

EIRO2.0: Bioenergy modelling – final report

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Contents

1.	Executive Summary.....	1
2.	Introduction.....	3
2.1.	Background.....	3
2.2.	Project Structure and Objectives	3
2.3.	Project Deliverables	3
3.	Bioenergy Value Chain Model (BVCM).....	4
4.	Model Scenario Configuration	5
4.1.	Scenarios Modelled	5
4.2.	Data Changes Common to All Scenarios.....	6
4.2.1.	Use of Other Biomass Feedstocks	6
4.2.2.	Crop Establishment Yield Fractions	7
4.2.3.	Imports of Biomass Feedstocks.....	7
4.2.4.	CO ₂ Sequestration Locations	7
4.3.	Scenario Specific Data Changes.....	8
4.3.1.	Land Area & Additional Considerations	8
4.3.2.	Energy & Greenhouse Gas Targets.....	10
5.	Results	12
5.1.	Central Assumption	12
5.1.1.	Relaxed Energy Targets & Cell-Based Limits.....	12
5.1.2.	SRF Target Brought Forward	18
5.2.	Reduced Ambition	22
5.2.1.	Relaxed Energy Targets & Cell-Based Limits.....	22
5.2.2.	SRF Target Brought Forward	27
5.3.	Discussion.....	32
6.	Conclusion	34
6.1.	Recommendations for Future Work	34
7.	Appendix A: Acronyms, References & Deliverables	36
7.1.	Acronyms.....	36
7.2.	References.....	36
7.3.	Project Deliverables List	38

8.	Appendix B: BVCM Cell Mapping & ITL1 Correlation	39
9.	Appendix C: CO2e Impacts of Each Scenario	41
10.	Appendix D: Phase 1 Results.....	42
	10.1.1. Phase 1 Data Changes.....	42
	10.2. Phase 1 Results.....	42
	10.2.1. Case A – Reference	42
	10.2.2. Case B – “10% Demand”	44
	10.2.3. Case C – “50% Demand”	46
	10.2.4. Discussion	48
11.	Appendix E: Regional Planting Scenario.....	50
12.	Licence/Disclaimer	52

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1. Executive Summary

Bioenergy is a significant UK renewable energy source. It will be key for Net Zero ambitions in the UK when coupled with carbon capture and storage technologies to deliver net negative emissions. The Department for Energy Security and Net Zero (DESNZ) commissioned Energy Systems Catapult to model planting scenarios for three energy crops: miscanthus, short rotation forestry (SRF) and short rotation coppice (SRC) willow. A “Central Assumption” and “Reduced Ambition” land area limit scenario was provided by DESNZ for each of the three energy crops. The modelling work was performed using the Catapult’s Bioenergy Value Chain Model (BVCM), an end-to-end model of bioenergy in the UK to 2050. BVCM answers the “what, where, when” questions for planting, transport, and bioenergy facilities under different targets and constraints. BVCM optimises for the entire bioenergy value chain on a 50x50km grid scale representing the UK, providing a useful spatial resolution as to where energy crops should be planted. This optimisation of planting locations considers amongst other things, the location of likely end users such as bioenergy with carbon capture and storage (BECCS).

The key planting trends in the 2050s for the three energy crops across all scenarios were:

- Miscanthus is typically planted along the east coast of England, from Humberside to as far south as Essex, and is used in BECCS facilities in East Norfolk or the Humber cluster. It is also frequently planted to a smaller degree in or around Merseyside and Teesside to supply BECCS facilities in these clusters.
- SRF was typically planted along the England and Wales border region to supply BECCS facilities in the Merseyside and South Wales clusters, or for use in large-scale combustion boilers for heat co-located with feedstock growth.
- SRC is typically planted across the north west and north of England, the west of Scotland, and Northern Ireland. SRC is used in BECCS facilities mostly in either Merseyside or Teesside, or in large-scale combustion boilers for heat co-located with feedstock growth.

One of the key observations across the scenarios is that the presence and location of end user facilities influenced where energy crops were grown. For example, Cornwall and the south coast of England presented little opportunity for planting due to the lack of nearby major end user facilities. The major end users were BECCS facilities (hydrogen or power BECCS), and these had to be located at or very close to CO₂ sequestration locations. An additional user was large combustion boilers for heat, but these were co-located where there was both the planting of feedstock and sufficient modelled heat demand. Beyond the planting trends and locational opportunities noted previously, this project has highlighted the importance of considering the location and scale of end user demand for energy crops, rather than simply the potential or yield of a parcel of land.

Recommendations for future work include additional scenarios considering detailed targets for bioenergy vectors and greenhouse gas removals, modelling scenarios with different levels of biomass imports, and standalone modelling of each nation of the UK, in particular Northern Ireland. Further details on these recommendations are included in the conclusion to this report.

About Energy Systems Catapult

Energy Systems Catapult is an independent research and technology organisation. Our mission is to accelerate Net Zero energy innovation.

Launched in 2015 by Innovate UK, the Catapult has built a team of more than 250 people, with a range of technical, engineering, consumer, commercial, incubation, digital, and policy expertise. They draw on sector-leading test facilities, modelling tools, and data collected from our back catalogue of more than 500 research projects.

We use that 'whole energy' system capability to support innovative companies – small and large – to test, trial and scale their new products and services. Our impact comes when those innovators attract new customers, new investment, and new grants so they can thrive in the future energy system.

Based in Birmingham, Energy Systems Catapult is part of a network of nine world-leading technology and innovation centres, established by Innovate UK. The Catapult Network fosters collaboration between industry, government, research organisations, academia, and many others to transform great ideas into valuable products and services.

2. Introduction

2.1. Background

The UK government's Biomass Strategy [1] has highlighted the importance of bioenergy in achieving the UK's target of Net Zero greenhouse gas emissions by 2050. Amongst other things, the Biomass Strategy discusses the importance of ensuring sufficient availability of biomass feedstocks, both domestically grown and imported from other countries. These feedstocks will likely be prioritized in the future for use in bioenergy with carbon capture and storage (BECCS) technologies.

Large-scale planting of biomass feedstocks to satisfy this future need will require a detailed understanding of the preferred planting locations. These locations will likely depend upon a variety of factors, including where end users are located, e.g. BECCS facilities.

The Department for Energy Security and Net Zero (DESNZ) commissioned Energy Systems Catapult to investigate scenarios for energy crop planting across the UK, using land use limits provided by the Department for Environment, Food & Rural Affairs (Defra). This was to be done using the Catapult's "Bioenergy Value Chain Model" (BVCM), an end-to-end model of bioenergy in the UK to 2050, from feedstock planting to end vectors.

2.2. Project Structure and Objectives

The overarching objective of this project was to produce spatial data sets showing where best to plant the following three energy crops: miscanthus, short rotation forestry (SRF) and short rotation coppice (SRC). This would aid the ongoing energy crops evidence gathering activity being performed by DESNZ. It could also potentially inform towards locationally targeted measures to incentivise energy crop planting.

The project was split into two delivery phases. In Phase 1, three scenarios were modelled using BVCM. These scenarios were a standard reference case, a second case with 10% of the energy and negative emission demands of the reference, and a third case with 50% of the energy and negative emission demands of the reference case. These scenarios were modelled to establish a reference baseline with no constraints. As the project evolved, they ultimately became less important as a finding: therefore, the analysis of the Phase 1 results has been placed in an appendix (section 10).

Following the delivery of "Phase 1", and further consideration to the needs and requirements of subsequent work, the project scope for "Phase 2" was revised in July 2023. Phase 2 was delivered from August to November 2023. In Phase 2, energy crop land area scenarios from Defra were supplied, and were to be modelled. An iterative process of modelling and feedback was performed through several cycles with the DESNZ team. Four scenarios were agreed with DESNZ as the "final" cases and are reported here.

2.3. Project Deliverables

A summary listing of all deliverables arising from the project is given in the appendix section 7.3.

3. Bioenergy Value Chain Model (BVCM)

The Bioenergy Value Chain Model (BVCM) was used for all modelling work in this project.

The Bioenergy Value Chain Model (BVCM) is a comprehensive and flexible toolkit for the modelling and optimisation of full system bioenergy value chains. It was delivered by a consortium for the Energy Technologies Institute (ETI) and was transferred to the Catapult on the closure of the ETI. BVCM has been designed to answer variants of the question:

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

BVCM is a spatial and temporal model of the UK, configured over 157 cells of 50km x 50km in size, operating on a decadal basis to the 2050s. As a pathway optimisation model, it can optimise across many potential bioenergy system pathways, accounting for economic and environmental impacts associated with the end-to-end elements of a pathway. These include crop production, forestry, waste, biomass pre-processing & conversion technologies, transportation, storage, and the sale & disposal of resources. It also caters for international biomass imports, as well as CO₂ capture by carbon capture and storage technologies and forestry. The overall structure of the model is shown in Figure 1.

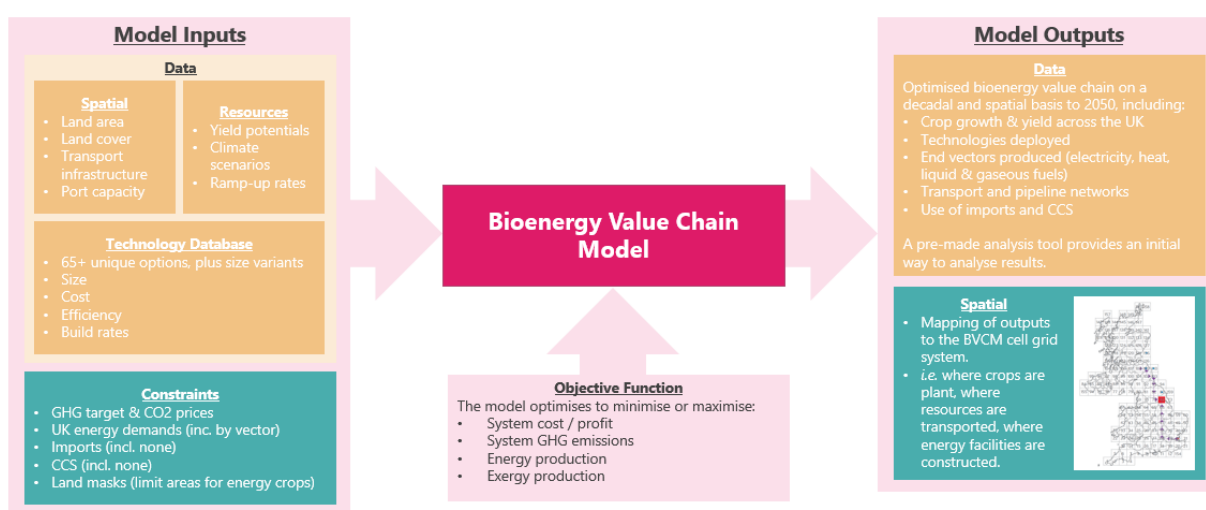


Figure 1: Structure of the Bioenergy Value Chain Model (BVCM).

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

The mathematical formulation of BVCM has been published and peer reviewed [2]. BVCM was extensively used by the ETI, under the UK's initial climate change target of an 80% reduction in emissions by 2050 [3]. BVCM has also been adapted for New Zealand and was recently used in a peer reviewed study of liquid biofuel value chains [4].

4. Model Scenario Configuration

4.1. Scenarios Modelled

The scenarios modelled across Phase 2 of the project are shown in Table 1. These are numbered in chronological order. The scenario development process was iterative over the course of the project in response to feedback from DESNZ, from scenarios 1 to 5.

The “final” results are therefore those of scenarios 4 and 5, which are presented in this report. Results from the earlier scenarios can be seen in the slide deck deliverables (refer to section 7.3).

Table 1: Scenarios modelled in Phase 2, numbered in chronological order as they were produced over the course of the project. Scenarios 4 and 5 were considered the “final” scenarios and are presented in this report.

#	Scenario	Central Assumption Land Limits	Reduced Ambition Land Limits
1	Base <i>(“higher” energy/GHG targets to ensure full planting of energy crops, SRF planting stops in 2030s due to lack of harvest in later decades)</i>	✓	✓
2	Base + SRF Target Brought Forward <i>(2040s SRF land area limit applied in 2030s to ensure SRF allocation is fully planted)</i>	✓	✓
3	Relaxed Energy Targets <i>(energy & GHG targets reduced whilst ensuring full planting, SRF planting stops in 2030s due to lack of harvest in later decades)</i>	✓	✓
4	Relaxed Energy Targets + Cell-Based Limits <i>(energy crop planting has cell-based land area limits, instead of a national average limit without cell-based limits which allows heavy planting in specific cells)</i>	✓	✓
5	Relaxed Energy Targets + Cell-Based Limits + SRF Target Brought Forward <i>(as in scenario 4, but 2040s SRF land area limit applied in 2030s to ensure SRF allocation is fully planted)</i>	✓	✓

To summarise the iterative scenario development process:

Scenario 1 was an initial base case. Energy and GHG removal targets were set relatively high to ensure complete planting of the energy crop land area limits. SRF was not fully planted to its 2040s limit, as planting stops in the 2030s in BVCM as the time to harvest concept means there are no harvests in later decades for the model to utilise. This is due to the way that SRF is represented in BVCM: SRF is planted (e.g. 2020s), thinned with a harvest in the subsequent decade (e.g. 2030s), and then harvested the decade after thinning (e.g. 2040s). SRF which is planted in the 2040s would only receive the smaller “thinning” harvest in the 2050s. The thinning harvest quantity for SRF planted in the 2040s is excluded in BVCM, hence why BVCM does not plant further SRF in the 2040s as there is no usable biomass arising. Note that this is a modelling artefact due to the 2050s Net Zero timespan

over which BVCM models, and of course in practice there would still be tangible benefits to later SRF planting which can be harvested into the late 2050s and beyond.

Scenario 2 brought the SRF land area limit forward to the 2030s, to see where the model would plant the additional hectares of SRF, if it had reason to. For example, this meant that for the Central Assumption, the SRF land area limit of 122,150 hectares which ordinarily applied in the 2040s was instead brought forward and applied as the 2030s land area limit. This gave the model freedom to plant more hectares of SRF, and from an analysis perspective showed where these additional hectares would be planted.

In scenario 3, energy and GHG targets were relaxed to a lower value that still ensured full planting of the energy crop land limits. The exception was SRF, which again ceased planting in the 2030s. This scenario was performed to ensure the model did not have to select high yielding cells to satisfy overall energy and GHG demands, which may be abnormally far from end user facilities. It should be noted that for reference the full set of energy and GHG targets for scenarios 1-5 are presented in the supplementary input data workbook (see section 7.3) with the final targets used in scenarios 4 and 5 presented in section 4.3.2, along with some further context.

Scenario 4 took the conditions of scenario 3, and implanted a cell-based limit as to the percentage of each cell's land type that could be used for energy crop planting. This was instead of a national average limit, as was the case in the previous scenarios, which had allowed for most of the hectares to be planted within a handful of cells.

Scenario 5 took the starting point of scenario 4, and once again brought forward the SRF land area limits from the 2040s to the 2030s, to see the impact of the additional SRF hectares on planting.

Across all scenarios, analysis focused on the 2050s timeframe, as this is the end point at which all the hectare allocations are planted.

One additional land area scenario was initially requested subject to further scoping. This was to use a regionalised data set supplied by Defra, based on agricultural land classifications. Following a review of this and the ability to implement it, the scenario was not modelled. Further information is given in the appendix section 11.

4.2. Data Changes Common to All Scenarios

The following BVCM data and configuration changes noted across sections 4.2.1-4.2.4 were implemented for all of the scenarios listed in Table 1.

4.2.1. Use of Other Biomass Feedstocks

Other biomass feedstock options, aside from miscanthus, SRF, and SRC, were disabled in the Phase 2 scenarios. These other feedstock options which were disabled include:

- Waste feedstocks, which were used to a significant degree in Phase 1 scenarios.
- "Food" crop feedstocks, such as wheat straw, sugar beet and rapeseed oil.
- Other forestry options, which encompasses long rotation forestry for bioenergy and long rotation forestry for CO₂ capture.

