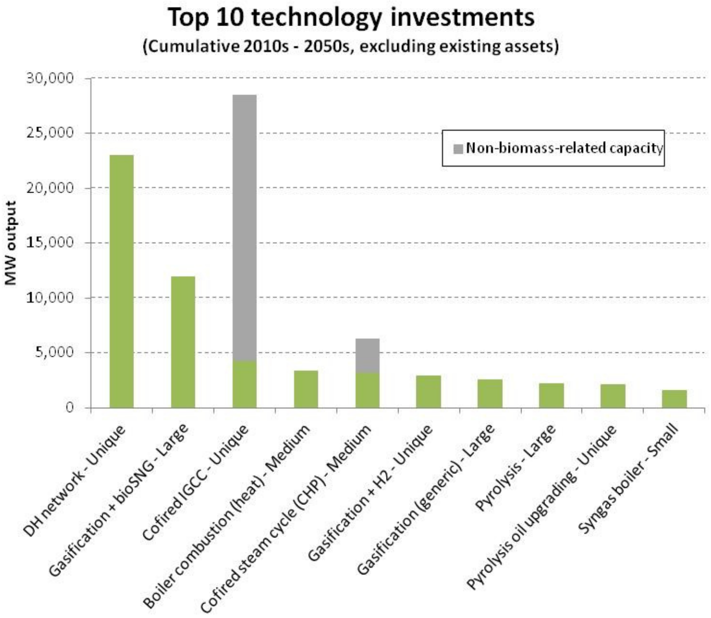
Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	14	70	172	288	360	TWh/year
	Power	1	11	46	62	63	TWh/year
	Heat	13	59	126	167	172	TWh/year
	Biomethane	0	0	0	42	84	TWh/year
	Hydrogen	0	0	0	0	24	TWh/year
	Transport fuels	0	0	0	2	2	MLge/year

Item		2010-2059	Unit
Costs	System total	21.16	£Bn/decade
	Average	11.7	£/MWh
Emissions	System total	4.3112	Mt CO_2/year
	Average	23.84	$kgCO_2$/MWh




Land use and efficiency
Share of UK land/energy consumption
80%
70%
60%
50%
40%
30%
20%
10%
0%
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency
MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency


Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
MW output
30,000
25,000
20,000
15,000
10,000
5,000
0
Non-biomass-related capacity
DH network - Unique
Gasification + bioSNG - Large
Cofired IGCC - Unique
Boiler combustion (heat) - Medium
Cofired steam cycle (CHP) - Medium
Gasification + H2 - Unique
Gasification (generic) - Large
Pyrolysis - Large
Pyrolysis oil upgrading - Unique
Syngas boiler - Small

9.6 Case study “CCS”

9.6.1 Description of case study

For this case study, the following 8 technologies from the TESBIC project were included:

i. Cofired combustion + amine CCS

ii. Biodedicated combustion + amine CCS

iii. Cofired oxy-fuel CCS

iv. Biodedicated oxy-fuel CCS

v. Cofired carbonate looping CCS

vi. Biodedicated chemical looping CCS

vii. Cofired IGCC + CCS

viii. Biodedicated IGCC

These were operated at their base case capture rates as per the TESBIC WP2 report.

9.6.2 Case study parameterisation

Several runs were executed:

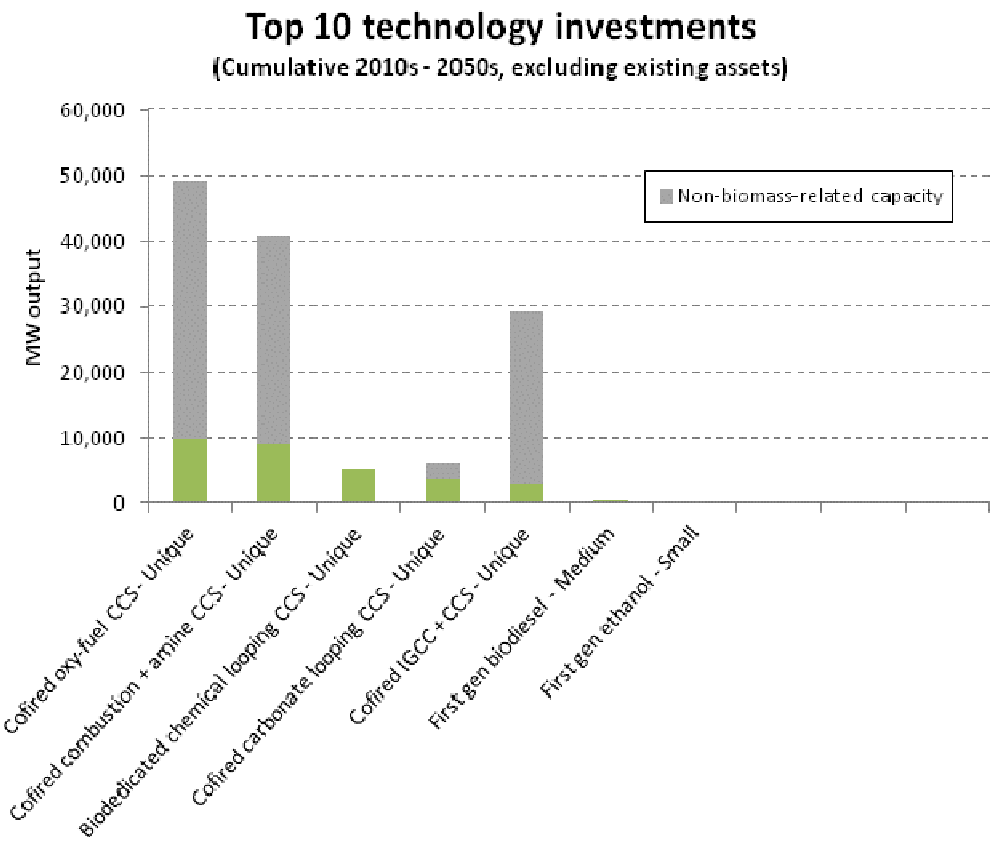
i. GHG minimisation, with biomass meeting a minimum 10% of UK energy demand in 2050 (as in the base case) with a total cost limit variation of £200 bn to 50bn with CCS

ii. GHG minimisation, with biomass meeting 10% of UK energy demand in 2050 (as in the base case) with a total cost limit of £50bn without CCS

9.6.3 Key results

At the upper end of the budget (£200bn total discounted cost over 50 years), 7120 TWh of energy are produced over the 5 decades at an average emission factor of -769 kgCO_2e/MWh. An average of 109M tonnes of CO2 can be sequestered per year. The approximate cost of energy averages out at about £81.3/MWh.

The main technology investments for this particular (extreme) scenario are shown below.



The trade-off curve showing the variation between average cost and emission factors and total CO2 sequestered is below.

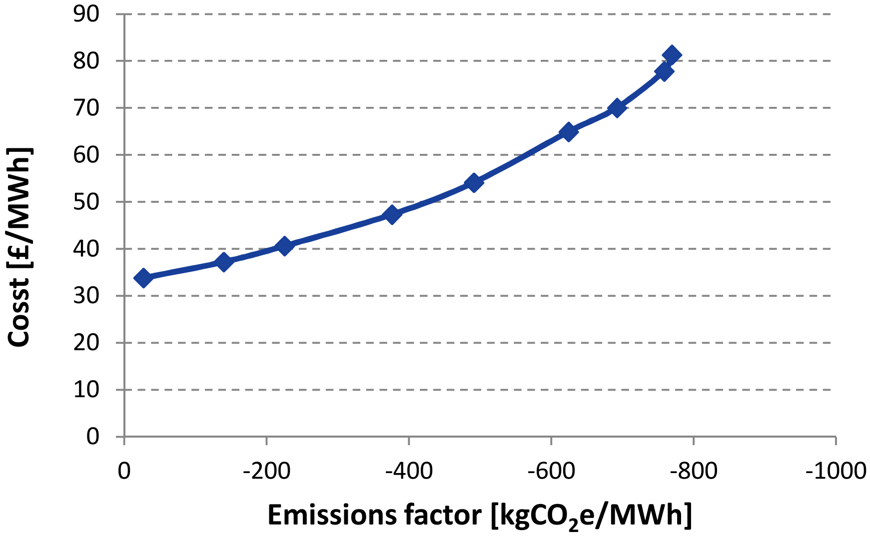


Figure 9-1 Cost versus degree of negative emissions

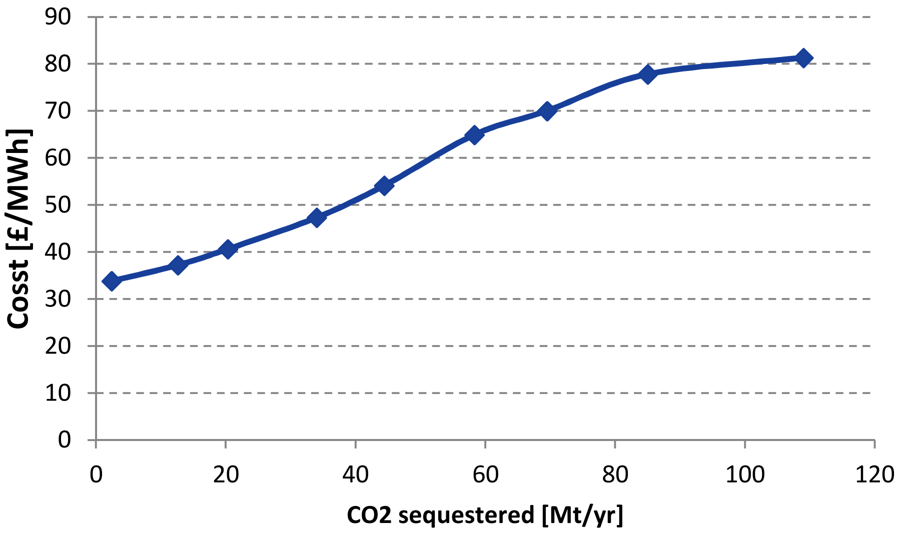
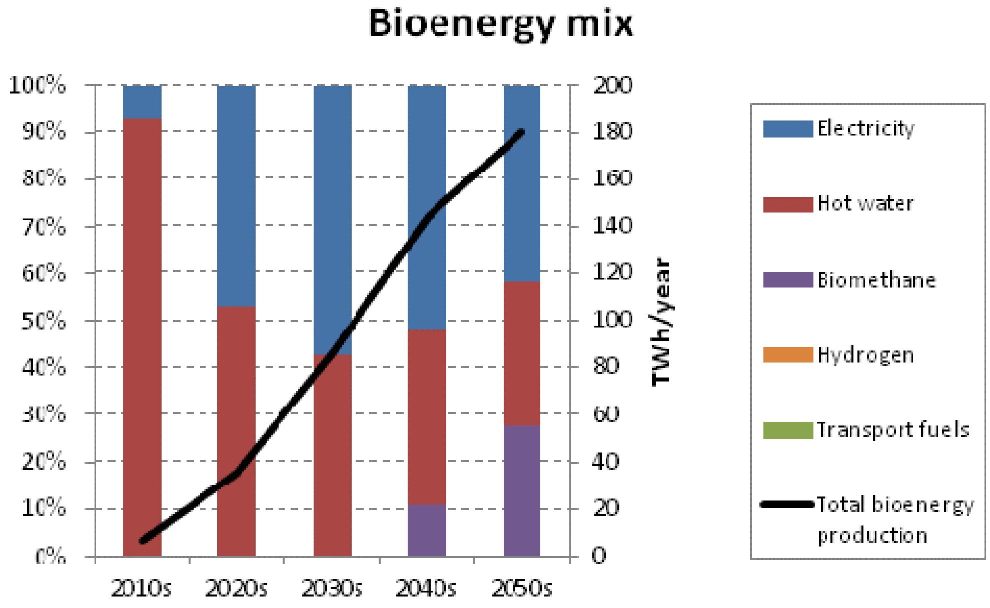
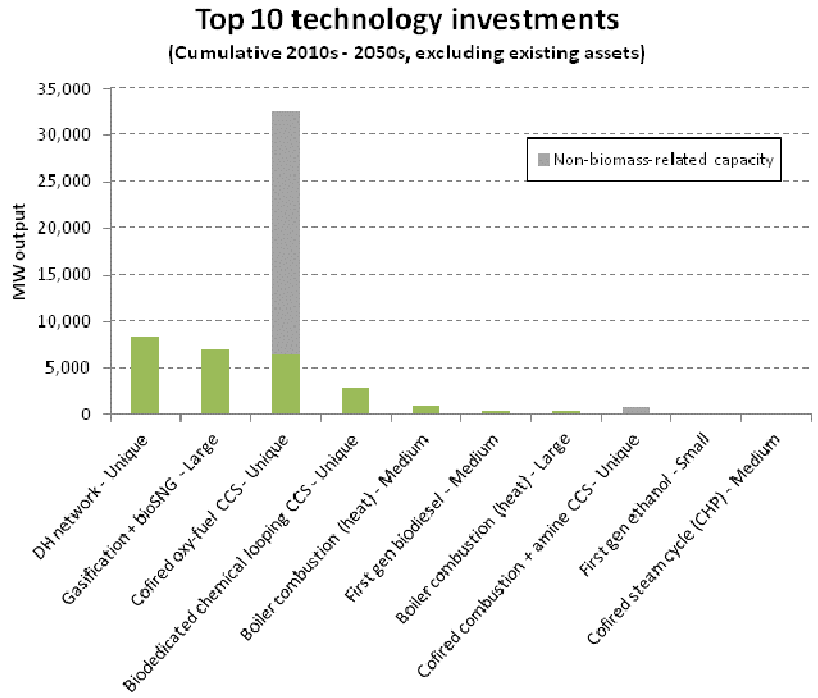
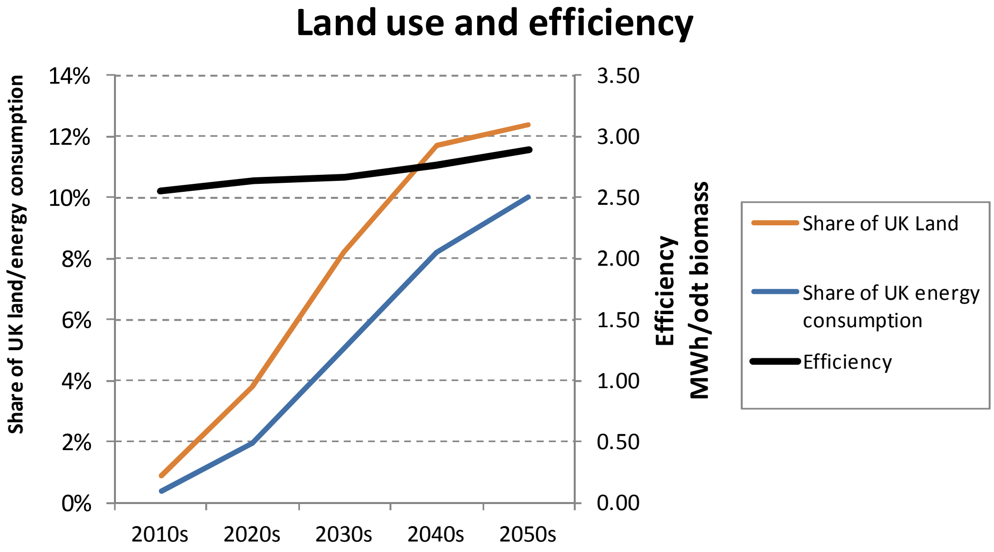


Figure 9-2 Cost vs millions of tons of CO_2 sequestered annually

The solution for the more modest case of total cost of £70bn, (£47.3/MWh and -376kgCO2e/MWh) is illustrated below.







A run was also performed with the ESME data on minimum energy demands met from bioenergy, with a cost constraint of £30bn and GHG minimised. The results were

Item		2010-2059	Unit
Costs	System total	5.176	£Bn/decade
	Average	63.4	£/MWh
Emissions	System total	0.3950	Mt CO_2/year
	Average	13.33	kgCO_2/MWh

The emissions are not quite negative due to the need to produce methane, heat and transport fuel (mainly via pyrolysis) as well as power. The negative CCS technology chosen was biodedicated chemical looping combustion.

However, when minimising on cost using ESME demand data, but with a carbon price of 10£/tonne CO_2, total emissions become negative (see below).

Item		2010-2059	Unit
Costs	System total	5.592	£Bn/decade
	Average	68.2	£/MWh
Emissions	System total	-5.1412	Mt CO_2/year
	Average	-172.77	kgCO_2/MWh

Emerging Technologies and Insights from the Runs

- Co-fired oxy-fuel CCS and biodedicated CCS with chemical looping are the most prevalent technologies across scenarios
- The more conventional co-fired plant with post-combustion amine capture also appears
- Calcium looping post-combustion capture appears to some extent
- Biodedicated IGCC with CCS is not selected on account of its high cost

9.7 Case study "Syngas and H_2 economy"

9.7.1 Description of case study

As seen in other case studies, syngas and hydrogen are already generated in large quantities in many of the runs. This indicates a high degree of scenario robustness. The syngas utilising technologies are proximate in the previous studies. Here, the effect of cheap syngas and hydrogen transport was explored.

9.7.2 Case study parameterisation

Two runs are executed, based on the Base Case

- Run 1: no inter-cell transport of syngas and H_2 allowed
- Run 2: inter-cell transport of syngas and H_2 allowed

9.7.3 Run 1 and 2: Minimise Cost, 10% UK 2050 energy demand

Constraints:

- As Base Case

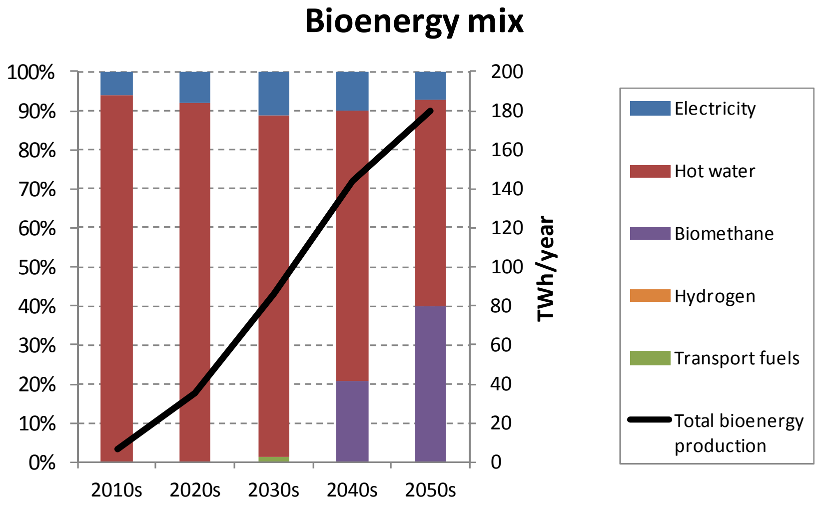
Main results

No inter-cell transport

Item		2010-2059	Unit
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh

With inter-cell transport

Item		2010-2059	Unit
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh



Emerging Technologies and Insights from the Runs

- Because power and natural gas are readily transported across the UK and heat is assumed to be used within a cell, the advantages of long-distance transport of bio-based syngas/H_2 were found to be marginal.

- However, in a case study with lower area level (Level 2 of land use), very low transport costs and a higher minimum penetration of electricity (>30%), syngas infrastructures such as the one below do appear.

