Programme Area: Bioenergy

Project: Biomass Value Chain Modelling

Title: Benefit Assessment Report

Abstract:

This deliverable provides the benefit case of accelerating - by means of a technology demonstrator - technologies identified as promising by analysis of the UK bioenergy system using the Biomass Value Chain Model (BVCM) toolkit. The benefit case is assessed based on two main criteria: value of technology acceleration and demonstrator benefits. Based on the analysis of a wide range of case studies using the BVCM toolkit, the benefit cases for biosynthetic natural gas (bioSNG), biohydrogen, pyrolysis fuels, and carbon capture and storage (CCS) technologies for power generation are assessed in detail. BioSNG technology emerges as the highest in terms of value of technology acceleration, and potential benefit of a UK demonstration activity in bioSNG exists, although a series of demo plants are already planned for the near future abroad.

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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Biomass System Value Chain Modelling

WP04.05

Benefit assessment report

Version 2.0

The BVCM Consortium

For the Energy Technologies Institute
18 June 2012

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Client	Energy Technologies Institute
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Contents

Executive summary

This report provides the benefit case of accelerating - by means of a technology demonstrator - technologies identified as promising by analysis of the UK bioenergy system using the Biomass Value Chain Model (BVCM) toolkit.

The benefit case is assessed based on two main criteria: value of technology acceleration and demonstrator benefits. The value of accelerating a technology is measured by estimating the additional energy system cost - compared to a reference case - if the development of that technology is delayed. As reference we have assumed a bioenergy system which meets, at lowest system costs, the requirements on bioenergy coming from the ETI ESME model. The demonstrator benefits are measured based on the technology innovation needs and the suitability of a demonstrator to meet such needs, and the competitive advantage of the UK over the rest of the world.

Based on the analysis of a wide range of case studies using the BVCM toolkit, the benefit cases for biosynthetic natural gas (bioSNG), biohydrogen, pyrolysis fuels, and carbon capture and storage (CCS) technologies for power generation are assessed in detail.

The benefit of accelerating CCS technologies - particularly dedicated chemical looping CCS, co-fired and dedicated oxy-fuel CCS, and cofired combustion with amine CCS - emerges as the highest amongst all bioenergy technologies. This is most notably due to the fact that development of biomass CCS technologies is required if negative emissions are to be achieved from the bioenergy sector[1]. Acceleration of biohydrogen would be required in order to meet the biohydrogen target from ESME, although the value addition of a UK demonstrator may be limited. BioSNG technology emerges as the highest in terms of value of technology acceleration, and potential benefit of a UK demonstration activity in bioSNG exists, although a series of demo plants are already planned for the near future abroad. Opportunities exist to accelerate the commercialisation of pyrolysis fuels, mostly based on UK competitive advantage, but their value to the energy system is modest compared to the previous options, due to the relatively small role expected for biofuels in ESME.

The benefit case analysis in this report is based on the BVCM toolkit developed as of end of May 2012. Although several additional model functionalities and scenarios have been envisaged for investigation in Phase 2 of the project, it is reasonable to say that a good level of confidence exists at this stage around the model results, given the number of scenarios explored during Phase 1 and the quality of the data currently in the model. It is therefore suitable to use current model results in helping defining the ETI bioenergy technology demonstrators.

[1]The assessment of the benefit of CCS technology demonstrator is not in the scope of this project, so the reader should refer to other related projects on this topic for more info, e.g. the ETI BioCCS project.

1 Introduction

1.1 Objectives

The main objective of this report is to estimate the benefit case of accelerating the technologies identified as promising by the Biomass Value Chain Model (BVCM) toolkit.

1.2 Acceptance Criteria

As per the technology contract, the acceptance criteria for the deliverable WP4-D5 state:

"[A] report that provides a clear UK benefits case, in line with the ETI objectives of secure, sustainable and affordable energy, for development, demonstration, and deployment of technologies identified for acceleration [...]"

1.3 Level of confidence

The benefit case analysis presented in this report is based on the BVCM toolkit developed as of end of May 2012.

Results in terms of acceleration opportunities have been presented to the ETI Bioenergy Steering Advisory Group (SAG) on March 27, 2012 and May 15 and 16, 2012. Although several additional model functionalities and scenarios have been envisaged for investigation for Phase 2, it is reasonable to say that a good level of confidence exists at this stage around the model results. It is therefore suitable to use them in helping define the ETI bioenergy technology demonstrators. The level of confidence around model results is discussed in more detail in the WP4-D4 deliverable (Technology Acceleration Opportunities and Roadmapping report), to which the reader should refer.

