Supergen Bioenergy Hub

UK Biomass Availability Modelling

Scoping Report

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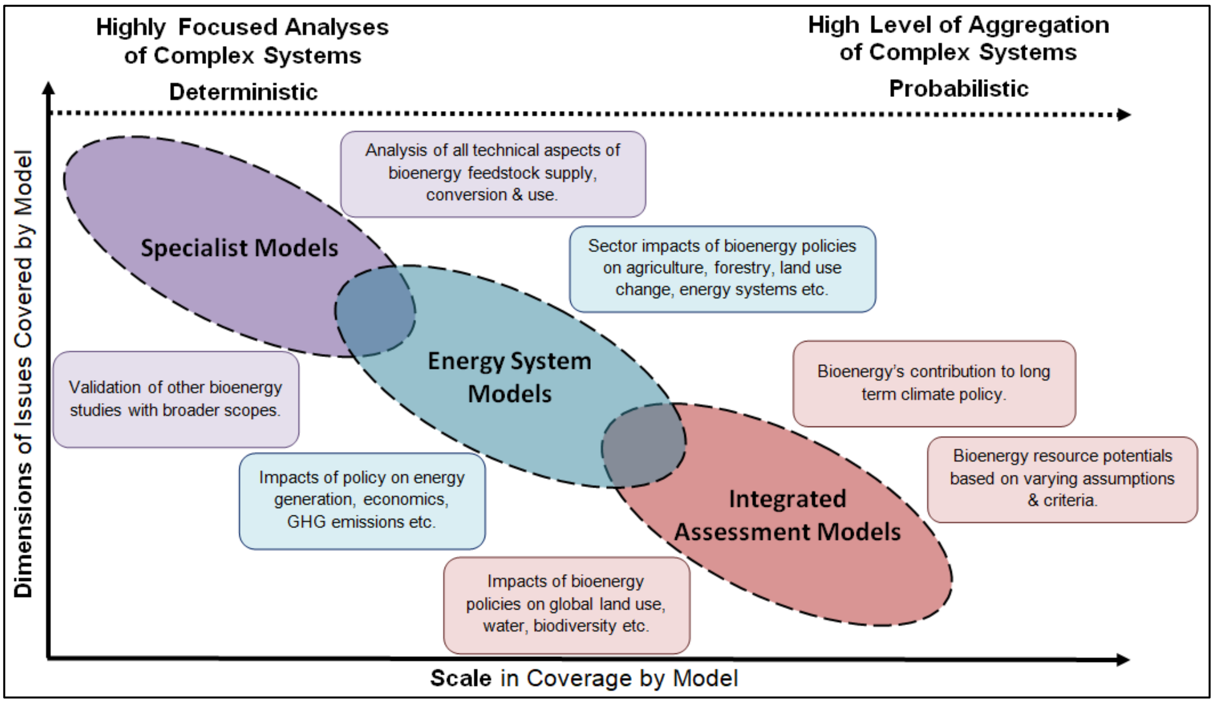
Executive Summary

Sustainably sourced biomass, such as from dedicated bioenergy crops, forestry and organic wastes, can provide feedstocks for a number of applications including renewable heat and power, transport fuels and materials and chemicals for the bioeconomy. Moreover, bioenergy when combined with carbon capture and storage (BECCS) is one of the technologies proposed by the Committee on Climate Change for greenhouse gas removal, and therefore to help the UK become net zero by 2050. To meet policy requirements, models of biomass resource need to be able to address a number of questions: Firstly, what is the sustainable supply of the biomass resource that is currently available and that may be available in the future; secondly, what is the level of competition between sectors/uses for this finite resource; and thirdly, how does supply and demand of the resource change through time and what are the factors that influence this. This Scoping Study focused on the current state of knowledge around UK biomass resource availability for the bioenergy sector to address these questions.

The study identified a hierarchy of models, shown below, based on the scale of coverage and dimensions of issues covered. Integrated Assessment Models (IAMs) focus on large global scale analyses whilst specialist models are often highly focused on specific bioenergy issues. Whilst the global nature of IAMs means they have to keep within a narrow number of issues they can analyse, albeit on a large scale, in contrast to the large number of dimensions, specialist models can address questions through their highly focused specialist analyses.



Policy makers should in theory always use the most appropriate models to address their specific questions, choosing models based on relevant criteria such as the inclusion of different technologies, time horizons, and granularity of expected results. However in reality, bioenergy modelling analyses informing policy are typically completed using a small number of established high profile models.

To develop energy systems, and a bioenergy sector, that enables transition towards a low carbon economy, it is important that the targets, strategies and roadmaps are designed with the support of the best possible analyses provided by models. Ideally bioenergy models would provide policy makers with information that allows them to develop policy that promotes sustainable bioenergy taking consideration of the many themes associated with bioenergy pathways. In reality it is not always feasible to develop an all-encompassing bioenergy model that covers all the linkages and that captures the nuances between different systems, therefore caution should be applied if decisions are developed from one category or one specific model. The next best option may be to use multiple models in parallel, each with different approaches in order to build more robust overall conclusions.

This could be achieved through developing a versatile framework of IAMs, energy system models and specialist models that could be integrated to provide a 'modular modelling approach' to utilise the strengths, and mitigate for the weaknesses, of any given individual model. In practice, using the example of the transport sector this could mean: using specialist models to identify and evaluate the performance of different alternative fuel/ transport options; using energy system model to analyse how these may be integrated with the wider energy systems and infrastructure; and IAMs to evaluate the GHG and wider macro-impacts of these technological interventions.

This Scoping Study identifies six categories of UK focused bioenergy models that have been developed to evaluate bioenergy from varying perspectives, scales and scopes. Energy System Models (ESM) that focus on bioenergy as part of the wider UK energy system; Full Biomass Resource Assessment Models (ESM / SPM) that assess that the potential availability of biomass for the bioenergy sector given different constraints; Environmental Assessments Models (SPM) that focus on specific environmental and sustainability themes relevant to bioenergy systems; Feedstock Specific Models (SPM) focusing on specific bioenergy feedstocks; Vector Specific Models (SPM) that focus on specific bioenergy vectors, and; Carbon Accounting Models (SPM) that assess the carbon performance of different resources, technologies and systems. For each category the Scoping Study discusses the strengths and weaknesses of the approach, and provides a case study example.

Based on the models identified and reviewed, we compiled a list of reports that have been produced and used by key organisations in policy, strategy and research (i.e. by bodies with some recognised responsibility and authority) and collated estimates of biomass resource availability at global, European and UK scales.

At the global scale central estimates for bioenergy demand range from 80500 PJ to 261000 PJ in 2050 suggesting significant divergence between models. A similar patterns is reported at the UK scale with central estimates of between 606 PJ and 3243 PJ. This variation arises both through different approaches to modelling and due to underlying model assumptions, such as diet, future populations, yield improvement, and land availability and constraints. Estimates of resource availability from crops and forestry exhibit the highest variation across models, whereas there is more consistency in assumptions about the use of waste.

In terms of sustainability our review of biomass resource models found that they consider a relatively narrow set of environmental, economic and social consequences of future demand pathways. Assessment of sustainability typically focus on decarbonisation, energy security, investment requirements and affordability, the pillars of the energy trilemma. This limited consideration on the energy trilemma seems short-sighted given that the UK has a range of national and international commitments relating to the environment (e.g. the Strategic Plan for Biodiversity; UN SDGs) that can be negatively impacted by the choice of energy pathways.

As detailed in the Government's 25-year Environment Plan, the coming decade will see an increasing focus on the value of public goods such as clean air and water. This shift will be concurrent with the UK's energy system undergoing a period of rapid transformation to meet targets to reduce greenhouse gas emissions. For example, delivering net zero is an underlying design principle in the Environment Land Management (ELM) scheme of the 2019-21 UK Agriculture Bill. The current approach to considering the implications of energy pathways based on the use of constraints acting as proxies for public goods, and the use of post hoc analysis to examine the implications of energy pathways may not deliver optimised solutions across all the policy commitments that we face.

The Scoping Study identifies four broad areas that should be considered to further develop the scope and performances of UK biomass resource models and to provide a policy framework that supports development of the bioenergy sector.

1. Natural Capital within Bioenergy Resource Models

There is a need to incorporate natural capital and ecosystem services within bioenergy resource models. This aligns with movement towards "public money for public goods" within the 25 year environment plan. This gap could be addressed in a number of ways;

1. Work should be carried out to improve our understanding of the role that bioenergy feedstocks can play in the provision of ecosystem goods and services recognising that natural capital is central to human wellbeing, and that there are significant policy drivers in this area.
2. We must recognise that natural capital and the provision of ecosystem goods and services has a significant spatial element. Future model development should consider appropriate spatial scales to capture spatial heterogeneity in the distribution of natural capital and the goods and services that flow from it.
3. Implement values for natural capital and ecosystem goods and services aligned to those measured by the ONS within energy system models. In doing so optimisation within models could identify deployment patterns that address targets around the energy trilemma, benefit land managers through PES schemes, and society through the delivery of public goods.

2. Human Actors within Biomass Resource Models

A substantial challenge exists in translating results from bioresource modelling into the real world. While bioenergy plays a critical role in many future scenarios that meet climate ambitions, deployment of dedicated bioenergy crops in the UK has so far been slow. It is essential that human and institutional actors are incentivized and empowered to implement the individual components of bioenergy systems (resource growth, supply chain aggregation, conversion and energy delivery) to deliver sustainable bioenergy systems in the long term, and policy measures need to consider how they affect individual actors within their own sphere of choice if they are to be effective. We would suggest that future work should:

1. Examine how farm scale dynamics that influence uptake of dedicated bioenergy crops are currently represented in models.
2. Examine methods that could be employed to capture these farm scale dynamics to understand the influence of different policy options.
3. Examine how "constraints" of bioenergy deployment might be more dynamically modelled.

3 - Dynamic Competition & Demands within Biomass Resource Models

Bioenergy is a key renewable energy technology targeted to provide options for decarbonising heat, power and transport energy in the UK. In addition, development of the bio-economy is a core element of the UK's industrial strategy. This scoping study highlights how competition and changing demands are analysed within many of the UK's existing models and has identified gaps and weaknesses. For example the supply and demands for different feedstocks is likely to be highly dynamic over the short medium and long terms; current models fail to capture the many interactions that will influence the extent that feedstocks may be available for different end uses. The Supergen Bioenergy Hub recommends that further work is undertaken to investigate the future dynamics of biomass resource demands and competition and specifically how this may potential impact development of the UK bioenergy sector and bio-economy. To achieve this we make the following broad recommendations:

1. Undertake analyses to build a better understanding of the current competing uses for the major categories of biomass and lands. This would be enhanced by also mapping locations of key resources and that of competing industries.
2. Firmer evidence is required that characterises the UK resource availability and demand in order to aid long term decision making. To provide this evidence base, research is required to evaluate the future changing resource demands of key sectors including that of the future bioenergy sector. This could be achieved through scenarios analyses to highlight future resource availability risks and opportunities.
3. Through consideration of economic, environmental and social indicators, research is required to map the best uses for different categories of biomass so specific resource pathways can be

prioritised/incentivised. Where potential impacts from increased competition for resources have been identified, it would be useful identify whether alternative resource solutions are available.

4. The Policy Factor

The development of the UK bioenergy sector and bio-economy will be limited by or will flourish upon a secure sustainable supply of feedstocks. The UK's future supply of feedstocks will be dependent upon the extents that resources are grown, produced and mobilised. Establishing robust supply chains will be aided or restricted by the design of policy framework – policies ideally being developed to require or incentivise the use of targeted biomass resources for energy end uses. To ensure policies are developed that prioritize sustainable and cost-effective bioenergy systems, the Supergen Bioenergy Hub strongly recommend that policy relating to bioenergy in different sectors and government departments is reviewed and co-ordinated across government departments, since bioenergy is so inextricably linked to land, people, industry processes and interactions between these as well as energy.

1. Introduction

1.1. Supergen's Understanding of the Department for Transport (DfT) Brief

To meet policy requirements models of biomass resource need to be able to address a number of questions: Firstly, the sustainable supply of the biomass resource that is currently available and that that may be available in the future; secondly, what is the level of competition between sectors for this finite resource, and; thirdly how does supply and demand of the resource change through time and what are the factors that influence this.

1.2. The Aim of this Scoping Study

Based on the work specifications provided by the DfT, Supergen developed a Scoping Study that focused on assessing the current state of knowledge around UK biomass resource availability for the bioenergy sector. The Scoping Study was developed with the following aims and objectives:

- Review and develop a summary of existing UK studies that have focused on assessing biomass resource availability for bioenergy, and provide a summary of the modelling frameworks that have been used to generate these scenarios.
- This synthesis will include outputs from the UK Supergen Bioenergy Hub's Bioenergy Literature Database, the UK Energy Research Centre, and will be supplemented by further research and expert knowledge from ongoing research currently taking place within the Hub.
- Given the tight timeline of the Scoping Study our approach will focus on the key biomass feedstocks widely regarded as providing the greatest potential opportunities for the UK bioenergy (wastes, residues and biomass crops grown for the bioenergy sector).
- Our objective will be it to provide a baseline understanding of the current state of knowledge for each of these feedstock categories.

2. Biomass & Bioenergy Models

The transition of energy systems towards renewable low carbon energy technologies is a key measure in climate change mitigation. Due to variability in geography, resource availability, infrastructure, financial constraints and sometimes very different historic approaches to energy; individual country's policy makers face unique sets of challenges in developing policy frameworks and strategies to drive the transition toward energy decarbonisation. To help develop strategies and evaluate the potential influence and impacts of different policy options, energy models are used by decision makers to road-test plans before they are implemented [1].

Models can provide the essential quantitative insights into alternative designs for energy scenarios, roadmaps or systems and thus decrease the pervasive uncertainties of different options - leading to better energy decisions [2]. With the rise in types of energy technologies available and the increased complexity and performance demands for energy systems there has been an equivalent rise in the number, types and approaches of energy models. Models may be grouped based on their varying objectives, scope, inputs and calculation approach adopted - all of which in turn characterise the capability, strengths and weaknesses of any given model. When policy makers, scientists and analysts use models to investigate energy questions it is important to be aware of the uncertainties and limitations of the models being used, and question whether the models used are suitable for the task [3].

2.1. The Role and Coverage of Bioenergy within Models

The focus of modelling when applied to energy research is typically on issues of fuel choice, energy technologies, costs, location of energy production or consumption, potential innovations and the policy landscape. When modelling bioenergy systems there are a whole range of models that focus on analysing the potential role of bioenergy and its integration, typically analysing one or more of the key stages intrinsic to any bioenergy system [3]:

1) **Biomass Resource Feedstocks** are the fuels requied by bioenergy systems. Models that cover bioenergy feedstocks typically focus on issues of sustainable resource supply, feedstock consistencies, the timings and spatial availability of supply and how these may limit the extent that bioenergy may be generated. The types and extent that different resources are available and the production/ mobilisation practices used will characterise supply chains and are fundamental in influencing the overall performance of a bioenergy system.

2) **Bioenergy Conversion Technologies** are used to generate different forms of energy, and different products such chemicals and fuels. Models focusing on bioenergy conversion technologies are typically designed to determine the forms and levels of bioenergy that may be generated, in addition to evaluating the economic and environmental performances of different technology options. How bioenergy technologies are characterised within models is a key factor that will determine the extent that bioenergy may contribute within scenarios for achieving energy or climate change targets.

3) **Bioenergy Systems Issues** will characterise the overall sustainability and feasibility of a bioenergy system. Unlike many other renewable technologies the sustainability of bioenergy systems and biomass feedstocks are often intrinsically linked to multiple natural systems, to industry sectors and to society and people. Models that focus on bioenergy system issues aim to evaluate the overall performance of given bioenergy systems through analysing there potential impacts and benefits from the perspective of environmental, societal and economic issues.