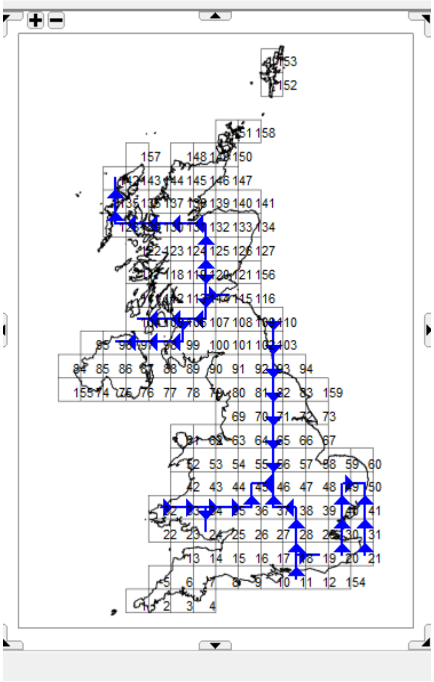
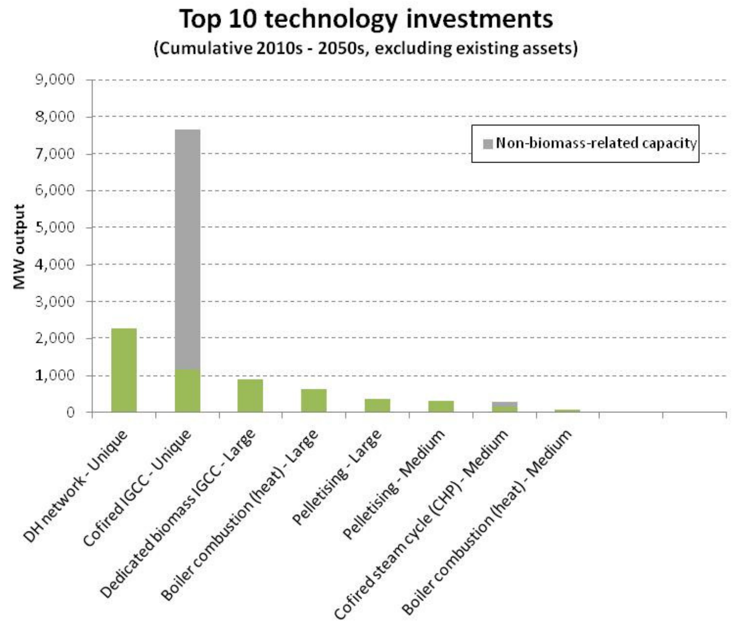
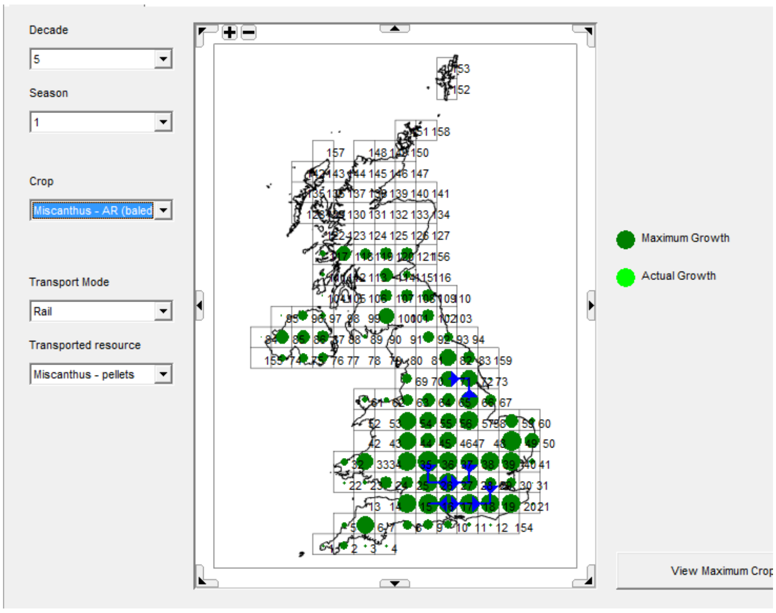


Figure 9-3 An example of possible syngas infrastructure

To explore transport issues further, a case with reduced transport costs (halved) and land constraints of 10% land in each category (1-4) available for bioenergy was run. This sees a considerable use of pellets and longer distance transport:



Pellet distribution


Decade: 5

Season: 1

Crop: Miscanthus - AR (baled

Transport Mode: Rail

Transported resource: Miscanthus - pellets

9.8 Case study "Vector focus: electricity"

9.8.1 Description of case study

This case study is intended to explore the effects of a bioenergy strategy emphasising high levels of electricity.

9.8.2 Case study parameterisation

This will be the same as the base case study, with the difference that transport fuel demand to be met is set to a fraction of the total energy demand for in the UK. A series of runs is executed, with minimum fractions of electricity production as below.

Note that in the model fractions are intended as multiplicative factors, so they can also be larger than 1.

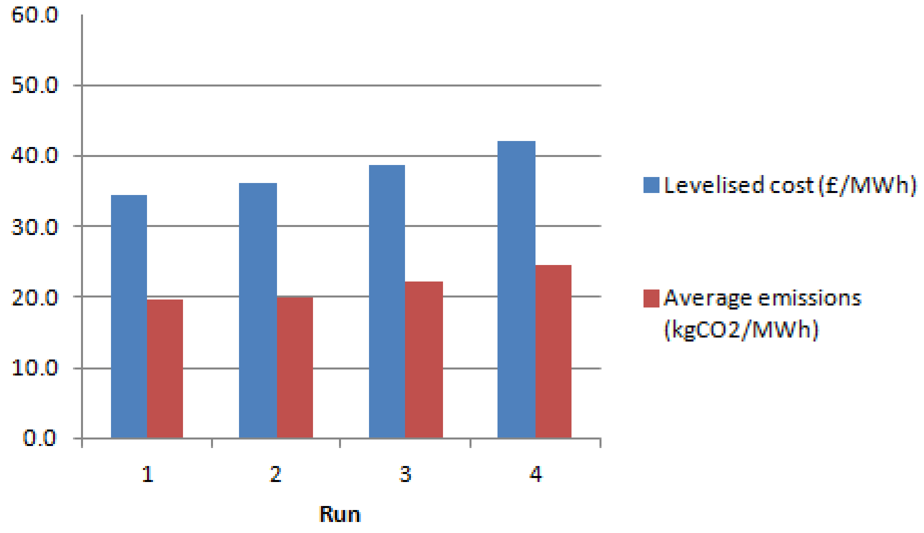
Decade	Minimum Energy Production (TWh)	Minimum Electricity Production (as a fraction of minimum total energy production)					
	0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
1	70	0.1	0.15	0.2	0.25	0.5	0.75
2	350	0.2	0.3	0.4	0.5	1	1.5
3	860	0.2	0.3	0.4	0.5	1	1.5
4	1440	0.2	0.3	0.4	0.5	1	1.5
5	1800	0.2	0.3	0.4	0.5	1	1.5

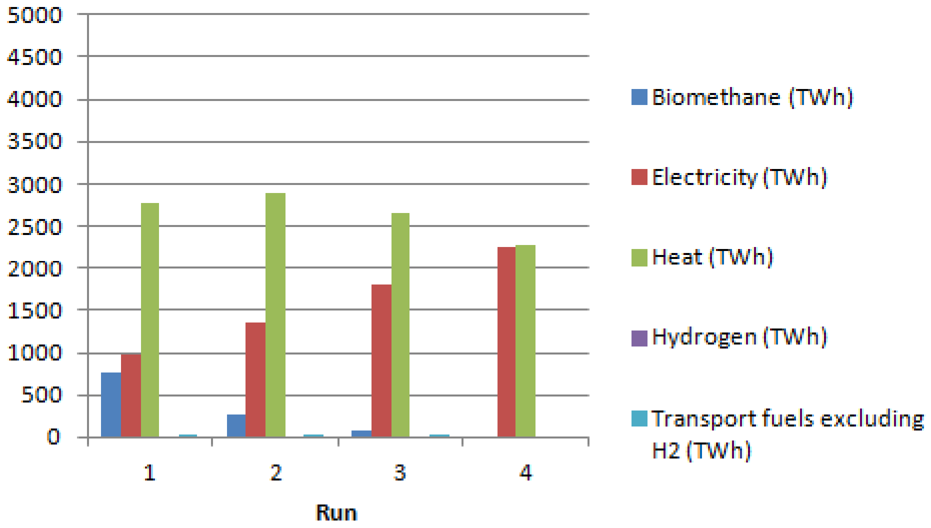
9.8.3 Run series 1 to 6: Minimise costs

Constraints:

- Minimum energy production as above
- Minimum fractions of electricity as above

Overall results





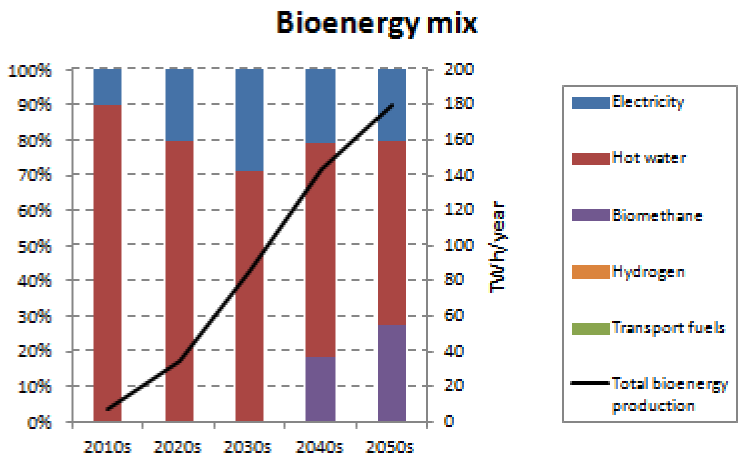
(Runs 5 and 6 are infeasible.)

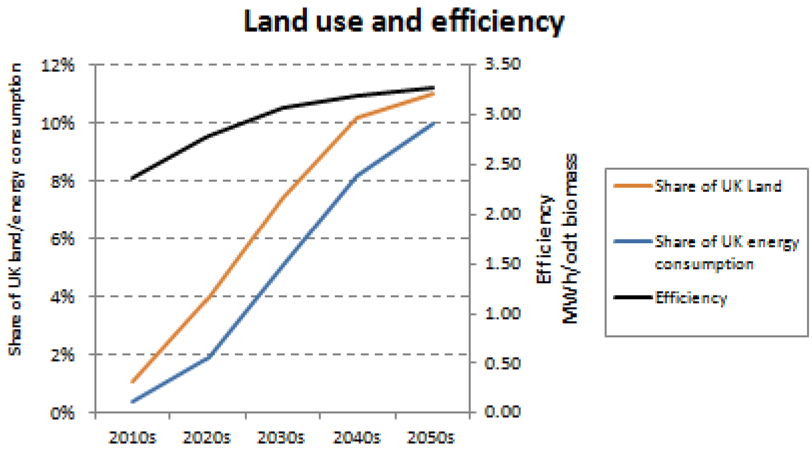
Run results and emerging technologies from representative runs

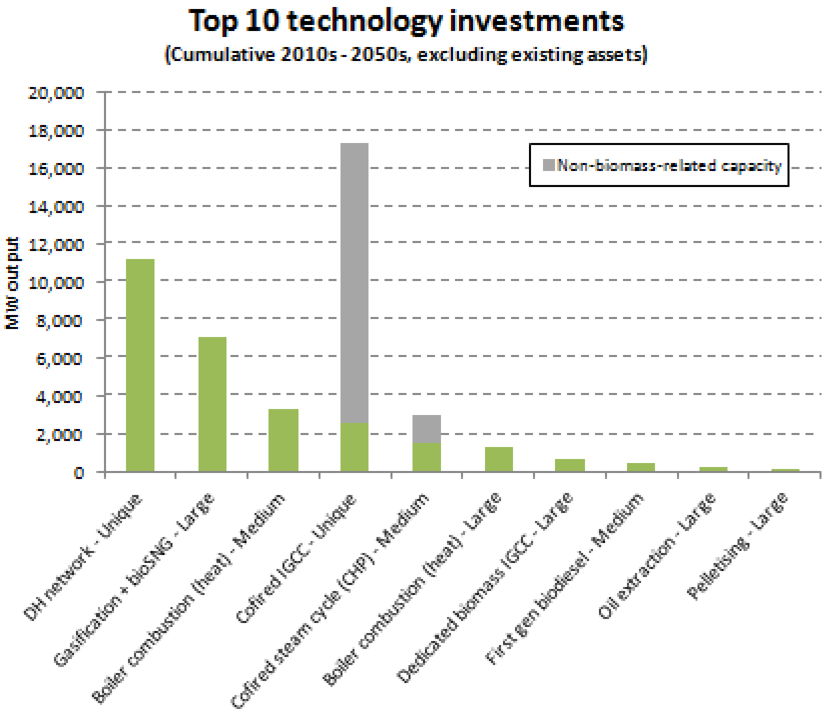
Run 1

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	1	7	25	30	36	TWh/year
	Heat	6	28	61	88	95	TWh/year
	Biomethane	0	0	0	27	49	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	10.173	£Bn/decade
	Average	34.4	£/MWh
Emissions	System total	1.7818	Mt CO_2/year
	Average	19.71	kgCO_2/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production

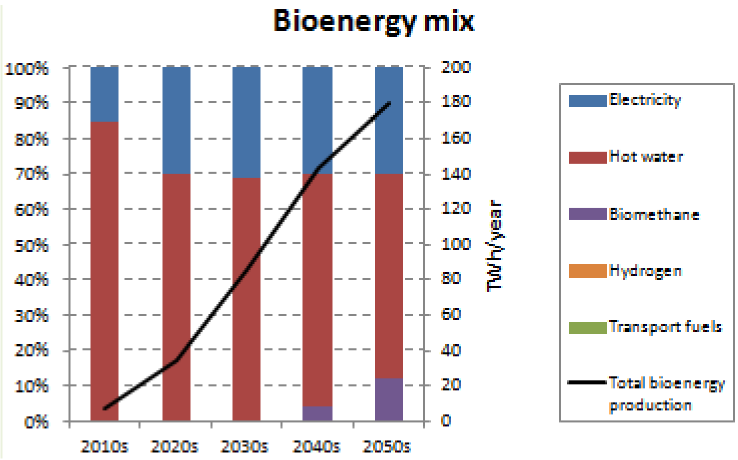

Land use and efficiency
Share of UK land/energy consumption
12%
10%
8%
6%
4%
2%
0%
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency
MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency

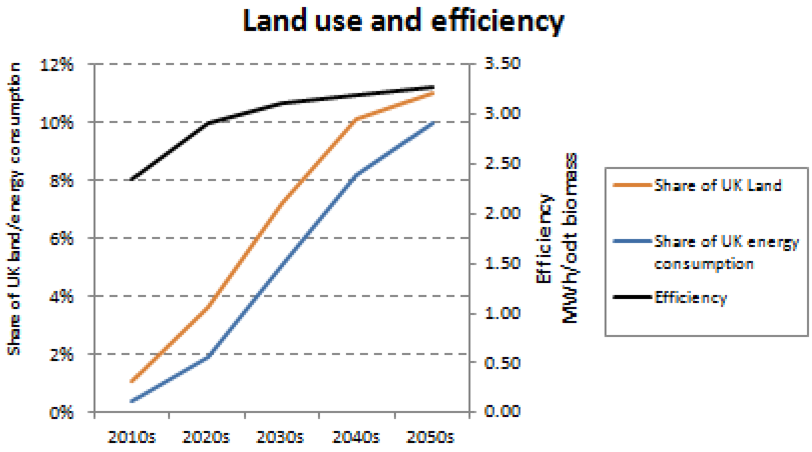

Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
MW output
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Non-biomass-related capacity
DH network - Unique
Gasification + bioSNG - Large
Boiler combustion (heat) - Medium
Cofired IGCC - Unique
Cofired steam cycle (CHP) - Medium
Boiler combustion (heat) - Large
Dedicated biomass IGCC - Large
First gen biodiesel - Medium
Oil extraction - Large
Pelletising - Large

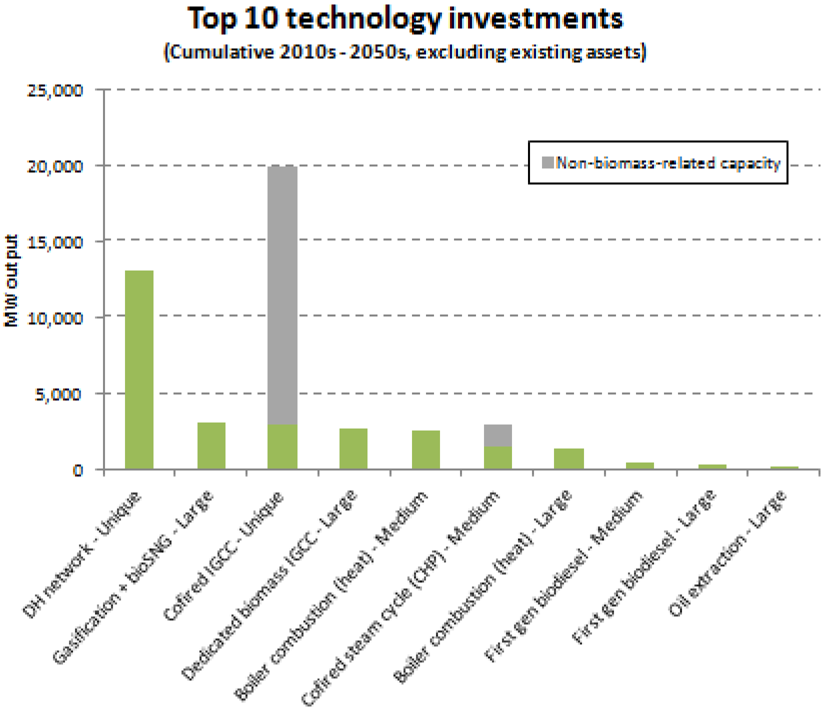
Run 2

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	1	10	27	43	54	TWh/year
	Heat	6	25	59	95	104	TWh/year
	Biomethane	0	0	0	6	22	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	10.710	£Bn/decade
	Average	36.2	£/MWh
Emissions	System total	1.8035	Mt CO_2/year
	Average	19.95	kgCO_2/MWh



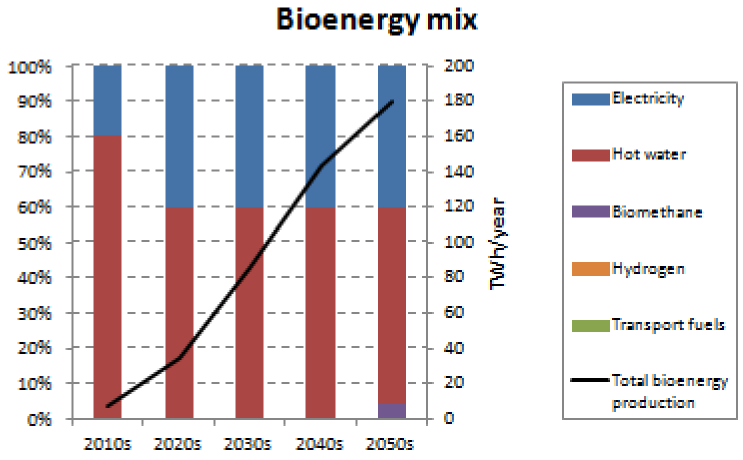


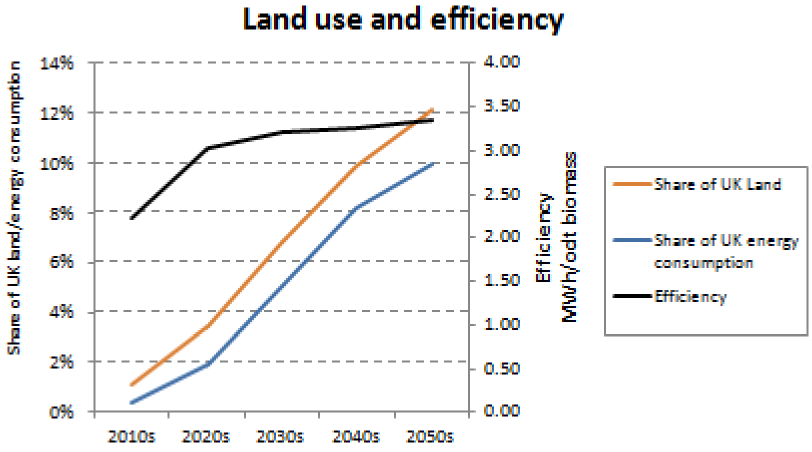


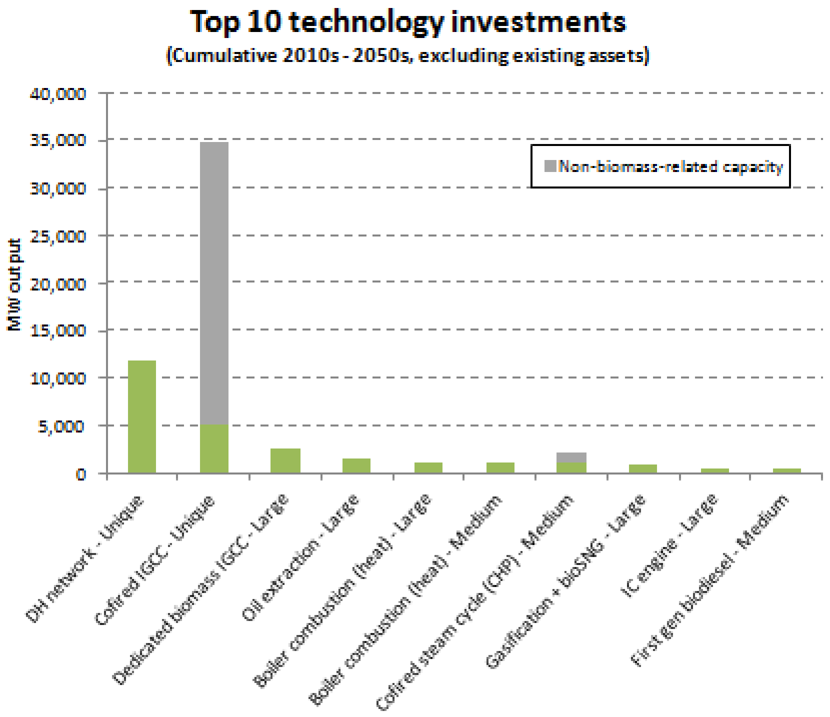
Run 3

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	1	14	34	58	72	TWh/year
	Heat	6	21	52	86	101	TWh/year
	Biomethane	0	0	0	0	7	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	11.478	£Bn/decade
	Average	38.8	£/MWh
Emissions	System total	2.0029	Mt CO_2/year
	Average	22.16	kgCO_2/MWh