2 Methodology for benefits case analysis

The benefit of accelerating the development, demonstration and deployment of a focused portfolio of technologies is assessed in line with the ETI objectives of providing secure, sustainable and affordable energy. In particular, the benefit assessment is based on the following steps:

1. **Model development**
   The Biomass Value Chain Model (BVCM) has been developed to investigate which bioenergy chains meet the ETI objectives of secure, sustainable and affordable energies (see WP2-D5 "Integrated Model" deliverable and associated guides for reference)
2. **Case study analysis**
   Case studies have been developed and run with the BVCM, which have provided a list of promising technologies (see WP4-D4 "Opportunity identification and roadmapping report" for references). These technologies have been shortlisted based on their Technology Readiness Level (TRL), so that – in line with ETI's remit – the benefit of demonstrating selected technologies in the TRL space from 3 to 6 is investigated (Step 3 below)
3. **Benefit analysis**
   The benefit of accelerating the development and deployment of the technologies as selected above is done in three sub-steps:
   a. First, we estimate the value, at UK system level, of accelerating the selected technologies. We evaluate this by executing optimisation runs assuming a delay in the technology capital cost reduction, and comparing the system costs with a reference case. In order to ensure applicability to UK requirements, a case derived from the ETI ESME model is used
   b. the benefit of possible demonstration is estimated, based on the development status and innovation needs, and the UK competitive advantage
   c. last, we rank the selected technologies based on the value of acceleration, and the value of demonstration, as assessed above.

Step 1 (Model development) has been detailed in other deliverables (see WP2-D5 "Integrated Model"), and will not be covered here.

In the next section, we will summarise the results of Step 2 (Case study analysis) and illustrate in detail Step 3 (Benefit analysis), which is the focus of this report.

3 Summary of the Case Study Analysis

By using the BVCM toolkit, a large number of optimisation runs were executed to identify key technologies of the bioenergy system under a wide range of scenarios. This was covered in the case study analysis provided in WP4-D4 "Acceleration opportunity identification and roadmapping report", to which the reader should refer for more details.

It is important to note the following:

- The shortlist is based on a large number of case study runs (more than 50)
- A broad range of case studies has been considered, so that a wide envelope of possible bioenergy scenarios is explored
- All technologies in the project scope (see WP3-D3 "Technology Modelling report" and the BVCM model itself for more info) have been included in the case studies.

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

	TRL 3-6	TRL > 6
Pre-treatment and densification technologies		• Pyrolysis • Pelletising (if there are tight land constraints)
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)**

In line with ETI focus on the TRL space from 3 to 6, the following technologies are selected for the benefit case analysis:

- Gasification coupled with synthesis of value-added fuels:
  - bioSNG
  - hydrogen
- Pyrolysis oil upgrading
- CCS technologies
  - Dedicated chemical looping CCS
  - Co-fired and dedicated oxy-fuel CCS
  - Cofired combustion + amine CCS

4 Benefit analysis

4.1 Value of technology acceleration

In this section we estimate the value, at UK system level, of accelerating the selected technologies from the case study analysis. We evaluate this by executing optimisation runs with a delay in the expected capital cost reduction in the selected technologies, and comparing the results with those from a reference case. In order to ensure full applicability of the analysis to the UK, we have chosen as reference case a model run in which bioenergy has to meet, at lowest system costs, the whole energy system requirements on bioenergy coming from the ETI ESME model (see Appendix 1 for details). In particular, we have assumed:

- The constraints on the total energy to be produced by biomass, as well as energy mix (the share between electricity, hydrogen, gaseous fuels, and heat), as coming from the central ESME run[2]
- CCS technologies available, with a requirement of net carbon sequestration from bioenergy in 2050s equal to 50 $MtCO_2$ per year[3]

By choosing an "ESME case" as reference case, we ensure that whole energy system requirements are taken into account, and that whole system level implications (e.g. lifecycle CO2 emissions) are considered. This also means, however, that the benefit case is dependent on the UK energy system resulting from ESME, so that if this system changes (e.g. with ESME model updates, technology breakthroughs, etc.), the benefit case from the BVCM may change as well.

For each technology, a delay in capital cost reduction of 1 and 2 decades is assumed[4]. The comparison with the reference case gives an "opportunity cost" indicator. This is the cost of not accelerating a technology in the portfolio of available options in order to meet the UK energy system requirements. The larger (positive) the opportunity cost, the stronger the economic case for the given technology to be accelerated. Based on results of the case study analysis, the value of acceleration has been calculated for the following technology options:

- Gasification coupled with synthesis of BioSNG
- Gasification coupled with synthesis of hydrogen
- Pyrolysis fuels[5]
- CCS technologies[6]
    - Dedicated chemical looping CCS

[2] Personal communication with Chris Heaton, May 2012.
[3] Personal communication with Paul Bennett, June 2012. It is assumed that the net carbon sequestration requirement from bioenergy will be 10, 20, and 50 $MtCO_2$/year in the 2030s, 2040s, 2050s respectively.
[4] In the BVCM model, the delay is implemented by shifting the capital cost of the selected technologies, one by one, by the chosen number of decades.
[5] In case of pyrolysis, we apply the delay in cost reduction to the whole pyrolysis fuel chain, i.e. to both pyrolysis and pyrolysis upgrading. The rationale being that the development and deployment of the two technologies will occur hand in hand
[6] For CCS technologies, the delay is applied to the 3 selected options simultaneously.

- Co-fired and dedicated oxy-fuel CCS
- Cofired combustion + amine CCS

Results in terms of value of technology acceleration are reported in Figure 4-1.