2.1.1. Bioenergy Modelling Categories vs. Modelling Approaches

Bioenergy models are designed to evaluate both broad ranging and highly specific bioenergy research questions and consequently apply many different modelling approaches to achieve this. It is possible to group bioenergy models within three broad categories based on these approaches:

- **Integrated Assessment Models** (IAMs) that analyse the interactions that energy technologies may have with human and natural systems, for example how large scale deployment of bioenergy technologies may be used to achieve climate change targets based on the levels of GHG emissions reductions that may be achieved;

- **Energy System Models** where the key focus is evaluating the performance of bioenergy technologies and how these may be deployed and integrated into wider energy systems;

- **Specialist Bioenergy Models** that are designed to focus on highly specific themes, technologies or processes.

Within each category of model, there are also a range of different approaches that are applied in how they undertake analyses. For example: computable general equilibrium (CGE) modelling and partial equilibrium (PE) are typically used to analyse the broad macro-economic impacts of different policy options – achieved through measuring the disruption to an equilibrium following interventions such as the introduction of a new policy regime; specialised bottom-up modelling may apply methods such as life cycle assessment (LCA) analysis, techno-economic analysis (TEA) to test the performance of specific case studies; whilst analysis techniques using geographic information systems (GIS) or developing a Process Model may be used to analyse specific questions around bioenergy technologies or supply chains [3].

Figure 1 provides a summary of the characteristics and typical approaches of the main categories of models introduced in this report. Also highlighting the influence these have on the types of bioenergy research outputs they produce. The axes of Figure 1 document the scale and dimensions to which the different categories of model focus. IAMs focus on large global scale analyses whilst specialist models are often highly focuses on specific bioenergy issues. Whilst the global nature of IAMs means they have to keep narrow dimensions of issues they can analyse, albeit doing these on a large scale, in contrast to the large number of dimensions specialist models can address through highly focused specialist analyses.

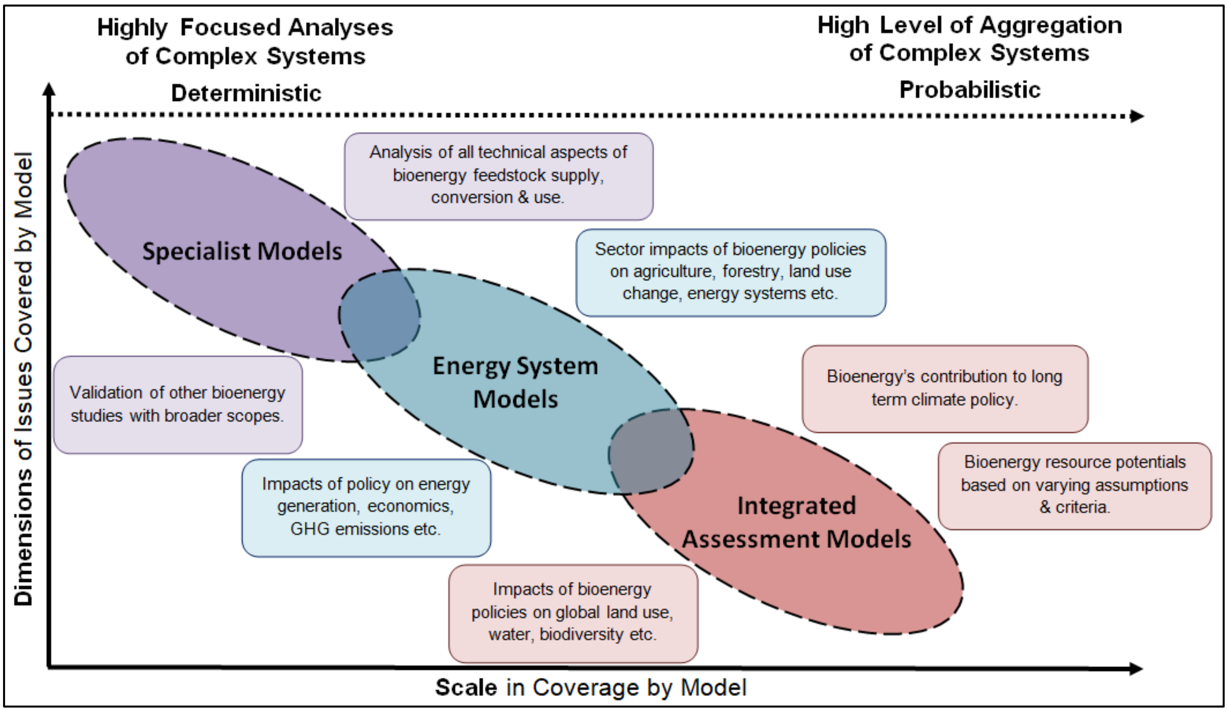


Figure 1: Energy Modelling Categories and their Approaches & Capability for Bioenergy Analyses [3]

2.2. Bioenergy within Integrated Assessment Models

Integrated Assessment Models (IAMs) are computer models developed to analyse the potential evolution of global energy systems alongside other large GHG sources such as agriculture, land use and the characteristics of economies. Analysis scenarios within IAMs are developed based on assumptions around economic and population dynamics and changes to wider ranging GHG sources and sinks. IAMs typically build from baseline scenarios that predict performance based on the continuation of trends and implementation of policy targets. Subsequent scenarios are then developed to provide alternative potential pathways to drive performance beyond the baseline to achieve targets such as achieving reduced GHG emissions or to limit global temperature changes to within specified goals [4].

There have been approximately 20 global scale IAMs developed to date which can be broadly categorised into two groups: i) Detailed Process (DP) IAMs, that focus on quantifying future development pathways to provide detailed sector information of complex processes, and; ii) Benefit-Cost (BC) IAMs that aggregate the costs of climate change and mitigation activities to estimate the total costs of different climate change impacts [5].

The IAMs share common approaches (land-use, energy system supply & demands, GHG emissions, fossil fuels, renewables, commodity trade etc), are based on similar assumptions (population, economic growth, inequality, GHG budget and targets, technology options etc), and generate similar outputs (energy technology choices, land-use change, emissions pathways, energy/ food dynamics, climate feedbacks etc).

2.2.1. Application of IAMs and the Relationship with Bioenergy

The primary role of IAMs is to evaluate the feasibility of achieving goals based on technological and economic parameters [6]. IAMs are therefore valuable tools for supporting decision makers and for informing policy development to support pathways to achieve targeted goals. The leading example where IAMs are currently applied is within climate modelling applications - much of the global scale analysis on climate mitigation and evaluation of pathways to achieve climate targets such as those of the Paris Agreement [7] has to date been heavily reliant on the outputs of IAMs. Since the IPCC's Second Assessment Report in 1996, outputs from IAMs have underpinned all the IPCC's major analysis themes and recommendations [4].

The results of these analyses are highly influential informing the targets and policy frameworks of Governments and Organisations worldwide. IAMs therefore remain critically important and influential, and if supplemented and paired with specialist targeted studies will remain the primary 'go-to' tool for climate analyses [8].

As IAMs are designed to forecast and analyse the long term interactions between land-use, agricultural, energy and climate systems, IAMs may therefore be applied to plot biomass supply and demand pathways taking account of changing dynamics of global systems and the many interactions between these [9]. Bioenergy forecasts from IAMs therefore not only take account of the implications from changing energy systems, but can also provide biomass resource supply forecasts that account for the limitations, trade-offs and synergies between different natural systems - such as the influence of changing dynamics from water, land use, temperature and the global carbon cycles [10].

IAMs allow analyses of a range of different categories of biomass feedstocks: all IAMs allow analysis of feedstocks grown specifically for the bioenergy sector such as energy crops; the majority of IAMs allow analysis of residue biomass feedstocks such as those generated by agriculture and forestry activities; a selection of IAMs allow analyses of waste biomass feedstocks such as municipal solid waste, but these are typically categorised as a 'residue' [11].

There are many examples where IAMs have been used to analyse the long term implications for bioenergy supply potentials based on changing global land use dynamics [12], or based on changing global water availability and biodiversity [13]. The premise of many of these IAM bioenergy analyses is to forecast biomass resource potentials based on designed sustainability constraints that will influence biomass availability. Through applying a series of macro level assumptions of the types and scale of biomass resource that may be produced on different categories of land, and through excluding lands deemed unsuitable, IAMs have been extensively used to calculate global tonnes/ yr^{-1} of biomass or EJ/ yr^{-1} of bioenergy that may be generated. However, bioenergy and biomass resource forecasts from IAMs can vary significantly. Comparison of the calculated outputs from different analysis scenarios from studies using both the same and different IAMs, highlight wide forecast ranges. These differences driven largely by the parameters and constraints applied within each scenario. An example is provided by Chum et al. [14], who place the bioenergy potential from all land-based bioenergy resources at between 50–1000 EJ yr^{-1}.

Through the use of IAMs by the IPCC and the inclusion of net negative emission technologies within many IPCC scenarios, IAMs have become intrinsically linked to and reliant upon large scale bioenergy with carbon capture and storage (BECCS) as the mechanism for achieving large scale rapid reductions in emissions [15]. Much bioenergy analyses using IAMs also focus on assessing the extent that bioenergy may contribute to energy strategies to meet climate change targets. Within these bioenergy studies the technical limits of biomass resource growth/ mobilisation are calculated and linked to calculations that compare the costs of bioenergy technology deployment to other energy technologies within the context of a pre-determined policy regime. Restricted by current estimates of cost and GHG life cycle data related to the growth/ mobilisation and supply of different types of biomass resource, in addition to the long analysis timeframes; bioenergy scenarios from IAMs will typically favour large scale use of agricultural and forestry residues, and lignocellulosic energy crops with limited or no production of 1st generation energy crops. The inbuilt economic costs and GHG implications of 1st generation energy crops within IAMs, mean these feedstocks typically selected less than alternative bioenergy or alternative renewable technologies for delivering cost effective pathways to achieving climate targets.

2.3. Bioenergy within Energy System Models

With the emergence of the climate change agenda and exponential growth of renewable technologies, there has been a reflective rise in the number and capability of energy system models that have been designed to analyse and deal with the new dynamics associated with the sometimes highly variable mixed technology energy systems we have today [16]. Energy models are now crucial in providing the evidence required to inform policy decisions that are driving the transition towards increasingly sustainable and low carbon energy systems [17].

Energy models have increasing adopted computable general equilibrium (CGE) simulation framework to analyse energy-economy-environment inter-dependencies. CGE models have become popular in energy and environmental policy analyses because they permit focus on a wide range of both direct and indirect, anticipated and unanticipated, economic responses to changes and disturbances that impact prices and incomes throughout the economy. Through their focus on modelling impacts on macro-economic indicators, fiscal balances and distributional consequences, CGE analyses allow a holistic view to be taken on how various climate and energy targets should be approached [18].

2.3.1. Computable General Equilibrium (CGE) Modelling Framework

Computable general equilibrium (CGE) models are widely applied to energy analyses to evaluate the effects of climate policies. CGE models are well suited to study bioenergy policies as their key characteristic is their encompassing scope – global CGE models cover the world economy disaggregated into countries, regions, individual sectors and specific economic activities. CGE models focus on identifying and assessing the direct and indirect feedback effects of certain policies or shocks across these sectors and countries etc [19].

Analyses using these models focus on measuring the disruption to this equilibrium and the processes of achieving new balances following interventions such as the introduction of a new policy regime. The economic impact such as the introduction of a new energy policy is modelled by comparing the economy before and after the new policy. A pre-policy baseline is modelled with focus on developing model equations and behavioural parameters to the base year data – this baseline is assumed to be a stable or ‘equilibrium position’. Following the introduction of the policy change, the economy converges to a new equilibrium, governed by the economic relationships as specified in the system of equations. CGE models derive ‘solutions’ by finding new sets of prices, allocation of resources and energy dynamics to bring the economy back to an equilibrium. This modelling approach allows a richer understanding of the evolution of the energy and economic transitions in response to given shocks [20].

The strengths of modelling analyses using the CGE approach stems from the depth of linkages and relationships that CGE models have between different economic sector markets. These linkages mean the wider impacts of policy interventional across multiple sectors can be analysed providing policy makers with valuable insights to the potential overall economic impacts of policy interventions.

CGE modelling approaches have been widely used to analyse the implications of biomass and bioenergy policies associated with the economics of different sectors and potential influencing forces these have on issues such as land use change [10]. CGE models are particularly useful when analysing the impacts of strategies for significant bioenergy deployments in the short to medium terms, when the modelling results may be used to identify the immediate impacts on different economic sectors such as agriculture or industry [21].

2.3.2. Partial Equilibrium (PE) Modelling Framework

PE models follow the same economic framework as CGE models but only cover selected economic sectors. This can provide both advantages over CGE models with the potential for increasing levels of flexibility and added details to analysis of the sectors that are covered, and disadvantage in that the outputs from PE will be limited with absent representations of non-included sectors.

PE models are therefore adopted to analyse specific research questions where the impacts on certain sectors are desired such as to agriculture or energy. In the context of bioenergy research this could be to analyse the primary effects of a new policy intervention on a particular feedstock market.

The MARKAL[1] family of models represents some of the most widely applied energy system models for bioenergy analysis using a PE modelling approach. These models provide a technology rich analysis platform that driven by assumptions such as the costs and performance of energy generation and infrastructure will produce energy supply options for achieving end-point targets. This approach of recommending energy systems based on an optimisation approach has been widely applied in bioenergy research to evaluate scenarios for how bioenergy may be used within different areas of the energy sector; the limits of bioenergy within different geographies based on varying sustainability constraints; demonstrating how bioenergy may be used in complement to other renewable technologies as energy systems transitions towards low carbon energy mixes; and increasingly how to best use and maximise the value of available biomass resource [3].

2.3.3. Energy System Modelling Approaches

Within the CGE and PE frameworks different energy system models apply different modelling approaches. The choice of modelling approach is typically driven by the types of analyses desired. These different approaches can be described through the following types of energy system models:

- **Bottom-up Optimisation Models** such as applied within the MARKAL model, and **Bottom-up Accounting Models** as used within the LEAP model – these focus on individual technologies or feedstocks, and analyse their potential for delivering energy services;
- **Top-down Econometric models** such as the DTI energy model, that analyse the energy demand characteristics of different sectors/ countries and then analyse the performance of different technologies in balancding these demands;
- **Hybrid Models** such as used within the POLES model aim to combine the technology coverage or bottom-up models with the economic richness of top-down models, and;
- **Planning** focused energy models such as used for electricity planning within the WASP model, that focus on analysing optimal long-term targets for specific energy technologies/ sectors.

Table 1 provides a comparison of these different modelling approaches summarising the characteristics of each.

Table 1: Comparison of Energy System Modelling Approaches & Typical Model Characteristics [3]

[1] The MARKAL (MARKet and ALlocation) numerical models are used to carry out economic analysis of different energy related systems at the country level to represent its evolution over a period of usually of 40–50 years.

Model Characteristics	Energy System Modelling Approach				
	Bottom-Up Optimisation	**Bottom-Up Accounting**	**Top-Down Econometric**	**Hybrid**	**Planning**
Geographical Scale	Local to Global, mostly National	Mostly National, can be Regional	National	National or Global	National
Themes	Energy Systems, Environment, Trading	Energy Systems, Environment	Energy Systems, Environment	Energy Systems Hybrid	Energy Systems, Electricity Planning
Time horizon	Medium to Long-Term	Medium to Long-Term	Short, Medium or Long-Term	Medium to Long-Term	Medium to Long-Term
Data Requirement	Extensive	Extensive but can Work with Limited Data	High	High to Extensive	Extensive
Data Disaggregation	High	High	Varied	High	N/A
Technologies Modelled	Extensive	Extensive but Pre-defined	Variable but Typically Limited	Extensive but Pre-defined	Extensive
Modeller Skill Requirement	Very High	High	Very High	Very high	Very High
Computing Requirement	High End	Not Demanding	Econometric Software Required	Potential Commercial Software Requirement	Potential Commercial Software Requirement
Capability to Analyse Price-Induced Policies	High	N/A	High	Typically Available	Available
Capability to Analyse Non-Price Policies	Good	Very Good	Very Good	Very Good	Good
New Technology Addition	Possible	Possible	Difficult	Possible but Limited	Possible
Informal Sector Analysis	Difficult	Possible	Difficult	Possible	Difficult

2.4. Specialist Bioenergy Models

Although much bioenergy research is carried out using IAMs energy system models, the vast majority of bioenergy analyses is undertaken using specialist bioenergy models. These are typicall highly bespoke models designed to analyse specific bioenergy feedstocks, supply chains, technologies or systems issues. These models may be developed for a specific purpose/ research project by an individual or research team, and therefore are often less publicised and accessible compared to the larger more widely used IAMs and energy system models [22].