This was implemented as including other feedstocks increased the complexity of scenario configuration. Each case had to optimise towards a given energy demand and CO₂ target. Enabling the other feedstocks gave the model a significant degree of freedom to optimise towards the target without having to fully plant the three energy crops (miscanthus, SRC, SRF), in addition to increasing the model solver time by multiple hours and requiring more cycles of iteration to get to a point where the three energy crops were fully planted. As the focus was on the planting of the three energy crops, it was decided to focus on only using these as the input feedstock options.

4.2.2. Crop Establishment Yield Fractions

Crop establishment yield fractions were adjusted for miscanthus and SRC. This criterion is used to reflect reduced yields in the first decade after planting. The fraction was set to 0.55 of the full yield for miscanthus and 0.78 of the full yield for SRC. This is in line with the guidance in the BVCM documentation, which arose from a 2013 study on energy crop economics and uptake by E4tech for the Energy Technologies Institute [5].

4.2.3. Imports of Biomass Feedstocks

Enabling imports and using import assumptions from DESNZ was initially considered. It was agreed in discussions with DESNZ to leave imports disabled for the Phase 2 cases, as was done in Phase 1, due to a lack of certainty around different levels of imports.

4.2.4. CO₂ Sequestration Locations

Future CO₂ sequestration locations and projections of quantities of CO₂ per annum that can be sequestered were also updated, as shown in Table 2. Some locations and CO₂ quantities were updated based upon current publicly available information around Track 1 and Track 2 clusters [6].

For other CO₂ sequestration locations, timings and capacity estimates were updated based upon current reasonable assumptions. The Thames CO₂ sequestration location was removed as there are no current plans for such a location. A new location in Northern Ireland was added and assumed as Warrenpoint Port south of Belfast, to reflect the future need for a CCS location in Northern Ireland. This was selected due to current investment in CO₂ import infrastructure, which could potentially be repurposed for CO₂ export via ship [7]. Similarly, a CO₂ sequestration location was added in Port Talbot, Wales to reflect the need for a CO₂ sequestration location for the South Wales Industrial Cluster [8]. This would also rely on CO₂ shipping. In both cases, the onward cost of this shipping was not factored in versus locations which offer offshore storage in geological storage.

Table 2: CO₂ sequestration locations and quantities. *Italics represents a new or revised value. For reference, a map of the BVCM cells is presented in an appendix (section 8, Figure 14).*

Maximum Sequestration Rate (MkgCO ₂ /decade) ¹							
BVCM Cell	Location	2010s	2020s	2030s	2040s	2050s	Justification
72	Easington (Humber)	0	90000	220000	300000	300000	Revised down for Track 1 plans versus original BVCM values.
93	Teesside	0	30000	40000	50000	50000	Revised down for Track 1 plans versus original BVCM values.
30	<i>Thames</i>	0	0	0	0	0	No plans for Thames CCS hub.
63	Merseyside	0	30000	100000	100000	100000	Cell changed to align with HyNet.
60	Bacton	0	0	50000	200000	200000	No track 1/2 plans, potential for some capture from late 2030s.
134	Peterhead	0	0	150000	150000	150000	Track 2; operation expected in the 2030's.
76	<i>Warrenpoint Port, Northern Ireland</i>	0	0	25000	50000	50000	Northern Ireland CO ₂ emissions as of 2021 were ~22.5Mt/yr. Therefore, assuming a maximum sequestration capacity of 2.5MtCO ₂ /yr in 2030's and 5MtCO ₂ /yr in 2040's & 2050's. Note that this is a speculative assumption given the lack of clarity over CCS in Northern Ireland. Advice by the Climate Change Committee suggested a need of 1.1MtCO _{2e} /yr for BECCS alone by the 2050s [9].
24	<i>Port Talbot</i>	0	0	20000	30000	40000	South Wales cluster region. Anticipated CO ₂ shipping option ports in future.

¹ Divide by 1000 to get MtCO₂ per decade value.

4.3. Scenario Specific Data Changes

The following BVCM data and configuration changes noted across sections 4.3.1-4.3.2 were made for specific scenarios listed in Table 1, rather than applied universally across all scenarios.

4.3.1. Land Area & Additional Considerations

Maximum land area allocations for SRC, SRF and miscanthus were supplied on a per year basis, from 2026 to 2050. They are summed to a decadal basis for BVCM, and then again on the basis of cumulative available land to the 2050s. The inputs for "central assumption" scenario are shown in Table 3, whilst those for "reduced ambition" scenario are shown in Table 4. The naming of these two cases as the "central assumption" and "reduced ambition" was as per the naming for these scenarios in the Biomass Strategy.

Table 3: Central Assumption maximum land areas for energy crops. Maximum hectares planted, cumulative total by decade.

Crop & Hectares	2010s ¹	2020s	2030s	2040s	2050s ²
SRF - Energy Crops Only - 10 year sum	0	11,200	66,150	122,150	122,150
SRC - Energy Crops Only - 10 year sum	2,032	11,972	61,672	111,372	111,372
Miscanthus (energy crops only) - 10 year sum	8,286	10,251	57,411	122,911	122,911

Table 4: Reduced Ambition maximum land areas for energy crops. Maximum hectares planted, cumulative total by decade.

Crop & Hectares	2010s ¹	2020s	2030s	2040s	2050s ²
SRF - Energy Crops Only - 10 year sum	0	7,000	40,950	75,950	75,950
SRC - Energy Crops Only - 10 year sum	2,032	7,002	31,852	56,702	56,702
Miscanthus (energy crops only) - 10 year sum	8,286	10,251	57,411	122,911	122,911

¹ Planting assumed as amounts of miscanthus and SRC planted per 2008-2020 Defra Statistics [10]. No further planting assumed for 2021-2025, with Defra upper limit projections beginning from 2026 onwards.

² Assumed no further planting in the 2050s, as no upper limits for land area were supplied for the 2050s.

No data or projections for planting were supplied for the period 2010-2026. Therefore, planting statistics for SRC and miscanthus from Defra from 2008 to 2020 were used as the limit for the 2010s decade [10]. As these areas are quite minimal, it was assumed that there was no significant additional planting from 2021 to 2025.

It was assumed and agreed with DESNZ that there was no further planting in the 2050s, as no upper limits were supplied for this decade.

With regards to SRF, due to the way BVCM considers SRF planting and harvesting cycles, any SRF planted in the 2040s sees no effective yield or harvest of material for energy purposes. This means that the model would not ordinarily plant any of the additional hectare allocations shown in Table 3 and Table 4 when moving from the 2030s to the 2040s. This therefore was the reasoning for the "SRF Brought Forward" scenarios noted in Table 1, to bypass this limitation. Note that by bringing forward the SRF limits by a decade, there were other minor impacts on technology deployment and planting of miscanthus and SRC (e.g. due to competition for land in specific cells), therefore these cases were not taken as the preferred set of results.

An additional land change was the implementation of cell-based limits, as noted for scenarios 4 and 5 in Table 1 which were the final scenarios. As noted in section 3, BVCM operates on a grid of 157 50x50km cells representing the UK, with the cell map shown in section 8. The implementation of cell-based limits restricted the fraction of arable land, grass land, and forest land in each cell that could be planted with energy crops. This was instead of a national average limit, which is the default. The national average limit had allowed for significant amounts of planting in a smaller number of cells, as long as the national average limit was not breached. The cell-based limits for each land type are listed in Table 5. These are the default values in BVCM and were not altered for the current project.

Table 5: Fraction of each land type allowable for energy crop planting, when applying cell-based limits.

Land Type	Fraction of Cell Land Type Allowable for Energy Crop Planting
Arable	0.15
Grass	0.08
Forest	0.10 *

* Note that only SRF was allowed for planting on forest land. In practice, BVCM did not plant on any forest land due to direct land use change implications. See also the results data workbook (listed in section 7.3).

4.3.2. Energy & Greenhouse Gas Targets

BVCM utilises an energy and greenhouse gas target as part of its objective function.

The energy target is a minimum and maximum value for total end energy demand (i.e. the MWh/yr of electricity, hydrogen, liquid biofuels, etc produced from biomass). The greenhouse gas (GHG) target is the per decade target for greenhouse gas emissions which is set to a negative value in many decades to necessitate the use of BECCS technologies. In all scenarios modelled here, only the minimum energy target was of concern as this is typically the "hurdle" for the model to hit and then stop, unless another target or constraint necessitates it to go higher. Energy and GHG targets were set through a process of iteration, to ensure that the land area limits for energy crops were fully planted. This was required, as without sufficiently high energy and GHG targets, the model would not fully plant all of the land area limits for miscanthus, SRC and SRF, as there would be no use for the material beyond achieving these targets. The project was focused on where, spatially, the hectares of the three energy crops would be planted, therefore it was important to ensure that all of these hectares were fully planted.

The energy and GHG targets for the final Central Assumption cases, discussed in this report, are shown in Table 6. The energy and GHG targets for the final Reduced Ambition cases, discussed in this report, are shown in Table 7.

Table 6: Energy and GHG targets for the Central Assumption scenarios discussed in this report.

Case Setting		Decade	Relaxed Energy Targets + Cell-Based Limits (Scenario #4 In Table 1)	Relaxed Energy Targets + Cell-Based Limits + SRF Targets Brought Forward (Scenario #5 In Table 1)
End Energy Demand (MWh/yr)	Minimum	2010s	0	0
		2020s	273,833	273,833
		2030s	4,958,801	4,000,000
		2040s	8,000,000	8,500,000
		2050s	12,000,000	12,500,000
	Maximum	2010s	410,749	410,749
		2020s	410,749	410,749
		2030s	7,438,201	7,438,201
		2040s	15,000,000	15,000,000
		2050s	25,000,000	25,000,000
	2010s	infinite	infinite	

Case Setting	Decade	Relaxed Energy Targets + Cell-Based Limits (Scenario #4 In Table 1)	Relaxed Energy Targets + Cell-Based Limits + SRF Targets Brought Forward (Scenario #5 In Table 1)
Greenhouse Gas Target (MkgCO2e/decade)	2020s	20,000	20,000
	2030s	-15,000	-15,000
	2040s	-60,000	-65,000
	2050s	-80,000	-85,000
Additional Case Change(s)	Cell-based limits for the percentage of each cell that can be used for energy crop planting, instead of a national average limit		SRF land area limit brought forward from 2040's to 2030s to encourage model to fully plant SRF allocation

Table 7: Energy and GHG targets for the Reduced Ambition scenarios discussed in this report.

Case Setting		Decade	Relaxed Energy Targets + Cell-Based Limits (Scenario #4 In Table 1)	Relaxed Energy Targets + Cell-Based Limits + SRF Targets Brought Forward (Scenario #5 In Table 1)
End Energy Demand (MWh/yr)	Minimum	2010s	0	0
		2020s	273,833	273,833
		2030s	2,250,000	2,250,000
		2040s	7,000,000	7,500,000
		2050s	10,250,000	10,750,000
	Maximum	2010s	410,749	410,749
		2020s	410,749	410,749
		2030s	7,438,201	7,438,201
		2040s	15,000,000	15,000,000
		2050s	25,000,000	25,000,000
Greenhouse Gas Target (MkgCO2e/decade)	2010s	Infinite	infinite	
	2020s	20,000	20,000	
	2030s	-15,000	-15,000	
	2040s	-47,000	-50,000	
	2050s	-64,000	-67,000	
Additional Case Change(s)		Cell-based limits for the percentage of each cell that can be used for energy crop planting, instead of a national average limit		SRF land area limit brought forward from 2040's to 2030s to encourage model to fully plant SRF allocation

5. Results

The results of the final scenarios are presented here. They are:

- Section 5.1: Results for the Central Assumption scenarios.
 - Section 5.1.1: Results for scenario 4 (Table 1) – relaxed energy targets and cell-based planting limits.
 - Section 5.1.2: Results for scenario 5 (Table 1) - relaxed energy targets, cell-based planting limits, and SRF land area limit brought forward from the 2040s to the 2030s.
- Section 5.2: Results for the Reduced Ambition scenarios.
 - Section 5.2.1: Results for scenario 4 (Table 1) – relaxed energy targets and cell-based planting limits.
 - Section 5.2.2: Results for scenario 5 (Table 1) - relaxed energy targets, cell-based planting limits, and SRF land area limit brought forward from the 2040s to the 2030s.
- Section 5.3: Discussion of the overall trends and key findings across all scenarios.

In addition to the results presented here, the quantitative land use and yield data for all scenarios has been tabulated in a separate workbook (see section 7.3). The workbook contains data both for each BVCM cell (see map in section 8, Figure 14) and in an aggregated format on the basis of the International Territorial Level 1 (ITL1) regions of the UK (section 8, Figure 15). Furthermore, the CO_{2e} impacts from crop production, direct land use change, and CCS for each of the four scenarios has been tabulated in an appendix section 9.

5.1. Central Assumption

5.1.1. Relaxed Energy Targets & Cell-Based Limits

Figure 2 presents the value chain map for miscanthus in the 2050s. These value chain maps have been produced for all the Central Assumption and Reduced Ambition scenarios, as they provide a clear visualisation of the growth locations, transport needs, and end users of the three energy crops. As a result, the maps give an insight into the reasoning behind the model choosing to plant in certain locations.

As can be seen from Figure 2, miscanthus is largely modelled as grown along the east coast of England. The quantitative data on hectares per each ITL1 region is tabulated in Table 8, where it is again evident that essentially all miscanthus is grown in regions E (Yorkshire & Humber), F (East Midlands) and H (East of England). It is transported to BECCS facilities via either a combination of barge and truck, or by ship. It is used in power BECCS and hydrogen BECCS facilities, which are located on cells that are CO₂ sequestration locations: Humber and Bacton (refer to Table 2). This highlights one of the key findings across all cases in the model, which is that crop growth locations are heavily influenced by the location of end users, which largely being BECCS locations must be located at or very close to CO₂ sequestration locations. This behaviour is further discussed in section 5.3.

Figure 3 shows the SRF value chain in the 2050s. SRF is largely grown around the central England and Wales border region, primarily in the West Midlands ITL1 region at just under 50,000 of the 66,150 hectares planted in total (Table 8). SRF is largely chipped and then transported to an end user, often by road. End users of SRF are power BECCS facilities and large-scale combustion boilers for heat.

Figure 4 shows the SRC value chain in the 2050s. As is evident, SRC is primarily grown across the north and north west of England (~54,000 hectares, Table 8), as well as the west of Scotland (11,000 hectares, Table 8), and the breadth of Northern Ireland (~30,000 hectares, Table 8). SRC is transported primarily by road across England, and via ship when moving between nations, e.g. from Scotland to Northern Ireland. SRC is used in power BECCS facilities in Merseyside and Northern Ireland, in a hydrogen BECCS facility in Teesside, and in smaller quantities within large combustion boilers for heat across Northern Ireland, England and Scotland.