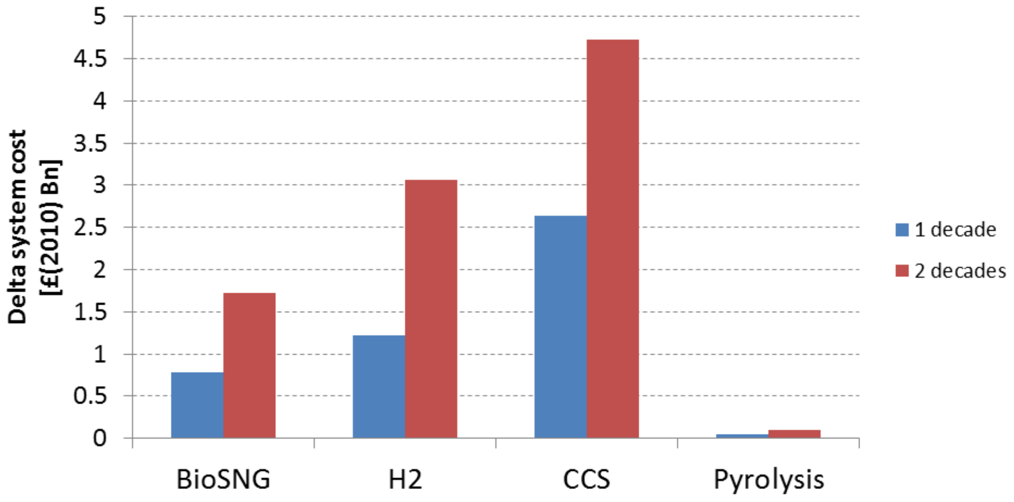


Figure 4-1 Value of technology acceleration. Value is expressed as variation in bioenergy system costs (over the whole 50 years period) compared to the reference case, based on a 1 and 2 decades delay in technology cost reduction.

The value of technology acceleration is greatest for CCS technologies. This is due to their relatively low TRL level, and the relatively large carbon sequestration requirement on bioenergy resulting from ESME. Biogenic hydrogen and biogenic synthetic natural gas follow CCS technologies in terms of value of acceleration. The value for pyrolysis is instead very modest, due to the low level of liquid fuels expected from bioenergy in ESME.

4.2 Demonstrator benefits

The benefit of a demonstrator programme is measured based on the technology innovation needs and the suitability of a demonstrator to meet such needs, and the competitive advantage of the UK over the rest of the world.

The suitability of a demonstrator is assessed based on the TRL of the stages in the fuel chains[7] (the closer to the TRL range of 3 to 6, the higher the suitability). The UK competitive advantage is based on the relative strength of UK activities compared to activities outside the UK. In Table 4-1 the suitability of demonstrator and UK competitive advantage are scored from low to high[8], and the overall demonstrator benefit is given as an average of the two. More details on how suitability and competitive advantage are being assessed are given in Appendix 2.

[7] The closer to the TRL range of 3 to 6, the higher the suitability. E.g. TRL 1 or 9 have low suitability, TRL 5 has high suitability.
[8] O = Low, OOO = High, (O) is a half score.

This analysis heavily draws from the E4tech's contribution to the recent UK Government Technology Innovation Needs Assessment (TINA) exercise. The demonstrator benefits for CCS technologies are not assessed here, as the detailed assessment of innovation needs, demonstrator suitability, and UK competitive advantage is not in the scope of the BVCM project. The reader should refer to other projects (e.g. the ETI BioCCS project or the CCS TINA documentation) for more information on these.

Value chain	Suitability for demonstrator	UK competitive advantage	Overall demonstrator benefit
Biomethane	OO(O) Potentially high for integrated systems using novel methanation reactor design	OO Higher in syngas cleanup and methanation, but lower in gasifiers. Also, some demo plants already being planned elsewhere.	**OO**
Biohydrogen	OO(O) Potentially high for integrated systems using novel, low cost H_2 separation technologies	O Relatively unpopulated arena, with no particular UK competitive advantage	**O(O)**
Pyrolysis fuels	OOO High across the chain	OO High competitive advantage, but arena already very crowded worldwide	**OO(O)**

Table 4-1 Overall demonstrator benefits

4.3 Overall benefit

In this section we rank the selected technology chains based on the value of technology acceleration and the demonstrator benefit, as assessed in the previous sections.

In Figure 4-2, the selected chains are charted on a two-by-two bubble chart based on these two criteria, on the x-axis the demonstrator benefits (from Low to High), on the y-axis the value of demonstrator (expressed as system cost increase from reference case), and with the size of the bubble indicating the relative share that each technology is expected to contribute to the bioenergy mix according to ESME. The red dashed line for CCS indicated that CCS demonstrator benefits have not been assessed in this project, so the x-position of CCS in the chart is indicative only.

From this analysis, it results that:

- The benefit of accelerating CCS technologies which employ biomass emerges as the largest in terms of opportunity costs. This is most notably due to the fact that biomass CCS technologies are the only technology option for carbon sequestration currently in the model[9]. However, the assessment of a demonstrator benefit is not in the scope of this project, so more investigation in this direction is needed.