Specialist bioenergy models usually apply a bottom-up approach to carry out detailed evaluations of specific technologies, processes, resources and their resulting environmental/ cost/ energy/ impacts. In contrast to the framework followed by CGE and PE models, these bottom-up models do not normally undertake the equivalent detailed analysis of economic markets so the wider impact on these are not captured, but they instead focus on providing detailed measurements of performances for specific processes, activities or interventions. The specialist focus of these models means they typically apply accurate current data relevant to performances within a defined analysis boundary.

Specialist models may also be categorised within multiple subgroups based on the methods and tools they apply and the focus of the analyses. Examples of the different applications for these models is listed below:

- Process-based technical models to test the function of performance of systems;

- Process-based biophysical models to assess crop suitability and growth;
- Bioenergy sustainability indicator models to evaluate performance of systems against specific environmental/ social criteria;
- Life-cycle analysis modelling to analyse the environmental footprint of bioenergy systems and supply chains;
- Biomass resource models assessing feedstock availability within geographies [23];
- Land use management models to analyse impacts of using different land types;
- Feedstock supply chain models to evaluate the performance of supply chains;
- Techno-economic models to assess the potential costs of different technology option, and;
- Feedstock and bioenergy supply and demand mapping.

3. UK Focused Bioenergy Models

The following sections introduce and review a number of UK focused bioenergy models that have been developed to evaluate bioenergy from varying perspectives, scales and scopes. These include energy system models (ESM) and specialist UK bioenergy models (SPM):

- **Energy System Models** (ESM) that focus on bioenergy as part of the wider UK energy system;
- **Full Biomass Resource Assessment Models** (ESM / SPM) that assess that the potential availability of biomass for the bioenergy sector given different constraints;
- **Environmental Assessments Models** (SPM) that focus on specific environmental and sustainability themes relevant to bioenergy systems;
- **Feedstock Specific Models** (SPM) focusing on specific bioenergy feedstocks;
- **Vector Specific Models** (SPM) that focus on specific bioenergy vectors, and;
- **Carbon Accounting Models** (SPM) that assess the carbon performance of different resources, technologies and systems.

Table 2 summarises the bioenergy analysis tools and models included in this Scoping Reports. Supergen have categorised these based on their aims, objectives and approaches and a review has taken place of at least one model from each category to demonstrate how they are designed and applied. The bioenergy analysis tools and models included in Table 2 were developed following consultation with key academic members of the UK Supergen Bioenergy Hub, with representatives of industry and with the UK Department for Transport.

Table 2: UK Bioenergy Analysis Tools & Models Listed, Categorised and Reviewed within this Scoping Report

UK Models Listed and Categorised within this Scoping Report (○)	**UK Models Reviewed within this Scoping Report** (●)

Bioenergy Analysis Tools & Models	**UK Bioenergy Focused Models**					
	Energy System Models	**Full Biomass Assessment Models**	**Environment Assessment Models**	**Feedstock Specific Models**	**Vector Specific Models**	**Carbon Accounting Models**
ETI's Bioenergy Value Chain Model (BVCM)		●				
BioGrace-II						○
Biomass Environmental Assessment Tool (BEAT2)			●			
DfT's Transport Energy Model (TEM)					●	
E4tech's Biomass Supply Curves Analysis		○				
CARBINE Forestry Carbon Accounting Model						●
CCC's Biomass in a Low Carbon Economy Analyses		○				
DECC 2050 calculator		●				
ETI's Energy System Modelling Environment (ESME)	●					
ETM-UCL built on the TIMES model generator	○					
Forest Growth SRC				○		
JULES land surface model			○			
MISCANFOR				●		
PopFor				○		
Renewable Heat Incentive Calculator					○	
Ricardo's UK and Global Bioenergy Resource Model		●				
Ofgem's UK Solid & Gaseous Biomass Carbon Calculator						○
The Foreseer Tool			○			
TIAM-UCL	○					
Tyndall Centre's Biomass Resource Model (BRM)		●				
UK MARKAL	○					
UK TIMES (successor to MARKAL)						
Whole electricity System Investment Model (WeSIM)					○	

3.1. UK Energy System Models

Energy system models are technology focused and are used to evaluate the current and potential future role of different energy technologies within the wider energy system. These models assess different technologies based on cost performances and a series of assumptions such as future energy demands, economic performances and environmental requirements. Energy system models undertake calculations to determine the most cost effective way of balancing energy demands given wider these constrains. Therefore the extent that bioenergy technologies are included within the outputs of these models depends on their relative performances against different energy technologies. Energy system models can provide an indication of the levels of biomass feedstock that may be required to fuel the bioenergy technologies within the energy system.

Leading examples applied in the UK include the **MARKAL** [24] 'family' of models that are designed to assess different energy technology options at periodic intervals over a timeframe. This is achieved through linear optimisation analyses to identify the simplest combination of energy technologies that will minimises discounted energy systems cost, given a wide variety of physical and policy constraints. The **UK TIMES** model [25] was developed as a successor to MARKAL to provide an updated bottom-up, technology-rich framework that enables cost optimisation assessments of energy systems through time. There have been a series of subsequent models that have been developed using the TIMES energy system model generator to focus on different questions, for example **ETM-UCL** [26] was designed as an 'E4 Energy Systems Model' – allowing assessment of energy systems taking account of energy, economic, environmental and engineering constraints.

TIAM-UCL [27] is a further energy system model that allows global optimisation analyses to investigate energy decarbonisatopm pathways taking account of the 'global E3' (energy-environment-economy). TIAM-UCL allows an evaluation of the global costs and benefits of many decarbonisation options and has been used to assess issues related to the UK's use of imported biomass resources from different global regions.

The ETI's **ESME** model [28] is a further energy system model that has been widely used to assess the role of bioenergy with the UK's future energy mix through applying a policy-neutral cost optimisation approach. A review of the ESME model is presented in the following section to provide an insight into the design, focus and approach of energy system models and how they are applied to assess bioenergy.

3.1.1. Case Study Model – Energy System Modelling Environment (ESME)

Developer(s)	Energy Technologies Institute, maintained by the Energy Systems Catapult
Model Overview	ESME is a least-cost optimisation model designed to explore technology options for a carbon-constrained energy system, subject to additional constraints around energy security and peak energy demand. ESME covers the power, transport, buildings and industry sectors, and the infrastructure that underpins them.
Modelling Approach	ESME is a design tool rather than a forecasting tool where the analysis approach is designed to allow policy-neutral cost optimisation assessments. The ESME optimisation method it to find the least cost energy system designs which meet stipulated sustainability and security targets; whilst taking account of technology operation, peaks in energy demand and UK geography. The aim of the model is to examine the underlying cost and engineering challenges of designing energy systems. ESME is a Monte Carlo model which considers the uncertainty in its problems, particularly related to future energy prices and the future cost and performance of energy technologies. This functionality allows users to explore system-level responses to user-specified uncertainty in the future values of key assumptions.
Input Data	Data to parameterise different scenarios is chosen from within the model. For each technology option this is grouped into different sections of the energy system: conversion, infrastructure, industry, buildings and transport. Further data is required to characterise product emission factors, resource prices, availability of resources and demand for energy services.

Model Output	The key outputs from ESME are energy system designs which specify the capacity and pattern of operation of technologies in future energy systems. ESME produces different 'products' as outputs that comprise: • Energy Resources - which are available from outside the energy system e.g. coal, nuclear fuel, wind resource, biomass etc.; • End Use Services - which the energy system must provide, for example passenger km of car transport (produced by various car technologies), tonne km of road freight(produced by various HGV technologies) etc; • Energy Carriers - which can be produced and consumed within the energy system such as electricity, hydrogen, space heat etc.; • Emissions - principally CO_2, but could be any product for which a net production is to be expected, and; • Emission Carriers – for example 'captured CO_2' through BECCS or CCS technologies. There ESME model does not provide outputs providing analyses of wider systems issues, such as the environmental implications - impacts on water, biodiversity etc.
Timeframes	The analysis runs from 2010 to 2050 with analysis steps and outputs generated at 5 year intervals over the timeframe.
Geographic & Spatial Coverage	ESME represents the UK energy system at a regional level via 12 onshore and 12 offshore regions. Energy demands, natural resources, technology choices and infrastructure are all represented at the regional level.
Feedstocks Coverage	Bioenergy feedstocks within the ESME model are aggregated into the following categories: UK biomass, biomass imports, dry wastes, wet wastes and biofuel imports.
Technology Coverage	Bioenergy technologies assessed within the ESME model are: • Biomass fired generation technologies (with and without CCS); • Converted biomass plant; biomass CHP (various scales up to district systems); • Waste incineration; • IGCC biomass with CCS; • Waste gasification (with and without CCS); • Anaerobic digestion (gas plant and CHP plant); • Biomass boilers (various scales up to district systems); • Bio-diesel, bio-kerosine, bio-petrol (with and without CCS).
Coverage of Key Bioenergy Issues	The bioenergy focus of ESME predominantly the different bioenergy technology options. Although ESME's 'whole system' scope also includes assessment of all the major flows of energy, including: • Electricity generation, • Fuel production, • Heating and energy use in buildings, • Energy use in industry, • Transportation of people and freight.
Further Information	[29]

3.2. UK Full Biomass Assessment Models

There are a number of biomass resource assessment models that have been developed for the UK that evaluate multiple categories of biomass resources and assess their potential use by the bioenergy sector. These models either provide bottom-up assessments of all resources within a chosen geography and then develop scenarios that forecast how much of the total resource may be available for bioenergy based on a series of constraint assumptions. These models can be used to identify the types and levels of biomass resources available within the UK and therefore those that may represent the greatest opportunities for the bioenergy sector.

There are further models that provide top-down assessments that calculate the extent that different types of biomass resource may be required to balance the demands of bioenergy technologies included within future energy system scenarios, once again considering a series of assumptions and constraints. These models can be used to identify the scale of biomass resource that would be required to fuel the bioenergy technologies deployed within a given scenario.

Biomass resource assessment models applied in the UK can be further categorised based on the types of assumptions and forms of constraints included within the analyses. Full resource assessment models are designed to provide an inventory of the potential availability of multiple categories of resources within a chosen geography. The levels of biomass identified as being potentially available for the bioenergy sector are calculated based on the extent that resources may be sustainably/ economically/ technically grown/ produced/ mobilised, and the extent that there may be competition for the resource with wider sectors. Such models include the ETI's **Bioenergy Value Chain Model** (BVCM) [30] that provides both localised and an overall national UK assessment of biomass feedstocks, and the Tyndall Centre's **Biomass Resource Model** (BRM) [23] that provides UK outputs at the national scale. A review of both the BVCM and BRM is presented below to provide an insight into the design, focus and approach of the model and how it may be applied to assess bioenergy questions.

Economic resource assessment models similarly provide analyses of multiple categories of biomass resources, but the availability of feedstocks is constrained based on economic parameters related to the costs it will take to grow/ produce/ mobilise different resources. Examples of such models include Ricardo's **UK and Global Bioenergy Resource Model** [31] and that described within E4tech's **Biomass Supply Curves Analysis** [32]. A review of the UK and Global Bioenergy Resource Model is presented below.

Emission focused biomass resource models such as that presented within the CCC's **Biomass in a Low Carbon Economy Analyses** [33] assess the potential role of UK biomass resources from the perspective of reducing emissions and achieving emissions targets, constrained by the availability of the resource and the emission performances of bioenergy technologies. The **DECC 2050 Calculator** [34] represent an example of a top-down assessment model that allows analyses of the demands of different biomass resources given the extent that bioenergy technologies are included within future scenarios designed to achieve the UK's emission targets. A review of the DECC 2050 Calculator is presented below.

3.2.1. Case Study Model – Bioenergy Value Chain Model (BVCM)

Developer(s)	E4tech and Imperial College Consultants for the Energy Technology Institute
Model Overview	The Bioenergy Value Chain Model (BVCM) is a comprehensive and flexible toolkit for the modelling and optimisation of full-system bioenergy value chains over a timeframe to 2050. The model is designed to allow assessment of the most effective way of delivering a particular bioenergy outcome in the UK taking account of the available biomass resources, the geography of the UK, time, technology options and logistics networks.
Modelling Approach	The BVCM divides the UK into 157 cells of uniform size and undertakes analyses within each to assess the bioenergy potential based on the varying characteristics - land use, yields, transport links and industry activity. This allows assessment of the bioenergy opportunities within different parts (cells) of the UK and to identify the optimal locations for bioenergy activities and deployments. The BVCM toolkit undertakes this analysis across a number of modelling components across different platforms. The core calculations take places within a 'mixed-interger linear programming (MILP) model developed in the AIMMS modelling platform. This draws upon data from a series of Excel workbooks and text files that are used to store all the data relating to the BVCM's technologies, resources, yield potentials, waste arising etc. A user friendly interface is provided in AIMMS that allows the calibration of the scenarios through

	manipulating a long series of parameters. Outputs from the model are provided through summary tables and network diagrams that are overlaid over a map of the UK. Further visualisation and summary results are provided through the linked Excel platform.
Input Data	Input source data is held within the BVCM with the user developing scenarios through varying parameters that characterise: • Bioenergy system costs and/ or profits; • Bioenergy system GHG emissions; • Energy production; • Exergy production; • Spatial elements of the analysis including the total area assess, land cover and the transport infrastructure within this area; • Resource elements including yield potentials, climate scenarios and ramp-up rates; • Technology choices such as the size, cost, efficiencies and build rates; • Greenhouse gas targets and CO_2 prices; • Energy demand dynamics including total energy and vector specific demands; • Biomass imports choices, either allowing these or not; • CCS choices, either including these technologies or not; choices relating to 'land masks', to avoid areas which are unsuitable for crop production and / or to limit production on certain land types.
Model Output	The primary output from the BVCM are scenarios of the optimal bioenergy value chain structure over the timeframe to 2050s. This includes information on: • Allocation of crops to available UK land; • Choice of technologies, where and when they are deployed and used; • End vectors generated (heat, power, liquid and gaseous fuels); • Transport and pipeline networks required; • Use of imports and CCS (where permitted).
Timeframes	The analysis timeframe runs to 2050 with decadal analysis intervals covering the 2010s, 2020s, 2030s, 2040s and 2050s. Further seasonal analysis is also undertaken to divide years into four seasons to capture and evaluate the seasonal nature of many biomass resources.
Geographic & Spatial Coverage	BVCM is a spatial and temporal model of the UK, configured over 157 cells of 50km x 50km size – the same analysis taking place in each cell to identify the bioenergy potential of different cells (areas of the UK), and the optimal locations for bioenergy activities and infrastructure.
Feedstocks Coverage	The BVCM toolkit is populated with 82 different energy resources with the option for users to add new ones via a database. The resource 'families' are: • Arable crops (e.g. winter wheat, oilseed rape, sugar beet); • Energy crops (e.g. miscanthus, short rotation coppice (SRC) willow); • Forestry (e.g. short rotation forestry (SRF), long rotation forestry (LRF)); • Wastes (e.g. wood, food, unseperated); • Intermediates (e.g. chips, pellets, torrefied pellets, pyrolysis oil, syngas), and; • Anaerobic digestion biogas.
Technology Coverage	The BVCM toolkit is populated with 61 distinct conversion technologies across a series of scales. These technology 'families' are: • Densification (e.g. chipping, pelletising, oil extraction); • Thermal pre-treatment (e.g. torrefaction, pyrolysis, mechanical biological treatment (MBT)); • Anaerobic digestion (e.g. anaerobic digestion, biogas upgrading); • Gasification (e.g. generic, bioSNG, H2); • First generation (1G) biofuels (e.g. 1G bio-ethanol, 1G bio-diesel, 1G bio-butanol); • Second generation (2G) biofuels (e.g. lignocellulosic bio-ethanol and bio-butanol); • Heating (e.g. boiler combustion, syngas boiler, district heating); • Combined heat and power (CHP) onsite (e.g. stirling engine, organic rankine cycle, internal combustion engine); • CHP for district heating (e.g. gas turbine, steam cycle, integrated gasification combined cycle);