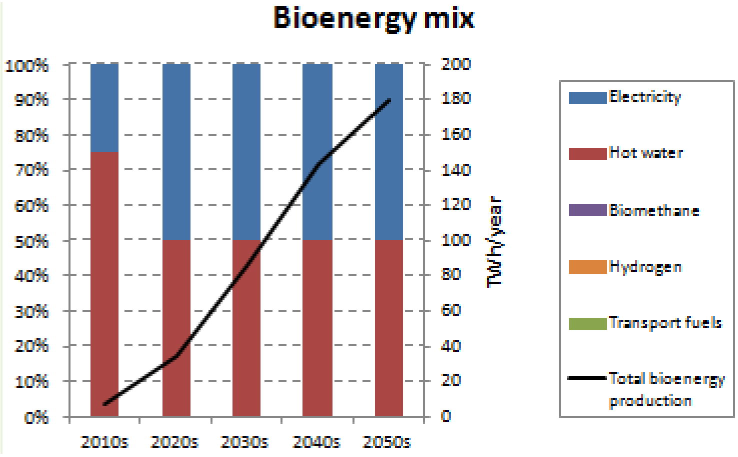


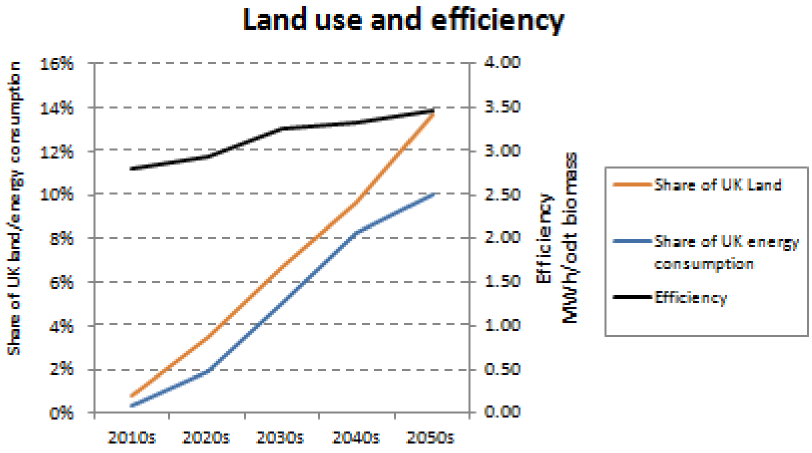


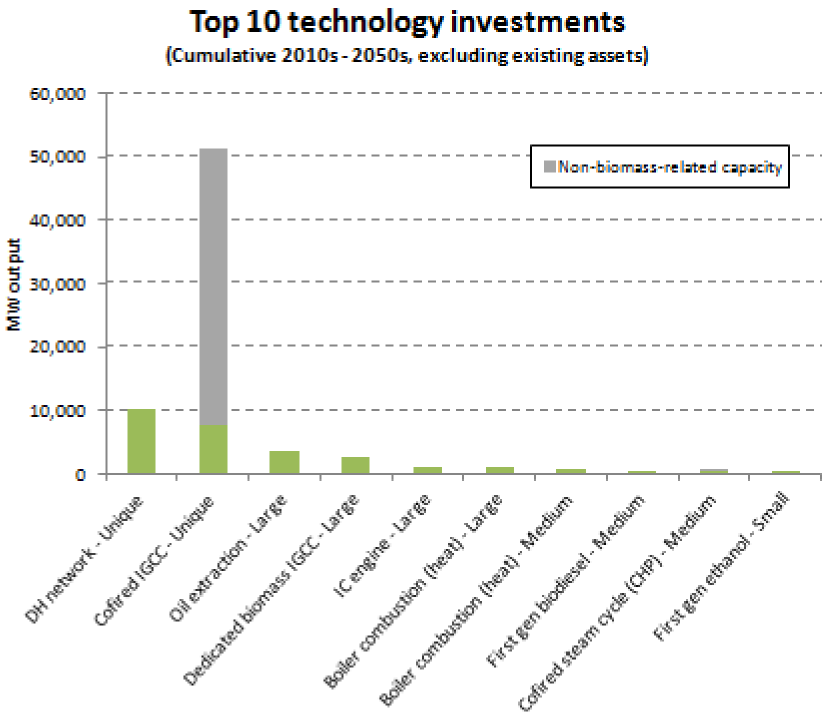
Run 4

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	2	17	43	72	90	TWh/year
	Heat	5	18	43	72	90	TWh/year
	Biomethane	0	0	0	0	0	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	12.438	£Bn/decade
	Average	42.1	£/MWh
Emissions	System total	2.2139	Mt CO_2/year
	Average	24.49	$kgCO_2$/MWh


Bioenergy mix


Land use and efficiency


Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)

9.8.4 Overall case study insights

- In order to produce more electricity, biomethane must be phased out almost completely and heat must reduce to a level roughly equal to that of electricity (heat to power ratio of about 1).
- Typically, heat production increases with increase in demand for electricity, as CHP technologies are chosen.
- The preferred technology for electricity production is co-fired IGCC.

9.9 Case study "Vector focus: transport fuels"

9.9.1 Description of case study

This case study is intended to explore the effects of a bioenergy strategy emphasising high levels of transport fuel.

9.9.2 Case study parameterisation

This will be the same as the base case study, with the difference that transport-fuel demand to be met is set to a fraction of the total energy demand for in the UK. A series of runs is executed, with minimum fractions of transport-fuel production as below.

Note that in the model fractions are intended as multiplicative factors, so they can also be large than 1. Also, hydrogen is considered a transport fuel but its production is given separately to the other transport fuels (biodiesel, bioethanol etc.), which are lumped together.

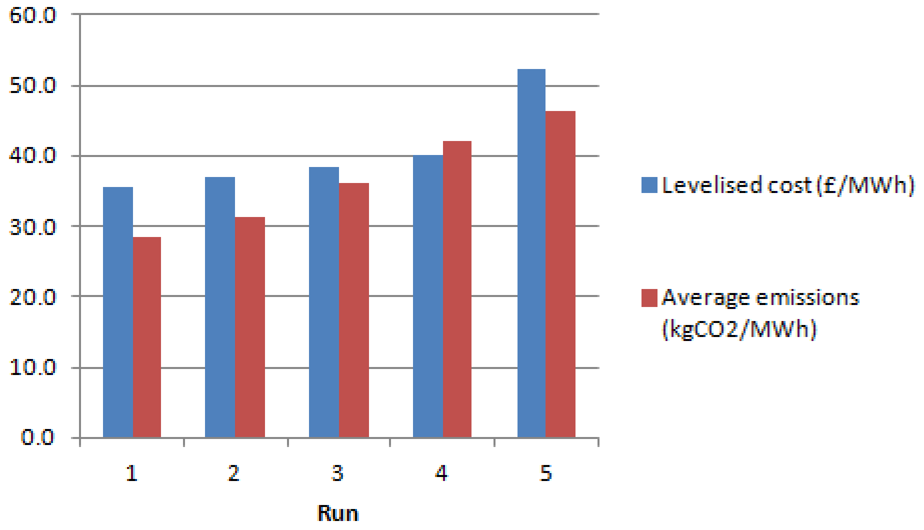
Decade	**Minimum Energy Production (TWh)**	**Minimum Transport Fuel Production (as a fraction of minimum total energy production)**					
	0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
1	70	0.1	0.15	0.2	0.25	0.5	0.75
2	350	0.2	0.3	0.4	0.5	1	1.5
3	860	0.2	0.3	0.4	0.5	1	1.5
4	1440	0.2	0.3	0.4	0.5	1	1.5
5	1800	0.2	0.3	0.4	0.5	1	1.5

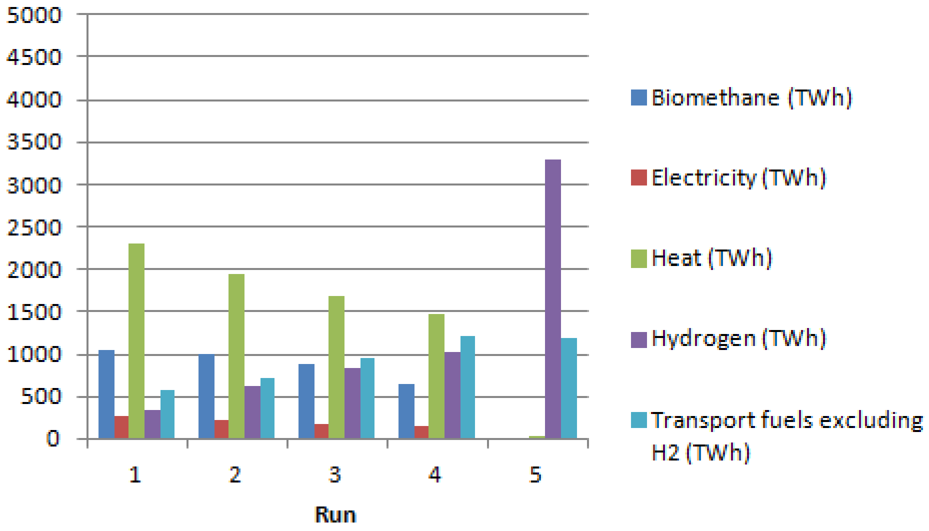
9.9.3 Run series 1 to 6: Minimise costs

Constraints:

- Minimum energy production as above
- Minimum fractions of transport fuel as above

Overall results





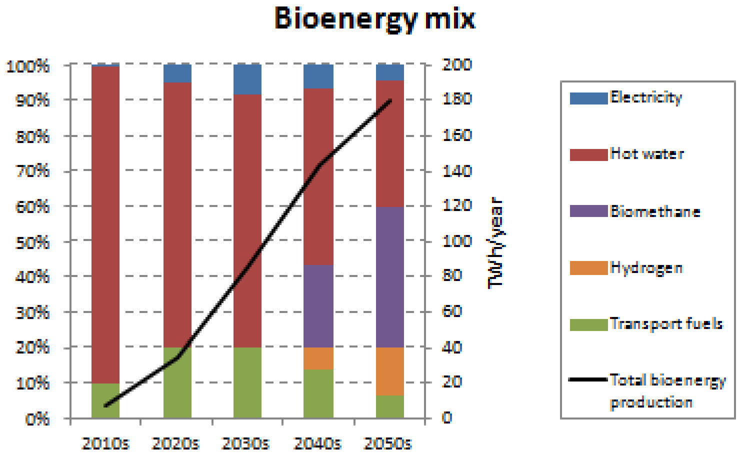
(Run 6 is infeasible.)

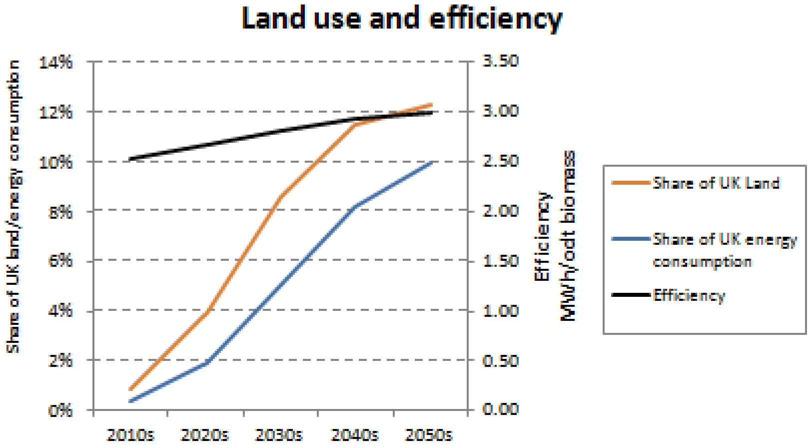
Run results and emerging technologies from representative runs

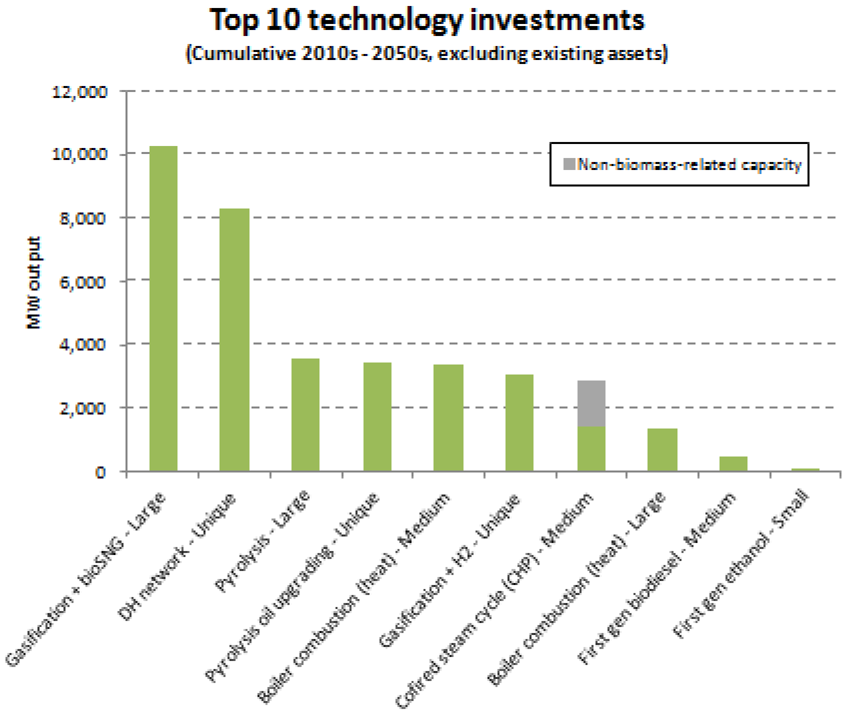
Run 1

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	2	7	10	8	TWh/year
	Heat	6	26	61	72	64	TWh/year
	Biomethane	0	0	0	34	72	TWh/year
	Hydrogen	0	0	0	9	24	TWh/year
	Transport fuels	0	1	2	2	1	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	10.485	£Bn/decade
	Average	35.5	£/MWh
Emissions	System total	2.5794	Mt CO_2/year
	Average	28.53	$kgCO_2$/MWh



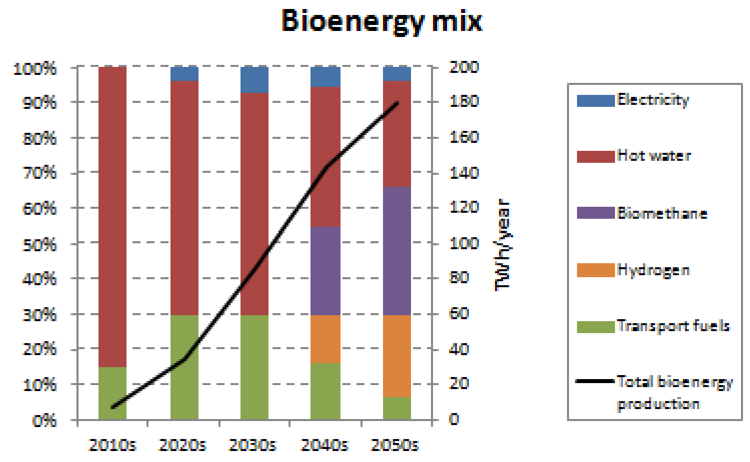


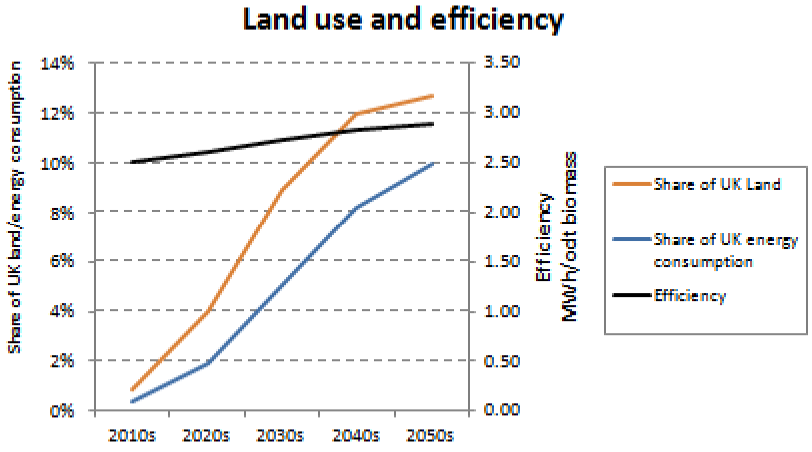


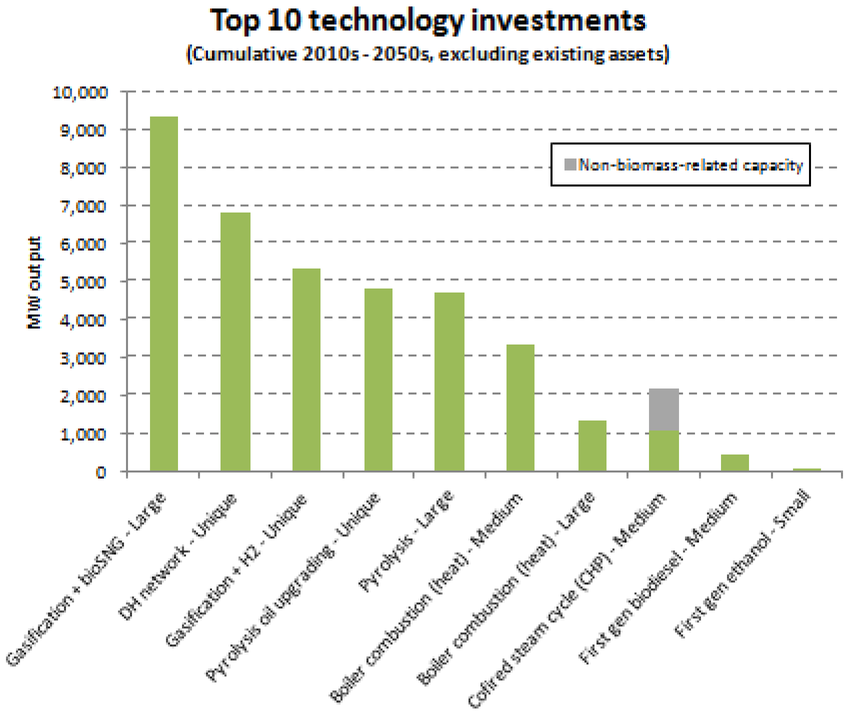
Run 2

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	1	6	8	7	TWh/year
	Heat	6	23	54	57	54	TWh/year
	Biomethane	0	0	0	36	65	TWh/year
	Hydrogen	0	0	0	20	43	TWh/year
	Transport fuels	0	1	3	3	1	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	10.950	£Bn/decade
	Average	37.0	£/MWh
Emissions	System total	2.8355	Mt CO_2/year
	Average	31.37	$kgCO_2$/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production

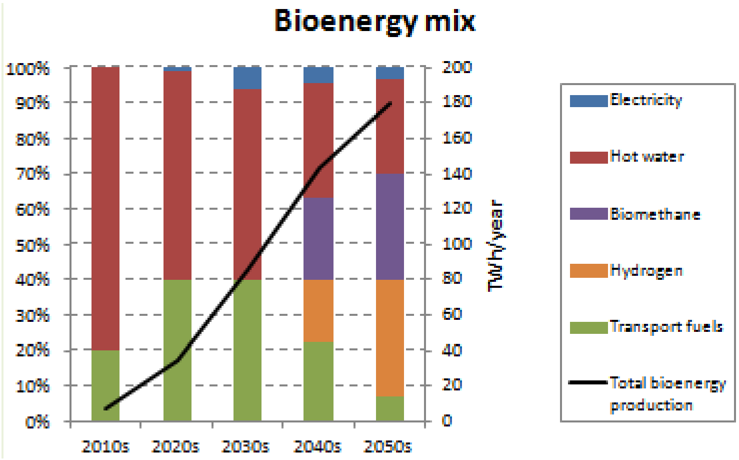

Land use and efficiency
14%
12%
10%
8%
6%
4%
2%
0%
Share of UK land/energy consumption
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency

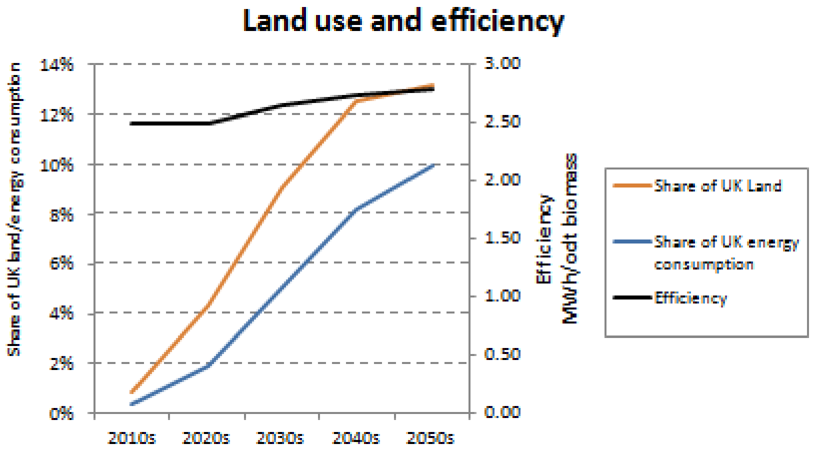

Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
MW output
Non-biomass-related capacity
Gasification + bioSNG - Large
DH network - Unique
Gasification + H2 - Unique
Pyrolysis oil upgrading - Unique
Pyrolysis - Large
Boiler combustion (heat) - Medium
Boiler combustion (heat) - Large
Cofired steam cycle (CHP) - Medium
First gen biodiesel - Medium
First gen ethanol - Small