- Acceleration of biohydrogen would be required in order to meet the ETI trilemma, although the value addition of a UK demonstrator may be limited.
- BioSNG technology emerges as the largest in terms of ETI trilemma requirements. Potential benefit of a UK demonstration activity in biomethane exists, although a series of demo plants are already planned for the near future abroad.
- Opportunities exist for pyrolysis fuels, mostly based on UK competitive advantage, but their value to the energy system is modest compared to the options above.

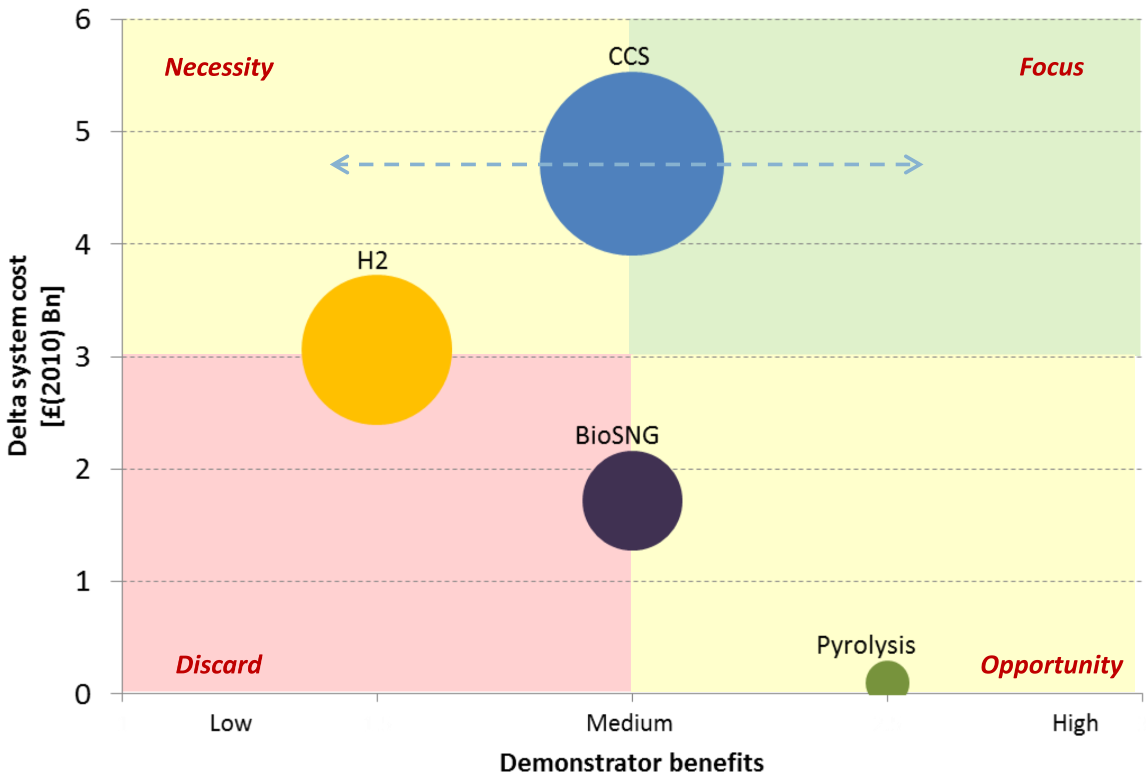


Figure 4-2 Overall benefit case

[9] Other "non-technology" options are available for sequestration, e.g. (re-)afforestation, which we will attempt at exploring during Phase 2 of the BVCM project.

5 Next steps

This is the last formal deliverable for the BVCM project as originally conceived in the Technology Contract. A follow-up Phase 2, which is already under way, will build on the existing model by adding functionalities such as imports, additional technologies, seasonality effects, etc.

In addition to the activities in Phase 2, we would recommend further integration of the BVCM with the ESME model. This means, for example, aggregating the BVCM results at a suitable level and feeding them back into the ESME for further iteration.

Technologies acceleration opportunities and benefit case reports will be updated accordingly at the end of Phase 2, expected in October 2012.

6 Appendix 1: Reference case

6.1.1 Description of case study

In this case study, we calculated the minimum cost solution of providing the energy and the carbon sequestration via biomass, as resulting from the cost optimal energy system wide solution (central case) calculated in the ETI ESME model.

6.1.2 Case study parameterisation

The following constraints on the total energy production and on energy vectors are imposed as constraints onto the BVCM[10]:

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[11]	0%	25%	15%	16%	24%	-
	Hydrogen	0%	0%	20%	51%	53%	-
	Transport fuels	0%	0%	3%	4%	5%	-

Following ESME, it is also assumed that a 10, 20, and 50 MtCO2/year of net carbon sequestration has to occur in the 2030s, 2040s, and 2050s[12].

In addition, the following assumptions apply for this case[13]:

- **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
  - Emissions:
    - Biomass cultivation emissions as calculated in the GHG model developed in WP1
    - No land use (both direct and indirect) emissions

[10] Personal communication with Chris Heaton, April 2012.
[11] 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.
[12] Personal communication with Paul Bennett, June 2012.
[13] With the exception of the CCS technologies availability, there are the same as in the "Base Case", in WP4-D4 "Opportunity identification and roadmapping" report.