	• Power (e.g. combined cycle gas turbines, plasma gasification, incineration, pyro-liquid biorefinery); • Power with CCS (e.g. oxyfuel, chemical looping); • Gaseous with CCS (e.g. gasification (bioSNG) + CCS, gasification (H2) + CCS).
Coverage of Key Bioenergy Issues	The BVCM allows analysis of biomass resource potentials based on assessments of land use dynamics, yields, industry activities, climate impacts and scenarios and available infrastructure.
Further Information	[35]

3.2.2. Case Study Model – Biomass Resource Model (BRM)

Developer(s)	Tyndall Centre for Climate Change Research at the University of Manchester
Model's Use	The BRM was developed to provide a tool of assessing the availability and bioenergy potential of terrestrial biomass resources within the UK. The model is used to analyse which categories of biomass resource may represent the greatest opportunities for the UK bioenergy sector, taking account of limitations and constraints of land availability, food systems, existing and competing uses for different categories.
Modelling Approach	The BRM applies a bottom-up modelling approach to calculate the maximum 'theoretical potential' availability of biomass resources for the bioenergy sector. Through the development of scenarios these values are constrained taking account of technical, economic and sustainability parameters to provide more realistic availability forecasts. The bioenergy potential of these available resources are calculated based on the energy content and characteristics of different feedstocks and the conversion efficiencies of the bioenergy technologies chosen within the modelled scenarios. These biomass resource availability assessments and bioenergy potential calculations are compared against energy and biomass demand forecasts.
Input Data	The BRM is designed with a default parameters that characterise 'base year' dynamics for variables related to land use, population, dietary choices and consideration of bioenergy within different industry sectors and supply chains. Users may develop alternative scenarios through adjusting the default parameters to model different potential pathways to 2050.
Model Output	The BRM provides outputs over a timeframe to 2050, including: i) an assessment of the types and scales of biomass resource available within the UK; ii) the level and forms of bioenergy that may generated from the available biomass; and iii) an assessment of the extent that the UK may potentially balance its biomass resource demands without imports.
Timeframes	The BRM operates over a timeframe from 2010 to 2050, with analysis outputs generated for 2010, 2015, 2020, 2030 and 2050.
Geographic & Spatial Coverage	The BRM is designed to analyse availability and bioenergy potential of UK terrestrial biomass resources at a national scale. Further BRMs have been developed to assess other key countries around the world, focusing on case studies of countries where the UK is likely to import bioenergy feedstocks.
Feedstocks Coverage	Coverage of all terrestrial biomass resources including: • Wastes (MSW, wood, sewage etc.), • Energy crops (miscanthus, willow, poplar etc), • Dedicated forestry biomass and forestry residues, • Agricultural wastes (cattle, poultry, pig manures), • Agricultural residues (cereal straws etc), • Other niche biomass resource categories such as arboricultural arisings.
Technology Coverage	Coverage of bioenergy technologies for generation of heat, power, CHP and transport fuels including combustion, pyrolysis, gasification and co-firing technology options.
Coverage of Key	The BRM allows assessment of biomass resource potential given different scenarios related to:

Bioenergy Issues	• Land-use; • Food security; • Waste management; • Forestry management • Use of different wastes and residues from industry.
Further Information	[23,36]

3.2.3. Case Study Model – UK and Global Bioenergy Resource Model

Developer(s)	Developed by Ricardo Energy & Environment for BEIS
Model Overview	This model builds on the previous work developed for DECC [37] that estimated the potential bioenergy resource available to the UK from domestically sourced and imported feedstocks from 2010 to 2030. The UK and Global Bioenergy Resource Model provides an update that estimates the potential UK and global bioenergy resource available to the UK over a timeframe to 2050 through the development of scenarios. Assessments in the updated model also consider: sustainability constraints for solid and gaseous biomass; sustainability criteria for liquid biofuels; inclusion of a placeholder for ILUC emissions, and; reporting of land use requirements for biofuels and perennial energy crops supply.
Modelling Approach	The model provides a full assessment of the unconstrained potential availability of UK bioenergy feedstocks for the bioenergy sector through analysis of land systems and industry sectors. Scenarios are then developed taking account of a series on constraint assumptions that narrow the resource availability forecasts – based on sustainability requirements, carbon targets, land-use dynamics and the existing and future competition for different biomass resources. A parallel global assessment is also undertaken focusing on key countries to determine the types and levels of feedstock that may be available to the UK through trade. For the UK the key constraints to feedstock availability analysed in the model are: • Policy Constraints including energy, environmental, waste agriculture and forestry policies; • Market Constraints that take account of the relative 'immaturity' of UK bioenergy feedstock markets; • Technical Issues that include those that may take investment to overcome, those that require standards or regulation to clarify, or those where further research and development is required to prove technologies; • Infrastructure Issues that enable or restrict the development of feedstock supply chains for the deployment of required technologies.
Input Data	The scenarios within the model are generated through a control panel where users are able to select the ease in which different bioenergy pathways may be deployed in the UK. For example for generating solid biomass/ biogas from UK waste wood, identifying whether this pathway has: 'no barriers to overcome', 'easy barriers to overcome', 'easy and medium barriers to overcome', or 'all barriers to overcome'. These choices drive the calculations where different data assumptions are applied within the model. The assumptions data is included within in-built data sheets, that include: • Sustainability data, • Assumed end use, • Land availability data, • Perennial energy crop data, • Biofuels data, UK crop yields, • Global constraint data, • Global demand data • Global demands.
Model Output	The primary outputs from the model are assessments of the total potential UK bioenergy resource available, and the total potential international resource available for trade (PJ / TWh); also the UK land area need to meet project bioenergy supply from the UK, and the land area

	needed outside the UK to meet the projected bioenergy supply to the UK from international sources (kha). These outputs are generated reflecting three scenarios: a business as usual (BAU) scenario, a high investment scenario, and; and low development scenarios.
Timeframes	The analysis timeframe runs from 2015 with outputs generated at 5 year intervals up to 2050.
Geographic & Spatial Coverage	The model provides a national level assessment of UK bioenergy feedstocks and a global assessment of feedstocks focusing on a series of key countries likely to export biomass for potential trade with the UK.
Feedstocks Coverage	Analysis of feedstocks within the model are categorised as: • Dry agricultural residues; • Agricultural wastes (e.g. manures); • Forestry products (e.g. stemwood, SRF, residues); • Industry residues (e.g. sawmill co-products); • Aboricultural arisings; • Wastes (e.g. wood, food, landfill, sewage); • Energy crops (e.g. perennial).
Technology Coverage	Bioenergy conversion technologies analysis are categorised as: • Co-firing, • Dedicated biomass, • Advanced conversion technology zand dedicated biomass with CHP – each with either chips, bales or pellets; • Advanced biofuels; • Biogas with grid injection; • Biogas for electricity; • Liquid biofuels for vehicle fuel.
Coverage of Key Bioenergy Issues	The model provides assessment of bioenergy feedstock availability covering key issues of: • Bioenergy value chain economics; • Sustainability (LCA GHG emissions, ILUC emissions); • Bioenergy technologies and conversion pathways; • End uses and vectors; • Crop yields; • Barriers/ constraints (infrastructure, policy etc).
Further Information	[31,37]

3.2.4. Case Study Model – DECC 2050 Calculator

Developer(s)	Department of Energy & Climate Change (DECC)
Model Overview	The 2050 Calculator provides a suite of tools that allow users to create their own energy pathway for a given country, considering all parts of the economy and the greenhouse gas (GHG) emissions attributed to each. The objective is to allow the development of different potential pathways for meeting energy and emission targets, with focus placed on highlighting the array of technologies and activities available and the degrees of effort/ deployment that will be required to meet targets.
Modelling Approach	The 2050 Calculator is a top down modelling tool rooted in scientific and engineering realities of what is physically and technically possible for each sector to decarbonise to meet emission targets. This analyses is achieved through a providing users with a framework of the choices and trade-offs we will have to make up to 2050. It is system-wide, covering all parts of the economy and all greenhouse gas emissions released in the UK.
Input Data	User prioritises deployment of different technologies and activities focusing on: • Electricity generation (including bioenergy supply);

	• Eenergy demands (transport, households, business); • Choices for meeting energy demands and emission targets (e.g. geo-sequestration, carbon storage and fossil fuels).
Model Output	Trajectories over the analysis timeframe that reflect the design and characteristics of modelled scenarios, including: energy supply and demand; breakdown of emissions across sectors, and; an assessment of energy security.
Timeframes	2010 to 2050 with outputs generated at 5 year intervals
Geographic & Spatial Coverage	Focused on the UK energy system and industry sectors. Although variant models have been developed by DECC/ BEIS focusing on multiple other countries.
Feedstocks Coverage	Dedicated production of biomass feedstock and wastes and residues generated by all sectors, aggregated as: • 1st and 2nd generation energy crops; • Dry biomass and wastes; • Wet biomass and wastes; • Gaseous wastes; • Imported biomass (solid/ liquid gaseous).
Technology Coverage	Calculations of bioenergy generation potential from available feedstock using default calorific value and conversion efficiency parameters. Choices available to prioritise deployment of general biomass co-firing power stations, carbon capture and storage facilities, biofuel, biogas, and biomass energy systems.
Coverage of Key Bioenergy Issues	Emissions performance of energy technology deployment scenarios. Assessment of bioenergy potentials given different land use choices.
Further Information	[38]

3.3. UK Environment Assessment Models

Environmental assessment models are designed to analyse biomass and bioenergy questions in the context of their environmental performances. Through modelling the many interactions between biomass production, supply chains, and conversion processes with environmental systems, these models are used to assess the environmental impacts and benefits that may be gained through pursuing a given bioenergy scheme. These models include coverage of themes related to land use, ecosystems and biodiversity, water systems, the carbon cycle etc. From the perspective of analysing feedstocks, environmental assessment models may be used to analyse the availability of different biomass resources given environmental constraints and may be used to investigate the specific environmental impacts and benefits that may result in their use within bioenergy systems.

Examples of biomass and bioenergy environmental assessment models applied in the UK include the **JULES** land surface model [39] that allows assessment of biomass production potential through the analysis of different land surface processes, such as the surface energy balance, hydrological cycle, carbon cycle, vegetation dynamics etc. Another example is **The Foreseer Tool** [40] that is designed to analyse energy potential with land and water system constraints. A prominent approach applied within environmental assessment models is life cycle assessment (LCA), where each step with a given bioenergy system is analysed to determine the impacts and benefits of individual processes and that of the overall system. The **Biomass Environmental Assessment Tool (BEAT2)** [41] provides an example of an LCA model where bioenergy systems are analysed based on both their greenhouse gas emissions performances and their potential environmental impacts and benefits. A review of the BEAT2 model is presented below.

3.3.1. Case Study Model – The Biomass Environmental Assessment Tool (BEAT$_2$)

Developer(s)	AEA and North Energy Associates for DEFRA, Biomass Energy Centre and the Environment Agency
Model Overview	The BEAT$_2$ tool is designed to provide the means of assessing the potential benefits and impacts, of bioenergy technologies. The tool: i) provides a comparison of greenhouse gas emissions from the proposed plant and fossil fuel based plant; ii) provides information on key potential environmental impacts; iii) identifies potential options for mitigating environmental impacts, and; iv) provides an estimate of production costs and of support mechanisms.
Modelling Approach	Attributional life cycle assessment of chosen bioenergy value chain.
Input Data	BEAT$_2$ allows the user to input information on different categories of bioenergy conversion plant and feedstock. Either a minimum level of information or detailed information specific to the plant and type of biomass production – the tool providing default parameters that may be altered.
Model Output	Energy and greenhouse gas balances and potential environmental impacts and benefits based on the input data. The outputs also highlight where values have been changed from the default setting.
Timeframes	Outputs characterising the specific value chain/ scheme/ supply chain assessed.
Geographic & Spatial Coverage	BEAT$_2$ is a UK-based tool and cannot be used to assess bioenergy options outside the UK or to assess the impact of internationally sourced feedstocks.
Feedstocks Coverage	• Energy crops (miscanthus), • Biofuel crops (oil seed rape, sugar beet etc), • Agricultural residues (straws, cereal milling residue etc), • Agricultural wastes (pig, dairy, poultry), • Dedicated forestry and forestry residues (chips and pellets), • Wastes (wood, oils, food).
Technology Coverage	Multiple technology options for combustion (power, heat, CHP), gasification (CHP), pyrolysis (power and CHP) and co-firing (existing UK plant).

Coverage of Key Bioenergy Issues	Attributed to each value chain assessed: • Life cycle emissions; • Benefits and impacts (biodiversity, flood risk, noise, odour, socio-economic, soil quality, visual impact, water quality, water resources); • Energy use; • Cultivation/ mobilisation dynamics; • Costs
Further Information	[42]

3.4. UK Feedstock Specific Models

Feedstock specific models are developed to analyse the many dynamics associated with the growth/ production/ mobilisation of specific biomass resources. The majority of these models focus on different crops species that are potential feedstocks for bioenergy. Analyses focuses on natural systems specific to a given field or wider site and model how these may influence crop yields and phenology. Typical features analysed include the weather and climatic conditions and the characteristics of the soils. These models can be used to predict the typical yields that may be achieved at a particular field/ site; to identify any limiting factors that may constrain resource production at a given field/ site, and; to identify the optimal geographic boundaries for producing different resources in order to locate the ideal locations to maximise productivity.

Examples of feedstock specific models developed for the UK include the **Forest Growth SRC** model [43] that focuses on production of poplar and willow in the UK using the short rotation coppicing (SRC) technique. The **MISCANFOR** [44] and **PopFor** [45] models are further examples of tools that allow analyses of potential miscanthus and poplar production at specific locations in the UK. A review of the MISCANFOR model is presented below.

3.4.1. Case Study Model – MISCANFOR

Developer(s)	MISCANFOR is developed by a team from the University of Aberdeen and Aberystwyth University [44], building on the existing MISCANMOD model [46].
Model Overview	The MISCANFOR model was produced to allow the prediction of the inter-annual variation of miscanthus production yields with consideration of occasional drought and frost events that kill the crop or severely reduce the yield. The model therefore is used to analyse miscanthus productivity yields for miscanthus and the natural range of the crop without additional irrigation or frost protection.
Modelling Approach	The MISCANFOR model enables analysis of miscanthus crop yields for different sites based on calculations of precipitation (Ppt), PAR, PET and irrigation evapo-transpiration, soil moisture content, photosynthetically active radiation (PAR), plant physiological time clock, water stress, hot and cold temperature stress, shoot and rhizome death, nutrient repartition to the rhizome and above ground DM moisture content. To evaluate the model, the predicted variables and the model outputs should be compared with field experimental data.
Input Data	The inputs required to model each site are defined by the desired timeframes and the nature of the analysis grid. The analysis is driven by input monthly precipitation and temperature data alongside soil and water properties.
Model Output	The outputs from the model are an assessment of miscanthus dry matter that is produced for the site over the analysis timeframe. This is produced as a daily increment value and the year-to-date sum of above the ground dry matter. These outputs should be compared to experimental data and statistics. The model can also map and calculate geographical scenarios yields.
Timeframes	MISCANFOR can be applied to any timeframes over multiple or single years based on the data available.
Geographic & Spatial Coverage	The model can be applied to single or multiple locations based on the analyses chosen and the data available. The MISCANFOR model has been previously applied to multiple UK and European cases.
Feedstocks Coverage	The MISCANFOR model focuses specifically on miscanthus production although further similar models have been produced to focus on other crops, for example the PopFor model developed to analyse poplar [45].
Technology Coverage	N/A
Coverage of Key	Crop productivity yields.