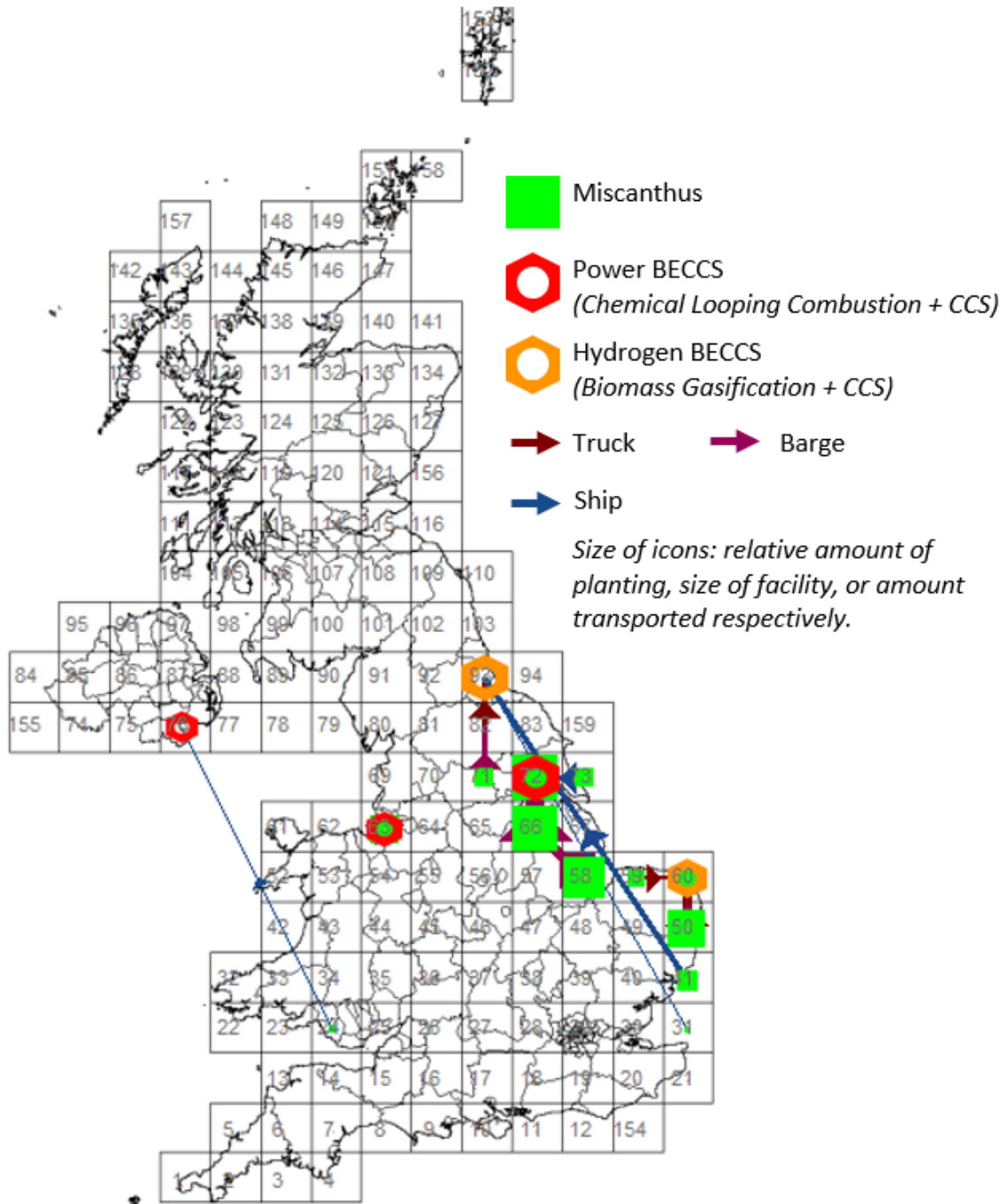


Figure 2: Miscanthus value chain map in the 2050s, for the Central Assumption scenario with relaxed energy targets and cell-based planting limits.

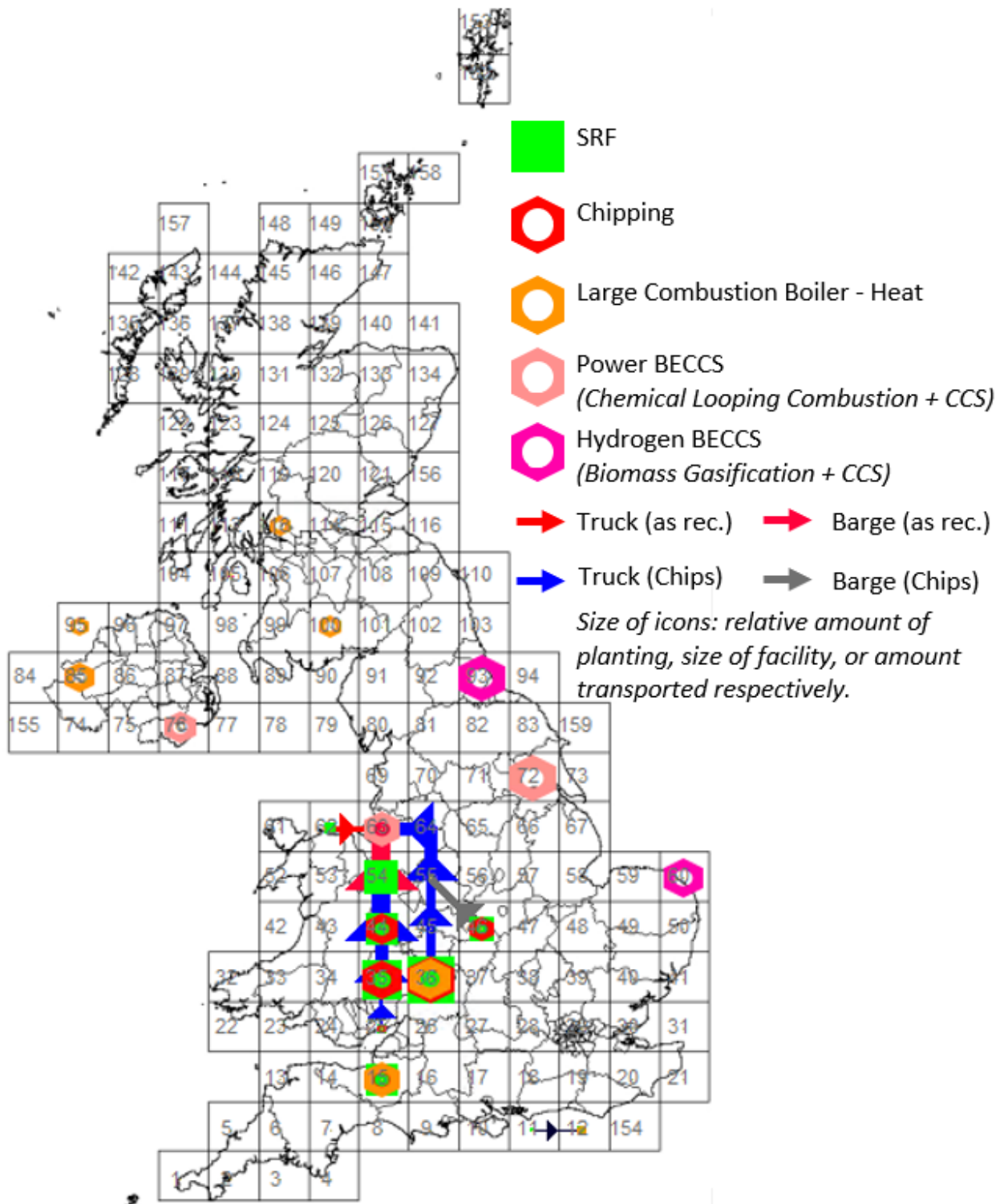


Figure 3: SRF value chain map in the 2050s, for the Central Assumption scenario with relaxed energy targets and cell-based planting limits.

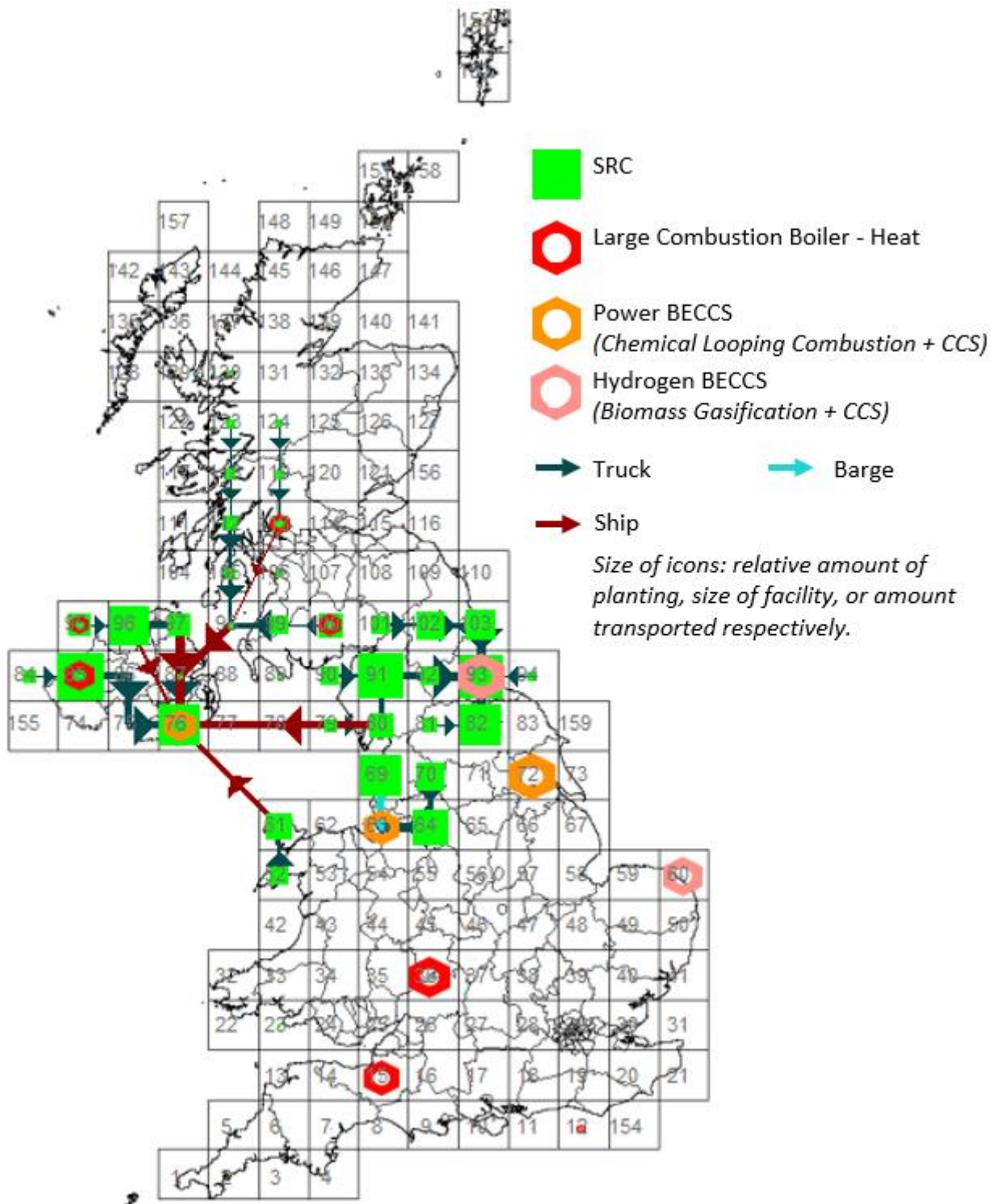


Figure 4: SRC value chain map in the 2050s, for the Central Assumption scenario with relaxed energy targets and cell-based planting limits.

Table 8: Land areas for each energy crop by ITL1 region for the Central Assumption scenario with relaxed energy targets and cell-based planting limits. Refer to section 8 for more information on the mapping of BVCM cells to ITL1 regions.

ITL1 NUTS Code	Land Type	Resource	2050s Hectares
C (North East)	Arable	Short Rotation Coppice	22,338
D (North West)	Arable	Short Rotation Coppice	12,401
D (North West)	Grass	Short Rotation Coppice	18,040
E (Yorkshire & Humber)	Arable	Short Rotation Coppice	10,076
E (Yorkshire & Humber)	Grass	Short Rotation Coppice	930
L (Wales)	Arable	Short Rotation Coppice	309
L (Wales)	Grass	Short Rotation Coppice	4,649
M (Scotland)	Arable	Short Rotation Coppice	6,010
M (Scotland)	Grass	Short Rotation Coppice	5,148
N (Northern Ireland)	Arable	Short Rotation Coppice	1,452
N (Northern Ireland)	Grass	Short Rotation Coppice	30,019
D (North West)	Arable	Miscanthus	9,404
E (Yorkshire & Humber)	Arable	Miscanthus	35,935
F (East Midlands)	Arable	Miscanthus	44,580
H (East of England)	Arable	Miscanthus	31,887
H (East of England)	Grass	Miscanthus	455
L (Wales)	Arable	Miscanthus	651
F (East Midlands)	Arable	Short Rotation Forestry	5,414
G (West Midlands)	Arable	Short Rotation Forestry	49,607
J (South East)	Arable	Short Rotation Forestry	641
K (South West)	Arable	Short Rotation Forestry	9,432
L (Wales)	Arable	Short Rotation Forestry	1,056

5.1.2. SRF Target Brought Forward

As discussed in sections 4.1 and 4.3.1, an alternative scenario was run for both the Central Assumption and Reduced Ambition, bringing forward the final SRF land area limit from the 2040s to the 2030s. This was because BVCM does not plant SRF in the 2040s, as SRF planted in the 2040s does not create a harvestable yield (as noted in section 4.1). Bringing forward this target by a decade does have some impact on results for all three energy crops, and the location of facilities in the 2050s, as the model optimiser has the combination of additional hectares of SRF to plant and utilise, as well as cell-based limits for planting energy crops which can often prevent the model simply planting more in the same cell(s). Therefore, value chain maps for all three energy crops are shown here.

Figure 5 shows the miscanthus value chain in the 2050s. Slight changes are evident versus the original case (Figure 2). Miscanthus is planted further south along the east coast, though it is clear from the ITL 1 quantitative data that the vast majority of miscanthus planting is still along the regions covering east coast of England (Table 9). The locations of power BECCS and hydrogen BECCS facilities have also been swapped, versus Figure 2. Power BECCS facilities are at Bacton and Teesside (instead of Merseyside and Humber), and hydrogen BECCS facilities are at Merseyside and Humber (instead of Teesside and Bacton).

Figure 6 shows the SRF value chain in the 2050s. As in the original case, there is planting in the central England border region with Wales, but there is additional planting both further into central England (~24,000 hectares in the East Midlands, Table 9), and around the east coast of England (~33,000 hectares, Table 9). This additional planting towards the east coast of England is likely to have been a key driver to the previously mentioned planting changes to miscanthus, pushing it to be planted further south along the east coast. The underlying cause of this is likely to be the cell-based limits for energy crop planting. SRF is almost entirely chipped and then transported. It is used mostly in hydrogen BECCS, in Merseyside, and power BECCS in Bacton. A smaller fraction used in large combustion boilers for heat, co-located with feedstock growth.

Figure 7 shows the SRC value chain in the 2050s. Planting patterns are very similar to the original case (Figure 4), with SRC being planted across the north and north west of England (~63,000 hectares, Table 9), the west of Scotland (~15,000 hectares, Table 9), and the north west of Northern Ireland (~12,000 hectares, Table 9). Minor amounts of planting also occur in the south west of England and in Wales (Table 9). There is reduced planting in Northern Ireland, and notably the absence of a BECCS facility in Northern Ireland versus the original case. This suggests that the Northern Ireland BECCS facility which was present in the original case (Figure 4) is a relatively marginal selection by the model optimiser, and is not a frequent choice, unlike for example facilities in Humberside and Merseyside which are deployed across all the scenarios. SRC is used primarily in power BECCS, and large combustion boilers for heat, with a small fraction used in hydrogen BECCS facilities. Versus the original case, SRF in general has been prioritised for hydrogen BECCS, with SRC instead used in large combustion boilers for heat co-located with feedstock growth.