- Emissions for fossil resources (e.g. natural gas) as in ESME (central values)
- No emission credit from co-products

  - 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[14]. 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)
- **Infrastructure:**
  - No hydrogen or syngas grid available
  - No constraints on CCS technology locations

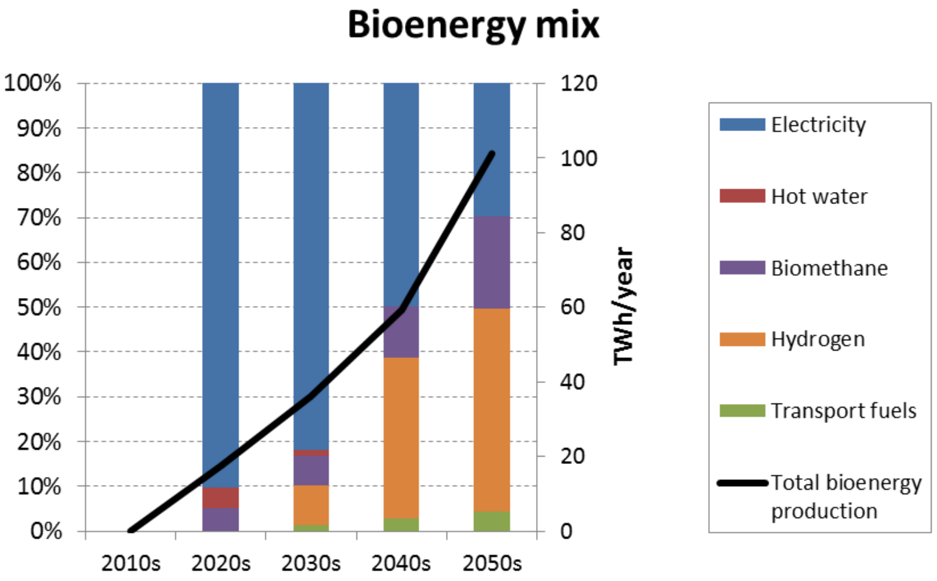
6.1.3 Results

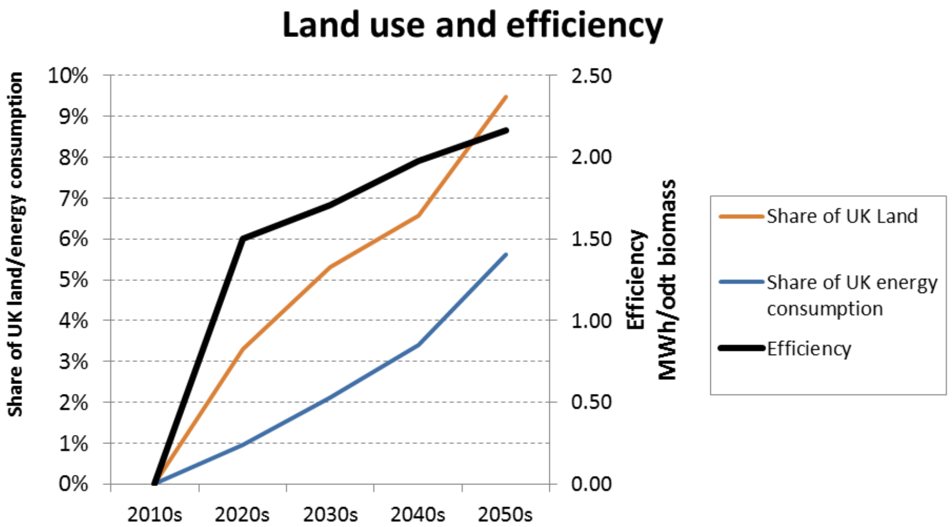
Item		2010s	2020s	2030s	2040s	2050s	Unit
Energy Provision	Total[15]	0	17	36	59	101	TWh/year
	Power	0	16	30	30	30	TWh/year
	Heat	0	1	0	0	0	TWh/year
	Biomethane	0	1	2	7	21	TWh/year
	Hydrogen	0	0	3	21	46	TWh/year
	Transport fuels	0	0	0	2	4	TWh/year

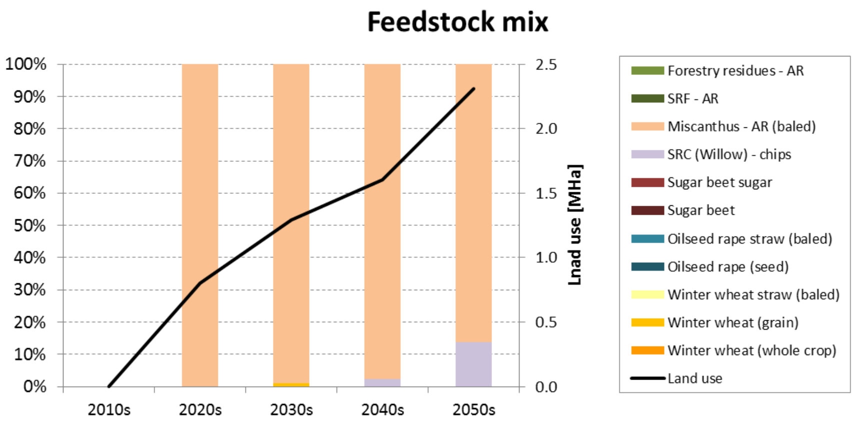
Item		2010-2059	Unit
Costs	System total	9.0	£Bn/decade
	Average	67.8	£/MWh
Emissions	System total	-16.0	Mt CO_2/year
	Average	-374.6	kgCO_2/MWh