Bioenergy Issues	
Further Information	[44]

3.5. UK Vector Specific Models

There are a number of UK models that have been developed focusing on specific energy vectors. These analyse questions related to the contribution of the bioenergy to the core energy vectors - transport, heat and power energy systems. These models vary in their approach and are designed to cover a broad range of different themes relevant to each vector. Therefore their coverage of different bioenergy feedstocks is highly variable dependent on the approach, aims and objectives of the model.

Examples of three different models that have been develop to focus on specific UK energy vectors albeit with different approaches, aims and objectives include: the **Renewable Heat Incentive Calculator** [47] for heat, **The Whole electricity System Investment Model (WeSIM)** [48] for power, and the **Transport Energy Model (TEM)** [49] for transport.

The Renewable Heat Incentive Calculator [47] is designed to be used by individual consumers and installers of eligible renewable heating systems in England, Scotland and Wales to estimate their potential domestic renewable heat incentive (RHI) payments, based on the performances of their installed energy technology. Therefore may be used to assess performances of the specific bioenergy heating technologies installed within dwellings.

The Whole electricity System Investment Model (WeSIM) [48] was developed to focus on the power sector, providing the means to analyse electricity systems by simultaneously balancing long term potential investment decisions against short term operational decisions, taking account of different generating technologies, transmission and distribution systems. From a bioenergy perspective the WeSIM model may be used to explore the potential contribution of bio-power technologies to the UK energy mix operating alongside other renewable and conventional technologies to balance the UK's energy demands within different energy cost and security scenarios.

Transport Energy Model (TEM) was developed to allow assessment of different transport technologies and transport fuels - providing a calculation of the impact of these over time by taking account of the respective GHG emissions and air pollution profile of each. A review of the TEM is presented below.

3.5.1. Case Study Model – Transport Energy Model (TEM)

Developer(s)	The TEM was developed by the Department for Transport, working with stakeholders from industry, academia, environmental groups and Government, including vehicle manufacturers, fuel suppliers, vehicle and environmental consultancies, environmental lobby groups and other Government Departments.
Model Overview	The TEM assesses the energy consumption, air quality pollutant emissions and greenhouse gas emissions of a range of road transport fuels and technologies over the period to 2050. This via a 'side by side' comparisons of various vehicle powertrain technology and fuel options for cars, vans, buses, trucks and HGVs.
Modelling Approach	The TEM allows side by side comparisons of energy consumption, greenhouse gas emissions and air pollutants of a range of vehicles. The TEM focuses on vehicle types which contribute substantially to road transport air pollutant and/or greenhouse gas emissions. The vehicles are: a medium car, a panel van, an 18 tonne heavy goods vehicle (HGV), a 44 tonne HGV and a double deck bus. Air pollutant emissions values are modelled for various Euro emissions standards (e.g. Euro 6 for the latest generation of vehicles). The TEM does not cover emissions from the manufacture or disposal of the vehicle. However, the model does include a sensitivity analysis of the additional energy and greenhouse gas emissions required to manufacture batteries for vehicles with electric powertrains. The TEM assesses a range of fuels including conventional fossil fuels (petrol and diesel), biofuels, natural gas (compressed natural gas (CNG) and liquefied natural gas (LNG)), liquefied petroleum gas (LPG), hydrogen and electricity. For biofuels there is potential issues related to the sustainability of feedstocks and the extent to which biofuels may meet demands across sectors. Major assumptions with the TEM's approach include: • Vehicle Energy Consumption – which has come from a range of sources including vehicle testing, industry data and research; • Fuel Emissions factors – where possible, Government greenhouse gas reporting factors are used;

	• Grid Electricity Emissions – Government projections have been used (with an uplift applied to account for fossil emissions associated with gas and coal production), and; Alternative • Fuel Emissions – a range of sources has been used including Renewable Transport Fuel Obligation statistics and the EU 'well to wheels' project.
Input Data	Inputs required to model different transport technologies includes: • Vehicle energy consumption assumptions (MJ/km); • Greenhouse gas emissions from energy production and use (gCO_{2e}/km); • Non-combustion greenhouse gas emissions (gCO_{2e}/MJ) such as nitrous oxide (N_2O); • Tailpipe NO_x and PM emissions (g/km) which are used directly as model outputs.
Model Output	The primary outputs for each transport technology is a calculation of GHG emissions and air pollitant emissions, presented as: • 'Total driving GHG emissions' (gCO_{2e}/km); • 'Tailpipe NO_x/PM emissions' (g/km).
Timeframes	The model analyses the performances of different transport modes/ technologies with estimates of future developments for selected technologies for 2020, 2030, 2040 and 2050.
Geographic & Spatial Coverage	The Transport Energy Model was developed to focus on UK transport systems.
Feedstocks Coverage	The model is largely driven by the target bioenergy vector (different transport fuels), feedstocks are only covered in the classification of different fuels, such as: crop bio-ethanol, crop bio-diesel, crop bio-methanol; waste bio-ethanol, waste bio-diesel and waste bio-methanol.
Technology Coverage	The model includes assessment of multiple modes and classifications of transport vehicles including: medium cars, panel vans, 18 Tonne HGV, 44 Tonnes HGV and double decker bus. Bioenergy conversion technologies included in the analyses include: fuel production from 1st Generation crops and wastes processes; fuel production from Advanced crops and wastes processes, and; anaerobic digestion.
Coverage of Key Bioenergy Issues	The TEM model focuses on the use of biofuels to be used within different transport technologies, calculating the energy, emissions and air pollution performances of each. Also through linking to the RTFO assessment criteria there is consideration of sustainability issues associated with of biofuel feedstock supply chains such as ILUC.
Further Information	[49]

3.6. UK Carbon Accounting Models

The GHG and carbon performance of bioenergy systems is a crucial analysis theme that has been the subject of many models. These have varying focus ranging from models that analyse the specific carbon dynamics related to the production of specific feedstocks, the emission performances of bioenergy technologies, through to models that provide overall GHG emissions performance values for whole bioenergy systems or bioenergy fuels. From a feedstock perspective these models may be used to: establish if/ to what extent a feedstock may be used to generate energy with lower GHG intensity values compared to that of fossil fuels; to establish harmonised bioenergy GHG performance values related to different feedstocks and technologies, and; to optimise the GHG performance of bioenergy systems through identifying processes and activities within a given bioenergy system that should be either be replicated or avoided based on the calculated GHG intensity of the process.

From a bioenergy system level perspective a prominent carbon accounting model applied in the UK is Ofgem's **UK Solid and Gaseous Biomass Carbon Calculator** [50], which was developed for calculating carbon intensity and GHG savings of solid biomass and biogas used for electricity and heat generation. The values within the UK Solid and Gaseous Biomass Carbon Calculator are derived applying the calculation methodology set out in the Renewable Energy Directive [51], and are also aided by models such as the **BioGrace-II** [52] calculation tool - designed to harmonise calculations of GHG emissions for electricity, heat and cooling from biomass throughout the European Union.

At the other end of the scale, Forest Research's **CARBINE** model [53] is a prominent model that focuses specifically on calculating the carbon dynamics associated with the production and management of UK forests – allowing assessment of the carbon impacts and benefits of utilising forestry biomass as a bioenergy feedstock. A review of the CARBINE model is presented below.

3.6.1. Case Study Model – CARBINE

Developer(s)	Forest Research
Model Overview	The CARBINE Model is designed to i) estimate the carbon stocks of stands and forests (in living and dead biomass and soil), and any associated harvested wood products, and; ii) estimate the greenhouse gas emissions avoided through the use of wood products that displace fossil fuels and fossil-fuel intensive materials.
Modelling Approach	The model consists of four sub-models or 'compartments' which estimate carbon stocks in the forest, soil, and wood products and, additionally, the impact on the greenhouse gas balance of direct and indirect fossil fuel substitution attributable to the forestry system.
Input Data	Forestry Estimates: • Stand-level carbon, • Area/age-class information, • Forest and national carbon stocks, • Yields, • Management scenarios.
Model Output	Carbon stock changes inferred from differences in carbon stock estimates at different times.
Timeframes	Current or historic dependent on data availability.
Geographic & Spatial Coverage	Can focus on individual stands, forests or national level analyses.
Feedstocks Coverage	Wood processing wastes and residues linked to the production of long-lived sawn timber, short-lived sawn timber, particleboard, paper.
Technology Coverage	N/A
Coverage of Key	GHGs and Carbon over lifecycles of forests and forest products

Bioenergy Issues	
Further Information	[54]

3.7. Summary

Each of the models assesed within this Scoping Report were developed to analyse different aspects of bioenergy systems and therefore have different approaches and varying coverage of bioenergy themes. Table 3 highlights the stages of bioenergy value chains where the analyses and calculations within each model focus. The coverage and performances of the key UK bioenergy models included within this Scoping Report may be summarised as follows:

- **ESME Energy System Model** - focuses on evaluating different technology options that will contribute to future UK energy systems based on their energy, economic and environmental performances. The model does not provide assessment of biomass resource availabilities, instead using theoretical estimates derived from scenarios from the BVCM. Biomass import estimates are based on scenarios from the UK and Global BRM.
- **BVCM Full Biomass Assessment Model** - allows analysis of complete bioenergy value chains, including coverage of multiple biomass feedstocks, intermediates and end-use energy vectors. BVCM does not prescribe a fixed pathway to the value chain and resources may undergo a number of transformations from harvested biomass to finished products. The model provides limited assessment of the sustainability and GHG performances of bionergy value chains.
- **Tyndall BRM Full Biomass Assessment Model** - provides a bottom up assessment covering all stages of bioenergy value chains, from biomass production/ mobilisations through to conversion to different bioenergy vectors. This model does not assessment of the sustainability, economics or GHG performances of bioenergy value chains.
- **UK & Global BRM Full Biomass Assessment Model** – provides analyses of full bioenergy value chains focusing on the production/ mobilisation of feedstocks given within pre-determined cost constraints followed by a calculation of the bioenergy potential of these resource applying different conversion technologies. The model provides limited assessment of the sustainability and GHG performances of bionergy value chains.
- **DECC Calculator Full Biomass Assessment Model** - provides top down analysis of bioenergy feedstocks and technologies with focus on the energy and GHG performances of technologies. Also provides indication of biomass availability given land and sustainability constraints.
- **BEAT2 Environment Assessment Model** - provides detailed analyses of the environmental performances bioenergy systems covering all stages of bioenergy value chains. The design of this model is limited to assessment of key environmental issues.
- **MISCANFOR Feedstock Specific Model –** is a calculation tool designed to allow assessment of the productivity and yields of feedstocks, focusing on the production stages of the value chain.
- **TEM Vector Specific Model** - calculatation tool allowing assessment of the energy, emissions and air pollution performances of the combustion of biofuels within various transport technologies. Through external links to the RTFO assessment criteria the TEM also provides consideration of sustainability issues associated with feedstock supply chains.
- **CARBINE Carbon Accounting Model** – calculation tool designed to analyse carbon dynamics with focus limited to the forestry growth, management and harvesting stages of the value chain.

Table 3: Stages of Bioenergy Value Chains where Key UK Bioenergy Models Focus

UK Models		**Bioenergy Value Chain**						
		Growth & Production	**Harvesting, Collection, Mobilisation**	**Biomass Transport**	**Processing**	**Fuel Transport**	**Conversion**	**Post – Conversion Management**
Energy System	ESME	Some Coverage	Some Coverage	Some Coverage	Some Coverage	Some Coverage	Primary Focus	Some Coverage
Full Biomass Assessment	BVCM	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus
	Tyndall BRM	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus
	UK & Global BRM	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus
	DECC Calculator	Some Coverage	Some Coverage	Some Coverage	Some Coverage	Some Coverage	Primary Focus	Some Coverage
Environment Assessment	$BEAT_2$	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus	Primary Focus
Feedstock Specific	MISCANFOR	Primary Focus	Primary Focus					
Vector Specific	TEM	Some Coverage	Some Coverage				Primary Focus	Some Coverage
Carbon Accounting	CARBINE	Primary Focus	Primary Focus					
Key:		**Primary Focus**			**Some Coverage**			

4. Performance of Models in Assessing Bioenergy Questions

Models are developed for many reasons and are often adapted and evolve to analyse research questions that may originally have never been foreseen when the model was first designed. Models are also always simplifications of reality for the sake of analysis and as a consequence there will always be models which don't adequately cover certain issues or features, or don't cover certain elements at all. Therefore there should always be a degree of caution when interpreting outputs from modelling tools and this is doubly important when models are used as tools to inform policy.

Table 4 provides an overview of the capability, performances, strengths and weaknesses of IAMs, Energy System Models and Specialist Models when used in bioenergy research. This is supported by Table 5 that is designed to provide a clear visual summary of the extent that different biomass and bioenergy themes are covered by the different categories of models as documented in literature published between 2000 and 2018. Table 5 highlights the proportional coverage of different issues by models - ranging from no coverage at all by certain models, to coverage where over 20% of published papers that apply a modelling approach also focus on a given bioenergy theme.

Each of the model types can be very successful at answering bioenergy questions that are compatible with the design and framework of assumption intrinsic to each. Problems, uncertainties and risks for policy occur when models are used out of context or elements and unforeseen impacts are not covered by the model are subsequently overlooked. These limitations are largely a result of the design of the models, for example:

- CGE and PE energy systems models have limitations that stem from the design and approaches built within the model architecture. These models are driven by key assumptions such as price changes, and are designed to have specific coverage of sectors of economic activity, therefore any wider outputs need to be analysed bearing in mind the focused scope of these models. For example PE models are only able to capture the techno-economic aspects of a system reflective of the sectors included in the model, therefore cannot be used to analyse any wider interactions relating to environmental or social systems that may result from the deployment of different technologies.
- Specialist models that apply a bottom-up analysis approach to focus on a specific question are capable of capturing rich technological, environmental, economic and social details, and through this can identify both attractive and inferior potential solutions. The limitations to this approach stem from the complexities required – relevance of outputs will be limited to the focused system boundaries of the questions being analysed, and there can be high computation requirements to achieve these. The high focus of this approach may also result in the non-coverage of macro-systems and feedbacks, leading to optimal solution identified by specialist models potentially not taking into account wider real-life systems.
- IAMs aim to include as many factors as possible with their analyses (economy, climate, society, environment) and to calculate the feedbacks between these. This comes as a cost, as to capture all these dynamics IAMs operate on coarse levels of detail and assumptions that ultimately filter through to the outputs generated. For example IAMs will likely only have limited representation of alternative technologies so the outputs are restricted to the assumptions around these. This can also lead to problems where IAMs share data files with wider models (soft-linked), achieving convergence and consistency between the models can be problematic stemming from the use of coarse values for the assumptions built within the IAM.

Therefore relying on a single category of model or just one specific model will likely only provide outputs that give insight on a limited range of themes. As bioenergy is intrinsically linked to people, processes and land and as such will impact and benefits each, there are many more themes that need consideration compared to other renewable technologies. It is not feasible to develop an all-encompassing bioenergy model that covers all these linkages and captures the nuances between different systems. This therefore leans towards a strong argument for the use of multiple models in parallel each with different approaches in order to build a more robust overall conclusions.