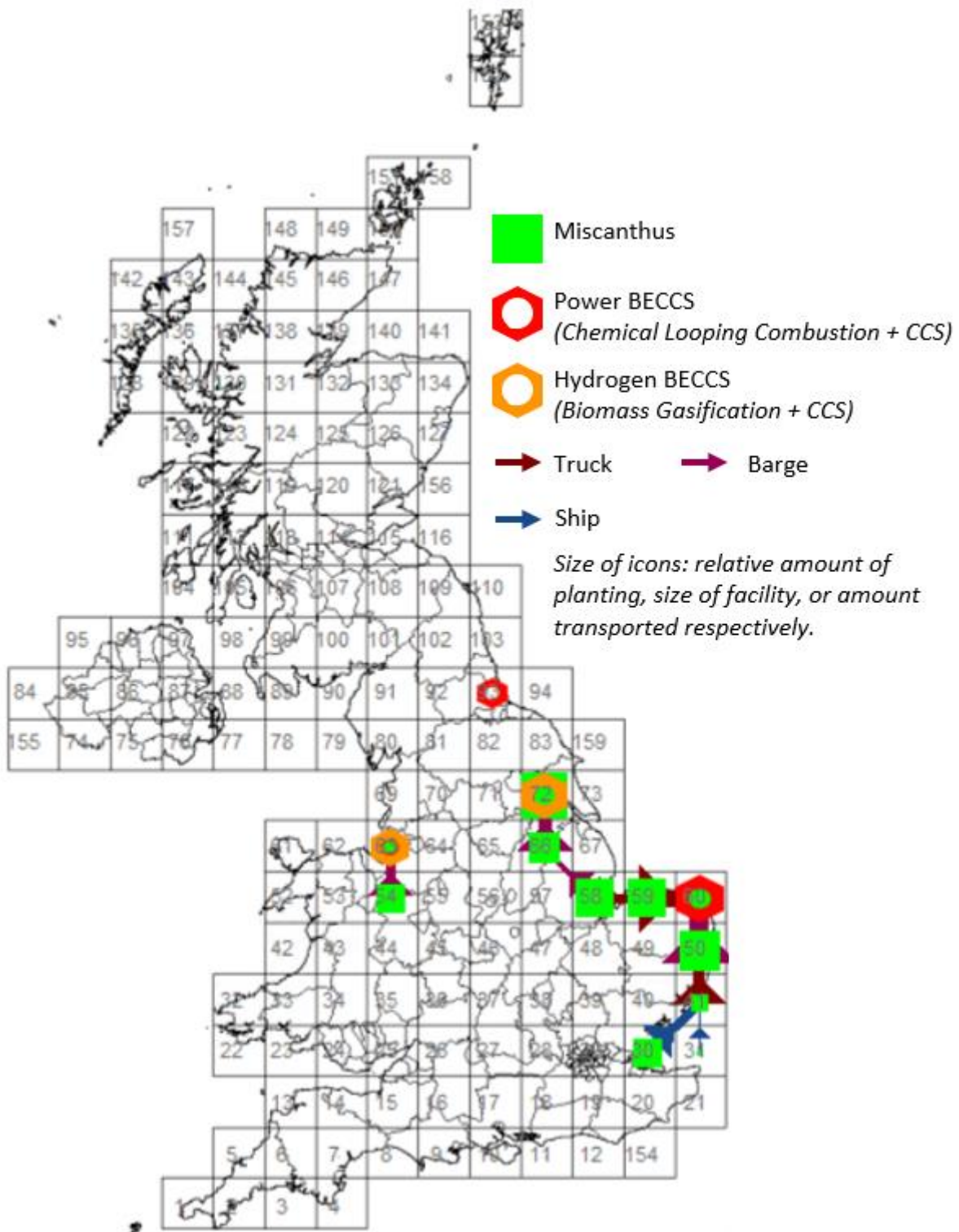


Figure 5: Miscanthus value chain map in the 2050s, for the Central Assumption scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s.

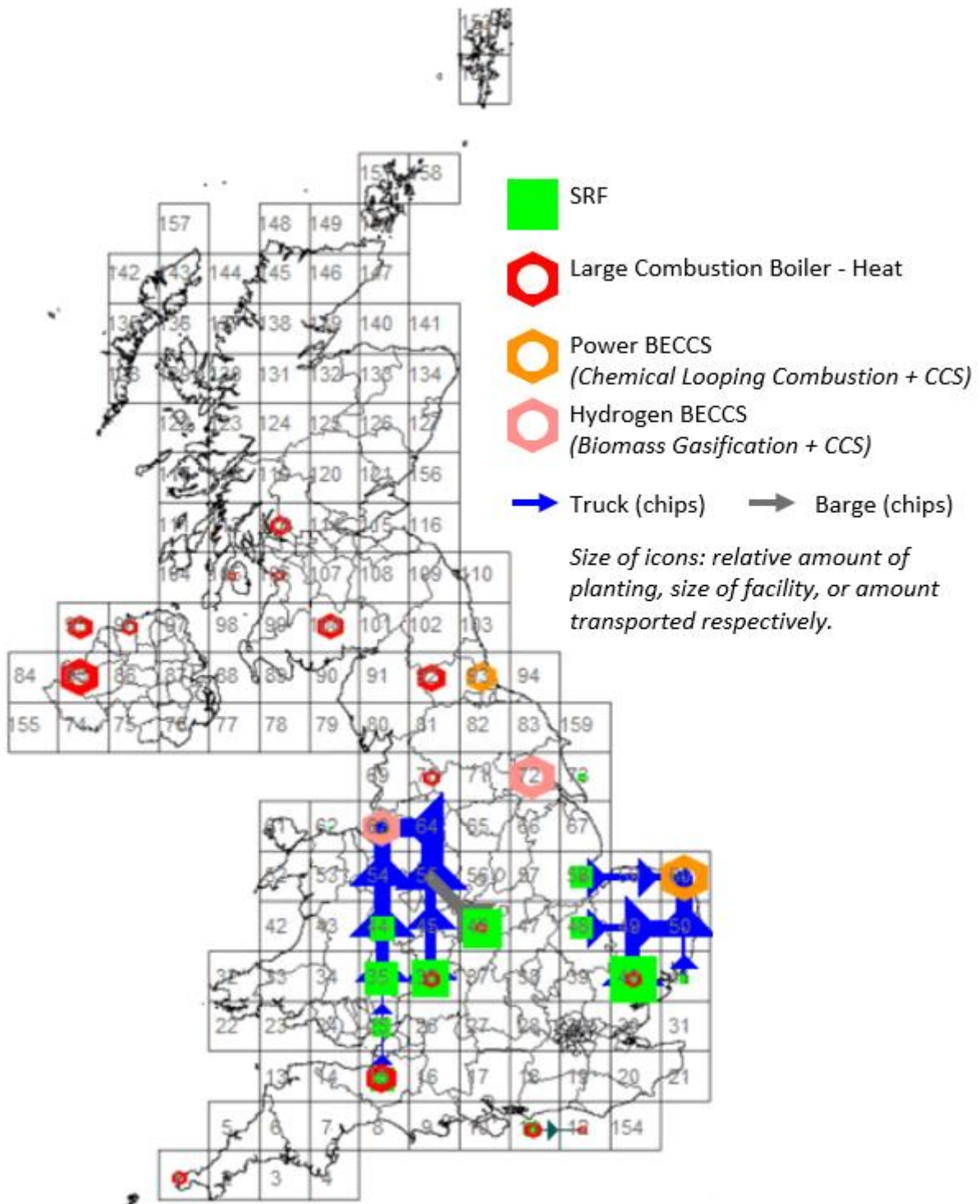


Figure 6: SRF value chain map in the 2050s, for the Central Assumption scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s.

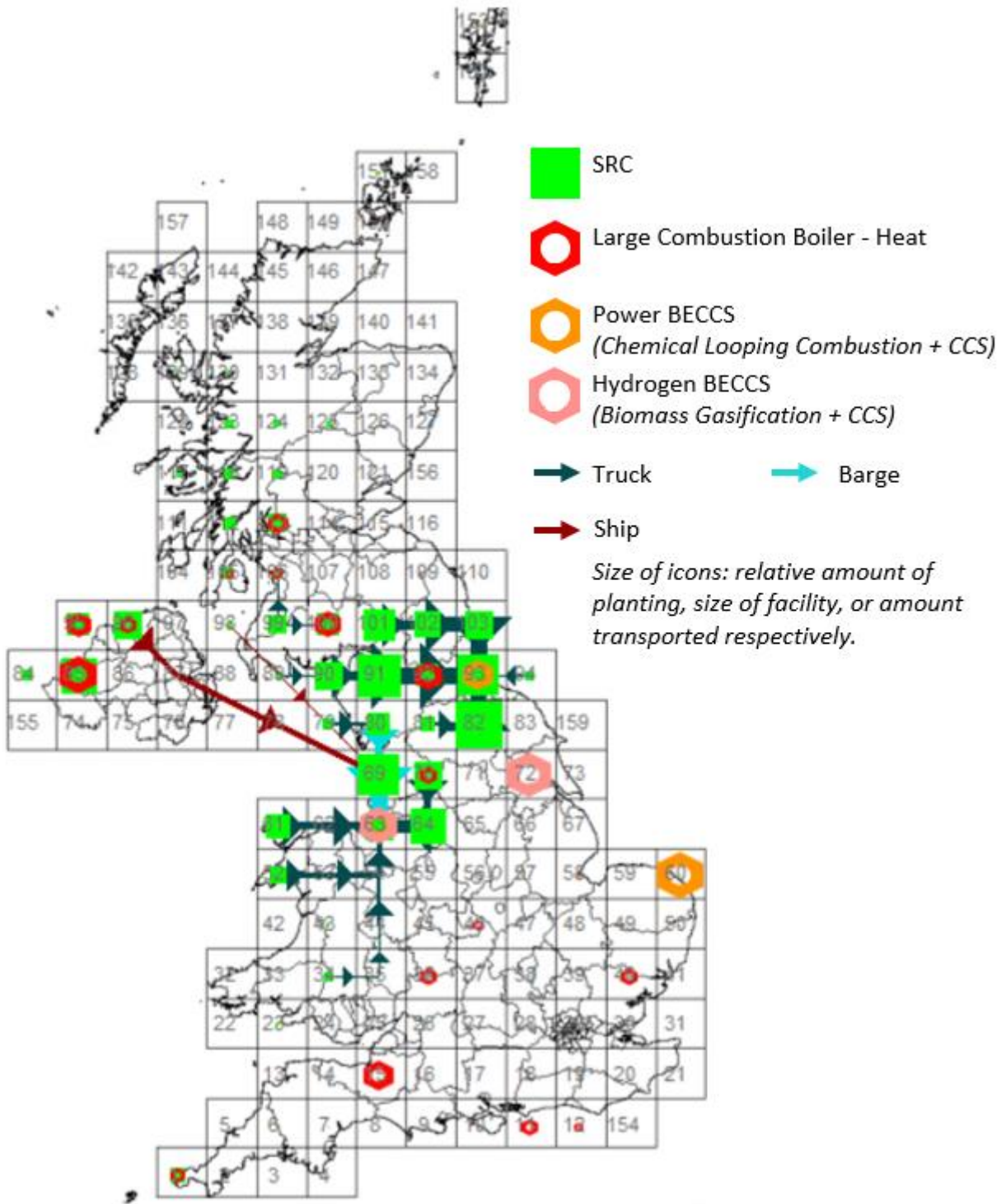


Figure 7: SRC value chain map in the 2050s, for the Central Assumption scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s.

Table 9: Land areas for each energy crop by ITL1 region, for the Central Assumption scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s. Refer to section 8 for more information on the mapping of BVCM cells to ITL1 regions.

ITL1 NUTS Code	Land Type	Resource	2050s Hectares
C (North East)	Arable	Short Rotation Coppice	22,338
C (North East)	Grass	Short Rotation Coppice	1,305
D (North West)	Arable	Short Rotation Coppice	17,194
D (North West)	Grass	Short Rotation Coppice	20,644
E (Yorkshire & Humber)	Arable	Short Rotation Coppice	14,130
E (Yorkshire & Humber)	Grass	Short Rotation Coppice	930
K (South West)	Arable	Short Rotation Coppice	1,286
L (Wales)	Arable	Short Rotation Coppice	991
L (Wales)	Grass	Short Rotation Coppice	4,649
M (Scotland)	Arable	Short Rotation Coppice	6,094
M (Scotland)	Grass	Short Rotation Coppice	9,160
N (Northern Ireland)	Arable	Short Rotation Coppice	795
N (Northern Ireland)	Grass	Short Rotation Coppice	11,857
D (North West)	Arable	Miscanthus	4,611
E (Yorkshire & Humber)	Arable	Miscanthus	26,753
F (East Midlands)	Arable	Miscanthus	27,162
G (West Midlands)	Arable	Miscanthus	10,090
H (East of England)	Arable	Miscanthus	52,395
H (East of England)	Grass	Miscanthus	1,900
E (Yorkshire & Humber)	Arable	Short Rotation Forestry	4,070
E (Yorkshire & Humber)	Grass	Short Rotation Forestry	38
F (East Midlands)	Arable	Short Rotation Forestry	24,154
G (West Midlands)	Arable	Short Rotation Forestry	39,517
H (East of England)	Arable	Short Rotation Forestry	33,640
J (South East)	Arable	Short Rotation Forestry	3,564
K (South West)	Arable	Short Rotation Forestry	16,110
L (Wales)	Arable	Short Rotation Forestry	1,056

5.2. Reduced Ambition

5.2.1. Relaxed Energy Targets & Cell-Based Limits

Figure 8 shows the miscanthus value chain map in the 2050s for the Reduced Ambition scenario. Miscanthus is grown along the east coast of England and used in BECCS facilities in Humberside and Bacton, as well as around the Merseyside region again for use in BECCS facilities. This is similar to the Central Assumption case (Figure 2). Some aspects differ versus the Central Assumption. There is miscanthus planting in the Teesside region, and the planting towards the south of the border between England and Wales. These planting differences are reflected in the quantitative data by ITL1 region for miscanthus as shown in Table 10, though once again the east of England and Yorkshire and Humber regions combined account for the majority of miscanthus planting at ~64,000 hectares.

Figure 9 shows the SRF value chain map in the 2050s. SRF is mostly grown along the England and Wales border region, though slightly more towards the south and into south west England in comparison to the Central Assumption (Figure 3). This is reflected in the quantitative data by ITL1 region, with ~16,000 hectares of SRF grown in each of the West Midlands and the south west regions (Table 10). In this case, there is also additional planting around the Humberside region. SRF is mostly chipped prior to use, and is used across power BECCS, hydrogen BECCS. A small quantity is used in large combustion boilers for heat (cell 36).

Figure 10 shows the SRC value chain map in the 2050s. SRC is planted across the north and north west of England (~42,000 hectares, Table 10), west of Scotland (~8,000 hectares, Table 10), and Northern Ireland (~4,500 hectares, Table 10). This is very similar to the trend seen in the Central Assumption scenario (Figure 4). SRC is mostly used in power BECCS facilities in Teesside and Merseyside, with a small proportion used in large combustion boilers for heat co-located with feedstock planting. SRC is mostly transported via a combination of road and ship.

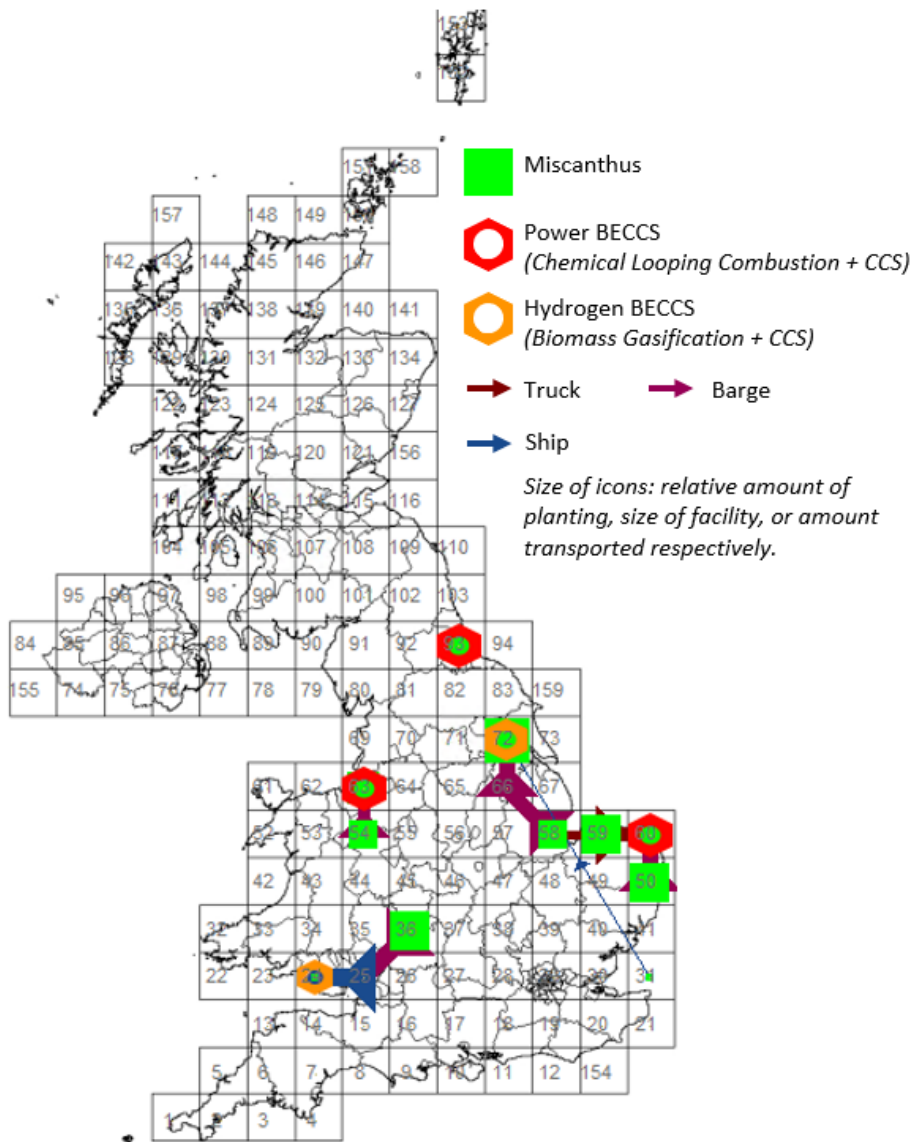


Figure 8: Miscanthus value chain map in the 2050s, for the Reduced Ambition scenario with relaxed energy targets and cell-based planting limits.