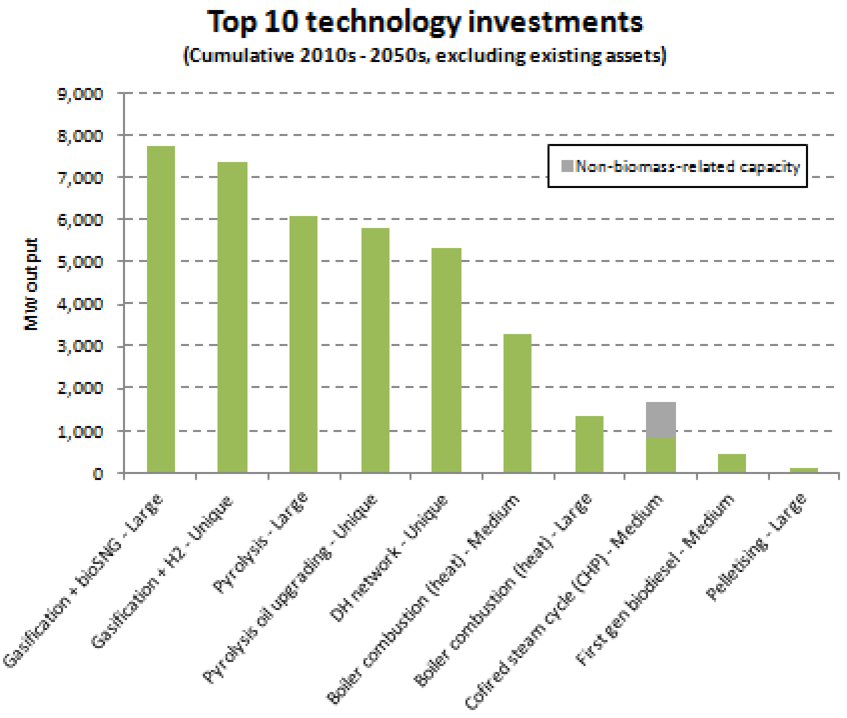
Run 3

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	0	5	6	6	TWh/year
	Heat	6	21	47	47	48	TWh/year
	Biomethane	0	0	0	33	54	TWh/year
	Hydrogen	0	0	0	25	59	TWh/year
	Transport fuels	0	2	4	4	1	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	11.352	£Bn/decade
	Average	38.4	£/MWh
Emissions	System total	3.2600	Mt CO_2/year
	Average	36.06	kgCO_2/MWh



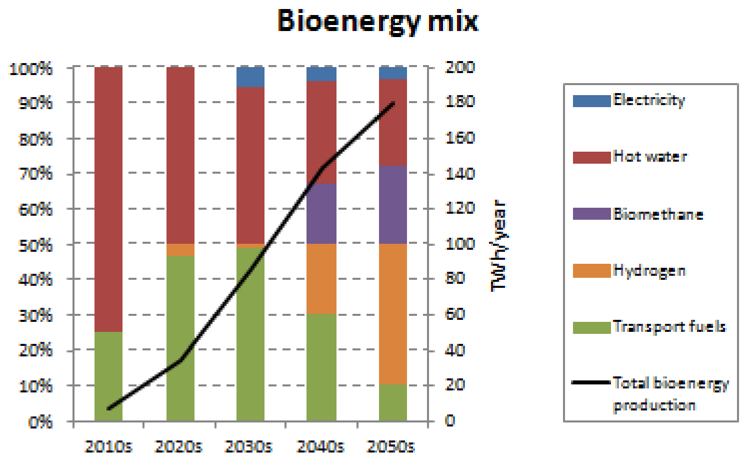


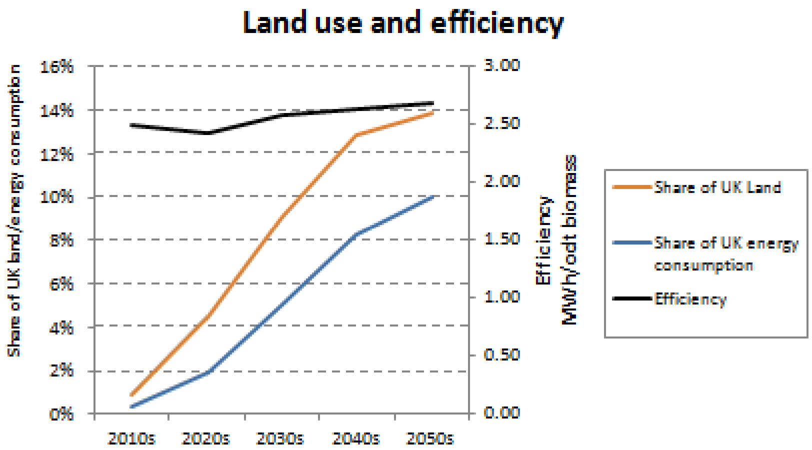


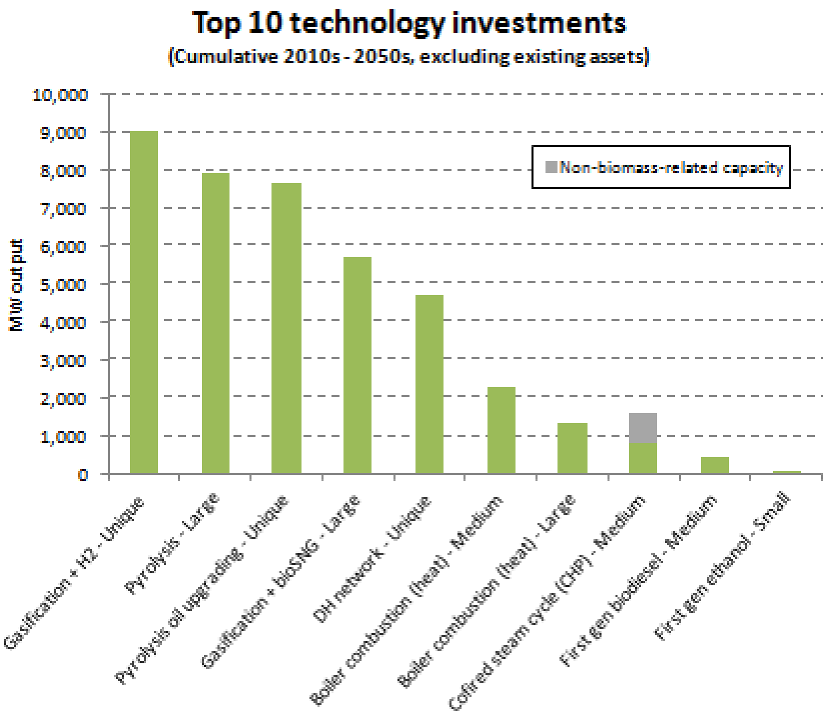
Run 4

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	0	5	6	6	TWh/year
	Heat	5	18	38	42	44	TWh/year
	Biomethane	0	0	0	25	40	TWh/year
	Hydrogen	0	1	1	29	71	TWh/year
	Transport fuels	0	2	5	5	2	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	11.889	£Bn/decade
	Average	40.2	£/MWh
Emissions	System total	3.7919	Mt CO_2/year
	Average	41.95	kgCO_2/MWh



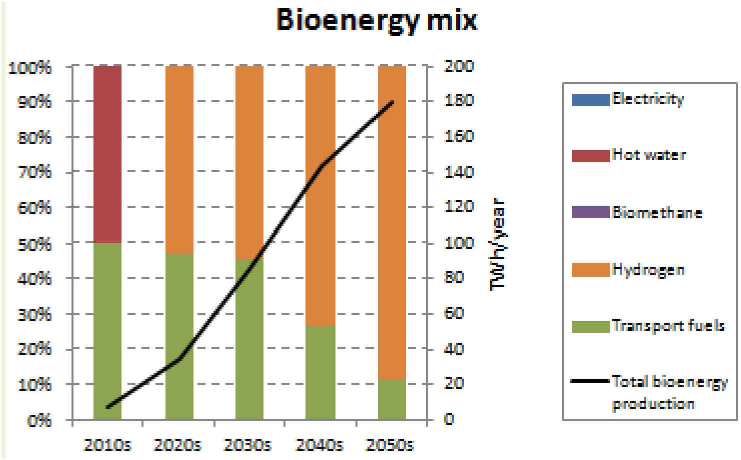


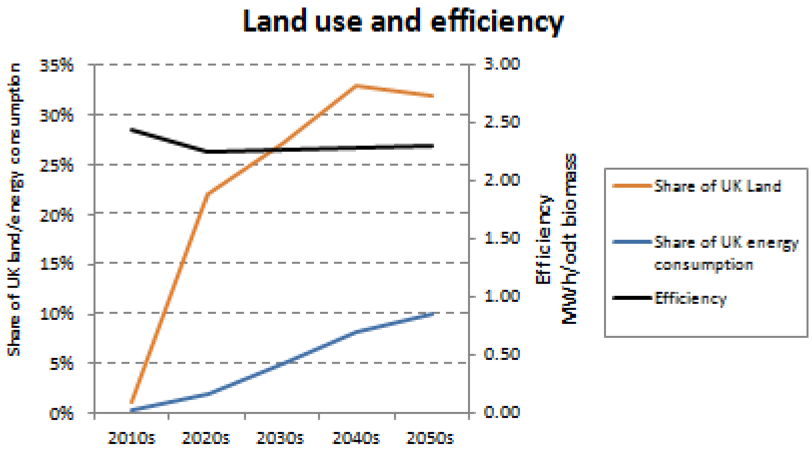


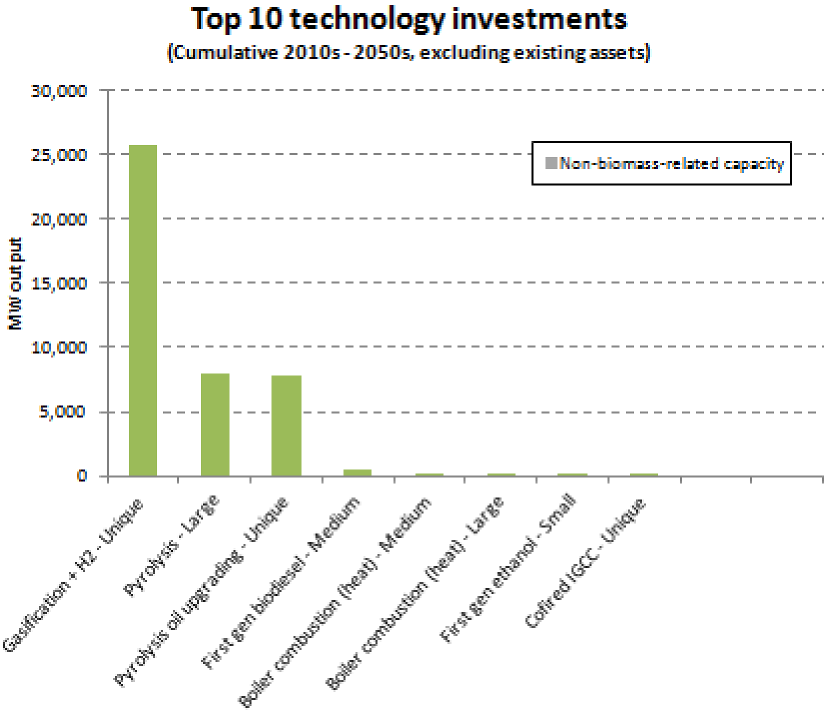
Run 5

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	0	0	0	0	TWh/year
	Heat	4	0	0	0	0	TWh/year
	Biomethane	0	0	0	0	0	TWh/year
	Hydrogen	0	18	47	106	159	TWh/year
	Transport fuels	0	2	4	4	2	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	15.485	£Bn/decade
	Average	52.4	£/MWh
Emissions	System total	4.1781	Mt CO_2/year
	Average	46.22	$kgCO_2$/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production


Land use and efficiency
Share of UK land/energy consumption
35%
30%
25%
20%
15%
10%
5%
0%
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency


Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
30,000
25,000
20,000
15,000
10,000
5,000
0
MW output
Non-biomass-related capacity
Gasification + H2 - Unique
Pyrolysis - Large
Pyrolysis oil upgrading - Unique
First gen biodiesel - Medium
Boiler combustion (heat) - Medium
Boiler combustion (heat) - Large
First gen ethanol - Small
Cofired IGCC - Unique

9.9.4 Overall case study insights

- For the focus on transport fuels, it is mostly heat that is steadily phased out; biomethane and electricity are also reduced but not by as much.
- In runs 1 to 4, hydrogen and the other transport fuels are produced in roughly equal proportions. By run 5, however, hydrogen production has increased more than other transport fuels, to roughly double (in energy terms).

9.10 Case study "Vector focus: heat"

9.10.1 Description of case study

This case study is intended to explore the effects of a bioenergy strategy emphasising high levels of biogenic heat.

9.10.2 Case study parameterisation

This will be the same as the base case study, with the difference that heat demand to be met is set to a fraction of the total energy demand for in the UK. A series of runs is executed, with minimum fractions of heat production as below.

Note that in the model fractions are intended as multiplicative factors, so they can also be larger than 1.

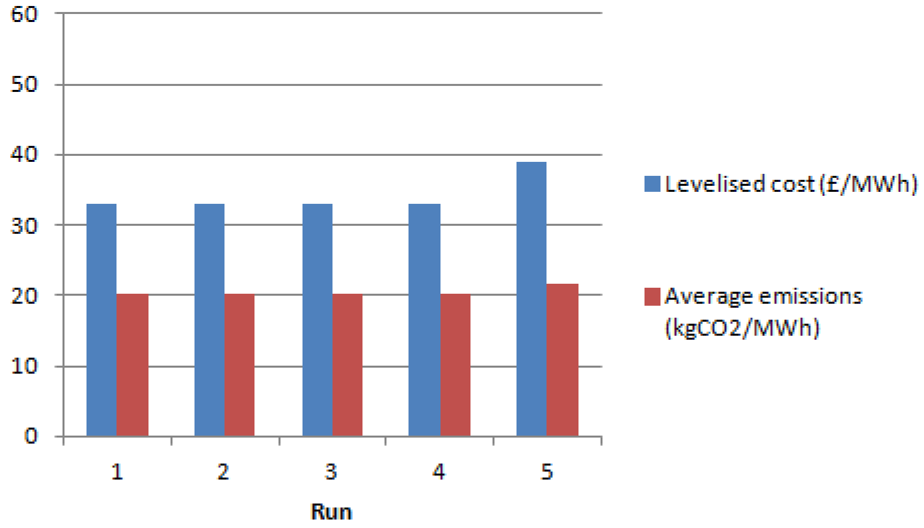
Decade	Minimum Energy Production (TWh)	Minimum Heat Production (as a multiple of minimum energy production)					
	0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
1	70	0.1	0.15	0.2	0.25	0.5	0.75
2	350	0.2	0.3	0.4	0.5	1	1.5
3	860	0.2	0.3	0.4	0.5	1	1.5
4	1440	0.2	0.3	0.4	0.5	1	1.5
5	1800	0.2	0.3	0.4	0.5	1	1.5

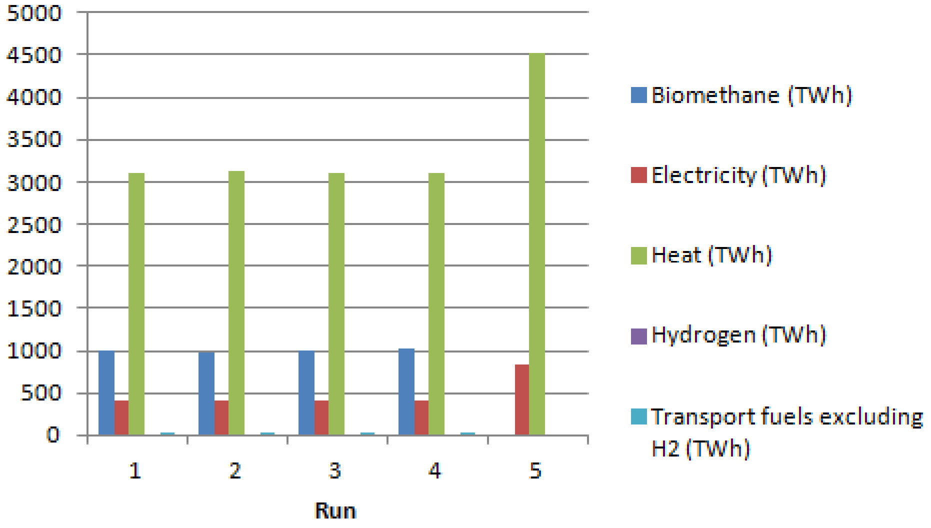
9.10.3 Run series 1 to 6: Minimise costs

Constraints:

- Minimum energy production as above
- Minimum fractions of heat as above

Overall results





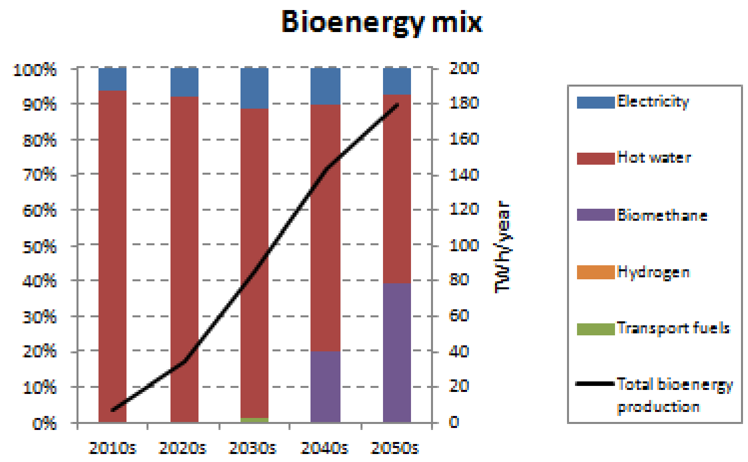
(Run 6 is infeasible.)