Table 4: Summary of the Capability & Characteristics of Different Categories of Models [3]

	Integrated Assessment Models (IAM)	**Energy System Models**		**Specialist 'Bottom-Up' Models**
		Computable General Equilibrium (CGE)	*Partial Equilibrium (PE)*	
Application	• Bioenergy resource potentials based on varying assumptions & criteria • Contribution to long term climate policy • Impacts of bioenergy policies on global land use, water and biodiversity	• Economic impacts of biomass & bioenergy policies • Policy Effects such as resulting GHG emissions	• Indirect substitutions such as land use & rebound effects on multiple sectors • Sector impacts of bioenergy policies on agriculture, forestry, land use change, energy system & GHG emissions	• All technical aspects of feedstock supply, conversion & use. • Validation of other studies with broader scopes.
Timeframe	• Long	• Short to Medium	• Short to Long	• Short to Long
Strength of Approach	• Integrating different systems in one modelling framework • Potential for analysing feedbacks between human & natural systems, trade-offs & synergies with political strategies • Developed around long term dynamics	• Comprehensive coverage of economic sectors & regions to account for inter-linkages • Explicit modelling of limited economic resources • Measuring economy-wide & global effects of bioenergy policies	• Detailed coverage of interest sectors with full market representation • Explicit representation of biophysical flows & prices	• Typically greater detail on regional aspects, policy measures & environmental indicators • Detailed insights into techno-economic, environmental & social characteristics & impacts of bio-based systems
Limitations of Approach	• High level of aggregation of highly complex systems • Unsuitable for short term assessments • Large number of assumptions	• Level of aggregation may mask the variation in the underlying elements. • Scope of CGE models necessitates simplified trends and outputs • Few or no explicit representation of quantities for biophysical flows	• Optimisation of agent welfare, but only the sectors represented in the model • No consideration of macro-economic balances & impacts on non-represented sectors	• Needs large number of assumptions for long term projections • No inclusion of indirect & induced effects outside the boundaries of the study - often deliberately ignoring interactions with other sectors
Strong Coverage of Bioenergy Themes	• Forestry & Wood Feedstocks • BECCS & CCS • Emissions & GHGs	• Forestry & Wood Feedstocks • Residue Feedstocks	• Emissions & GHGs	• Forestry & Wood Feedstocks • Emissions & GHGs
No Coverage of Bioenergy Themes	• Bioenergy Processes & Technologies (other than BECCS + CCS) • Pre-treatment Processes • ILUC • Water Issues • Bio-chemicals	• ILUC • Water Issues	• Alternative Transport Biofuels (non-road) • Pre-treatment Processes	Coverage of all Bioenergy Themes

Table 5: Coverage of Key Bioenergy Issues by Different Categories of Models, Evidenced by Publications 2000 to 2018 [3]

Themes		IAMs	Energy System Models	Specialised Models	General Modelling
Bioenergy Feedstocks	Forestry	●●●	●●●	●●●	●●●
	Algae	●	●●	●	●●
	Briquettes	X	●	X	●
	Pellets	●	●	●	●
	Chips	●	●	●	●
	Wood	●●●	●●	●●●	●●
	Wastes	●●	●●	●●	●●
	Residues	●	●●●	●●	●●
	Lignocellulosic	●	●	●●	●●
	Energy Crops	●●	●	●	●
	1st Generation	●	X	●	●
	2nd Generation	●	●	●	●
	3rd Generation	●	X	X	●
Bioenergy Processes & Technologies	BECCS & CCS	●●●	●●	●●	●
	Combustion	●●	●	●	●●
	Pyrolysis	●	●●	●	●●
	Gasification	●●	●●	●●	●●
	Torrefaction	X	X	X	●
	Anaerobic Digestion	X	●	X	●
	Co-firing	●	X	●	●
	Thermo-chemical	●	X	X	●
	Catalysis	●	●●	●	●●
	Bio-chemicals	●	●●	●●	●●
	Fermentation	X	●●	●●	●●
	Drying	●●●	●●●	●●●	●●●
	Chipping	X	X	X	●
	Pelletising	X	X	X	●
Bioenergy Systems Issues	Bio-economy	●●	●●	●●	●●
	Environment	●●	●●	●●	●●
	Emissions & GHGs	●●●	●●●	●●	●●●
	ILUC	X	X	X	●
	Sustainability	●●	●●	●●	●
	Climate Change	●●	●●	●●	●●
	Yields & Productivity	●●	●●	●●	●●
	Trade	●	●	●	●
	Water	X	X	X	●
	Deforestation	●	●	X	●
	Forestation	●	●	●	●
	Ecosystems & Biodiversity	●	●●	●●	●●
	Jobs, Training & Skills	●	●	●	●
	Land Use	●●	●●	●●	●●
Bioenergy Vectors	Bio-Power	●●	●●	●●	●●
	Bio-Heat	●	●	X	●
	Transport Biofuels	●●	●●	●	●●
	Aviation	●	X	X	●
	Heavy Goods Haulage	X	X	X	●
	Maritime	X	X	X	●
	Bio-chemicals	X	●	●	●
	Bio-Syngas	●	X	X	●
	Ecosystem Services	●	●	●	●

Key	X	No Coverage of Bioenergy Issue within Bioenergy Research Papers
	●●●	Bioenergy Issue Covered by More than 20% of Bioenergy Research Papers
	●●	Bioenergy Issue Covered by between 5 – 20% of Bioenergy Research Papers
	●	Bioenergy Issue Covered in Less than 5% of Bioenergy Research Papers

4.1. Use of Modelling within Bioenergy Research and Policy Development

With the outputs of energy models influencing decisions and policy development, it is important that that the methods and approaches of models are scrutinised to ensure that validity of the recommendations they help inform. Policy makers should in theory always use the most appropriate models to address their specific questions, choosing models based on relevant criteria such as the inclusion of different technologies, time horizons, and granularity of expected results. However in reality, bioenergy modelling analyses informing policy is typically completed using a small number of established high profile models that have been developed over a number of years.

Although high profile 'named' models provide highly valuable assessment tools, they currently don't and can't capture the whole story. In reality these high profile models are only represented within a small minority of the overall body of bioenergy research. As Figure 2 demonstrates, over the past 20 years bioenergy research methods have moved away from using large institution models and are instead increasingly developing and using specialist bespoke tools. These specialist models being developed and applied to focus on the full spectrum of bioenergy research themes. This means that there is a great body of bioenergy research currently taking place using bespoke models that won't necessarily have the same established dissemination pathways through to policy decision makers, who continue to use the established models [3].

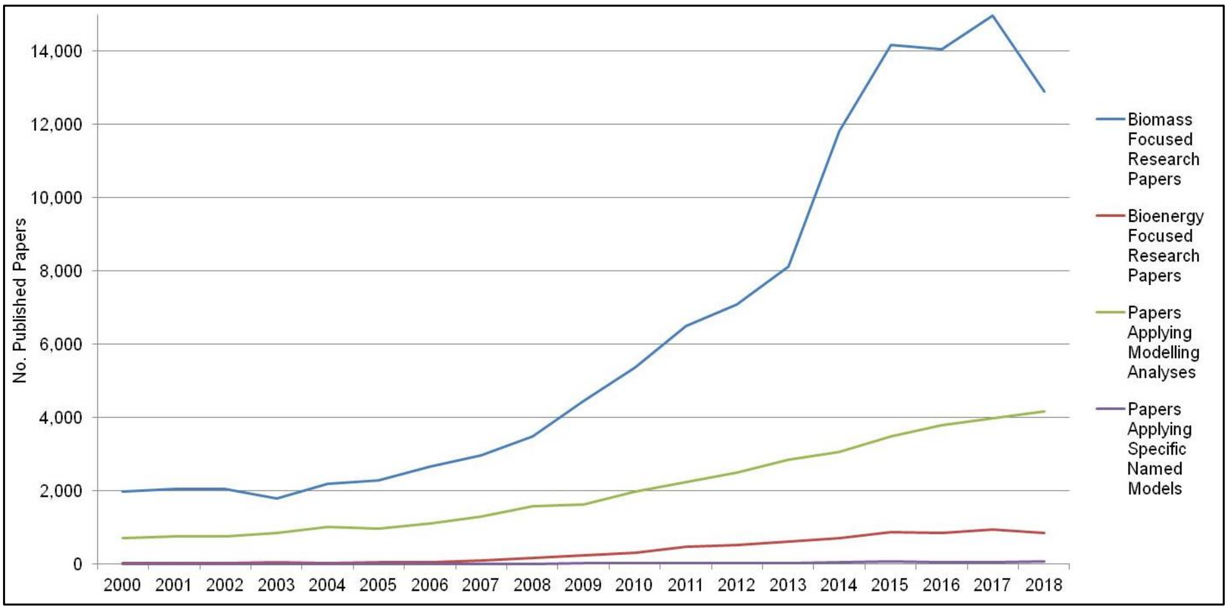


Figure 2: Total Number of Bioenergy Research Paper Published each Year [55]

4.2. Recommendations for Using Energy Models to Inform Bioenergy Decision Making

To develop energy systems and a bioenergy sector that enables transitions towards low carbon economies, it is important that the targets, strategies and roadmaps are designed with the support of the best possible analyses provided by models. Ideally bioenergy models would provide policy makers with information that allows them to develop policy that promotes sustainable bioenergy taking consideration of the many themes associated with bioenergy pathways. In reality it is not feasible to develop an all-encompassing bioenergy model that covers all the linkages and captures the nuances between different systems, therefore caution should be applied if decisions are developed from one category or one specific model. The next best option may be to use multiple models in parallel each with different approaches in order to build a more robust overall conclusions.

This could be achieved through developing a versatile framework of IAMs, energy system models and specialist models that could be integrated to provide 'modular modelling approach' to utilise the strengths and mitigate for the weaknesses of any given individual model. In practice using the example of the transport sector this could mean: using specialist models to identify and evaluate the performance of different alternative fuel/ transport options; using energy system model to analyse how these may be integrated with the wider energy systems and infrastructure; and IAMs to evaluate the GHG and wider macro-impacts of these technological interventions.

5. Future Projections of the Biomass Resource

This section provides an overview of projections of the biomass resource availability and demand in the future. The review is focused primarily around those models identified in Table 2. We exclude analysis of UK feedstock models as these are concerned with growth/production/mobilisation based on projections of yield with no consideration of demand. Outputs of these feedstock models are used as inputs into other models, for example the ETI's Biomass Value Chain Model, which we do include in our analysis.

5.1. Approach

For each of the models identified in Table 2 we compiled a list of reports that have been produced and used by key organisations in policy, strategy and research i.e. by bodies with some recognised responsibility and authority. These are summarised in Table 6. For each study we accessed the primary data and extracted values for biomass resource availability and demand for each year that was available. Where primary data were not accessible, we digitised results presented in the reports using ImageJ software and extracted values for biomass resource availability and demand. As the models identified in Table 2 are primarily concerned with UK biomass resources, we supplemented results from these reports with a dataset compiled by Fuss et al. of global studies of biomass resource availability. This resulted in a database containing 1,237 individual datapoints of which 266 are derived from models of the global resource, 24 are from models that analyse the EU resource and 947 are from models that relate to the UK resource.

The temporal window considered by the models varies considerably. A number of models (e.g. UK Times) present 5 yearly steps in their models runs, others provide a single date usually 2050 given its policy relevance. We attempted to extract data on biomass resource availability in 2025, 2030, 2035, 2040, 2045, 2050 and 2100. Results from models primarily focus on the year 2050 with 479 datapoints.

As discussed in the sections above, the models are designed to address a wide range of questions and this is reflected in the outputs that they provide. To provide a level of comparability between the studies we have standardised the results in a number of ways.

First, across the studies examined the unit of energy used to compare estimates are gigawatts (GW), terawatt hours per year (TwH/yr), petawatt hours per year (PwH/yr), exajoules (EJ) and petajoules (PJ). We converted TwH/yr, PwH/yr and EJ into the standard unit of PJ. As GW cannot be readily converted, we excluded the minor number of results that were presented in this unit from further analysis.

Secondly, the models provide a wide variety of descriptions of what they are modelling within the energy system. Examples include supply, electric capacity, use, resource availability, and potential. By reading the descriptions within the models and what they are trying to represent we standardise these to; (i) primary energy which we define as the energy within the resource before being subjected to transformation (e.g. crop resource, forestry resource); (ii) final energy which we define as the energy produced within a conversion process that reaches the consumer (e.g. biomass CCS); and (iii) use, which we define as the final use that the bioenergy resource is being put to (e.g. transport, electric generation).

Thirdly, across the models there are 57 different description of energy vectors (e.g. biomass CCS, forestry, AD, Biomass with CHP etc.; see Section 4). Some models provide a high-level description of future energy systems with "bioenergy" in all its various forms representing one energy vector along with gas, oil, wind etc. In other energy system models there is a high level of granularity in the description of the energy system. For example the Appropriate Use of Biomass model considers 2000 technologies. For ease of interpretation we standardised into 7 categories. The first four of these represent distinct vectors namely crops, forestry, residues, and waste. The remaining three vectors are biomass, biofuels, and bioenergy. Based on the descriptions of the models we have made every attempt to standardise these three cateogries as follows. Biomass is taken to be the solid form of bioenergy. Biofuels are taken to be the liquid form of bioenergy. Bioenergy itself is taken as a catchall term that includes both biomass and biofuels.

Interpretation of the results must be done with care. The most valid comparisons are within the categories of crops, forestry, residues, and waste as there is reasonable consistency in what constitutes each of these vectors. Comparisons between these four categories is also useful due to consistency in terminology. Comparisons both within and between the biomass, biofuel and bioenergy categories is perhaps more problematic, although still useful. The limitation relates to the specific vectors that are considered within the resource models. For example some models may not consider waste and this will lead to lower estimates of bioenergy resource availability.

Table 6: Models and reports accessed to compile future projections of biomass resource availability.

Model	Title	Year	Lead	Region
DECC Calculator	The Carbon Plan	2011	DECC	UK
	2050 Pathways Analysis	2010	DECC	UK
	Fourth Carbon Budget	2010	CCC	UK
Energy System Modelling Environment (ESME)	ESME model 4.3 run	2014	ETI	UK
	Biomass in a low carbon economy	2018	CCC	UK
ETM-UCL	Techno-Economic Scenarios for Reaching Europe's Long-Term Climate Targets	2014	CECILIA 2050	Europe
UK MARKAL	The UK Energy System in 2050	2013	UKERC	UK
	Energy 2050: the Transition to a Secure, Low-Carbon Energy System for the UK	2011	UKERC	UK
	Fourth Carbon Budget	2010	CCC	UK
	The Carbon Plan	2011	DECC	UK
	Pathways to a low carbon Economy	2009	UKERC	UK
TIAM-UCL	Nationally Determined Contributions under the Paris Agreement and the costs of delayed action	2019	Winning	Global
	Modelling Leadership-Driven Scenarios of the global mitigation effort	2019	CCC	Global
Biomass Resource Model (BRM)	Increasing biomass resource availability through supply chain analysis	2014	Welfle	UK
Bioenergy Value Chain Model (BVCM)	Bioenergy - Insights into the future UK Bioenergy sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)	2015	ETI	UK
	BVCM: A comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – Mathematical formulation	2015	Samsatli	UK
Transport Energy Model (TEM)	The Road to Zero. Next steps towards cleaner road transport and delivering our industrial strategy	2018	HMG	UK
UK and Global Bioenergy Resource Model	UK Bioenergy Strategy	2012	DECC	UK
	UK Bioenergy Strategy Analytic Index	2012	DECC	UK
Biomass Environmental Assessment Tool (BEAT2)	Carbon impacts of using biomass in bio-energy and other sectors: energy crops	2011	ADAS	UK
UK TIMES	Clean Growth Strategy	2017	BEIS	UK
	Pathways to Deep Decarbonisation in the UK - 2015	2015	SDSN - IDDRI	UK
Whole electricity System Investment Model (WeSIM)	An analysis of electricity system flexibility for Great Britain	2016	Carbon Trust	UK
	Value of baseload capacity in low-carbon GB electricity system	2018	Ofgem	UK
	Whole-system cost of variable renewables in future GB electricity system	2016	RWE Innogy, ScottishPower Renewables	UK

5.2. Presentation of Results

Where sufficient data are available we present boxplots depicting the range of values for each energy vector across models. Figure 3 provides a guide to interpretation of boxplots. In subsequent sections we summarise our results based on the median value (as a measure of the middle estimate for the resource among model outputs) and the interquartile range (the distance between the upper and lower quartile). We take this range to represent the central estimate of resource availability across models.