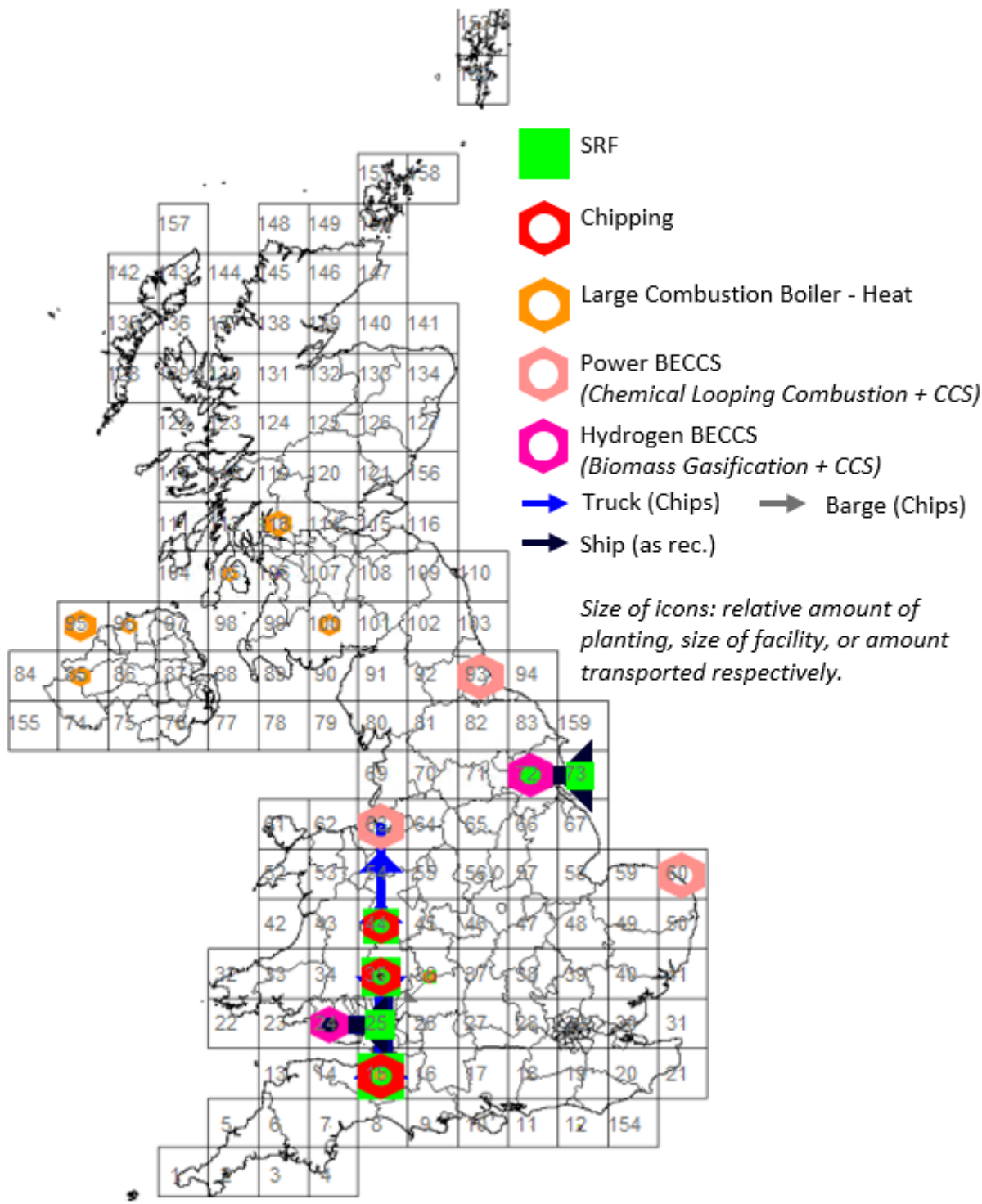


Figure 9: SRF value chain map in the 2050s, for the Reduced Ambition scenario with relaxed energy targets and cell-based planting limits.

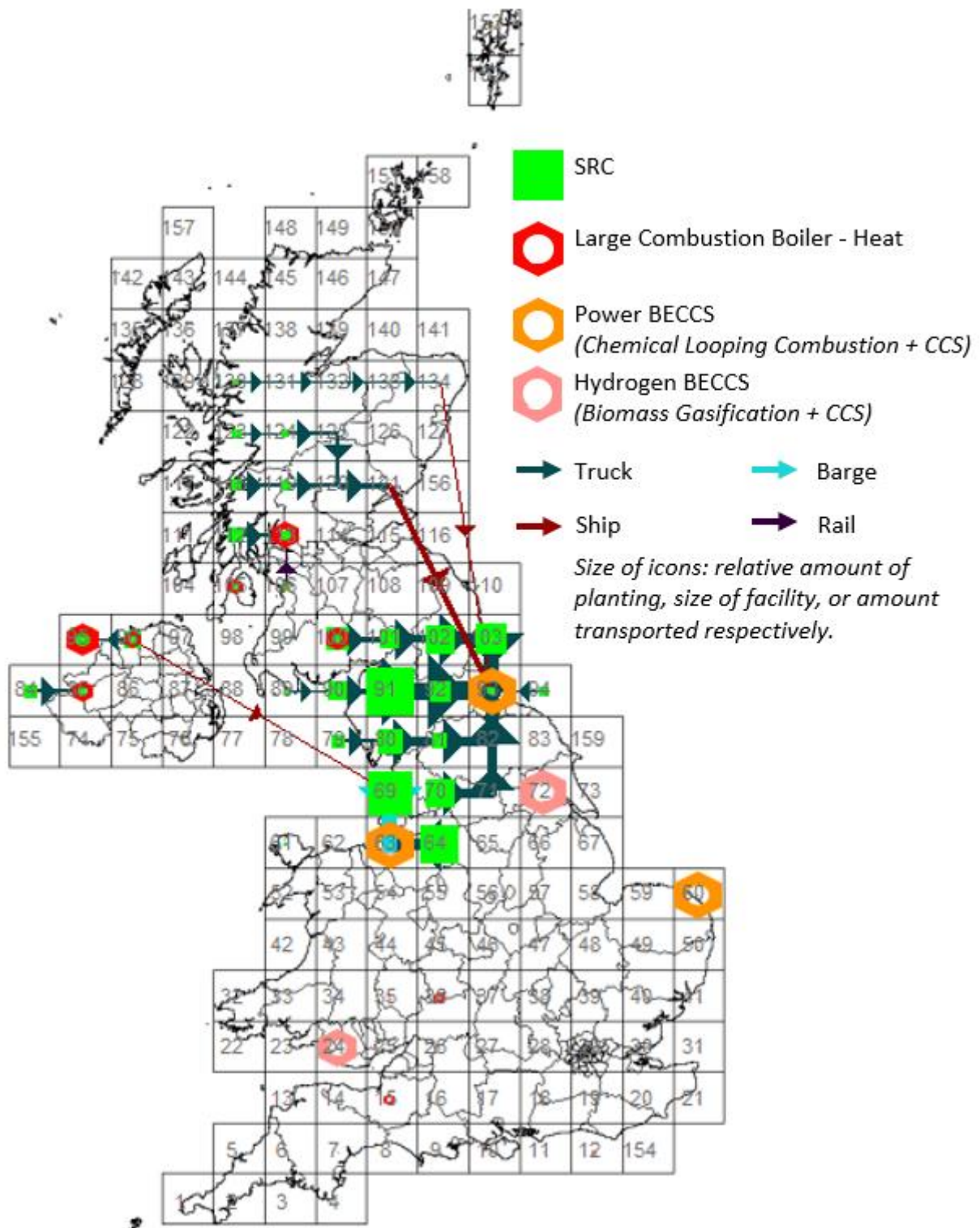


Figure 10: SRC value chain map in the 2050s, for the Reduced Ambition scenario with relaxed energy targets and cell-based planting limits.

Table 10: Land areas for each energy crop by ITL1 region for the Reduced Ambition scenario with relaxed energy targets and cell-based planting limits. Refer to section 8 for more information on the mapping of BVCM cells to ITL1 regions.

ITL1 NUTS Code	Land Type	Resource	2050s Hectares
C (North East)	Arable	Short Rotation Coppice	11,867
C (North East)	Grass	Short Rotation Coppice	369
D (North West)	Arable	Short Rotation Coppice	12,401
D (North West)	Grass	Short Rotation Coppice	18,040
E (Yorkshire & Humber)	Grass	Short Rotation Coppice	930
L (Wales)	Arable	Short Rotation Coppice	135
M (Scotland)	Arable	Short Rotation Coppice	5,883
M (Scotland)	Grass	Short Rotation Coppice	2,570
N (Northern Ireland)	Arable	Short Rotation Coppice	735
N (Northern Ireland)	Grass	Short Rotation Coppice	3,772
C (North East)	Arable	Miscanthus	10,470
D (North West)	Arable	Miscanthus	9,404
D (North West)	Grass	Miscanthus	2,407
E (Yorkshire & Humber)	Arable	Miscanthus	23,106
F (East Midlands)	Arable	Miscanthus	8,918
G (West Midlands)	Arable	Miscanthus	26,561
H (East of England)	Arable	Miscanthus	40,820
H (East of England)	Grass	Miscanthus	455
L (Wales)	Arable	Miscanthus	770
E (Yorkshire & Humber)	Arable	Short Rotation Forestry	7,717
G (West Midlands)	Arable	Short Rotation Forestry	16,447
J (South East)	Arable	Short Rotation Forestry	676
K (South West)	Arable	Short Rotation Forestry	16,110

5.2.2. SRF Target Brought Forward

Figure 11 shows the miscanthus value chain map in the 2050s for the Reduced Ambition scenario, after bringing forward the SRF planting area limit by a decade. As noted for the equivalent Central Assumption scenario in section 5.1.2, adjusting the SRF area limit does have an impact on the overall planting of all three energy crops. From Figure 11, it is evident that miscanthus planting shifted in the east coast of England region, with some occurring further inland versus the standard scenario (Figure 8). Planting has been maintained in the Humberside region, Merseyside region, and towards the south of the England and Wales border similar to the standard scenario. These planting trends are also clear within ITL1 tabulation of miscanthus planting data (Table 11) where the majority of the miscanthus planting occurs across the east of England, East Midlands, and Yorkshire & Humbers regions (a total of ~89,000 hectares). Miscanthus is heavily used in power BECCS, with a smaller fraction used in hydrogen BECCS.

Figure 12 shows the value chain map for SRF in the 2050s. SRF is once again grown along the England and Wales border, though more so into the south west of England. SRF is additionally planted in the east of England. This is likely a driver of the shifting of miscanthus planting patterns in this area, and is the same behaviour exhibited when moving from the normal SRF land area target scenario to bringing forward the SRF land area target for the Central Assumption (section 5.1). It is also evident within the quantitative ITL1 data, with SRF planting relatively evenly spreads across the East Midlands, West Midlands and south west regions (Table 11). SRF is mostly chipped and then transported and used across a split of power BECCS and hydrogen BECCS.

Figure 13 shows the value chain map for SRC in the 2050s. SRC planting is more so across the north west of England, rather than the full breadth of the north of England. This is evident in the quantitative data (Table 11) where ~27,000 hectares are planted in the north west, but only ~5,500 hectares in the north east. SRC is also planted across the west of Scotland (~8,500 hectares, (Table 11) and Northern Ireland (~12,000 hectares, (Table 11), as seen in prior scenarios. There is also some very minor planting across Wales. It is largely transported by road, and used in either power BECCS in Merseyside, or in large combustion boilers for heat co-located with feedstock growth, a behaviour seen across a variety of the scenarios reported here.

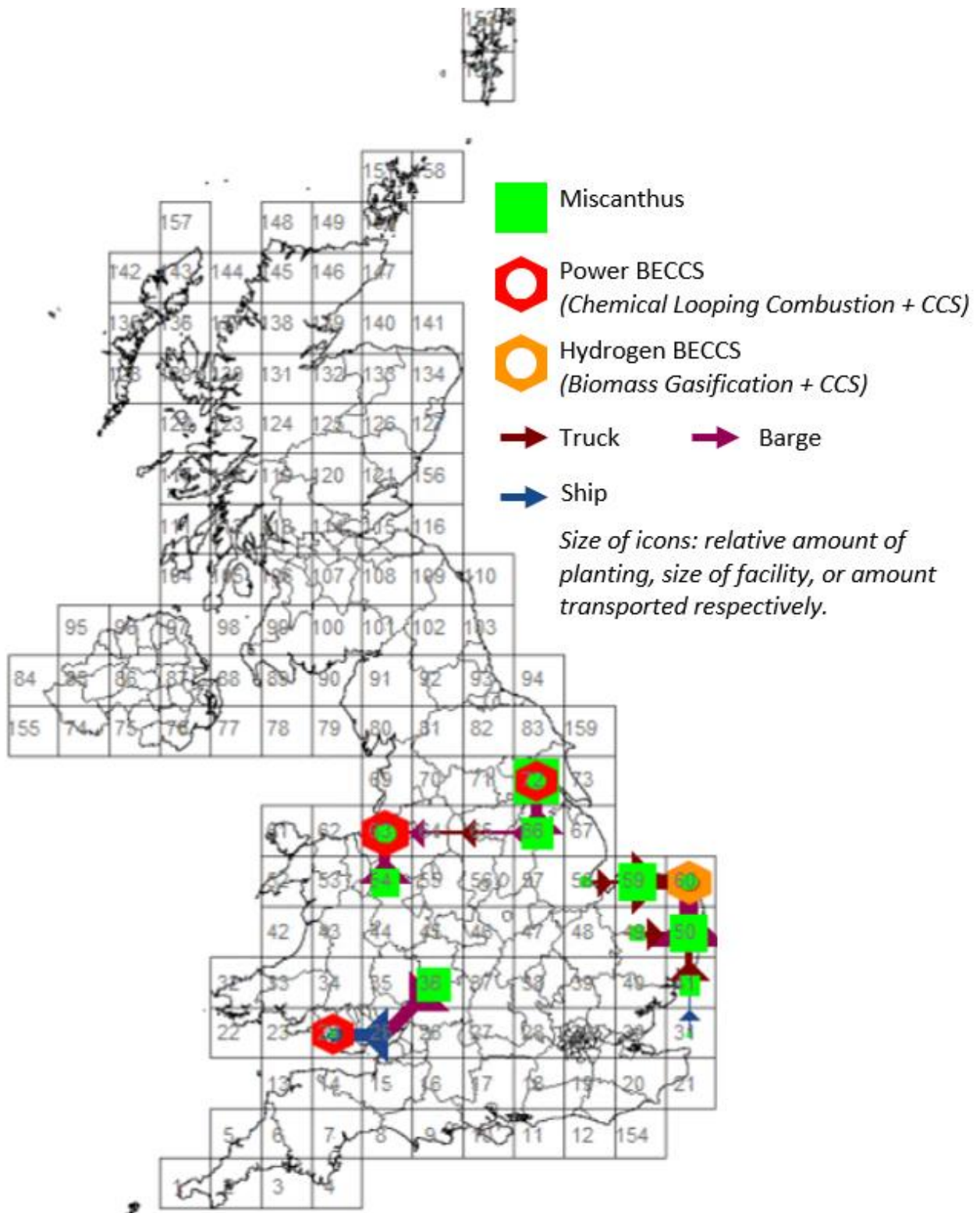


Figure 11: Miscanthus value chain map in the 2050s, for the Reduced Ambition scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s.