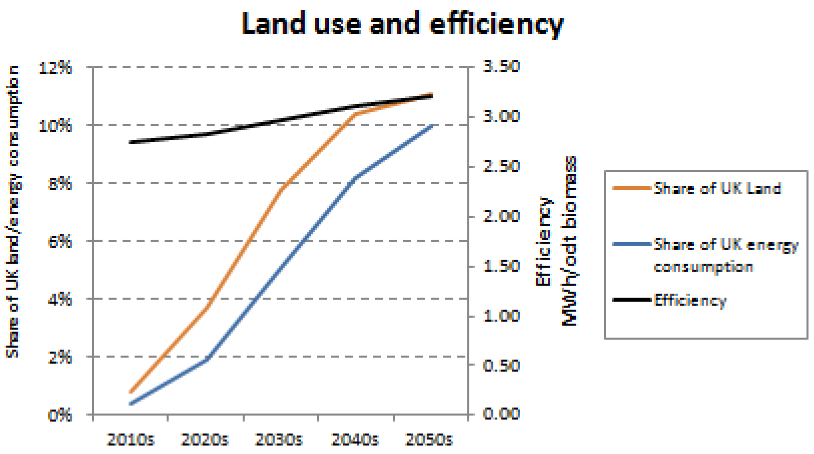
Run results and emerging technologies from representative runs

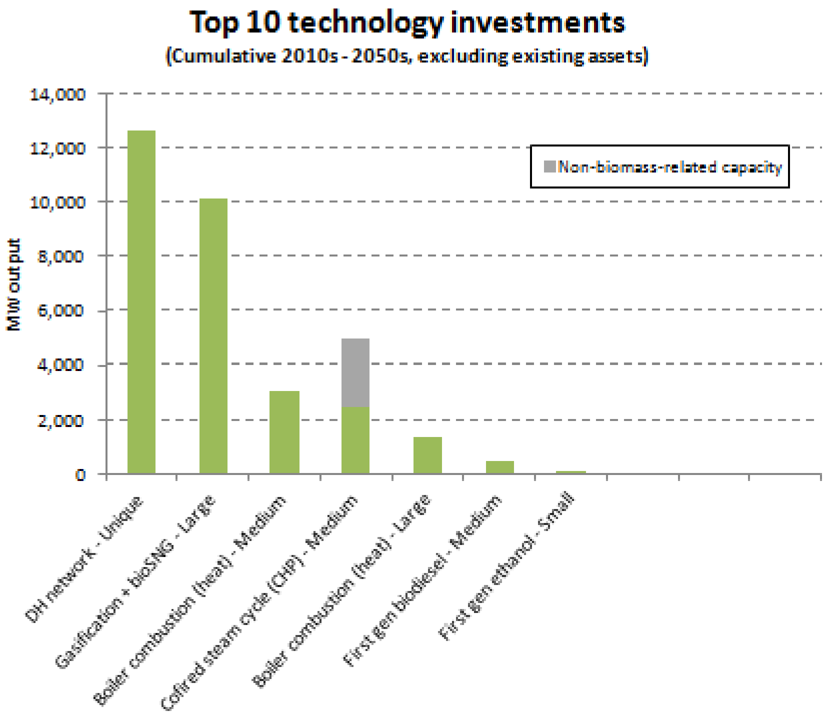
Run 1

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	9	14	13	TWh/year
	Heat	7	32	75	101	96	TWh/year
	Biomethane	0	0	0	29	71	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh
Emissions	System total	1.8391	Mt CO_2/year
	Average	20.34	kgCO_2/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production

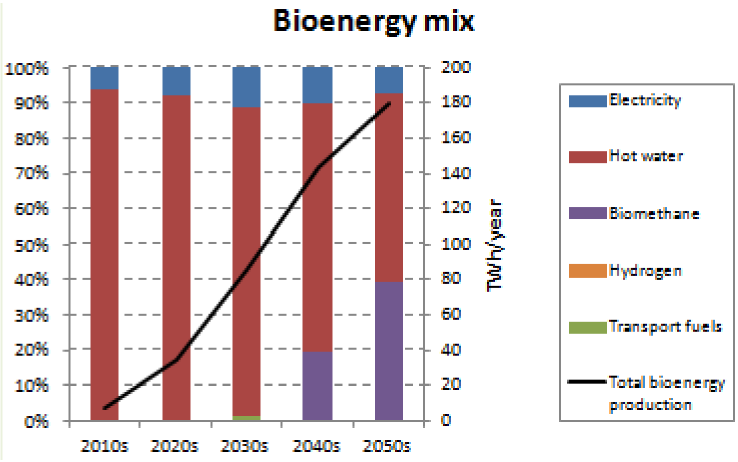

Land use and efficiency
Share of UK land/energy consumption
12%
10%
8%
6%
4%
2%
0%
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency

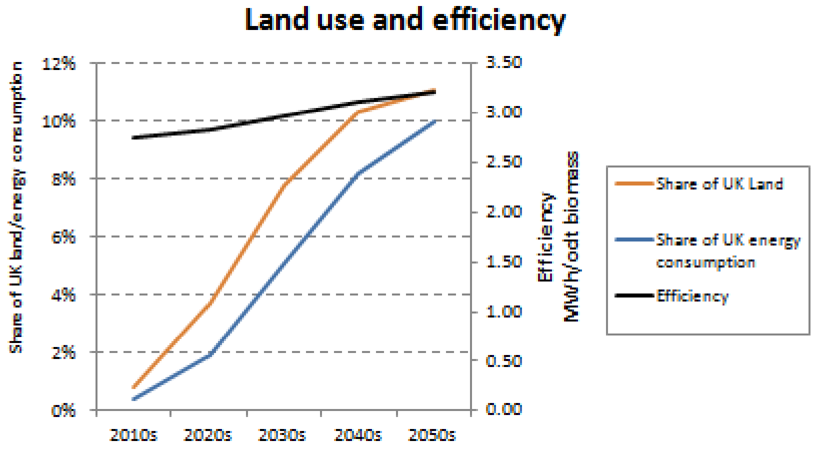

Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
MW output
Non-biomass-related capacity
DH network - Unique
Gasification + bioSNG - Large
Boiler combustion (heat) - Medium
Cofired steam cycle (CHP) - Medium
Boiler combustion (heat) - Large
First gen biodiesel - Medium
First gen ethanol - Small

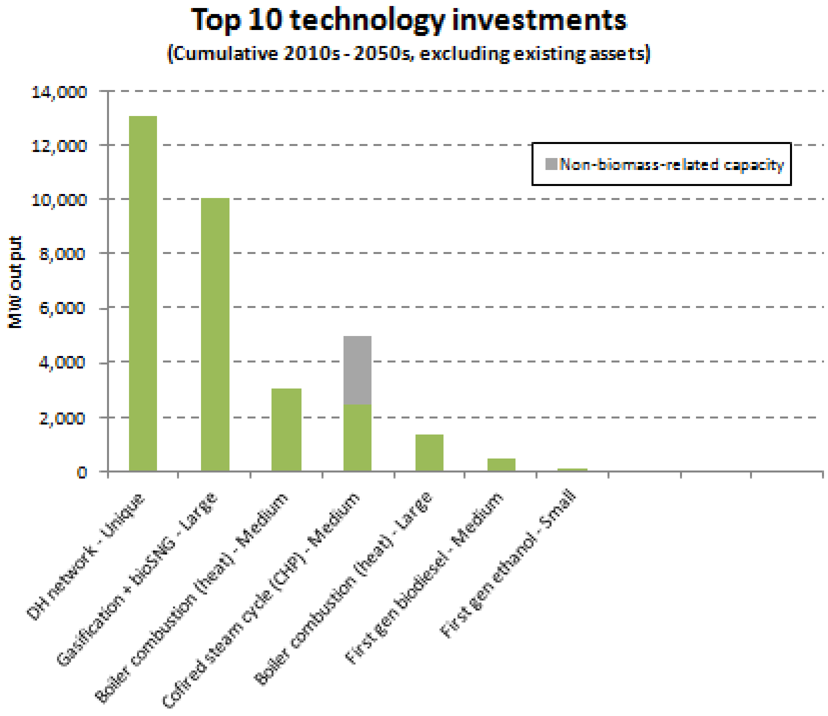
Run 2

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	9	14	13	TWh/year
	Heat	7	32	75	101	96	TWh/year
	Biomethane	0	0	0	28	70	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh
Emissions	System total	1.8390	Mt CO_2/year
	Average	20.34	$kgCO_2$/MWh



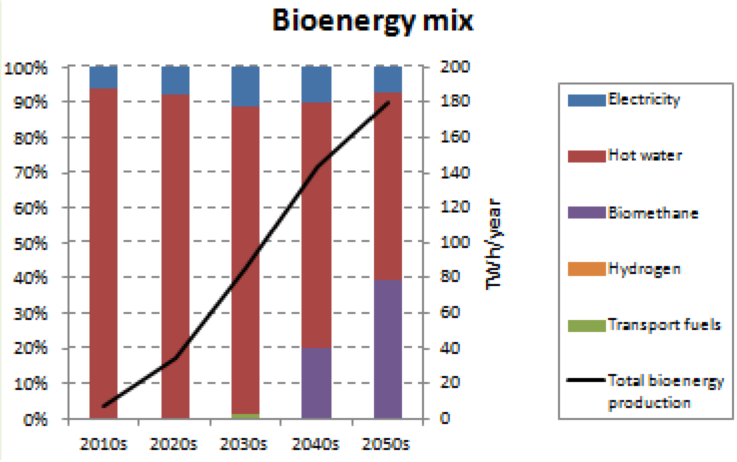


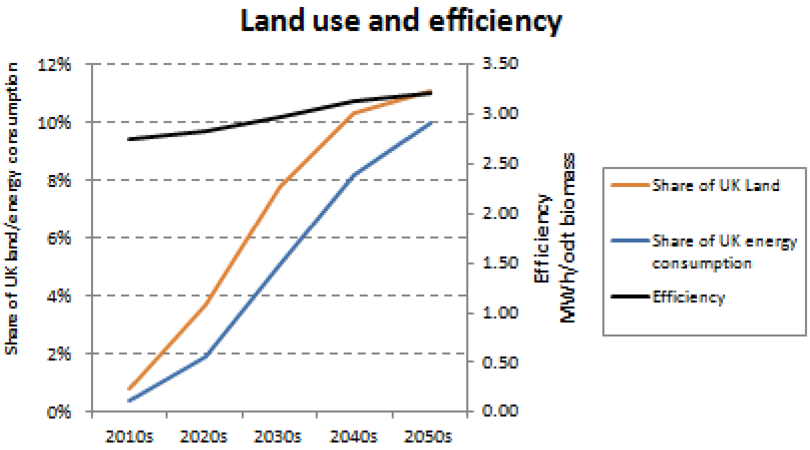


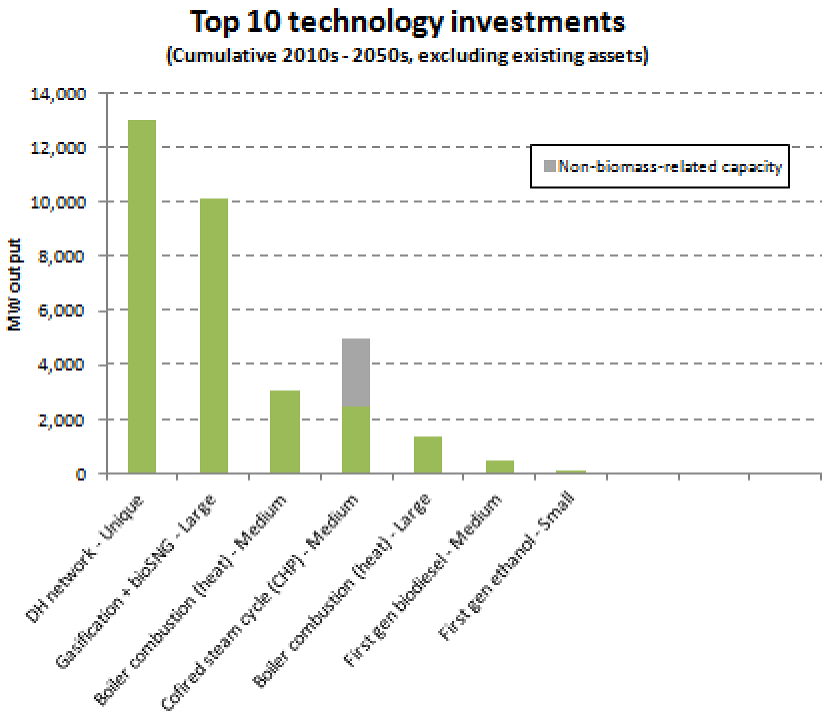
Run 3

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	9	14	13	TWh/year
	Heat	7	32	75	101	96	TWh/year
	Biomethane	0	0	0	29	71	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh
Emissions	System total	1.8394	Mt CO_2/year
	Average	20.35	$kgCO_2$/MWh



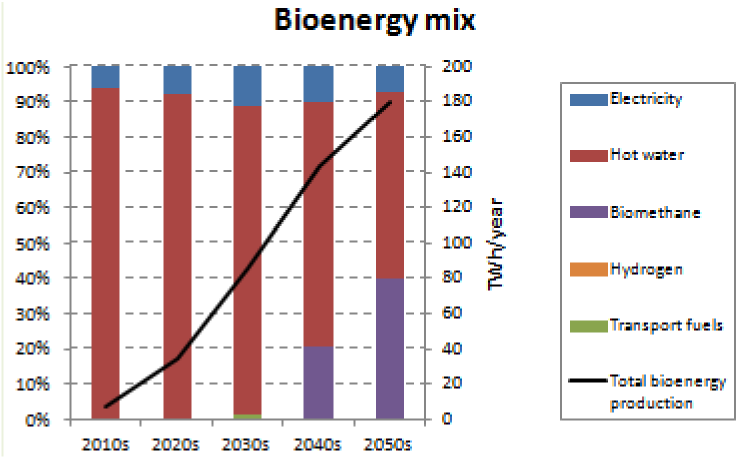


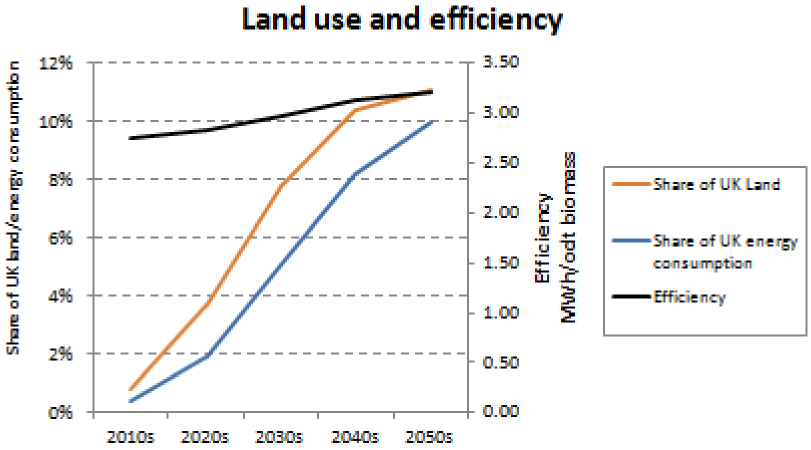


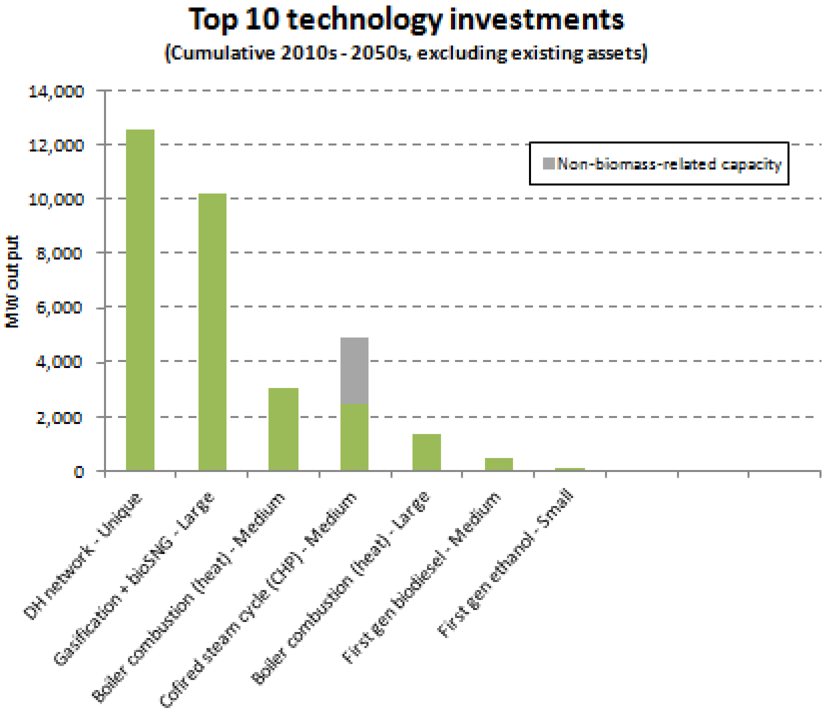
Run 4

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	9	14	13	TWh/year
	Heat	7	32	75	100	95	TWh/year
	Biomethane	0	0	0	30	72	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	9.742	£Bn/decade
	Average	32.9	£/MWh
Emissions	System total	1.8384	Mt CO_2/year
	Average	20.34	$kgCO_2$/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production

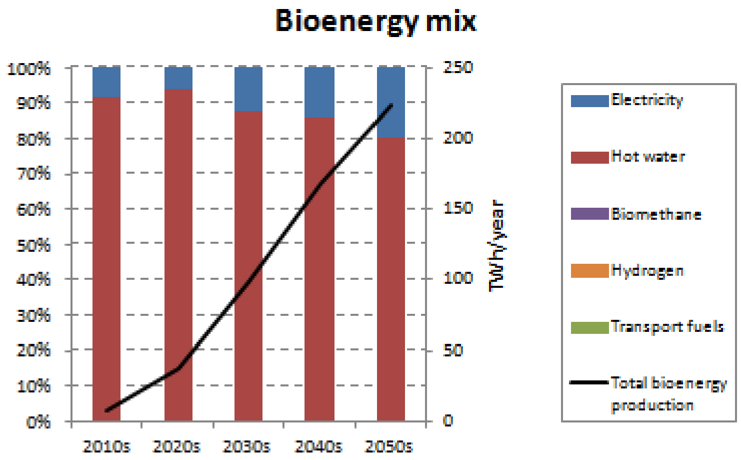

Land use and efficiency
12%
10%
8%
6%
4%
2%
0%
Share of UK land/energy consumption
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency

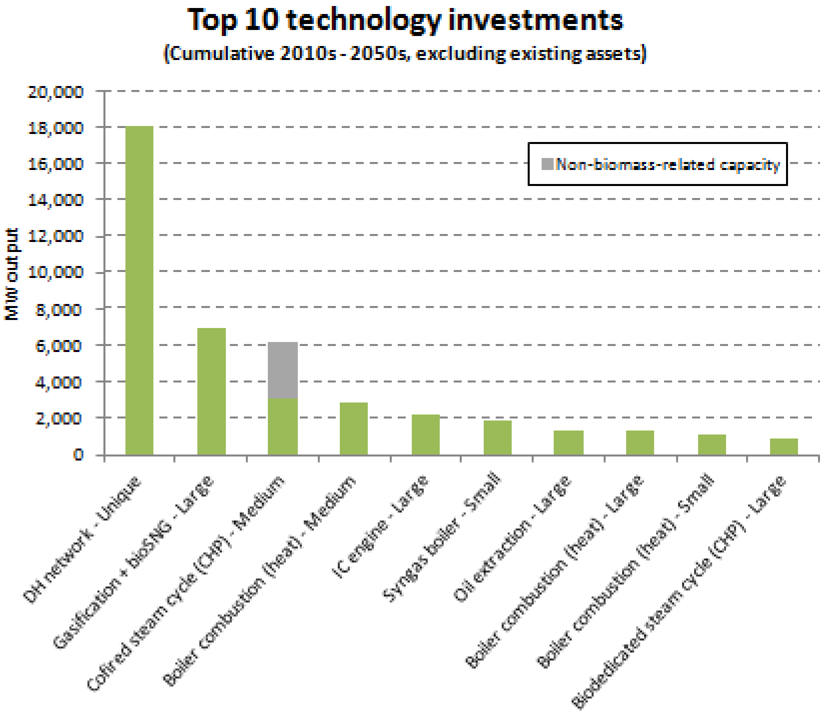

Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
MW output
Non-biomass-related capacity
DH network - Unique
Gasification + bioSNG - Large
Boiler combustion (heat) - Medium
Cofired steam cycle (CHP) - Medium
Boiler combustion (heat) - Large
First gen biodiesel - Medium
First gen ethanol - Small

Run 5

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	37	98	168	224	TWh/year
	Power	1	2	12	24	44	TWh/year
	Heat	6	35	86	144	180	TWh/year
	Biomethane	0	0	0	0	0	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	13.314	£Bn/decade
	Average	38.9	£/MWh
Emissions	System total	2.3173	Mt CO_2/year
	Average	21.70	$kgCO_2$/MWh





9.10.4 Overall case study insights

- When minimising cost, heat production is predominantly used to meet the minimum total energy production constraint. Therefore the first four runs have very similar solutions: the cost-optimal solution is to provide more heat than required in runs 1-4. Only in run 5, where the heat production is equal the minimum total energy, does the cost increase. In run 6, it is not possible to provide 50% more heat than the minimum total energy production requirement.
- In most runs, electricity is produced alongside heat and some biomethane is produced in the last two decades. When heat production finally increases, in run 5, the biomethane production is displaced by it.
- The predominant technologies are Gasification+BioSNG, Boilers, and Cofired Steam Cycle (CHP). When the heat production is forced to increase, in run 5, the CHP technology takes over from boilers as the second most utilised technology. There is also a larger mix of technologies in run 5.

9.11 Case study “Vector focus: biomethane”

9.11.1 Description of case study

This case study is intended to explore the effects of a bioenergy strategy emphasising high levels of biomethane[26].

9.11.2 Case study parameterisation

This will be the same as the base case study, with the difference that transport-fuel demand to be met is set to a fraction of the total energy demand for in the UK. A series of runs is executed, with minimum fractions of biomethane production as below.

Note that in the model fractions are intended as multiplicative factors, so they can also be large than 1.