The overall shape of each boxplot can tell us important things about the underlying data;

- Where an individual boxplot is **compact** this means that there is a high level of agreement in the estimate of this resource availability between models. This will be reflected in the central estimate of resource availability which will be comparatively small.
- Where an individual boxplot is **tall** it suggest that models differ in their assessment of the availability of this resource. This will be reflected in the central estimate of resource availability which will be comparatively large.
- Where the sections of an individual boxplot are **uneven** it suggests that there is agreement about resource availability at certain parts of the scale, but at others there are divergent views.
- Agreement around the median but **differences in the overall shapes** of boxplots across the figure indicates agreement around resource availability between models for some vectors and disagreement around resource availability for other vectors. Agreement and disagreement may simply reflect difference in scenarios explored, or may represent more systemic difference in underlying model assumptions or architectures.
- **Differences in the height** of the boxplots for different vectors is indicative of different levels of resource availability for each vector. However, as discussed above, care must be taken with the most valid comparison being between crops, forestry, residues and wastes.

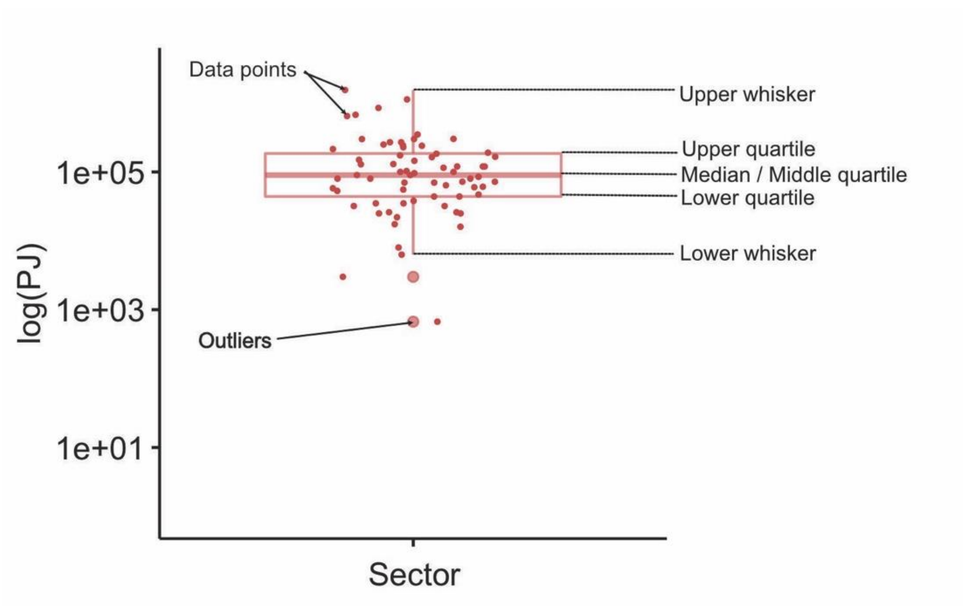


Figure 3: Schematic indicating key features of boxplots used in subsequent analysis.

5.3. Global Biomass Resource Availability

5.3.1. Primary Energy

There is a paucity of estimates of global biomass resource availability for years other than 2050 (Figure 4; Table 7). Estimates for 2030 are provided primarily by the CCC Bioenergy Technical Paper 2 who explored a range of scenarios based on land availability. Across the scenarios this report suggests that crops (median 17100 PJ) and waste (median 16700 PJ) will be the dominant vectors. Indeed the report places a special emphasis on waste, which it considers to be largely non-tradeable. Forestry (median 5328 PJ) and residues (median 3312 PJ) will play a lesser, though still significant, role.

Estimates for 2100 are derived from the TIAM-UCL model in a report that explored leadership-driven scenarios of the global mitigation effort. Again, results from this model suggest important roles for crops (median 31400 PJ) and waste (median 27800 PJ). The modelling runs in this report specifically examined large scale afforestation as a strategy for climate mitigation. The assumption in these modelling runs is that rather then adopting a BECCS strategy, afforestation will provide the negative emissions reguired to meet the ambitions of the Paris Agreement. This explains the absence of forestry as a primary energy resource.

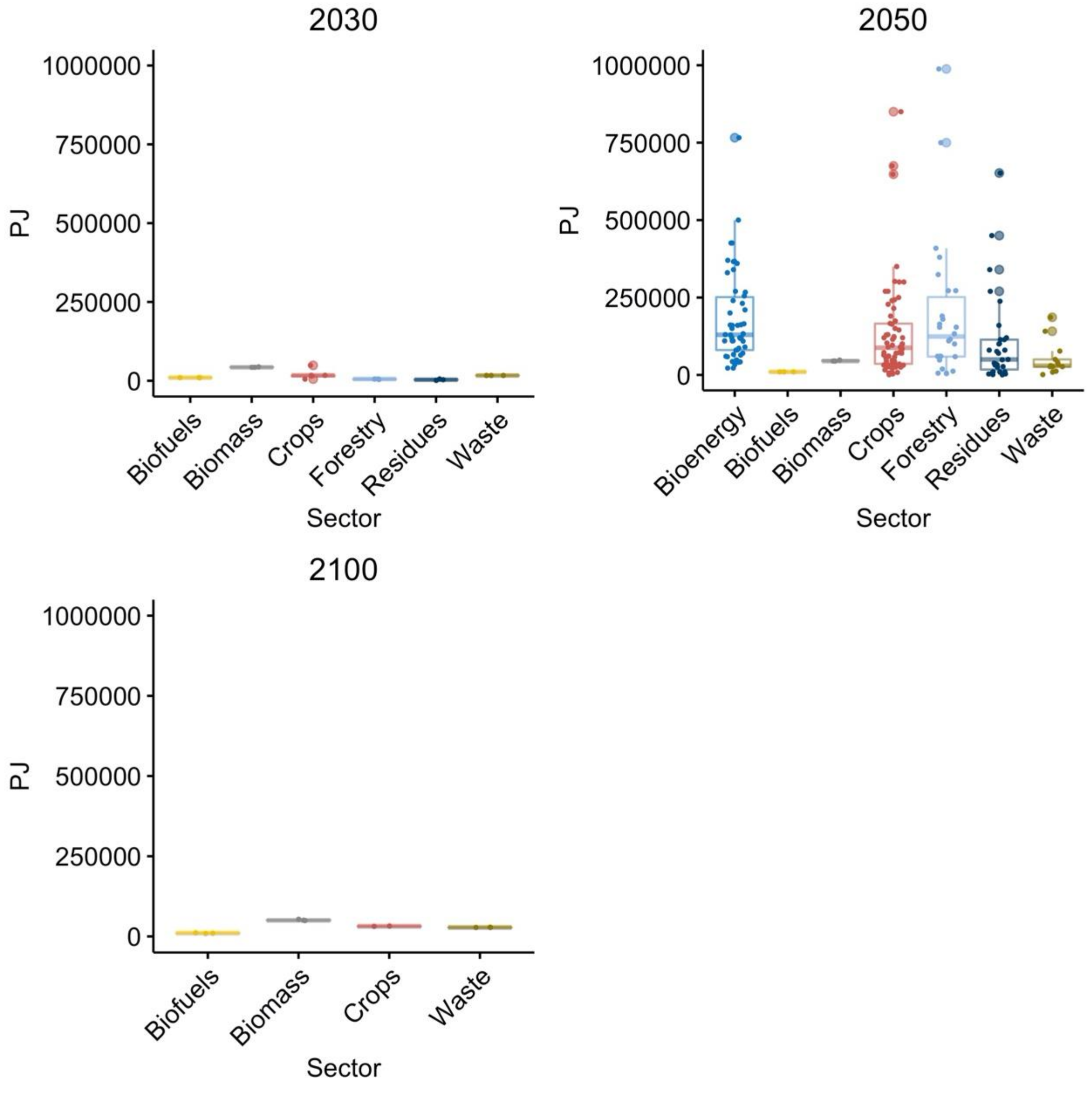


Figure 4: Estimates for global primary energy (PJ) potential in 2030, 2050, and 2100. Boxplots indicate the median (central line), interquartile range (upper and lower edge of box), min and max value (whiskers) and outliers (large dots). Small dots on the figure represent an individual data point from a model output. For this figure we limited the y-axis to display values up to 1000000 due to extreme outliers for 2050 estimate.

As shown in Figure 4 the majority of studies considered the year 2050 in their modelling. Estimates for “bioenergy” as an aggregate indicate a median value of 130000 PJ of resource available. Central estimates in the model range from 80500 PJ to 261000 PJ suggesting significant divergence between models. This variation arises both through different approaches to modelling and due to underlying model assumptions, such as diet, future populations, yield improvement, and land availability.

Models that consider specific vectors, summarised here as crops, forestry, residues and waste, exhibit similar variation across the estimate of biomass resource availability (see Table 7). For example, estimates for forestry range from 4140 PJ to 3000000 PJ. As discussed by Fuss et al. lower estimates are often driven by strict controls on land availability to prioritises biodiversity conservation and prevent deforestation, or make assumptions such as limiting availability to only immediately available residues from current production. Studies also limit deployment to marginal and degraded lands in order to not compete with food production. Higher estimates relax these criteria in a number of ways. For example by allowing conversion of grassland to dedicated bioenergy crops. Towards the top end of the estimates modelling results relax many of the constraints to examine aggressive deployment strategies, and make optimistic assumptions about yield improvements. At the extreme, one estimate is based on the use of all aboveground net primary production for bioenergy production, excluding that required for food, feed or fibre production. Such extremes do not represent realistic estimates but rather serve to explore purely hypothetical options.

Table 7. Summary statistics for estimate of global primary energy (PJ) potential. Note – as detailed in the introduction to this section we use the following terms. Biomass is taken to be the solid form of bioenergy. Biofuels are taken to be the liquid form of bioenergy. Bioenergy itself is taken as a catchall term that includes both biomass and biofuels. Every effort has been made to standardise results.

Vector	Min	25th percentile	Median	75th percentile	Max	Count	Year
Biofuels	9600	9600	9600	9600	9600	3	2030
Biomass	42600	42600	42600	43350	44100	3	2030
Crops	5076	14580	17100	17100	48816	5	2030
Forestry	3960	4644	5328	5382	5436	3	2030
Residues	1080	2196	3312	4428	5544	3	2030
Waste	16700	16700	16700	16700	16700	3	2030
Bioenergy	22000	80500	130000	261000	1272000	51	2050
Biofuels	9600	9600	9600	9600	9600	3	2050
Biomass	44800	44800	44800	46400	48000	3	2050
Crops	670	37250	90000	178000	1548000	68	2050
Forestry	4140	59750	143500	285000	3.00E+06	28	2050
Residues	410	25000	70000	120000	1272000	33	2050
Waste	1000	26600	30000	50000	186000	13	2050
Biofuels	9600	9600	9600	9600	9600	3	2100
Biomass	50000	50000	50000	51350	52700	3	2100
Crops	31400	31400	31400	31400	31400	2	2100
Waste	27800	27800	27800	27800	27800	3	2100

5.3.2. Resource Availability in Terms of Final Energy and End Use

No data was available across the models that we examined for end use. In terms of final energy one study using the TIAM-UCL model examined nationally determined contributions under the Paris agreement under three different scenarios. In 2030 these projected final energy from biomass with a median of 7142 PJ, a minimum of 2110 PJ and a max of 8279. In 2050 these projections for final energy from biomass were revised up to a median of 25161 PJ, a minimum of 11363 PJ and a max of 27757.

5.4. EU Biomass Resource Availability

5.4.1. Primary Energy, Final Energy and Energy Use

At the European scale we identified no studies that examined primary energy or energy use. We identified one study using the ETM-UCL model that examined final energy. The study considered three scenarios for reaching Europe's long-term climate targets for decades between 2020 (not considered here) and 2050 (Fig. 5). A "reference" scenario provided a business as usual emissions pathway consistent with a 6ºC global average temperature rise. A "fragmented" policy scenario sees significant mitigation effort but failure to implement all measures that would achieve a below 2ºC rise. Finally, policy success projects mitigation action consistent with a 2ºC trajectory.

For biomass the Reference scenario sees a steady ramp up of biomass within the energy mix from 3328 PJ to 4371 PJ between 2030 and 2050. Fragmented policy sees a slight decline from 4674 PJ to 4196 PJ over this time frame. Interesting Policy Success projects a sharp ramp up of biomass in final energy by 2030 to 4545 PJ, then sharp decline to 2372 PJ by 2050 as it is replaced by hydrogen as an energy vector.

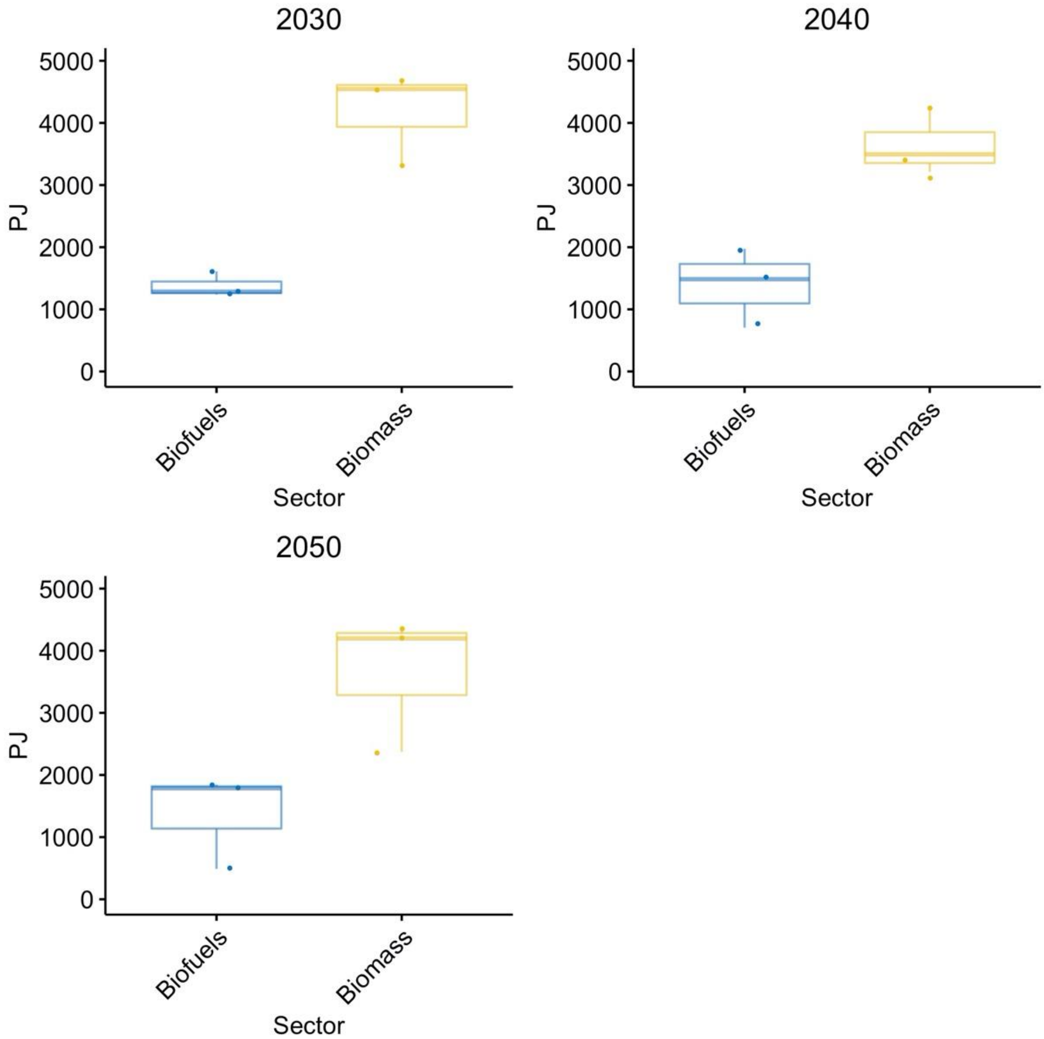


Figure 5: Estimates for final energy (PJ) potential in 2030, 2040, and 2050. Boxplots indicate the median (central line), interquartile range (upper and lower edge of box), min and max value (whiskers) and outliers (large dots). Small dots on the figure represent an individual data point from a model output.