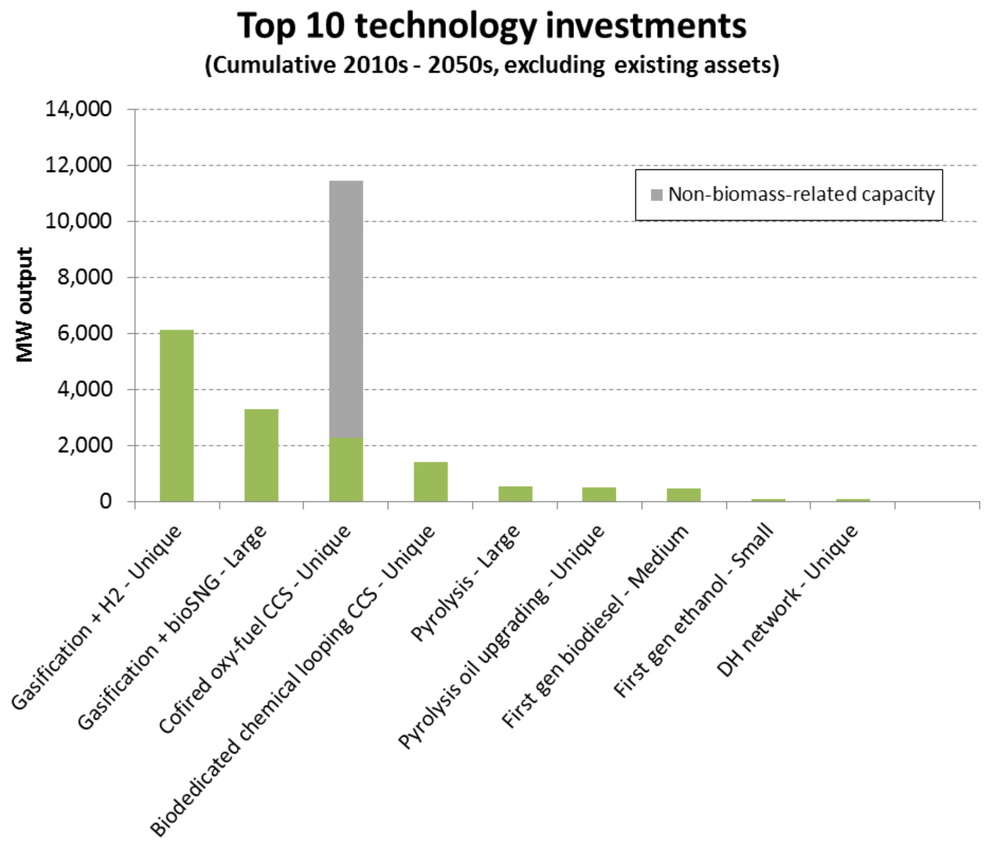
[14] We are assuming that factors that may cause larger amount of land for domestic food production in the UK (e.g. increase in population, increase in food security, etc.) are balanced by factors that imply use of less land (e.g. dietary changes, technology and yield improvements, etc.)

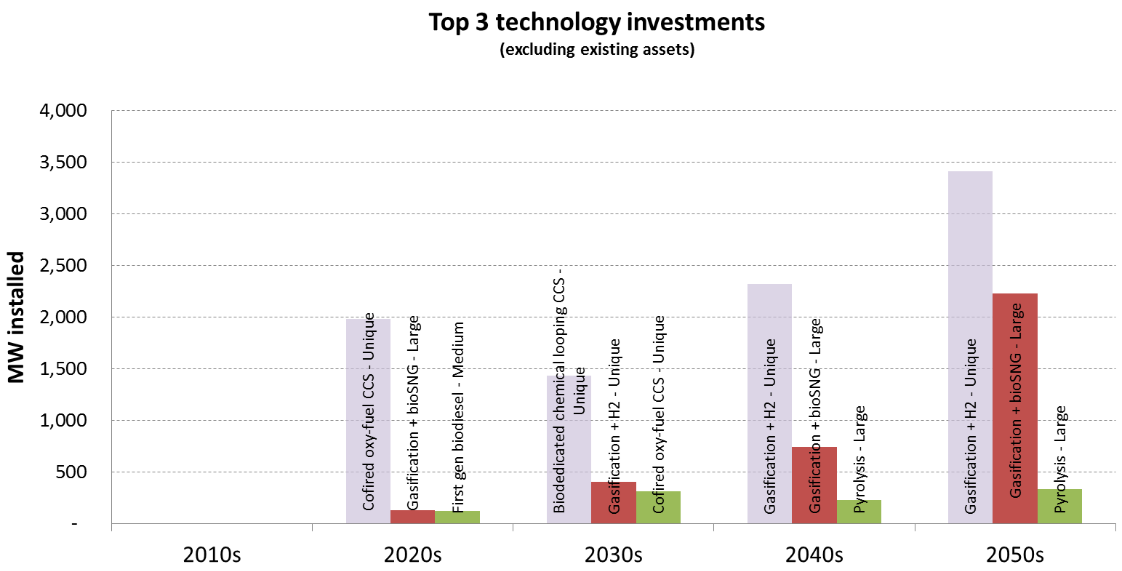
[15] The total energy produced is higher than the minimum requirements from ESME. This is because more CCS power is required to be installed than the minimum required, in order to meet the CO_2 sequestration constraint.