Decade	**Minimum Energy Production (TWh)**	**Minimum Biomethane Production (as a fraction of minimum total energy production)**					
	0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
1	70	0.1	0.15	0.2	0.25	0.5	0.75
2	350	0.2	0.3	0.4	0.5	1	1.5
3	860	0.2	0.3	0.4	0.5	1	1.5
4	1440	0.2	0.3	0.4	0.5	1	1.5
5	1800	0.2	0.3	0.4	0.5	1	1.5

9.11.3 Run series 1 to 6: Minimise costs

Constraints:

- Minimum energy production as above
- Minimum fractions of biomethane (as BioSNG) as above

Overall results

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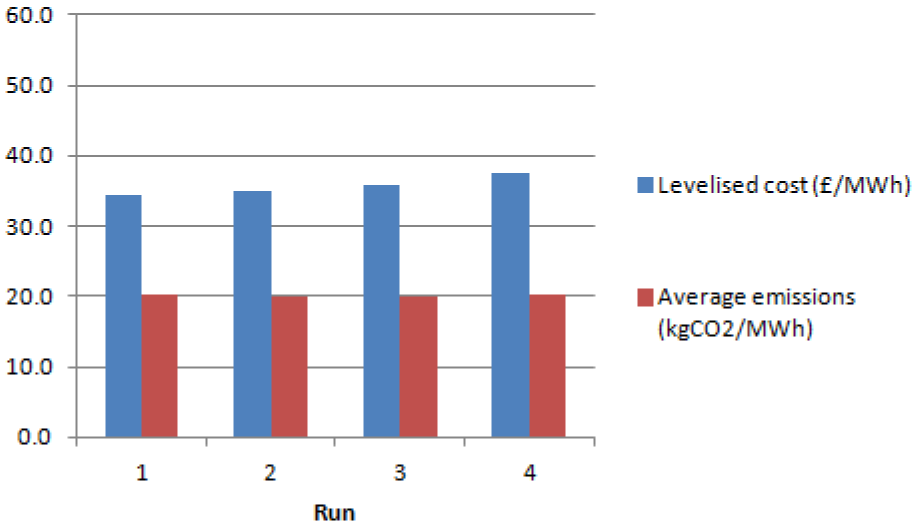
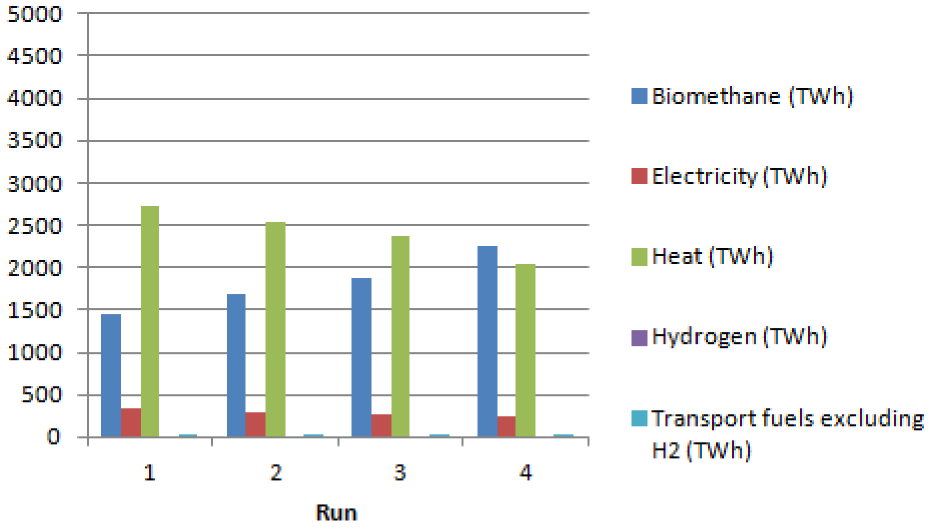
[26] In this case study, as In the rest of the report, biomethane is to be intended as biogenic synthetic natural gas (bioSNG). No anaerobic digestion technologies are included in the current model, but will included in Phase 2.





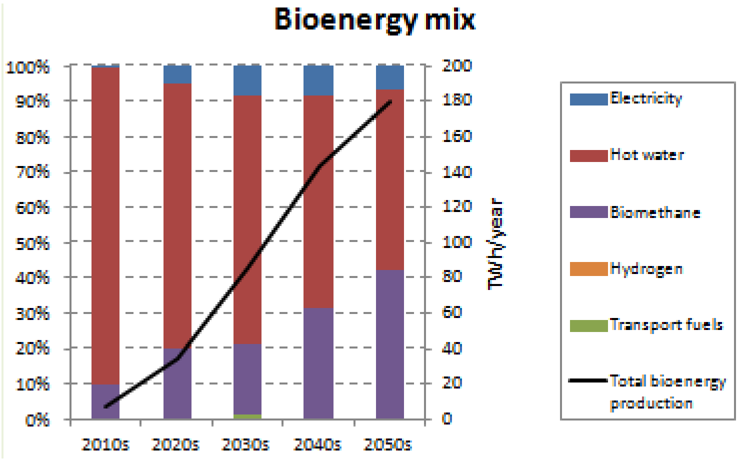
(Runs 5 and 6 are infeasible.)

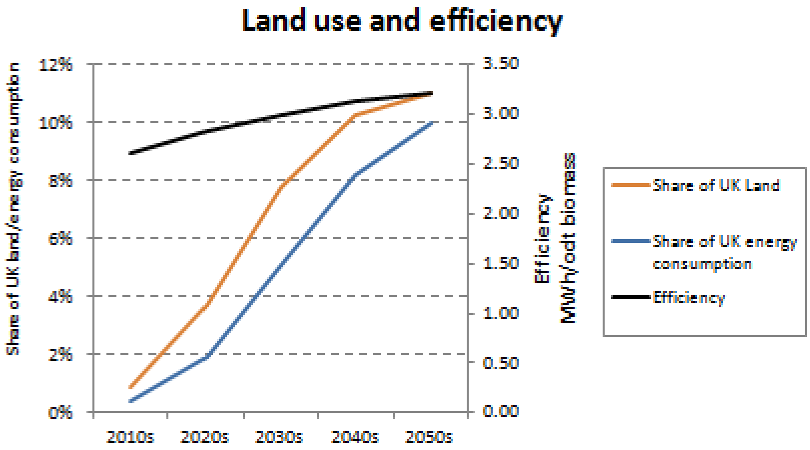
Run results and emerging technologies from representative runs

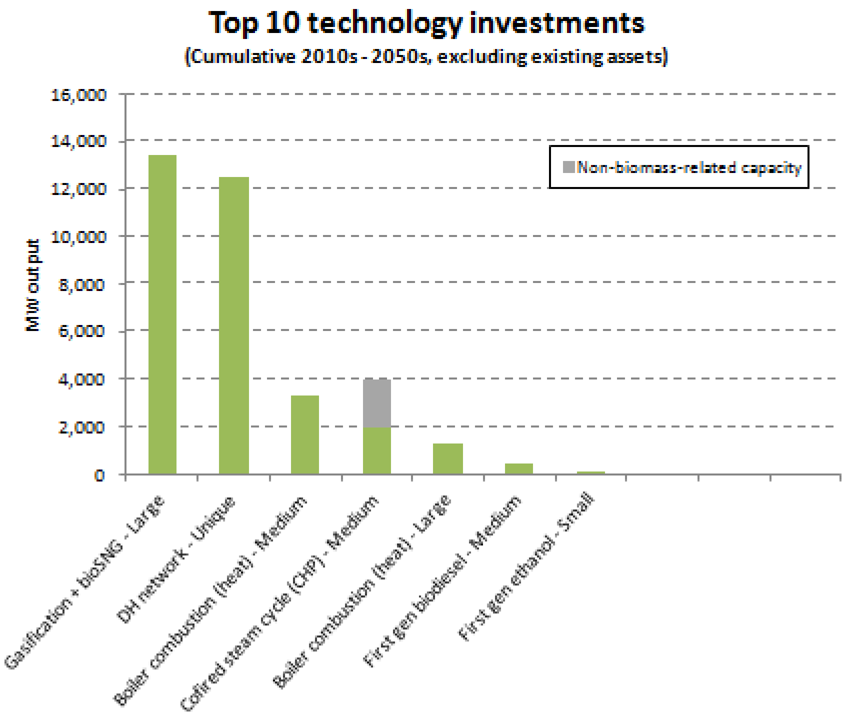
Run 1

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	2	7	12	12	TWh/year
	Heat	6	26	61	87	91	TWh/year
	Biomethane	1	7	17	45	76	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	10.138	£Bn/decade
	Average	34.3	£/MWh
Emissions	System total	1.8201	Mt CO_2/year
	Average	20.13	$kgCO_2$/MWh



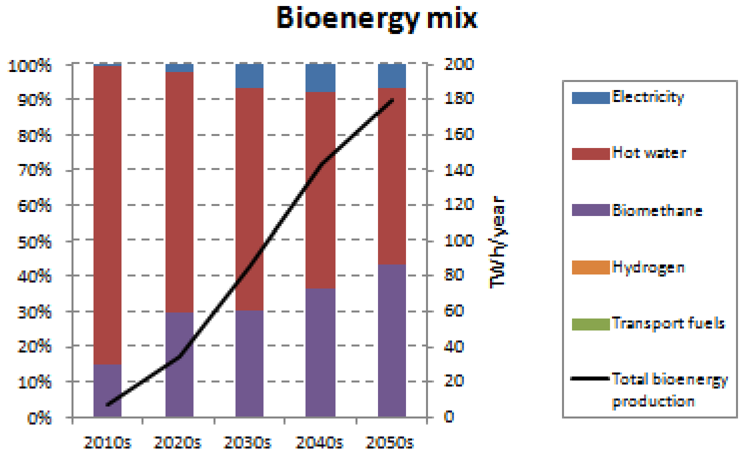


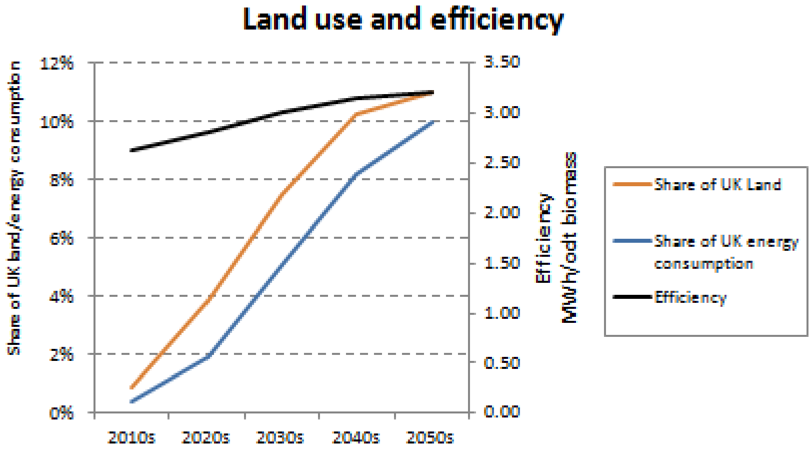


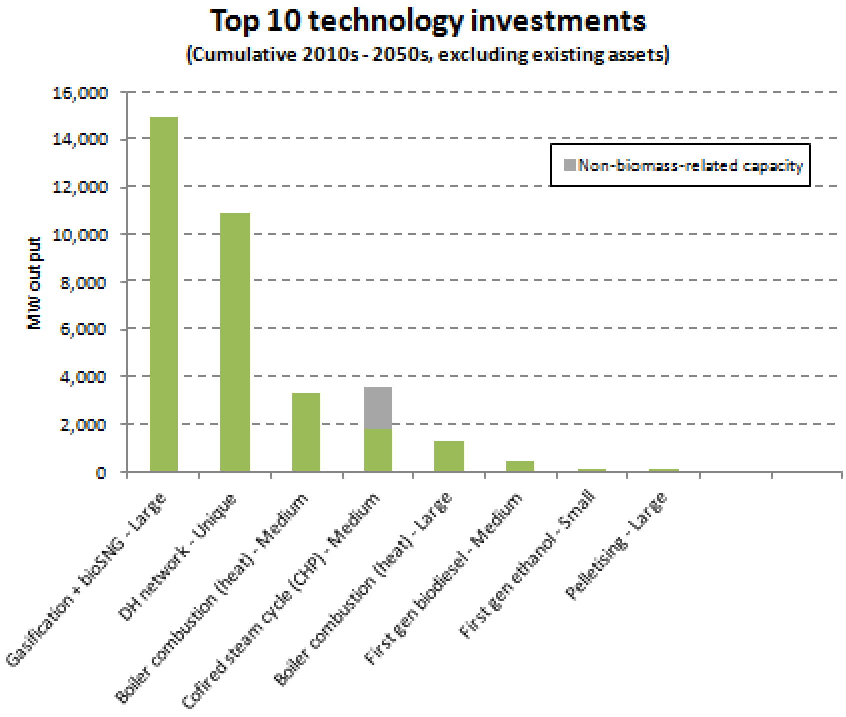
Run 2

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	1	6	11	12	TWh/year
	Heat	6	24	54	81	90	TWh/year
	Biomethane	1	10	26	52	78	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		2010-2059	Unit
Costs	System total	10.338	£Bn/decade
	Average	35.0	£/MWh
Emissions	System total	1.7979	Mt CO_2/year
	Average	19.89	kgCO_2/MWh


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
200
180
160
140
120
100
80
60
40
20
0
TWh/year
2010s
2020s
2030s
2040s
2050s
Electricity
Hot water
Biomethane
Hydrogen
Transport fuels
Total bioenergy production

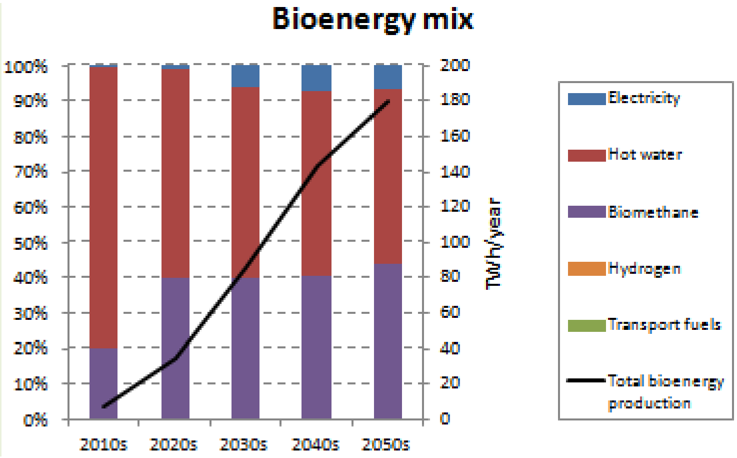

Land use and efficiency
Share of UK land/energy consumption
12%
10%
8%
6%
4%
2%
0%
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Efficiency MWh/odt biomass
2010s
2020s
2030s
2040s
2050s
Share of UK Land
Share of UK energy consumption
Efficiency

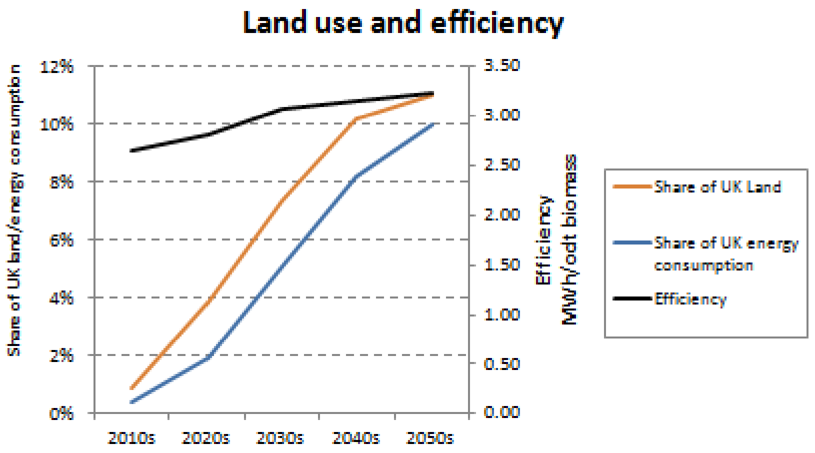

Top 10 technology investments
(Cumulative 2010s - 2050s, excluding existing assets)
MW output
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Non-biomass-related capacity
Gasification + bioSNG - Large
DH network - Unique
Boiler combustion (heat) - Medium
Cofired steam cycle (CHP) - Medium
Boiler combustion (heat) - Large
First gen biodiesel - Medium
First gen ethanol - Small
Pelletising - Large

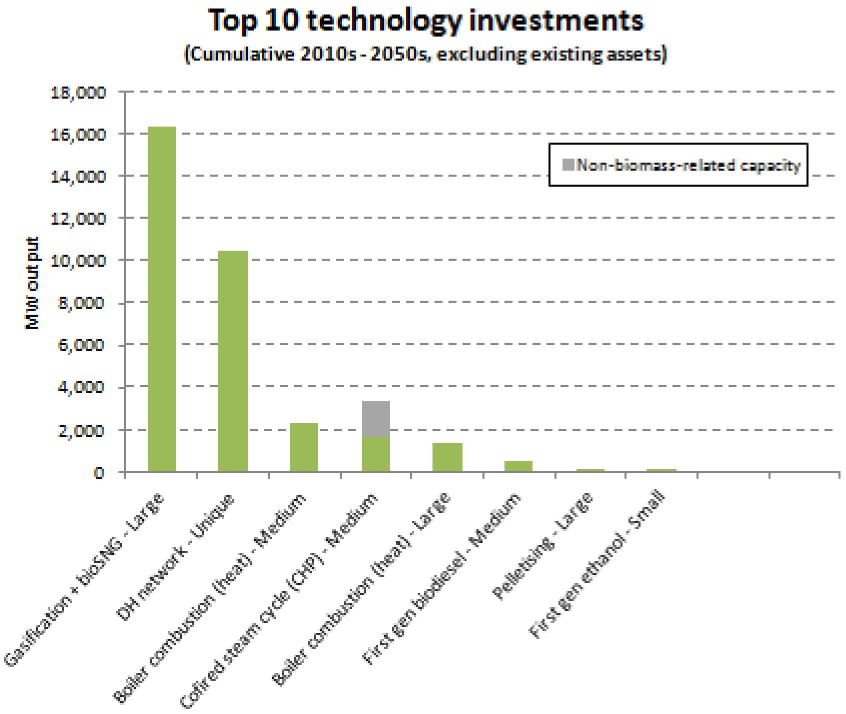
Run 3

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	0	5	10	12	TWh/year
	Heat	6	21	46	75	89	TWh/year
	Biomethane	1	14	34	59	79	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	10.610	£Bn/decade
	Average	35.9	£/MWh
Emissions	System total	1.8149	Mt CO_2/year
	Average	20.08	$kgCO_2$/MWh



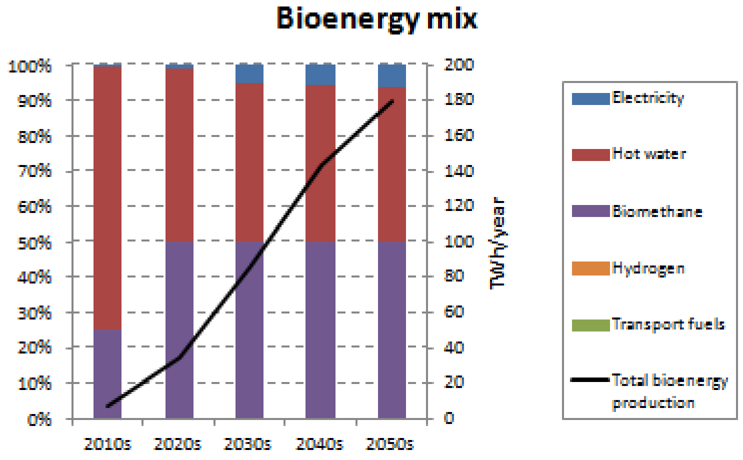


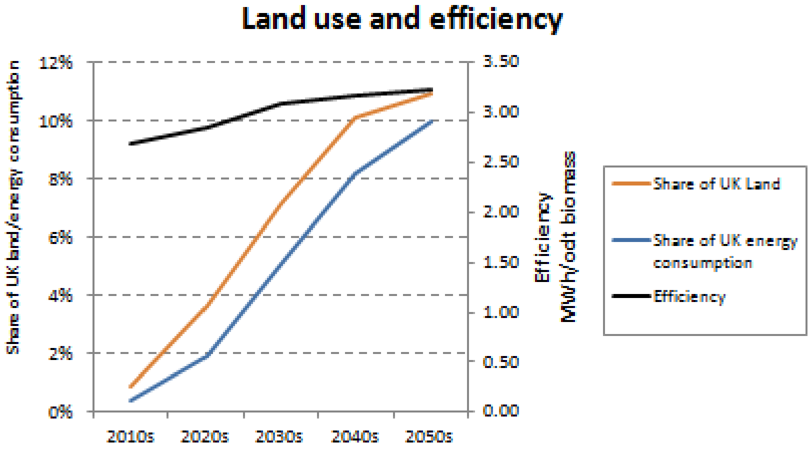


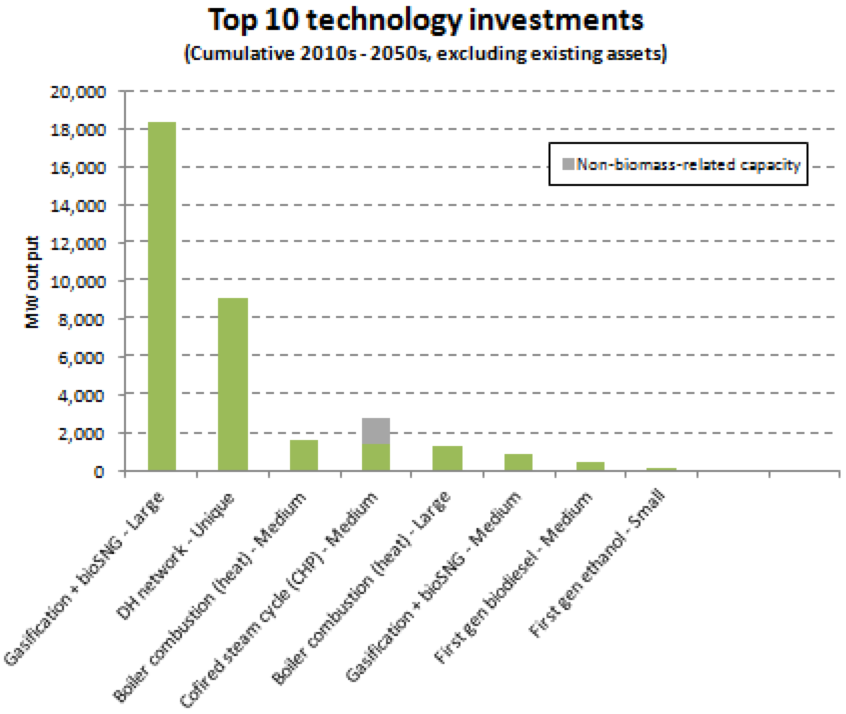
Run 4

Item		**2010s**	**2020s**	**2030s**	**2040s**	**2050s**	**Unit**
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	0	4	8	10	TWh/year
	Heat	5	17	39	64	79	TWh/year
	Biomethane	2	17	43	72	90	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	11.084	£Bn/decade
	Average	37.5	£/MWh
Emissions	System total	1.8264	Mt CO_2/year
	Average	20.20	$kgCO_2$/MWh







9.11.4 Overall case study insights

- Only heat is phased out in favour of biomethane (as BioSNG) in this study; electricity production remains fairly constant.
- Biomethane is much harder to produce than the other energy vectors in these “focus” studies: when the demand is increased to be equal to the total minimum production (case 4) it is no longer possible to produce enough. This indicates that biomethane production is limited by technology build rate.
- Since the focus is on biomethane, the most dominant technology is BioSNG.