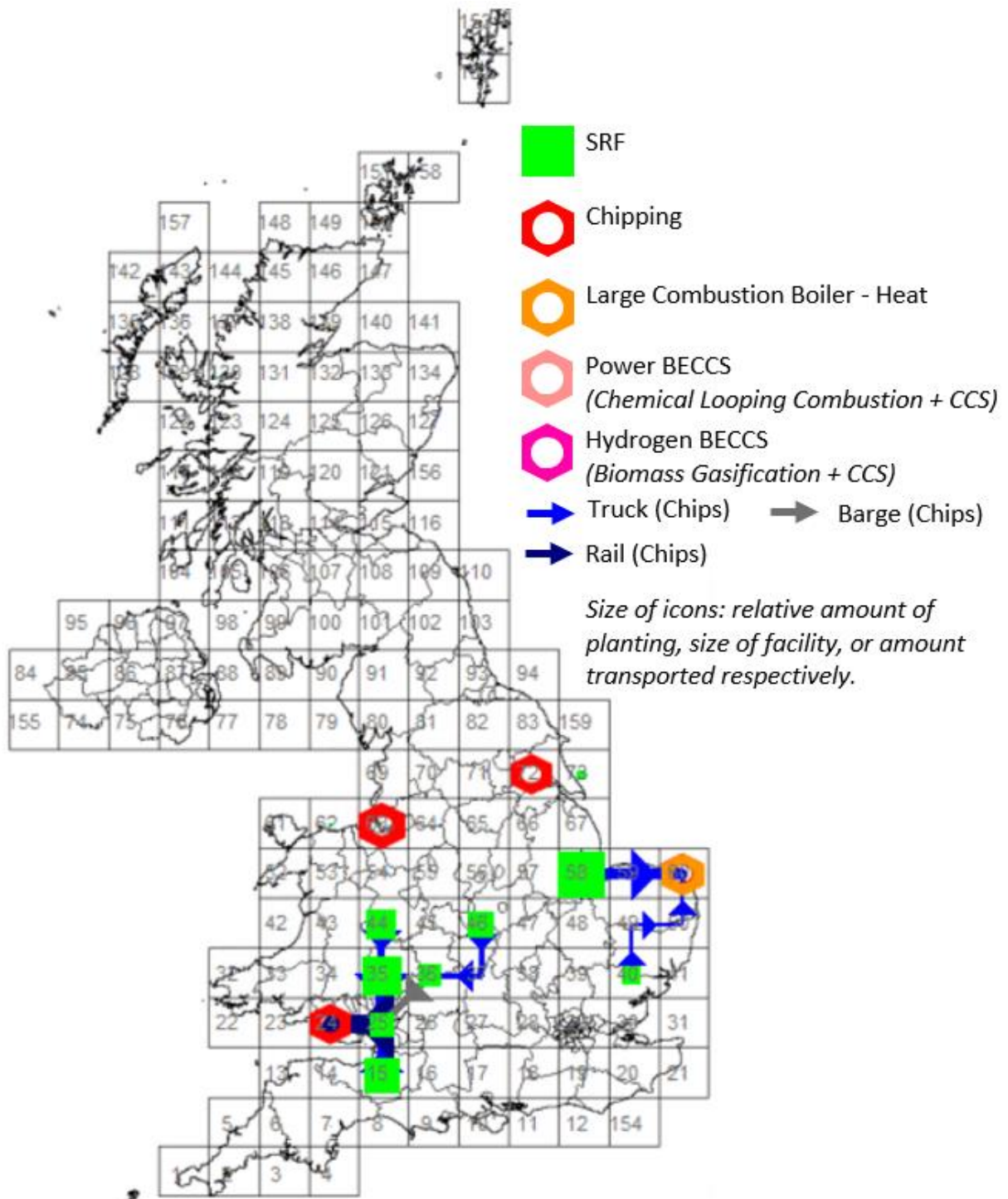


Figure 12: SRF value chain map in the 2050s, for the Reduced Ambition scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s.

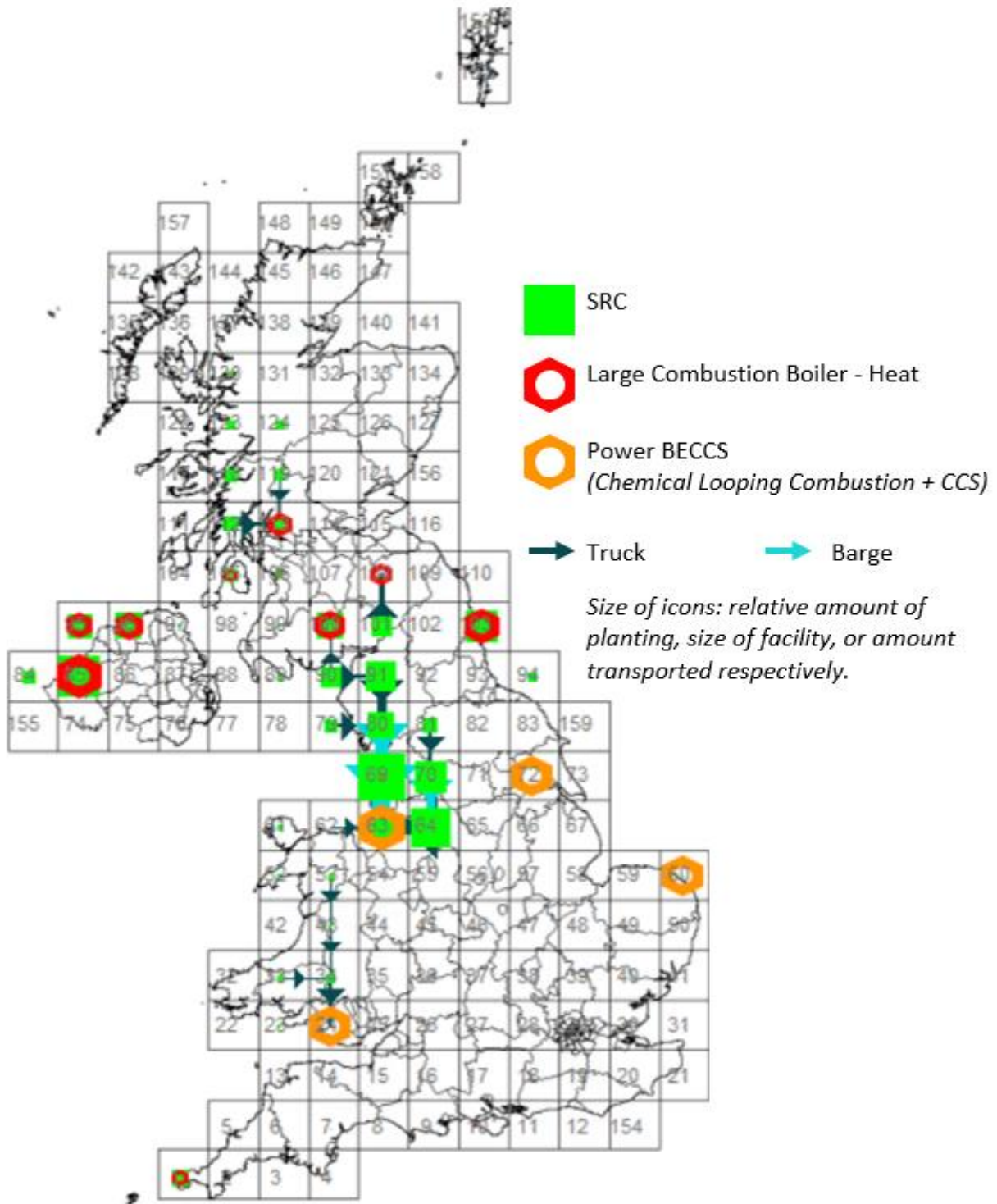


Figure 13: SRC value chain map in the 2050s, for the Reduced Ambition scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s. Note that for some cells transport arrows are not present – this is due to rendering limits in the model, as arrow sizes are proportional to material flows which are very small for some cells.

Table 11: Land areas for each energy crop by ITL1 region, for the Reduced Ambition scenario with relaxed energy targets, cell-based planting limits, and the SRF planting limit brought forward from the 2040s to the 2030s. Refer to section 8 for more information on the mapping of BVCM cells to ITL1 regions.

ITL1 NUTS Code	Land Type	Resource	2050s Hectares
C (North East)	Arable	Short Rotation Coppice	5,459
D (North West)	Arable	Short Rotation Coppice	15,174
D (North West)	Grass	Short Rotation Coppice	12,030
E (Yorkshire & Humber)	Grass	Short Rotation Coppice	930
K (South West)	Arable	Short Rotation Coppice	1,286
L (Wales)	Arable	Short Rotation Coppice	1,461
M (Scotland)	Arable	Short Rotation Coppice	6,010
M (Scotland)	Grass	Short Rotation Coppice	2,560
N (Northern Ireland)	Arable	Short Rotation Coppice	735
N (Northern Ireland)	Grass	Short Rotation Coppice	11,056
D (North West)	Arable	Miscanthus	6,631
D (North West)	Grass	Miscanthus	2,407
E (Yorkshire & Humber)	Arable	Miscanthus	26,753
F (East Midlands)	Arable	Miscanthus	14,517
G (West Midlands)	Arable	Miscanthus	23,240
H (East of England)	Arable	Miscanthus	48,243
H (East of England)	Grass	Miscanthus	455
L (Wales)	Arable	Miscanthus	666
E (Yorkshire & Humber)	Arable	Short Rotation Forestry	4,070
E (Yorkshire & Humber)	Grass	Short Rotation Forestry	38
F (East Midlands)	Arable	Short Rotation Forestry	24,988
G (West Midlands)	Arable	Short Rotation Forestry	26,368
H (East of England)	Arable	Short Rotation Forestry	3,379
K (South West)	Arable	Short Rotation Forestry	16,110
L (Wales)	Arable	Short Rotation Forestry	997

5.3. Discussion

Common across both variants of the Central Assumption and Reduced Ambition scenarios was miscanthus planting along the east coast of England, from the Humber region to as far south as Essex. This miscanthus was used in BECCS facilities in the Humber cluster or at Bacton. Where there was the additional need for SRF hectares to be planted, this typically caused miscanthus planting to also occur slightly inland in the east of England. Miscanthus was often also planted on or immediately around the Merseyside and Teesside clusters to supply BECCS facilities in these clusters. In the Reduced Ambition scenario, some limited planting was also seen towards the south of the border between England and Wales, for use in a BECCS facility in South Wales.

With regards to SRF, under the standard planting profile for both the Central Assumption and Reduced Ambition, planting occurred largely in the England and Wales border region. In the Reduced Ambition scenario specifically, it was shifted slightly southwards more towards the south west of England. Under the alternative scenarios for each, when the SRF planting limit was brought forward to ensure full planting of the final decades' hectares, additional SRF planting occurred close to the coast in the east of England, between Humber and Bacton as BECCS locations.

Across all the scenarios, SRC was consistently planted mostly in the north and north west of England, with a smaller proportion of planting in the west of Scotland and Northern Ireland. SRC planting typically occurred across many cells, and frequently relied on road transport to end users.

With regards to the end user technologies, across all cases in the 2050s BECCS facilities (either power or hydrogen) were the main users, alongside large combustion boilers for heat. The use of some large combustion boilers for heat may stand out, given the governments future focus on BECCS for bioenergy resource, stated in the Biomass Strategy [1]. However, it should be noted that the energy facilities built by BVCM are influenced by the energy and GHG removal demands specified as part of the objective function of the model (as shown in Figure 1). The energy and GHG demands set in this work were not supplied by DESNZ and were instead set iteratively based on ensuring full planting of all land area allocations for each of the three energy crops. Therefore, an avenue for further work would be to utilise any future government targets for the production of different energy vectors from bioenergy (e.g. production of electricity, hydrogen, aviation fuels) as well as future any future government targets for GHG removals from BECCS to 2050. This would help to further refine the bioenergy pathways produced here.

One of the key observations across all of the scenarios presented here is that the locations of BECCS facilities, which were influenced by the location of CO₂ sequestration infrastructure, which then drove a lot of the planting choices. This is a result of BVCM optimising the combination of where resources are planted, how and the distance over which they are transported, and the end user energy facility location. A few BECCS locations were common across all of the scenarios for both the Central Assumption and Reduced Ambition cases. These locations were Bacton, Humber and Merseyside. The secondary locations for BECCS facilities, i.e. those which featured in some but not all of the

scenarios, were Teesside, South Wales, and Northern Ireland. Of these, Teesside was the most common, and thus would appear to be the most attractive of these “secondary” locations. South Wales was also relatively common, though would necessitate CO₂ shipping to storage, thus incurring additional costs. The importance of considering both planting locations and the locations of BECCS facilities was highlighted in prior work using BVCM by the ETI [3]. Broadly, this suggests that one of the key factors to consider into the future is ensuring the alignment of where and when BECCS facilities will be developed, with the location of large-scale feedstock planting efforts.

6. Conclusion

This project has investigated the planting locations of miscanthus, SRF and SRC in 2050 using a Central Assumption and Reduced Ambition land area limit for each. The key planting trends in the 2050s for the three energy crops across all scenarios were:

- Miscanthus is typically planted along the east coast of England, from Humberside to as far south as Essex, and used in BECCS facilities in East Norfolk or the Humber cluster. It is also frequently planted to a smaller degree in or around Merseyside and Teesside to supply BECCS facilities in these clusters.
- SRF was typically planted along the England and Wales border region to supply BECCS facilities in the Merseyside and South Wales clusters, or for use in large-scale combustion boilers for heat co-located with feedstock growth.
- SRC is typically planted across the north west and north of England, the west of Scotland, and Northern Ireland. SRC is used in BECCS facilities mostly in either Merseyside or Teesside, or in large-scale combustion boilers for heat co-located with feedstock growth.

One of the key observations across the scenarios is that the presence and location of end user facilities influenced where energy crops were grown. For example, Cornwall and the south coast of England presented little opportunity for planting due to the lack of nearby major end user facilities. The major end users were BECCS facilities (hydrogen or power BECCS), and these had to be located at or very close to CCS infrastructure locations. An additional user was large combustion boilers for heat, but these were again co-located where there was both the planting of feedstock and sufficient heat demand.

Beyond the planting trends and locational opportunities noted previously, this project has highlighted the importance of considering the location and scale of end user demand for energy crops, rather than simply the potential or yield of a parcel of land.

A final point of note is that whilst waste feedstocks were not modelled in the final Central Assumption and Reduced Ambition scenarios, wastes were the "first choice" feedstocks before planting of energy crops as seen in Phase 1 of this project (see appendix section 10). This prioritisation behaviour should also be considered for future work around the total availability and utilisation of biomass resource in the UK.

6.1. Recommendations for Future Work

There are several areas for future work that may be of interest following on from this study:

- Modelling scenarios with a more detailed view of end energy demand targets and GHG removals from BECCS. Work here has shown the importance of considering planting locations and end users together. It would therefore be of interest to add detail to end energy demands, for example with regards to domestic production of sustainable aviation fuels, production of hydrogen from biomass, and BECCS GHG removal needs.
- Modelling scenarios with biomass imports. Imports of biomass were not considered in the present scenario but may account for a significant amount of future UK

biomass supply in the future. It would be of interest to consider scenarios with varying levels of import availability, and how this impacts planting and end user facility construction.