Bioenergy mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
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
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
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


Feedstock mix
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2.5
2.0
1.5
1.0
0.5
0.0
Lnad use [MHa]
2010s
2020s
2030s
2040s
2050s
Forestry residues - AR
SRF - AR
Miscanthus - AR (baled)
SRC (Willow) - chips
Sugar beet sugar
Sugar beet
Oilseed rape straw (baled)
Oilseed rape (seed)
Winter wheat straw (baled)
Winter wheat (grain)
Winter wheat (whole crop)
Land use


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
Gasification + H2 - Unique
Gasification + bioSNG - Large
Cofired oxy-fuel CCS - Unique
Biodedicated chemical looping CCS - Unique
Pyrolysis - Large
Pyrolysis oil upgrading - Unique
First gen biodiesel - Medium
First gen ethanol - Small
DH network - Unique


Top 3 technology investments
(excluding existing assets)
MW installed
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
Cofired oxy-fuel CCS - Unique
Gasification + bioSNG - Large
First gen biodiesel - Medium
Biodedicated chemical looping CCS - Unique
Gasification + H2 - Unique
Cofired oxy-fuel CCS - Unique
Gasification + H2 - Unique
Gasification + bioSNG - Large
Pyrolysis - Large
Gasification + H2 - Unique
Gasification + bioSNG - Large
Pyrolysis - Large
2010s
2020s
2030s
2040s
2050s

7 Appendix 2: Demonstrator benefits

7.1 Biomethane (BioSNG) chain

Component	Innovation required	Suitability for demonstrator (TRL match)	UK Competitive advantage	
			UK position	Activities outside the UK
Sizing & drying	▪ Heat integration to minimise heat requirement for drying	O ▪ Low per se, but higher in the context of integration (see below)	O ▪ No distinctive capabilities in woody biomass. ▪ Several companies with waste separation, pre-treatment and refuse-derived fuel expertise (e.g. New Earth Energy, Aerothermal Group, SITA, and Ethos Energy)	OOO ▪ Globally, numerous large engineering firms also supply sizing and drying equipment; e.g. Andritz, Foster Wheeler, Siemens
Gasification	▪ Ensure spill-over from innovation in other gasification-based routes, including coal to liquid (CTL), especially when scaling up ▪ Understand ash behaviour and operation with high ash content feedstock	OOO ▪ High for understanding of operational issues ▪ Lower for novel designs (TRL<3)	O ▪ No UK firms with large gasifier technologies, and a decreasing number of small gasifiers for heat & power applications being deployed ▪ UK academic development only focused on small-scale gasifiers	OOO ▪ Dual gasifiers are being developed and successfully demonstrated in Europe and the US; e.g. Repotec, SilvaGas, ClearFuels. There are also research strengths at Karlsruhe Institute of Technology (KIT), VTT (Technical Research Centre of Finland), Cutec, GTI, and several major EU projects
Syngas cleanup & conditioning	▪ Ensure successful tar cleaning, with either multiple stage cleaning steps, or with novel approaches such as hot gas cleaning or plasma cleaning.	OOO ▪ Novel approaches at TRL 5-6	OO ▪ Johnson Matthey working on novel cleaning in EU project "GREENSYNGAS" ▪ Advanced Plasma Power developing plasma cleanup	OOO ▪ Strong R&D experience globally (VTT, Lund, Delft, Munich, KIT, Bologna and ECN) and several large firms (Linde, Lurgi, Air Products)

			▪ Research activity at Nottingham, Sheffield and Newcastle Universities	already offer syngas cleaning equipment
Methanation & injection	▪ Optimise catalysts for desired products composition and yields, minimum contaminants, and longer lifetimes of equipment ▪ Lower costs for small scale equipment for compression, metering and odourisation ▪ Novel reactor design for process intensification opportunities, with higher yields, efficiency and reduced capital cost	OO ▪ Technology is at TRL>8, but existing novel reactor design are at much earlier stage ▪ Catalyst optimisation can be done at bench scale, not necessarily demo scale ▪ Lower costs for equipment is from deployment	OOO ▪ Commercial methanation catalysts available from Johnson Matthey ▪ Velocys micro-channel reactor is also being developed by Oxford Catalysts, applicable to methanation process intensification	OO ▪ Commercial methanation catalysts available from companies like Sud-Chemie and Haldor Topsoe.
Integration	▪ Optimise design and heat integration, e.g. recovered steam can be used for gasification, fuel drying, or power generation	OOO ▪ Whole system integration is at TRL ~4, but could increase in the next future depending on the success of planned demo and first commercial scale plants.	OO(O) ▪ National Grid, Advanced Plasma Power and Progressive Energy working on an end-to-end system to convert waste into bioSNG	OO ▪ Few developers currently focusing on integration for bioSNG ▪ Some pilot plants and first commercial plants being planned for 2014 and beyond (GoBiGas in Göteborg by Göteborg Energi, GAYA demo project led by GDF Suez)
Overall		**OO(O)** [16] **Potentially high for integrated system using novel methanation reactor design**	**OO** [17] **Higher in syngas cleanup and methanation, but lower in gasifiers. Also, some demo plants already being planned elsewhere.**	