9.12 Case study “Policy driven”

9.12.1 Description of case study

This would be the same as the base case study with the following differences: instead of increasing energy targets by decade, there will be either one target in 2050 or two targets in 2020 and 2050.

9.12.2 Description of case study

In the first run, we consider that 10% of UK energy demand in 2050 has to be met by bioenergy, with no other targets in the previous decades.

In the second run, in addition to the 2050 target, we consider 2020 targets in line with existing policy settings, i.e:

- 5% of road transport fuel by volume (based on the RTFO obligation), which equates to 21.55 TWh
- 41 TWh of electricity from biomass, as set out in the UK Renewable energy roadmap by DECC in 2011[27]
- 67 TWh of heat from biomass, based on the Renewable Heat Incentive Impact Assessment by DECC in 2011[28]

9.12.3 Run 1: Minimise costs, 2050 target only

Constraints:

- As in Base case, with180 TWh energy target from biomass in 2050 only

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	0	0	0	0	180	TWh/year
	Power	0	0	0	0	10	TWh/year
	Heat	0	0	0	0	74	TWh/year
	Biomethane	0	0	0	0	42	TWh/year
	Hydrogen	0	0	0	0	51	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

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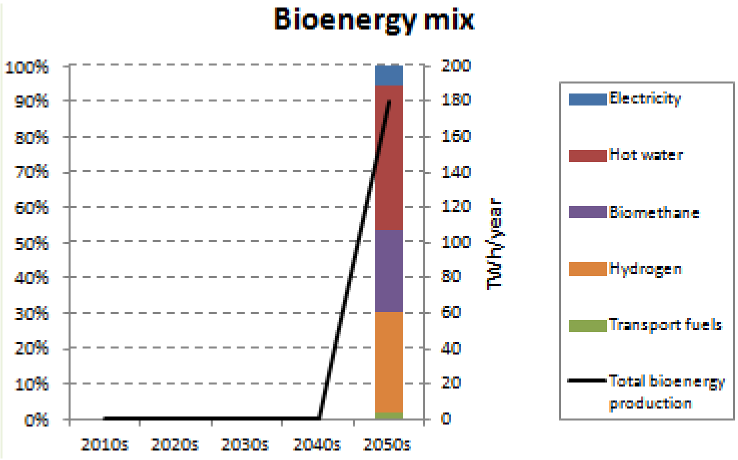
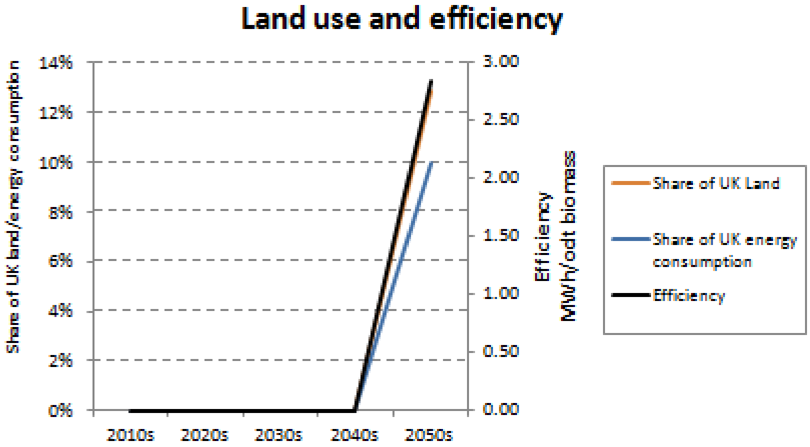
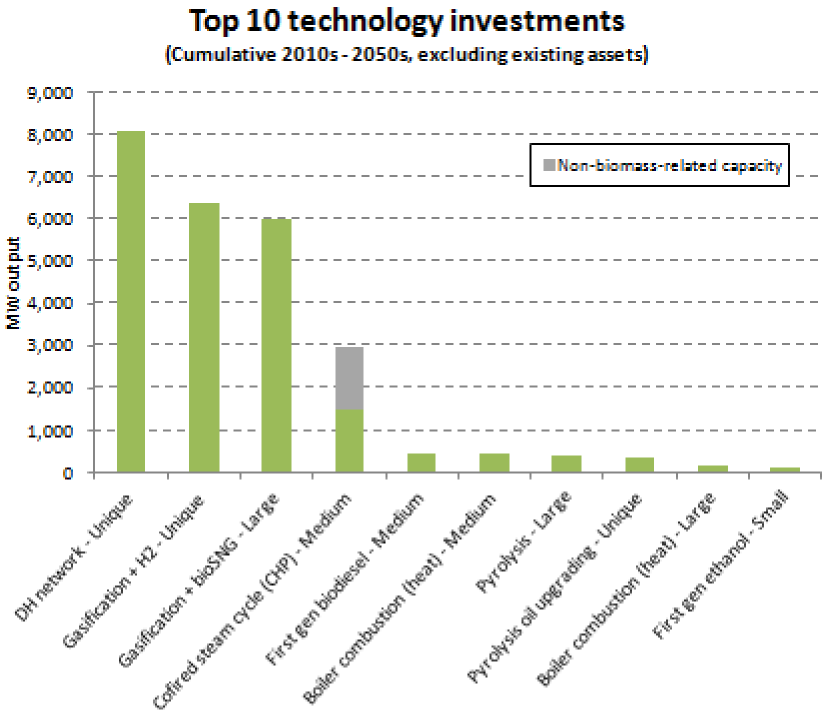
[27] Average between 32 and 50 TWh, page 14 http://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/renewable-energy/2167-uk-renewable-energy-roadmap.pdf

[28] Page 9, http://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/renewable-energy/3775-renewable-heat-incentive-impact-assessment-dec-20.pdf

Item		2010-2059	Unit
Costs	System total	5.954	£Bn/decade
	Average	76.1	£/MWh
Emissions	System total	0.8211	Mt CO_2/year
	Average	22.81	kgCO_2/MWh







9.12.4 Run 2: Minimise costs, 2020 and 2050 targets only

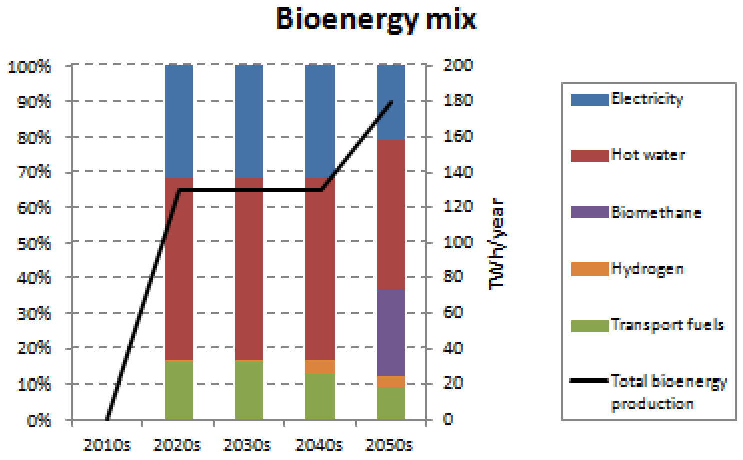
Constraints:

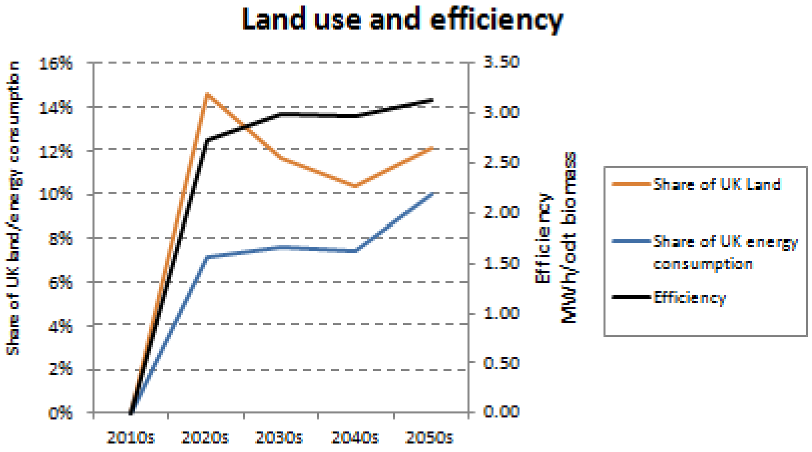
- As in base case, but
  - 2050 target: 180 TWh energy from biomass
  - 2020 target: 21.55 TWh for transport, 41 TWh for electricity and 67 TWh for heat from biomass. It is assumed that the 2020 target remains in place till 2050s.

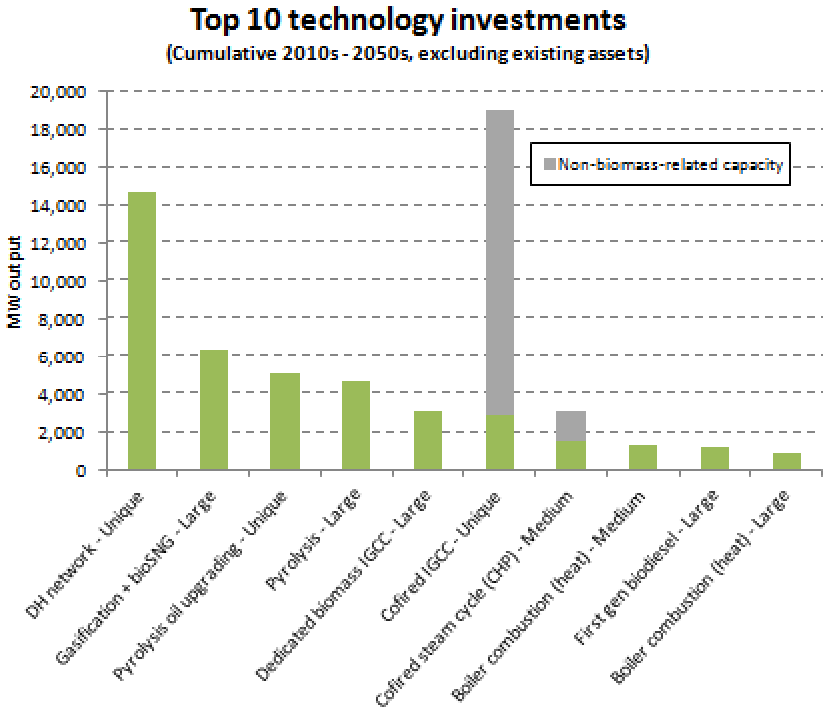
Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	0	130	130	130	180	TWh/year
	Power	0	41	41	41	37	TWh/year
	Heat	0	67	67	67	77	TWh/year
	Biomethane	0	0	0	0	44	TWh/year
	Hydrogen	0	0	0	5	5	TWh/year
	Transport fuels	0	2	2	2	2	MLge/year

Item		**2010-2059**	**Unit**
Costs	System total	16.168	£Bn/decade
	Average	37.8	£/MWh
Emissions	System total	3.4927	Mt CO_2/year
	Average	30.72	$kgCO_2$/MWh







9.12.5 Overall insights from case study

- bioenergy targets by decade matter, if cumulative emissions savings from 2010 to 2050 need to be achieved.
- a target of 10% energy from biomass in 2050 can be met even if no biomass technology is deployed in 2010 and 2020, assuming that costs reductions and efficiency improvements in the 2010-2020 period are achieved nonetheless. However, realistically, inaction in 2010 and 2020 will have impacts on final bioenergy targets.

9.13 Case study "Land constraint"

9.13.1 Description of case study

This case study is intended to explore the impact of land constraints on the optimal provision of energy/GHG reduction.

9.13.2 Case study parameterisation

This will be the same as the Base case study with the following differences: the Land constraint will be successively changed from Level 4 (most optimistic) to Level 3, Level 2, and Level 1 (most pessimistic).

All other parameters are the same as those used for the base case, including the agricultural land set aside for food production (4.6 million hectares).

9.13.3 Run 1: Minimise costs, 10% UK 2050 energy demand, Level 3 land only

Constraints:

- Only Level 3 allowed

Main results

Item		**2010-2059**	**Unit**
Costs	System total	9.746	£Bn/decade
	Average	33.0	£/MWh
Emissions	System total	1.8487	Mt CO_2/year
	Average	20.45	kgCO_2/MWh

9.13.4 Run 2: Minimise costs, 10% UK 2050 energy demand, Level 2 land only

Constraints:

- Only Level 2 allowed

Main results

Item		**2010-2059**	**Unit**
Costs	System total	9.896	£Bn/decade
	Average	33.5	£/MWh
Emissions	System total	1.9246	Mt CO_2/year
	Average	21.29	kgCO_2/MWh

9.13.5 Run 3: Minimise costs, 10% UK 2050 energy demand, Level 1 land only

Constraints:

- Only Level 1 allowed

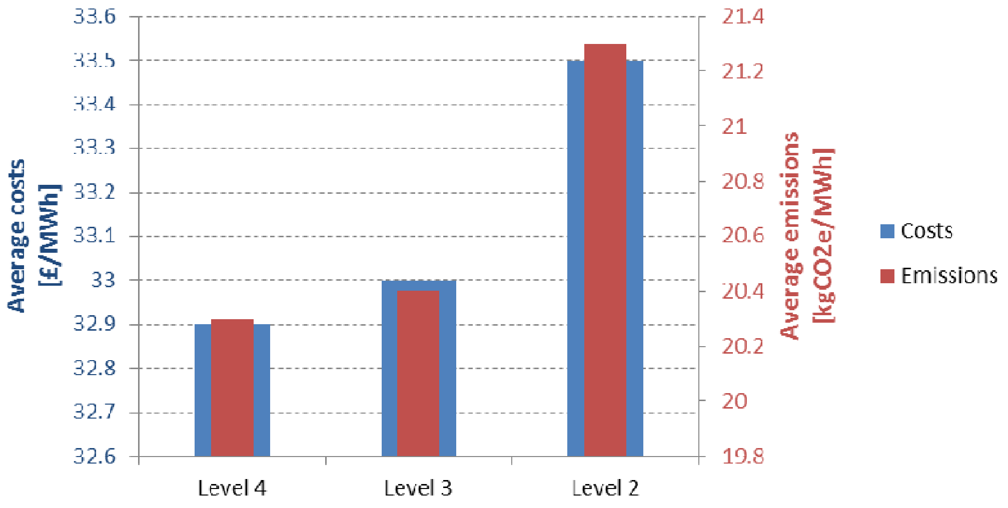
Main results

Run is infeasible.

9.13.6 Overall insights from case study

When increasing land constraint is applied:

- there is no major change in terms of resources and technologies selected in relation to the base case.
- costs and emissions increase with increasing land constraints (see below), but changes are relatively small
- There is not enough Level 1 land, in addition to that already used for food production, to meet the target of 10% of UK 2050 energy demand by bioenergy.



9.14 Case study "Food priority"

9.14.1 Description of case study

This case study is intended to explore the impact of prioritising domestic food production over energy production on the optimal provision of energy/GHG reduction.

9.14.2 Case study parameterisation

In this case study, all Level 1 land (i.e. arable land) is set aside to produce food.

All other parameters are the same as those used for the base case.

9.14.3 Run 1: Minimise costs, 10% UK 2050 demand

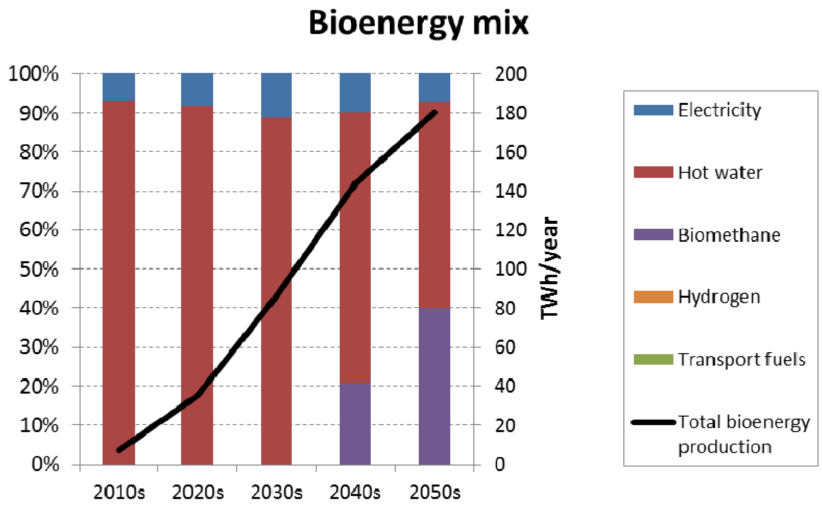
Constraints:

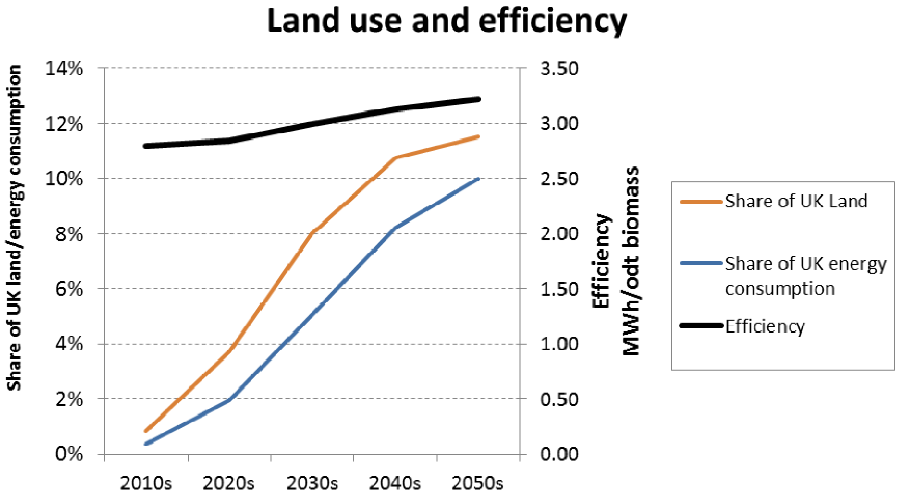
- No Level 1 land available

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	7	35	86	144	180	TWh/year
	Power	0	3	10	14	13	TWh/year
	Heat	7	32	76	100	95	TWh/year
	Biomethane	0	0	0	30	72	TWh/year
	Hydrogen	0	0	0	0	0	TWh/year
	Transport fuels	0	0	0	0	0	MLge/year

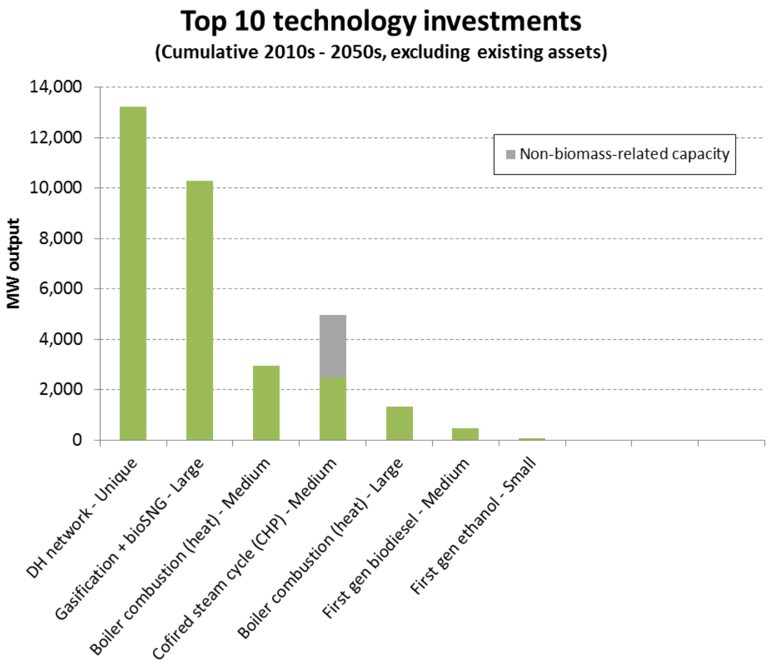
Item		2010-2059	Unit
Costs	System total	9.761	£Bn/decade
	Average	33.0	£/MWh
Emissions	System total	1.8374	Mt CO_2/year
	Average	20.33	kgCO_2/MWh





Emerging Technologies and Insights from the Run

- No significant variation from the corresponding base case occurs.