- Modelling of each nation of the UK. One aspect highlighted over the course of the project was that most planting occurred in England, with limited opportunities in other nations. This led to the standalone Northern Ireland Assessment, which was not a modelling-based study (see report noted in section 7.3). The devolved administrations will have differing ambitions with regards to future land use, energy crop planting, and the role of bioenergy. BVCM as a toolkit can be configured to enable or disable any or all of the UK cells. Therefore, it would be possible to set up separate studies looking at any or all of the four nations within the UK, and then cross compare versus reference cases for the UK as a whole.
- The analysis process performed in the standalone Northern Ireland assessment noted that there appeared to be uncertainty with regards to CCS options for Northern Ireland (see report noted in section 7.3). This was principally around transport and storage options, which would consequently impact BECCS potential, as would energy crop growth potential in Northern Ireland. It may be of interest to perform a broader modelling study around CCS, BECCS and perhaps also direct air capture options for Northern Ireland to achieve its' decarbonisation goals. This would provide clarity and help alignment with efforts across the other nations within the UK.

7. Appendix A: Acronyms, References & Deliverables

7.1. Acronyms

ALC	Agricultural Land Classification (England and Wales)
BECCS	Bioenergy with carbon capture and storage
BVCM	Bioenergy Value Chain Model
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
Defra	Department for Environment, Food and Rural Affairs
DESNZ	Department for Energy Security and Net Zero
ETI	Energy Technologies Institute
GHG	Greenhouse gas
ha	Hectare
ITL1	International Territorial Level 1
LHV	Lower heating value
Mt	Million tonne
MWh	Megawatt-hour
RDF	Refuse derived fuel
SRC	Short rotation coppice
SRF	Short rotation forestry
TWh	Terawatt-hour

7.2. References

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7.3. Project Deliverables List

Table 12: Project deliverables list.

Deliverable File Name	Format	Description
EIRO2.0 BVCM Modelling_Final Report	PDF	This Final Report document
EIRO 2.0 BVCM Modelling_Central Assumption Results Full Slide Deck	PowerPoint	All results presented on the various Central Assumption scenarios (scenarios listed in Table 1)
EIRO 2.0 BVCM Modelling_Reduced Ambition Results Full Slide Deck	PowerPoint	All results presented on the various Reduced Ambition scenarios (scenarios listed in Table 1)
EIRO2.0 BVCM Modelling_Input Data Summary	Excel Workbook	BVCM input data changes and settings for each "Phase 2" case modelled.
EIRO2.0 BVCM Modelling_Results Land and Yield Data	Excel Workbook	Land area and yield data for all scenarios. Data is presented both on a per BVCM cell format and aggregated up to ITL1 regions.
EIRO2 BVCM Modelling_NI Assessment	PDF	Short standalone report covering the Northern Ireland assessment
EIRO2.0 BVCM Modelling_NI BECCS & Bioenergy Crop Potential	Excel Workbook	Data & analysis associated with the standalone Northern Ireland assessment.
EIRO2.0 BVCM Modelling_Phase 1 Summary	PowerPoint	Summary slide deck covering the results of Case A, B, and C from "Phase 1" of the project.

8. Appendix B: BVCM Cell Mapping & ITL1 Correlation

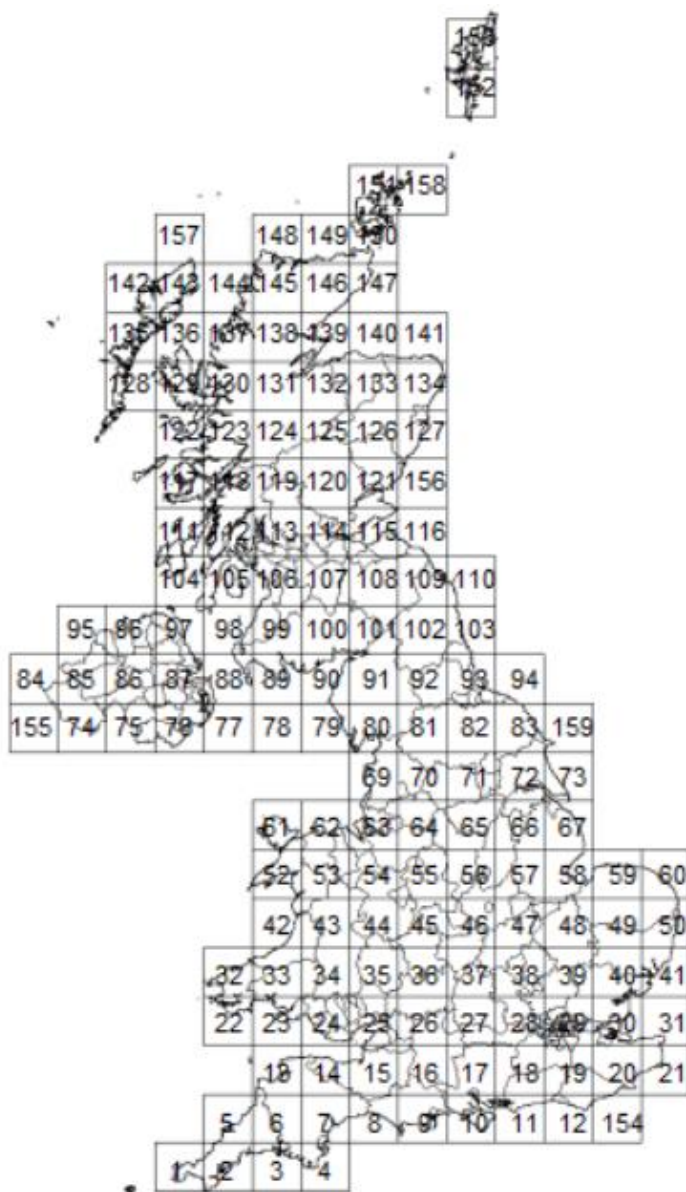


Figure 14: Map of the cells in BVCM.

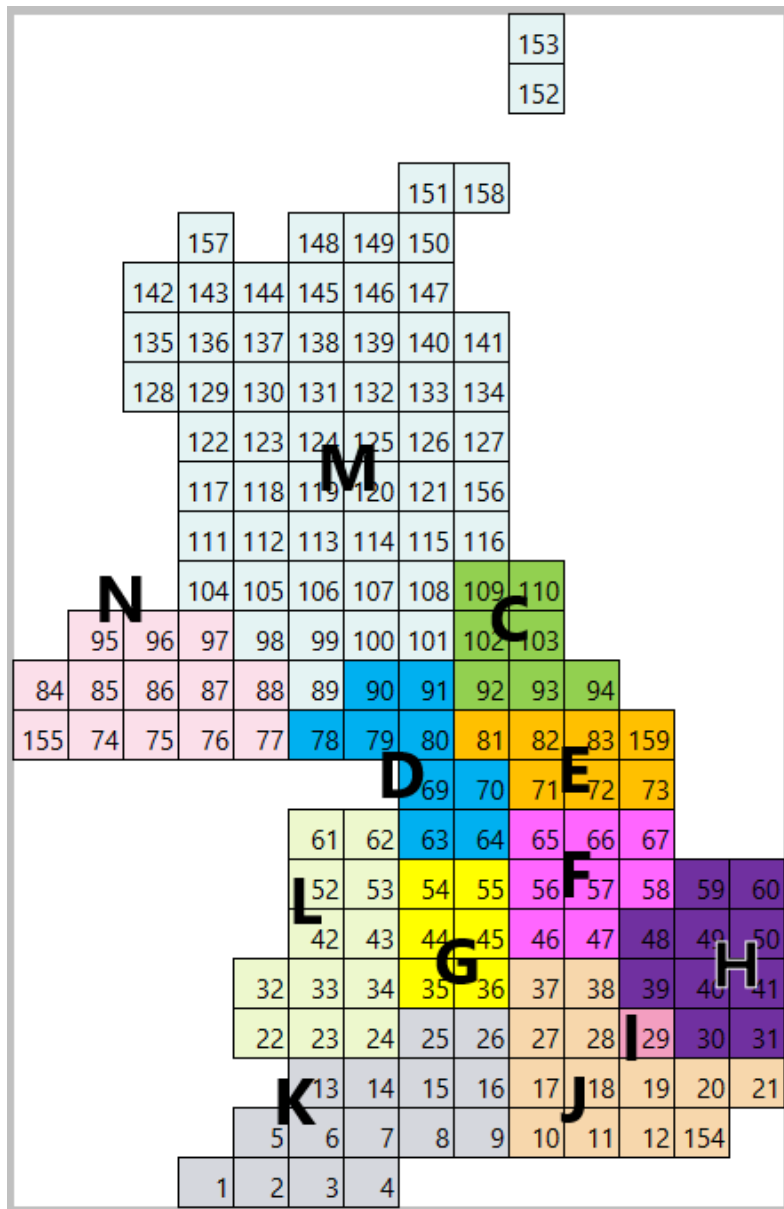


Figure 15: Mapping of the BVCM cells to the ITL1 regions, by colour shading. C = North East, D = North West, E = Yorkshire & Humber, F = East Midlands, G = West Midlands, H = East of England, I = London, J = South East, K = South West, L = Wales, M = Scotland, N = Northern Ireland. This data is tabulated within the "Results Land and Yield Data" workbook (see table in section 7.3).

9. Appendix C: CO_{2e} Impacts of Each Scenario

The CO_{2e} impacts from CCS, direct land use change (dLUC), and crop production are tabulated below for each of the four scenarios discussed in section 5 of the report.

Table 13: CO_{2e} impacts for Central Assumption - Relaxed Energy Targets & Cell-Based Limits

	MtCO _{2e} (decadal basis)					
	2010s	2020s	2030s	2040s	2050s	Total
Crop production	0.000	0.117	0.799	1.879	2.089	4.884
Direct Land Use Change	0.000	-0.507	-3.497	-14.376	-8.954	-27.333
Carbon Capture & Storage	0.000	0.000	-12.457	-48.200	-74.142	-134.800

Table 14: CO_{2e} impacts for Central Assumption - Relaxed Energy Targets & Cell-Based Limits & SRF Targets Brought Forward.

	MtCO _{2e} (decadal basis)					
	2010s	2020s	2030s	2040s	2050s	Total
Crop production	0.000	0.136	0.879	1.926	2.154	5.095
Direct Land Use Change	0.000	-0.563	-5.386	-19.203	-11.782	-36.934
Carbon Capture & Storage	0.000	0.000	-10.726	-48.422	-76.555	-135.703

Table 15: CO_{2e} impacts for Reduced Ambition - Relaxed Energy Targets & Cell-Based Limits.

	MtCO _{2e} (decadal basis)					
	2010s	2020s	2030s	2040s	2050s	Total
Crop production	0.000	0.090	0.801	1.809	2.003	4.704
Direct Land Use Change	0.000	-0.401	-5.051	-10.934	-7.069	-23.456
Carbon Capture & Storage	0.000	0.000	-10.970	-38.624	-59.772	-109.366

Table 16: CO_{2e} impacts for Reduced Ambition - Relaxed Energy Targets & Cell-Based Limits & SRF Targets Brought Forward.

	MtCO _{2e} (decadal basis)					
	2010s	2020s	2030s	2040s	2050s	Total
Crop production	0.000	0.035	0.784	1.834	2.041	4.694
Direct Land Use Change	0.000	-0.092	-4.595	-14.398	-8.820	-27.906
Carbon Capture & Storage	0.000	0.000	-11.433	-37.882	-61.051	-110.367

10. Appendix D: Phase 1 Results

10.1.1. Phase 1 Data Changes

In Phase 1 of the project, a “built-in” reference case was used as the basis with a few limited changes. The end energy demand from bioenergy and net greenhouse gas removals required were varied from 100% of the standard reference case (Case A), to 10% (Case B) and 50% (Case C) of the standard reference case. The intention of this was to see the impact of planting patterns, and if any “rules of thumb” could be determined and applied by DESNZ elsewhere.

10.2. Phase 1 Results

In the Phase 1 cases, only the end energy demand from bioenergy and the cumulative CO_{2e} removal amount were varied in the objective function. These settings are detailed in Table 17.

Table 17: Summary of the different objective functions for cases A, B, and C modelled in Phase 1.

Case	End Demand from Bioenergy (TWh/yr) ¹	Cumulative CO ₂ removal by 2050's (MtCO _{2e})
Case A – Reference	86.6-128	-800
Case B – “10% demand”	8.6-12.8	-80
Case C – “50% demand”	43.3-63.9	-400

¹ i.e. demand across electricity, hydrogen, transport fuels, etc.

Case A is a standard “reference case” in BVCM. The objective of running this was to see where the model would choose to plant bioenergy crops and build bioenergy facilities, given relatively few constraints.

In Case B, the energy demand and cumulative CO₂ removal demand was reduced to 10% of the reference case. The objective was to compare how different planting locations and patterns were versus Case A, and if for example it would be possible to create a simple “rule of thumb” as to the first-choice planting locations for energy crops.

Following the results of Case B, Case C was modelled as 50% of the energy demand and cumulative CO₂ removal demand of Case A. Here, the objective was again to see how planting patterns and deployment of bioenergy facilities differed, and to see what the commonalities between the three cases were.

The following sections 10.2.1-10.2.4 summarise the planting location results. The full set of results and maps are given in the summary slide deck for Phase 1, as listed in the deliverables summary (section 7.3).

10.2.1. Case A – Reference

Figure 16 shows the miscanthus planting locations across the UK in the 2050s for Case A. Planting is biased towards the east and south east of England. Miscanthus is used as a feedstock for power BECCS facilities, with the CO₂ sequestration location being a hub in the Thames region. A smaller amount of miscanthus is planted in the north west of England, again for used in a local power BECCS facility. It should be noted that chemical

looping combustion was used as the 2050s power BECCS technology here and in all cases across both phases of this project, due to its high overall energy conversion efficiency.

Figure 17 shows the SRC planting locations across the UK in the 2050s. These are biased towards the north west, with a smaller amount additionally grown in central Scotland. SRC is used for hydrogen BECCS facilities, as well as additional feedstock for power BECCS.

No SRF was grown. The primary driver of this is likely to be that “by default” in BVCM, SRF planting is only allowed on existing forest land, as opposed to also being allowed on grass land or arable land. Allowing SRF on additional land types would be more attractive from a land use change emissions perspective. This is something that was changed in the “Phase 2” scenarios in the main body of the report, where SRF was allowed to be grown on all land types.

Waste resource has not been shown here, though was fully utilised across the UK. It was turned into refuse derived fuel (RDF), used in gasifiers for syngas production, with this syngas then burned in combined cycle gas turbines (CCGTs) with CCS for net negative emissions. This was enabled based on a syngas pipeline network being available, either constructed or re-purposing gas pipelines.

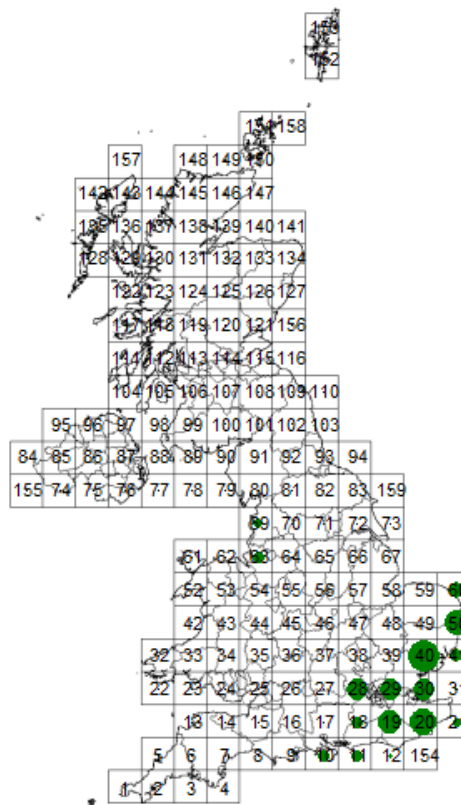


Figure 16: Case A miscanthus planting locations (green circles denote relative quantities) in the 2050s.