[16] Here and in the following tables, the overall score is given as average of each score in the related category.
[17] Here and in the following tables, the overall score is calculated as follows: if "UK position" score is higher/lower/equal than the "Activities outside UK" score, then the "UK competitive advantage" score is high/low/medium respectively. The overall score is then given as average of the score calculated for each part of the chain.

7.2 Biohydrogen fuel chains

Component	Innovation required	Suitability for demonstrator (TRL match)	UK Competitive advantage	
			UK position	Activities outside the UK
Sizing & drying	▪ See Biomethane chain	O ▪ See Biomethane chain	O See Biomethane chain	OOO ▪ See Biomethane chain
Gasification	▪ See Biomethane chain	OOO ▪ See Biomethane chain	O ▪ See Biomethane chain	OOO ▪ See Biomethane chain
Syngas cleanup & conditioning	▪ Improve efficiency and reduce cost penalties of existing technology ▪ Develop novel approaches such as hot gas cleaning or plasma cleaning.	OOO ▪ See Biomethane chain	OO ▪ See Biomethane chain	OOO ▪ See Biomethane chain
H_2 separation, purification, compressions	▪ Reduce significantly capital costs ▪ Ensure high adsorption rates by molecular sieves ▪ Improve membrane temperature stability and selectivity for ceramic membrane for separation ▪ Hybrid separation schemes that combine membrane and Pressure Swing Adsorption are also investigated	OO ▪ Some technology (pressure swing adsorption) are commercial, but alternative earlier stage technologies are under development (e.g. ceramic membranes)	OO ▪ Air Products is active in developing PSA technology for syngas applications ▪ Some activity in hydrogen purification by PSA at Imperial College London	OO ▪ All major international gas companies (e.g. Air Liquide, Linde) have designed and operated pressure-swing adsorption plants ▪ Some large players involved in ceramic membranes (DuPont, Dow Chemicals, GE, Koch)
Integration	▪ Optimise design and heat integration, especially to improve the H_2 separation step	OOO ▪ Whole system integration is at TRL ~4	O ▪ Air Products are planning a 49MWe waste gasification power plant for 2014 in Teeside, UK, and have mentioned the possibility of future hydrogen production for local industry applications.	O ▪ There are no known developers working with a focus on biomass to hydrogen routes

			However, the primary focus is currently only power	
Overall		**OO(O)** **Potentially high for integrated system using novel, low cost H_2 separation technologies**	**O** **Relatively unpopulated arena, with no particular UK competitive advantage**	

7.3 Pyrolysis fuel chain

Component	Innovation required	Suitability for demonstrator (TRL match)	UK Competitive advantage	
			UK position	Activities outside the UK
Pyrolysis	▪ Improve efficiencies and product selectivity ▪ New processes to produce better quality oils directly, thus requiring less upgrading	OOO ▪ High, as some of the technology considered are early stage (TRL 3-6) such as microwave pyrolysis	OOO ▪ Several high quality research groups working on pyrolysis in (Aston, Leeds, Imperial, Southampton) ▪ York researching novel pyrolysis using microwaves	OOO ▪ Strong presence abroad (Ensyn, UOP Dynamotive, Kior, BTG) ▪ Other academic groups in the Netherlands, US
Pyrolysis upgrading	▪ 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	OOO ▪ High for new process ▪ Demo for co-processing in refinery interesting, as way of de-risking	OOO ▪ Carbon-Trust backed FutureBlends company, following the Carbon Trust Pyrolysis Challenge ▪ High quality research from Imperial College, University of Aston, York, Leeds and Birmingham ▪ BP, CARE Ltd, Rotawave, CPI, Catal International, Greenergy, Oxford Catalysts and Johnson Matthey could add industrially relevant expertise	OOO ▪ Active academic community in the Netherlands, Finland and US ▪ US DoE-funded 4 projects up to $12m involving W. R. Grace, PNNL, GTI, Batelle. Have also funded UOP and Ensyn (Envergent JV), DynaMotive, NREL, and provided $1bn loan guarantee to KiOR ▪ EU projects: BIOCOUP looking at refinery co-processing, CatchBio for novel catalysis routes ▪ Other active players include Shell, Arkema, Albermarle, Licella, ConocoPhillips, Sasol, Sabic and Haldor Topsoe (using PetroAlgae's biocrude)
Overall		**OOO** **High across the chain**	**OO** **High competitive advantage, but arena already very crowded worldwide**	