9.14.4 Run 2: Minimise costs, 20% UK 2050 demand

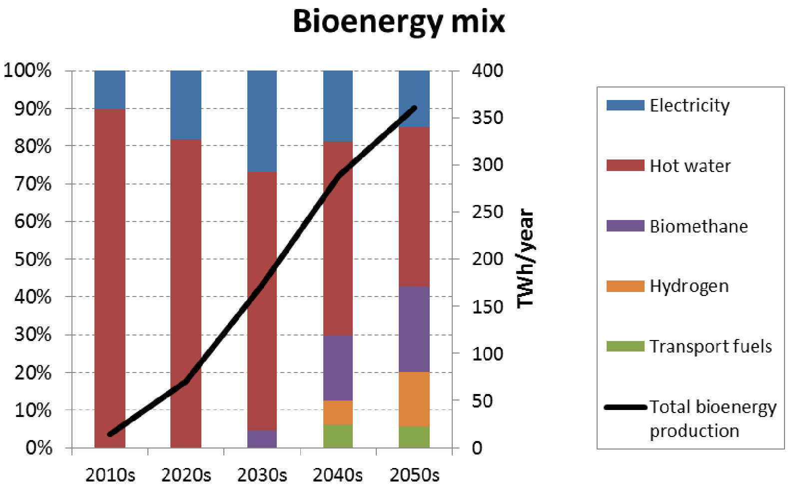
Constraints:

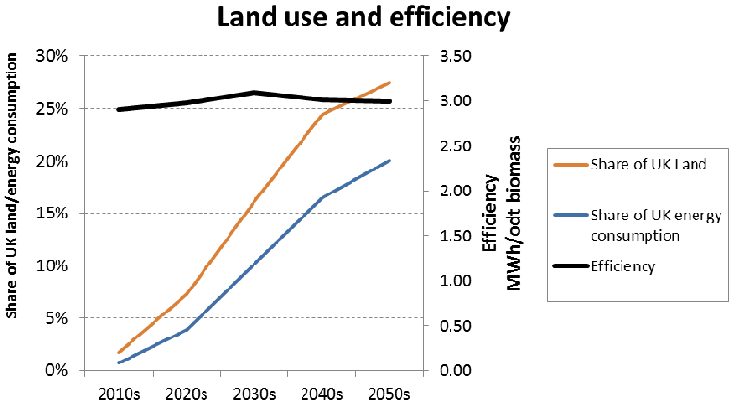
- As previous run, with double the demand of energy to be met

Main results

Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total	14	70	172	288	360	TWh/year
	Power	1	13	46	54	54	TWh/year
	Heat	13	57	118	148	152	TWh/year
	Biomethane	0	0	8	50	82	TWh/year
	Hydrogen	0	0	0	18	52	TWh/year
	Transport fuels	0.0	0.0	0.0	2.0	2.2	MLge/year

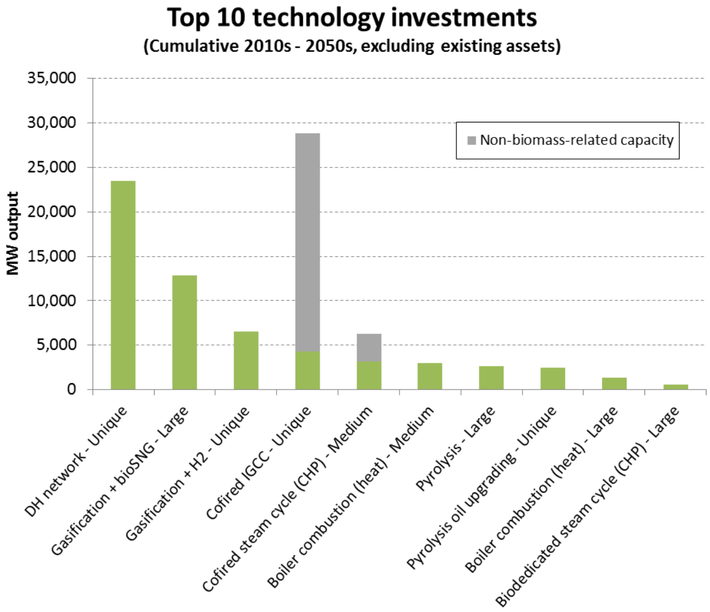
Item		2010-2059	Unit
Costs	System total	21.572	£Bn/decade
	Average	36.5	£/MWh
Emissions	System total	4.5037	Mt CO_2/year
	Average	24.91	$kgCO_2$/MWh





Main results

- No significant variation from the corresponding base case occurs.



10 Appendix 2 – Land cover

10.1 CORINE Land Cover definitions

Level 1

- **2.1 Arable land**
  Cultivated areas regularly ploughed and generally under a rotation system.
  - *2.1.1. Non-irrigated arable land*
    Cereals, legumes, fodder crops, root crops and fallow land. Includes flower and tree (nurseries) cultivation and vegetables, whether open field, under plastic or glass (includes market gardening). Includes aromatic, medicinal and culinary plants. Excludes permanent pastures.
  - *2.1.2. Permanently irrigated land*
    Crops irrigated permanently and periodically, using a permanent infrastructure (irrigation channels, drainage network). Most of these crops could not be cultivated without an artificial water supply. Does not include sporadically irrigated land.
  - *2.1.3. Rice fields*
    Land developed for rice cultivation. Flat surfaces with irrigation channels. Surfaces regularly flooded.
- **2.4 Heterogeneous agricultural areas**
  - *2.4.1. Annual crops associated with permanent crops*
    Non-permanent crops (arable lands or pasture) associated with permanent crops on the same parcel.
  - *2.4.2. Complex cultivation*
    Juxtaposition of small parcels of diverse annual crops, pasture and/or permanent crops.
  - *2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation*
    Areas principally occupied by agriculture, interspersed with significant natural areas.
  - *2.4.4. Agro-forestry areas*
    Annual crops or grazing land under the wooded cover of forestry species.

Level 2

As Level 1, plus:

- **3.2 Shrub and/or herbaceous vegetation association**
  - *3.2.1. Natural grassland*
    Low productivity grassland. Often situated in areas of rough uneven ground. Frequently includes rocky areas, briars, and heathland.
  - *3.2.2. Moors and heathland*

Vegetation with low and closed cover, dominated by bushes, shrubs and herbaceous plants (heath, briars, broom, gorse, laburnum, etc.).

- *3.2.3. Sclerophyllous vegetation*
  Bushy sclerophyllous vegetation. Includes maquis and garrige.
  Maquis: a dense vegetation association composed of numerous shrubs associated with siliceous soils in the Mediterranean environment.
  Garrigue: discontinuous bushy associations of Mediterranean calcareous plateaus. Generally composed of kermes oak, arbutus, lavender, thyme, cistus, etc. May include a few isolated trees.

- *3.2.4. Transitional woodland/shrub*
  Bushy or herbaceous vegetation with scattered trees. Can represent either woodland degradation or forest regeneration/colonisation.

- **3.3 Open spaces with little or no vegetation**
  - *3.3.1. Beaches, dunes, and sand plains*
    Beaches, dunes and expanses of sand or pebbles in coastal or continental , including beds of stream channels with torrential regime.
  - *3.3.2. Bare rock*
    Scree, cliffs, rocks and outcrops.
  - *3.3.3. Sparsely vegetated areas*
    Includes steppes, tundra and badlands. Scattered high-attitude vegetation.
  - *3.3.4. Burnt areas*
    Areas affected by recent fires, still mainly black.
  - *3.3.5.Glaciers and perpetual snow*
    Land covered by glaciers or permanent snowfields.

Level 3

As Level 2, plus:

- **2.2 Permanent crops**
  Crops not under a rotation system which provide repeated harvests and occupy the land for a long period before it is ploughed and replanted: mainly plantations of woody crops. Excludes pastures, grazing lands and forests.
  - *2.2.1. Vineyards*
    Areas planted with vines.
  - *2.2.2. Fruit trees and berry plantations*
    Parcels planted with fruit trees or shrubs: single or mixed fruit species, fruit trees associated with permanently grassed surfaces. Includes chestnut and walnut groves.
  - *2.2.3. Olive groves*

Areas planted with olive trees, including mixed occurrence of olive trees and vines on the same parcel.

- **2.3 Pastures**
    - *2.3.1. Pastures*
      Dense, predominantly graminoid grass cover, of floral composition, not under a rotation system. Mainly used for grazing, but the fodder may be harvested mechanically. Includes areas with hedges (bocage).

Level 4

As Level 3, plus:

- **3.1 Forests**
    - *3.1.1. Broad-leaved forest*
      Vegetation formation composed principally of trees, including shrub and bush understories, where broadleaved species predominate.
    - *3.1.2. Coniferous forest*
      Vegetation formation composed principally of trees, including shrub and bush understories, where coniferous species predominate.
    - *3.1.3. Mixed forest*
      Vegetation formation composed principally of trees, including shrub and bush understories, where broadleaved and coniferous species co~dominate.

- **1.4 Artificial non-agricultural vegetated areas**
    - *1.4.1. Green urban areas*
      Areas with vegetation within urban fabric. Includes parks and cemeteries with vegetation.
    - *1.4.2. Sport and leisure facilities*
      Camping grounds, sports grounds, leisure parks, golf courses, racecourses, etc. Includes formal parks not surrounded by urban zones.

10.2 Amount of land

The amounts corresponding to each level of land are summarised in Table 10-1.

Level of land use	Amount [Mha]	Increase from previous level [Mha]	Share of total UK land
1	7.6	n/a	31%
2	13.2	5.5	54%
3	20.0	6.8	82%
4	22.3	2.3	92%

Table 10-1 Land levels

11 Appendix 3: Technology status and innovation needs

This section builds on the technology status and barrier analyses carried out in WP3 and it is intended to outline the innovation needed to ensure deployment.

For each technology or technology chain, information is provided about:

- technical innovations required
- cost, scale and efficiency targets.

11.1 Pyrolysis oil upgrading

11.1.1 Technology overview

Crude pyrolysis oil, also called ‘bio-oil’, is a dark brown viscous liquid. It contains a complex mixture of oxygenated hydrocarbons, water, and potentially solid char particles. The crude oil can be used in some applications without further treatment. However, for others, including advanced boiler systems, industrial gas turbines, or combined cycle systems and for transport fuels, further processing is needed. Primary objectives of the upgrading processes are to remove the oxygen present in the oil and to crack and isomerize the longer hydrocarbon chains to yield the required fuel characteristics. Upgrading can be divided into three main routes: gasification, hydrotreating, and zeolite cracking.

If the oil is gasified, the resulting syngas can serve as a feedstock for processes of fuel synthesis from syngas. Under zeolite cracking, oxygen is removed through cracking in either liquid or vapour phase. Unfortunately, pyrolysis oils tend to coke easily in this process. Much of the work on upgrading of pyrolysis oils is therefore focused on hydrotreating where the oil is exposed to hydrogen and a catalyst under high temperature and pressure.

11.1.2 Current status

This upgrading process is still in development (TRL 4) with significant problems with catalyst life being reported. There are a relatively large number of companies and research institutions conducting work in the area of pyrolysis oil upgrading research. However, most of the research is still at bench or small scale, with the most advanced of this work now moving into pilot scale demonstration (TRL 4).

11.1.3 Required innovation

- Co-processing of pyrolysis oil in conventional refinery units using existing infrastructure and commercial technologies, in order to achieve significant cost savings
- New processes for upgrading pyrolysis oils with lower hydrogen requirements, e.g. hydrothermal processing
- New catalytic processes to produce better quality oils directly, thus requiring less upgrading

11.2 Gasification with high value product synthesis

This section covers the following technologies (in order of priority as emerging from the case study analysis):

- Gasification with catalytic methane synthesis (bioSNG)
- Gasification with hydrogen production
- Gasification with catalytic Fischer-Tropsch synthesis
- Gasification with catalytic methanol synthesis

The reason for combining these technologies is that they have in common some processes and innovation requirements.

11.2.1 Technology overview

Gasification with catalytic methane synthesis (bioSNG)

This technology involves converting lignocellulosic feedstocks into biomass-derived methane (bioSNG). It consists of a gasification step, which converts the feedstock into syngas, and a methanation step, which catalytically converts the syngas into methane, as shown in Figure 11-1. Heat and power are also commonly produced as valuable by-products.

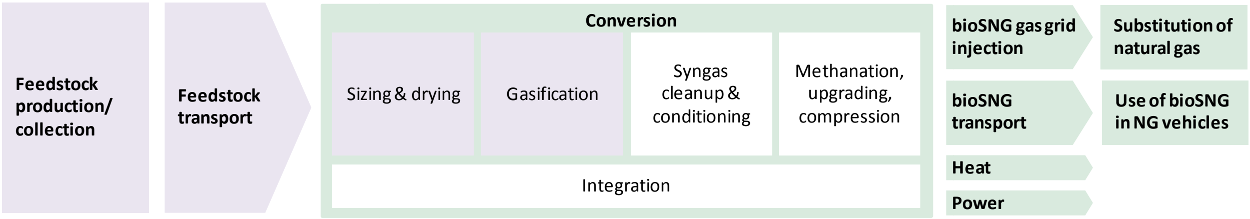


Figure 11-1 Process schematic for production of bioSNG

Gasification with catalytic Fischer-Tropsch synthesis

This technology involves converting lignocellulosic feedstocks into petrol, diesel or jet fuel. Gasification is used to thermo-chemically convert the feedstock into syngas, which is then catalytically converted into Fischer-Tropsch liquids, before upgrading to petrol, diesel or jet, as shown in Figure 11-2. Naphtha and power are also commonly produced as valuable by-products. An option for cost improvement is the production of “syncrude” that is refinery-compatible and takes advantage of existing petroleum refineries and their economies of scale and process integration.

Currently the FT reaction is successfully used for fuel production from coal (Coal-to-Liquids, CTL) or natural gas (Gas-to-Liquids, GTL).

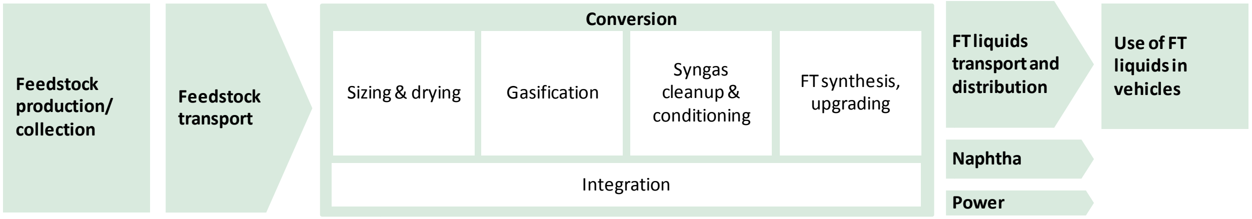


Figure 11-2 Process schematic for production of FT liquids from biomass

Gasification with hydrogen production

This technology involves converting lignocellulosic feedstocks into hydrogen. Gasification is used to thermo-chemically convert the feedstock into syngas, which is then catalytically shifted and/or reformed into hydrogen, before compression for numerous potential downstream uses, as shown in Figure 11-3. Heat and power are also commonly produced as valuable by-products.

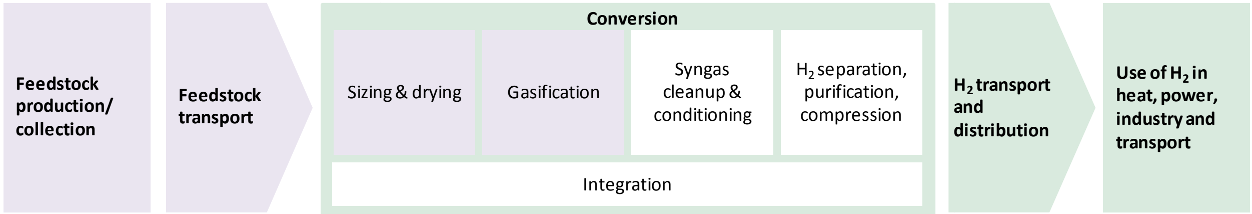


Figure 11-3 Process schematic for biomass gasification + hydrogen production

The route shares many similarities with that of biomass to FT liquids, including suitable gasifier types and syngas cleanup, and only differs significantly by not having a final fuel synthesis step – instead H_2 is produced as a result of the syngas conditioning.

Gasification with catalytic methanol synthesis

This technology involves converting lignocellulosic feedstocks into methanol. Gasification is used to thermo-chemically convert the feedstock into syngas, which is then catalytically converted into methanol, as shown in Figure 11-4.

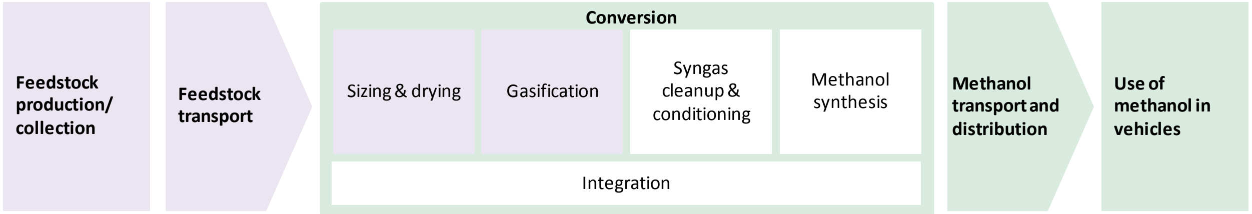


Figure 11-4 Process schematic for biomass gasification + methanol production

The route shares many similarities with that of biomass to FT liquids, including suitable gasifier types and syngas quality requirements, and only differs significantly in the final synthesis step (and hence the resulting end products).

11.2.2 Current status

In general, part of the processes of the gasification-based pathways above involve mature technologies, already used at large scale for fossil fuel feedstocks, e.g. gasification, methanation, FT synthesis, etc. However, the system integration of the whole process is still in a pre-commercial stage, with TRL from 4 to 7 (Figure 11-5)

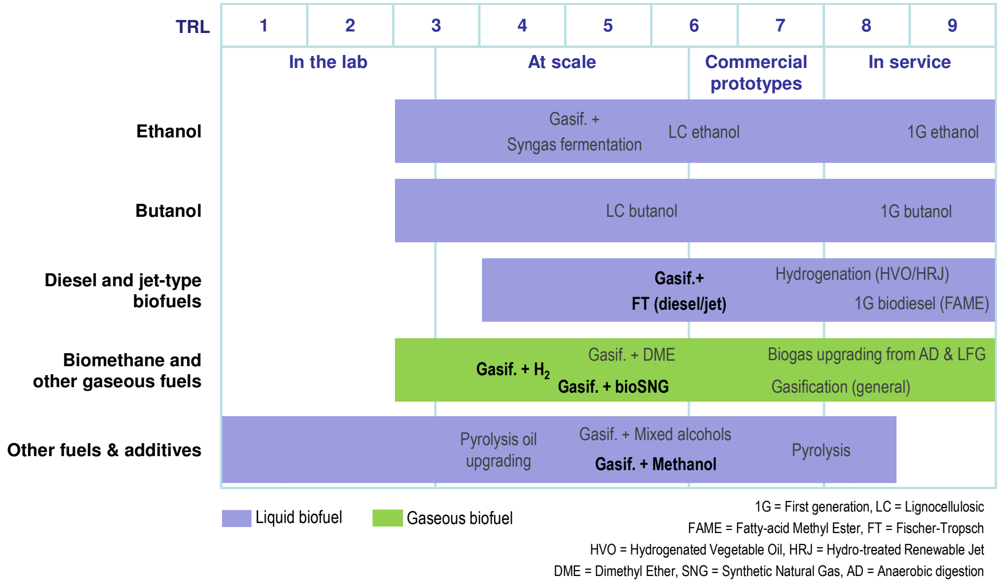


Figure 11-5 Development status of the technologies for production of value added fuels via gasification (in bold), as emerging from the BVCM

11.2.3 Required innovation

- Ensure spill-over and cross-fertilisation from innovation, learning, and best practice to be achieved in other gasification-based routes, including coal to liquid (CTL), especially when scaling up
- Understand ash behaviour and operation with high ash content feedstock, in order to minimise slagging, agglomeration and corrosion
- Ensure successful tar cleaning, with either multiple stage cleaning steps, or with novel approaches such as hot gas cleaning or plasma cleaning.
- Optimise catalysts for desired products composition and yields, minimum contaminants, and longer lifetimes of equipment
- Novel reactor design for process intensification opportunities, with higher yields, efficiency and reduced capital cost
- optimise design and heat integration, e.g. recovered steam can be used for gasification, fuel drying, or power generation