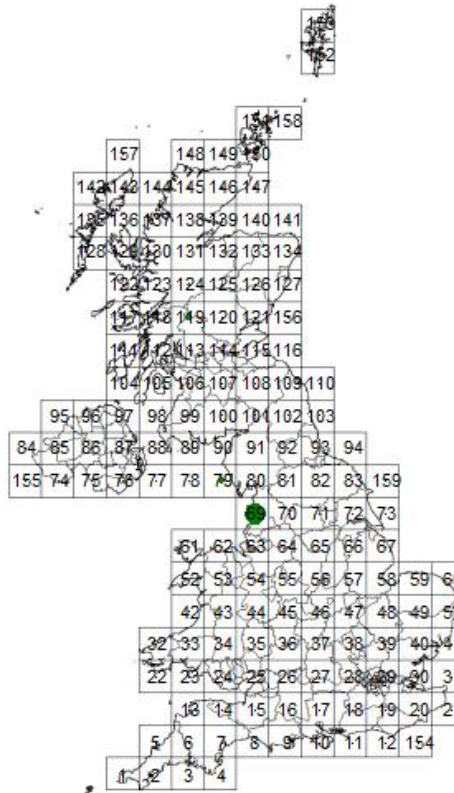


Figure 17: Case A SRC planting locations (green circles denote relative quantities) in the 2050s.

10.2.2. Case B – “10% Demand”

In Case B, only sugar beet and winter wheat were grown as crop options. This is because the very low energy demands of this case could be satisfied through liquid biofuels, with the remaining land used to grown sugar beet as a crop for revenue. Figure 18 shows winter wheat growth locations in the 2050s. These are biased towards the east, south east, and south coast. A similar pattern is seen in Figure 19 with the sugar beet growth locations.

Across Case B, transport fuel production was largely in the form of biobutanol, with facilities in the east, south east and south west to align with the locations of sugar beet crop. Negative emissions were delivered through a combination of long rotation forestry, and combined cycle gas turbines with CCS located in the south east, burning syngas from gasifiers.

In comparison to Case A, with regards to crops and crop planting, the only apparent similarity is the bias towards planting in the east & south east and the north west. With regards to technologies the results are significantly different. This is likely because in Case B, the energy and negative emissions optimisation targets are low and easy to achieve (in comparison to Case A), whilst the land availability for crop planting remains the same, therefore BVCM prioritises planting crops for profit.

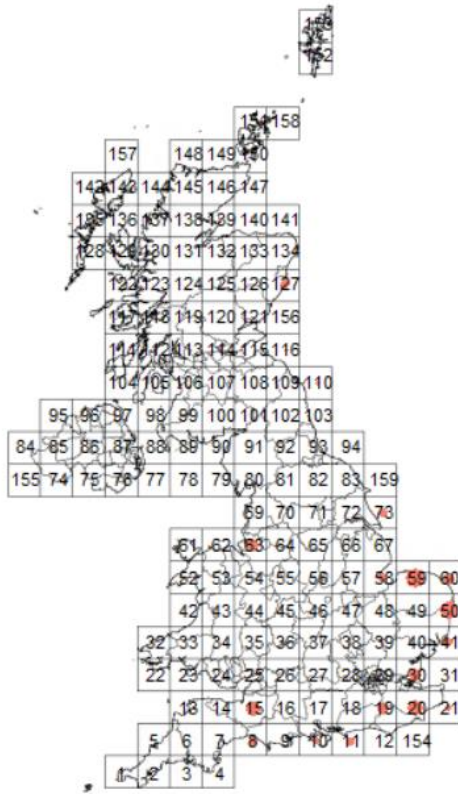


Figure 18: Winter wheat growth locations in the 2050s in Case B.

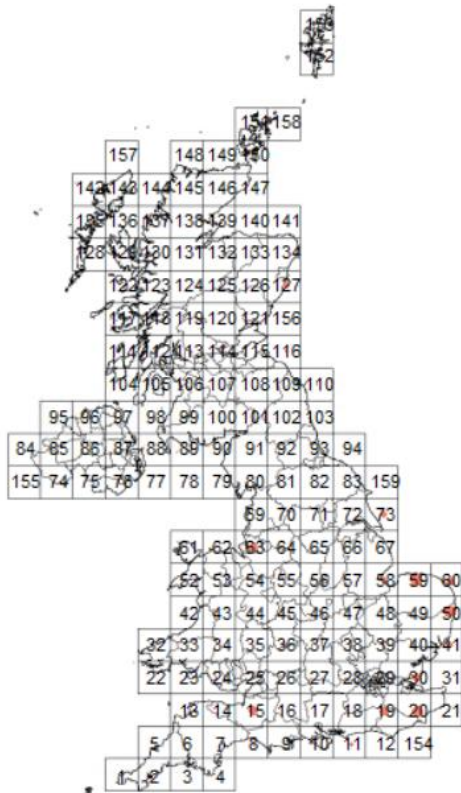


Figure 19: Sugar beet growth locations in the 2050s in Case B.

10.2.3. Case C – “50% Demand”

Figure 20 shows miscanthus growth locations in the 2050s. These are biased towards the south east and east of England, and are primarily in power BECCS facilities. Miscanthus is also used in some cases for gasification to syngas which is then used in CCGTs with CCS, though waste is the primary fuel for this process. This is similar behaviour to as was seen in Case A.

Figure 21 shows SRC growth locations in the 2050s. Similar to Case A, these are planted in the north west of England, and used in power BECCS facilities.

Figure 22 shows winter wheat growth locations in the 2050s. The patterns are similar to those of Case B, with planting mostly occurring in the east, south east and south coast of England. This resource is then used for butanol biofuel production.

Figure 23 shows sugar beet growth locations in the 2050s. As was seen in Case B, these are again largely along the east and south east coast, as well as some amounts in the north west. Sugar beet is grown and sold for revenue.

Overall, Case C showed a mixture of the crop planting and technology behaviours seen in Cases A and B. Waste utilisation for energy purposes remains high and appears to be the “first choice” due to cost and impact. Energy crops are grown and utilised primarily in power BECCS processes. Remaining land is used to grow and sell crops for revenue.

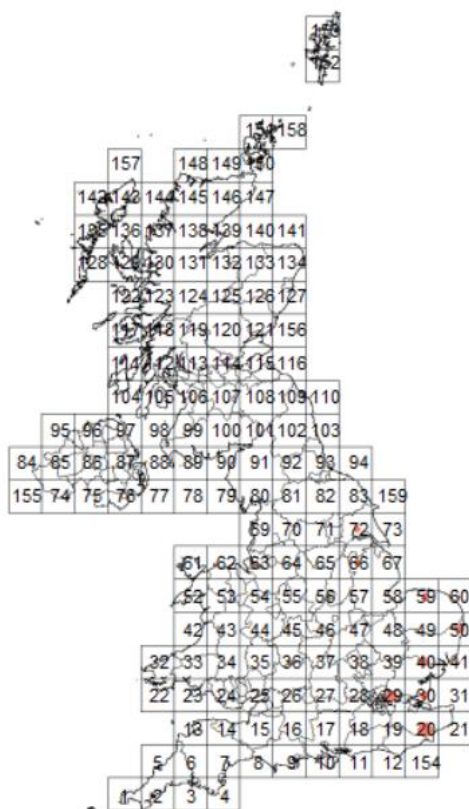


Figure 20: Miscanthus growth locations in the 2050s in Case C.

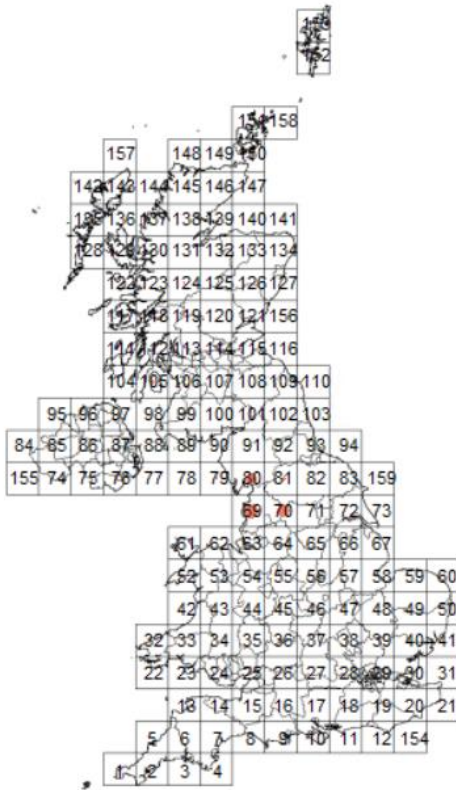


Figure 21: SRC growth locations in the 2050s in Case C.

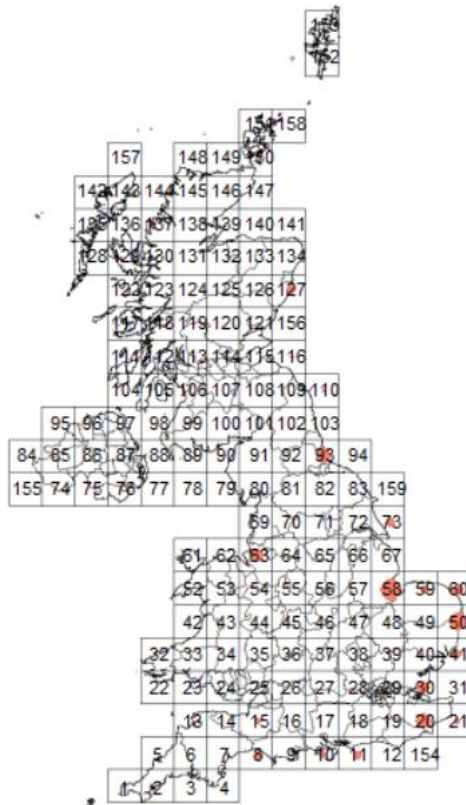


Figure 22: Winter wheat growth locations in the 2050s in Case C.

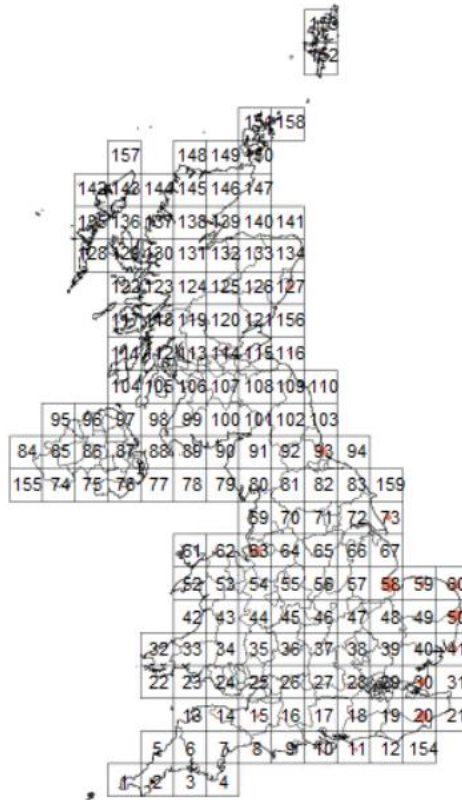


Figure 23: Sugar beet growth locations in the 2050s in Case C.

10.2.4. Discussion

There are a few trends, similarities, and differences worth noting across Cases A, B and C.

The first is that there were no similarities, or “rules of thumb” evident when moving from Case A to Case B due to the latter having only 10% of the energy and greenhouse gas removal demands. However, Case C, which was closer to a mid-point of the two, showed some trends and patterns present in Case A and B, both in terms of crops and land use, and energy technologies deployed.

These differences reveal some of the key drivers of BVCM when used in a relatively unconstrained reference case. Waste is often one of the first resources “chosen” for energy facilities thus is utilized to the point where no more remains, at which point energy crops (typically miscanthus and SRC) are then used. Where there is “excess” land available to the model, the model opts to plant crops for revenue, typically sugar beet and winter wheat.

Waste as a fuel is typically upgraded to RDF, which is then gasified into syngas. This syngas is then piped along a syngas piping network to CCGTs burning syngas with CCS for negative emissions. However, given the lack of any plans to create syngas networks in the UK, it appears unlikely that such a network would materialise, even in the 2040s and 2050s. Gas networks, if converted, will likely move to hydrogen pipelines and even these may be limited in nature (i.e. to industrial sites only).

With regards to energy crops, miscanthus and SRC willow are primarily used for power BECCS facilities. Miscanthus is typically planted and used for facilities in the south east and east of England, whilst SRC is typically planted and used for facilities in the north west of

England. Chemical looping combustion with CCS is selected as a preferred power BECCS technology in the 2040s and 2050s, at the same point in time at which needs for CO_{2e} removal become significant.

Winter wheat, when grown in cases where there is “excess” land available and lower energy and CO_{2e} removal targets, is used for biobutanol production from the 2040s onwards. Smaller amounts are also sold for revenue. Sugar beet, also grown in cases with “excess” land and low targets, is grown primarily as an additional revenue source.

A key aspect to BVCM as a model is that it considers the entire bioenergy value chain, from growth of feedstock, through to conversion to an energy end vector and (optionally) sequestration of CO₂. Therefore, growth locations for biomass resource are not optimized solely on yield potential for a given cell, but also on the location of the energy conversion facility in which they are used, the transport chain to move the resource to the facility, and the CO₂ sequestration location (if required). For example, a Thames CO₂ sequestration hub is enabled in the default BVCM reference case, which drove a lot of miscanthus planting towards this location (due to high yields), with miscanthus used in power BECCS facilities in this region. Given current plans for CCS clusters, it is unlikely that such a hub will materialize over the next couple of decades. Therefore, the CO₂ sequestration options were updated for the Phase 2 cases as was described in section 4.2.4. More broadly though, the concept of finding ways to optimize the co-location of energy crop planting, energy conversion facilities, and CO₂ transportation and storage options is one that is universal beyond the model.

11. Appendix E: Regional Planting Scenario

One of the initial scenarios requested by DESNZ was to use a regionalised crop area limit data set supplied by Defra. Data was supplied on the planting of energy crops based on aggregations of ITL1 regions of the England and Agricultural Land Classifications (ALCs). This was then to be translated into the cell format of BVCM, such that it could be determined, for example, where exactly in the East & East Midlands to plant the 10% allocation of a given energy crop. Planting was to be on land of:

- ALC grades 4 & 5 for SRF (poor and very poor quality agricultural land)
- ALC grades 4, 5 and 3B for SRC (where 3b is moderate quality agricultural land)
- ALC grade 3a (good quality agricultural land) for miscanthus

The ITL1 regional planting limits that were supplied are summarise in Table 18.

Table 18: Regional planting data supplied for the three energy crops, to be translated into BVCM.

ALC	Crop	England planting region (% of total planting)					Unallocated (Miscanthus)
		East & East Midlands	North West & West Midlands	South East & London	South West	Yorkshire & North East	
ALL		21	16	10	16	16	22
ALC4&5 (>5ha parcels)	Afforestation (all)	26	22	16	20	16	
	Exotic SRF	40	0	0	60	0	
	Native SRF	28	23	33	0	17	
	Conifer SRF	0	41	0	0	59	
ALC4&5 (<5ha parcels) and ALC3b)	SRC Willow	30	20	8	23	19	
ALC3a	Miscanthus	100 (Not spatially assigned)					100

The feasibility of this was reviewed, however it was determined that this was not possible given the current structure of BVCM for a few reasons as set out below. It could however be an area where BVCM is further developed in the future to give this functionality.

The principal issues with implementing this data are that BVCM does not have any representation of regions, nor does it have any ability to restrict crop planting to ALC. BVCM representation of the UK is across 50x50km cells arranged in a grid. Whilst these cells can be mapped to the ITL1 regions of the UK this is not an exact mapping. There are overlaps between regions when attempting to assign the best grid fit to the regions.

As there is no representation of the ITL1 regions of the UK in BVCM, it is also not possible to set planting limits or targets on the basis of these regions of aggregations of them. The closest possible way to do this would be to disable all cells except those in one region in Table 18, run the model on the basis of energy and greenhouse gas removal targets for this region, and then repeat this process for each region. This would result in a very disjointed process as in reality at the national scale, it may be the case that the optimal planting approach is to plant energy crop towards one side or border of a region, but

utilise them in energy facilities in the adjacent region. Setting regional energy and greenhouse gas removal targets would influence the type, location and size of energy facilities, and thus also the planting patterns of energy crops within that region.

The secondary issue as mentioned is that BVCM does not have any representation of ALCs. This means it is not possible to directly restrict crops to, for example, only ALC 4&5. Instead, only generic restrictions can be applied, for example that only 10% of the arable land in a cell can be used for energy crop purposes.

These issues could be overcome with additional model development beyond the scope of the current project.

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