5.5. UK Biomass Resource Availability

5.5.1. UK Primary Energy

Estimates of resource availability for UK primary energy were available in 5-year steps between 2025 and 2050 (Fig. 6). For 2025, 2035 and 2045 UK-Times, ESME and the Biomass Resource model provide data points. For 2050 additional estimates are provided by the DECC Calculator, ETM-UCL and UK MARKAL from the studies highlighted in Table 6.

Estimates for “Bioenergy” as an aggregate category at the median show an increase over time out to 2045 to 3132 PJ before decreasing to 1276 PJ in 2050 (Table 8). However, this median value is accompanied by wide difference in central estimate of circa. 1000 PJ for years up to 2045. In 2050 the inclusion of more modelling studies serves to widen this central estimate to between 606 PJ and 3243 PJ, a difference of 2637 PJ in estimates of UK primary energy from biomass resources. Differences across the models reflect differening views across models of the role that bioenergy may play in the future UK energy system and uncertainties about the amount of bioenergy resource that will be available in the future given limited UK capacity for production and international competition.

Waste as a UK biomass resource consistently returns a median of circa. 200 PJ of availability. With the exception of 2030, the range within the central estimates for waste is comparatively small suggesting broad agreement across a limited set of model runs. In 2050 there are a number of outliers that are primarily associated with alternate waste strategies derived from DEFRA forecast scenarios within the Biomass Resource Model.

For crops, forestry and residues there are consistent estimates for the median resource availability of between 100 – 200 PJ. However, there is far more variation than is seen with waste resources with central estimate ranging by over 100 PJ in most cases, and difference between minimum and maximum estimates in the region of 200 – 300 PJ. One reason for this is that an exploratory approach to model inputs based on tightening or loosening of regulatory frameworks in these areas. For example, in terms of the utilisation of forestry residues modelling, the Biomass Resource model considers a full range of possible extraction levels from 10% to 100%. Higher extraction levels are unrealistic in the real world however, exploring such upper limits is a common feature of such modelling exercises which seek to examine theoretical potential unconstrained by broader environmental, social or economic considerations.

Other drivers of differences in the estimates include those already noted for crops in relation to the global resource, with limits placed on land availability for conservation of biodiversity and the production of food. For example, within the ETI’s Biomass Value Chain Model a set of constraints on the availability of land for perennial bioenergy crops are employed. These are based on biophysical limits (e.g. slope for harvesting), existing land use (e.g. exclusions from high organic carbon soils), and areas designated for conservation or cultural value (e.g. national parks, SSSI’s).

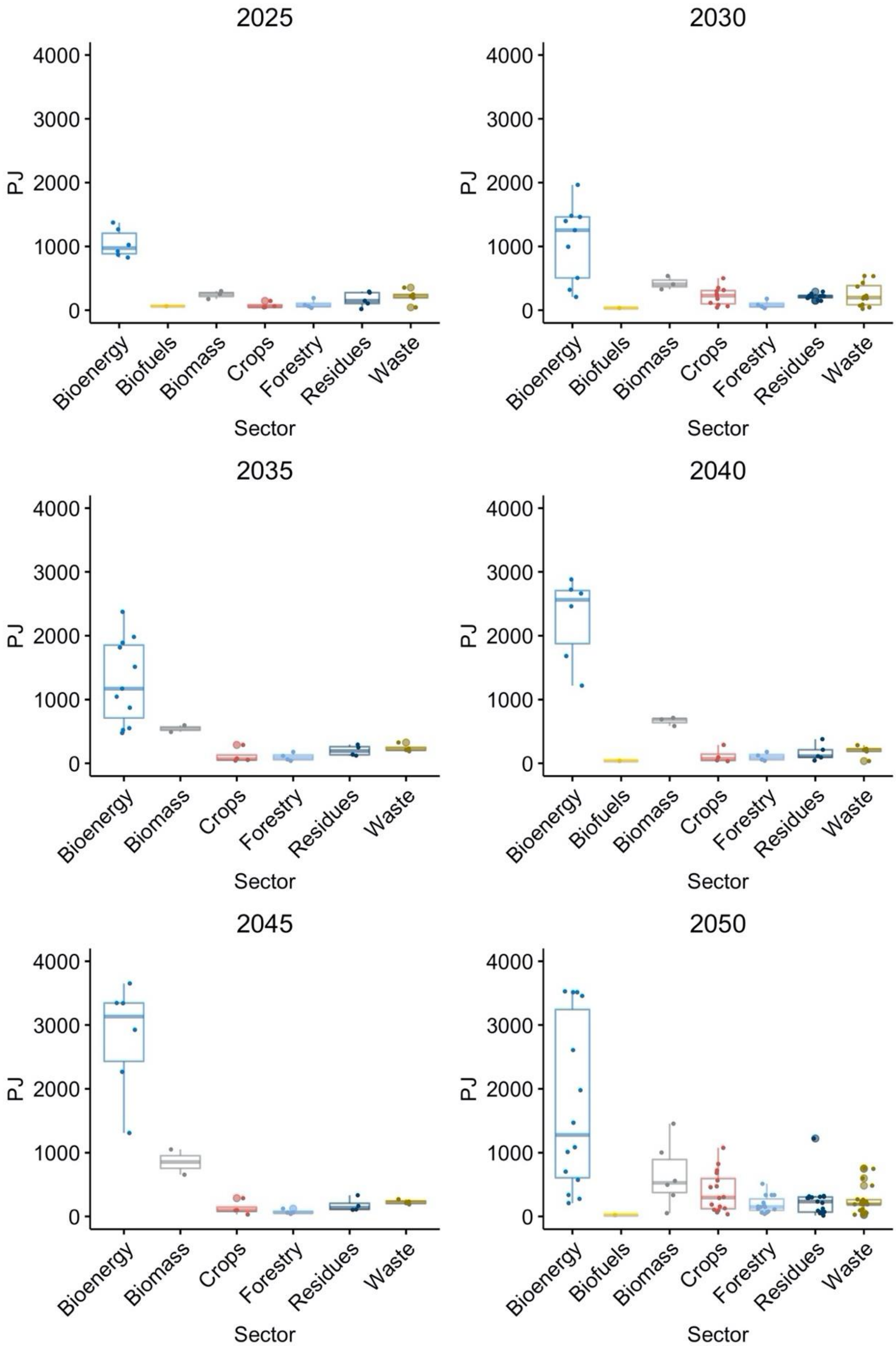


Figure 6: Estimates for UK primary energy (PJ) potential between 2025 and 2050. Boxplots indicate the median (central line), interquartile range (upper and lower edge of box), min and max value (whiskers) and outliers (large dots). Small dots on the figure represent an individual data point from a model output.

Table 8. Summary statistics for models runs of UK Primary energy (PJ) potential.

Vector	Min	25th percentile	Median	75th percentile	Max	Count	Year
Bioenergy	825	883	974	1206	1374	6	2025
Biofuels	61	61	61	61	61	1	2025
Biomass	176	214	253	276	300	3	2025
Crops	44	47	56	84	146	4	2025
Forestry	35	54	71	109	190	4	2025
Residues	18	106	148	276	292	5	2025
Waste	44	193	219	247	354	5	2025
Bioenergy	208	506	1254	1462	1964	9	2030
Biofuels	32	32	32	32	32	1	2030
Biomass	328	367	406	471	537	3	2030
Crops	42	99	228	307	500	11	2030
Forestry	31	50	72	110	179	4	2030
Residues	148	198	216	226	291	12	2030
Waste	20	85	198	385	538	12	2030
Bioenergy	476	711	1169	1853	2375	11	2035
Biomass	491	518	544	571	598	2	2035
Crops	43	50	65	130	288	4	2035
Forestry	39	54	88	132	179	4	2035
Residues	121	134	194	260	294	4	2035
Waste	191	205	218	251	326	4	2035
Bioenergy	1217	1876	2562	2708	2881	6	2040
Biofuels	36	36	36	36	36	1	2040
Biomass	586	638	690	701	713	3	2040
Crops	33	43	72	145	288	4	2040
Forestry	40	53	90	137	179	4	2040
Residues	44	92	112	213	379	5	2040
Waste	35	187	209	226	284	5	2040
Bioenergy	1307	2431	3133	3344	3651	6	2045
Biomass	655	754	853	952	1051	2	2045
Crops	30	78	97	146	286	4	2045
Forestry	39	54	60	77	123	4	2045
Residues	104	108	137	207	332	4	2045
Waste	189	204	221	242	269	4	2045
Bioenergy	208	606	1276	3244	3528	14	2050
Biofuels	18	18	18	18	18	1	2050
Biomass	50	374	527	891	1454	6	2050
Crops	33	120	295	594	1075	16	2050
Forestry	39	95	149	275	511	15	2050
Residues	14	67	234	305	1222	19	2050
Waste	23	191	192	262	753	21	2050

5.5.2. UK Final Energy

The ESME models, WeSIM, ETM-UCL and DECC calculator provide estimates of biomass resource availability in terms of UK Final Energy (Fig. 7). For 2025, 2035, 2040 and 2045 estimate of biomass resource use in final energy were available from ESME and ETM-UCL. These models estimate UK final energy from biomass of between circa. 25 PJ and circa 130 PJ out to 2045. For waste there are single point estimates of less than 40 PJ out to 2045.

In 2050 the inclusion of model output from WeSIM and the DECC Calculator produce estimates of biomass and waste resource availability an order of magnitude higher than other years. For example, in 2045 the maximum estimate for biomass resource availability was 133 PJ, this rises to 1352 PJ in 2050. Similarly, for waste the maximum estimate in 2035 is 39.6 PJ rising to 1162 PJ in 2050.

In common across all the models considered, in 2050 central estimates around waste exhibit far less variation than other vectors with a central estimate ranging from 865 PJ to 903 PJ. This contrasts with central estimates for biomass which range over nearly 1000 PJ from 494 PJ to 1352 PJ.

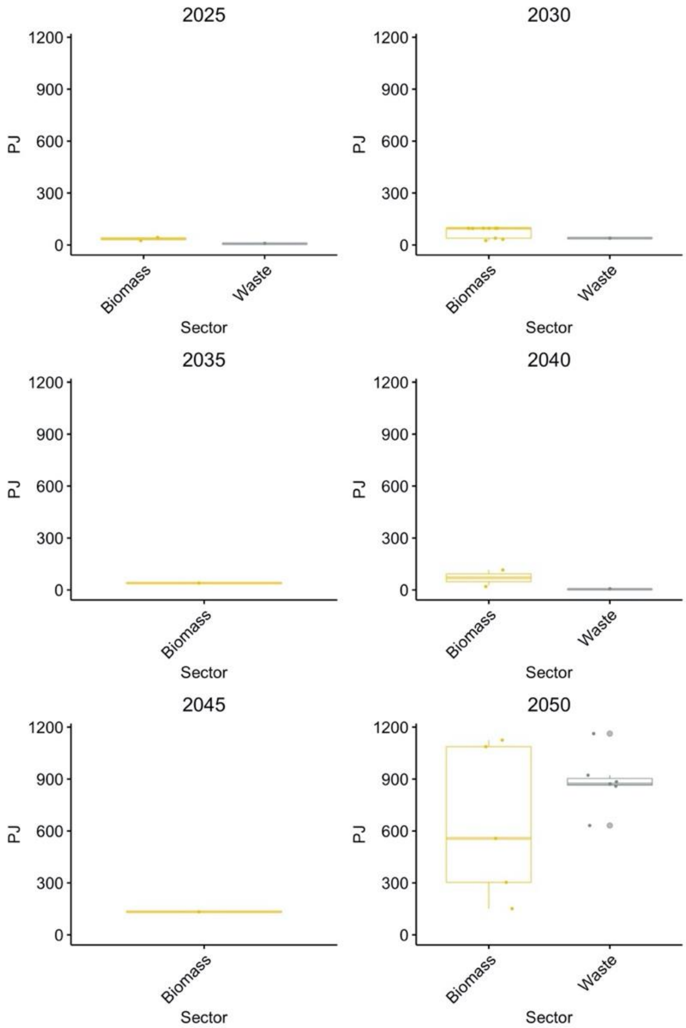


Figure 7: Estimates for UK final energy (PJ) potential between 2025 and 2050. Boxplots indicate the median (central line), interquartile range (upper and lower edge of box), min and max value (whiskers) and outliers (large dots). Small dots on the figure represent an individual data point from a model output.

5.5.3. UK Use

Estimates of sectoral use are provided by the BVCM, the UK and Global Bioenergy Resource Model, UK MARKAL, and UK TIMES. For 2025, 2035, 2040, and 2045 estimates are derived solely from the UK and Global Bioenergy Resource Model (Fig. 8). Variation in terms of the use of biomass for energy, heat and transport represent different scenarios within the model in terms of the resource that is available for the specific sector. Within this model the use of bioenergy within the transport sector is consistently an order of magnitude higher than the energy and heat sectors. What is interesting in this model is that is projects a rapid switching from non-CCS liquid biofuels in the medium term, to hydrogen produced by biomass CCS between 2045 and 2050. In the accompanying report the authors themselves note that this is not a realistic projection as it implies that international shipping and aviation would shift back to fossil sources of fuel, and that there was a readily available fleet of hydrogen vehicles. The authors of this study note that it is likely indicative of a tipping point in the energy system. See Table 9 for further details.

For years with estimates from multiple models, in 2030 central estimates for use of the biomass resource for Energy and Heat are reasonable consistent across models varying by no more than 130 PJ. For transport the central estimates show considerable variation ranging from 77 PJ to 646 PJ. There is a similar picture in 2050 where the median estimate of 529 PJ for the transport sector is nearly three times that of any of the other sectors. However, the central estimates for the transport sector range from 235 PJ to 738 PJ suggesting divergent views about the importance of biomass as an energy vector in the transport sector.

Table 9: Summary statistics for models runs of UK use (PJ).

Vector	Min	25th percentile	Median	75th percentile	Max	Count	Year
Energy	81	116	174	185	257	7	2025
Heat	134	142	162	174	196	7	2025
Transport	355	391	419	441	471	7	2025
Agriculture	20	20	20	21	23	3	2030
Energy	36	78	118	201	353	19	2030
Heat	4	99	133	148	153	8	2030
Industry	125	128	130	137	145	3	2030
Residential	11	20	28	47	67	3	2030
Services	15	36	57	78	99	2	2030
Transport	36	77	124	646	817	20	2030
Energy	49	65	69	82	93	7	2035
Heat	62	73	100	115	133	7	2035
Transport	447	913	1024	1078	1106	7	2035
Energy	49	58	62	71	248	9	2040
Heat	16	64	79	93	127	8	2040
Transport	179	809	1179	1327	1439	8	2040
Energy	34	35	41	74	135	7	2045
Heat	43	59	68	95	134	7	2045
Transport	278	1001	1215	1283	1744	7	2045
Agriculture	5	5	5	5	5	1	2050
Energy	12	125	206	314	658	19	2050
Heat	15	65	69	98	181	8	2050
Industry	8	51	163	193	202	7	2050
Residential	2	32	158	181	445	9	2050
Services	32	59	124	291	373	8	2050
Transport	8	235	529	740	1646	20	2050

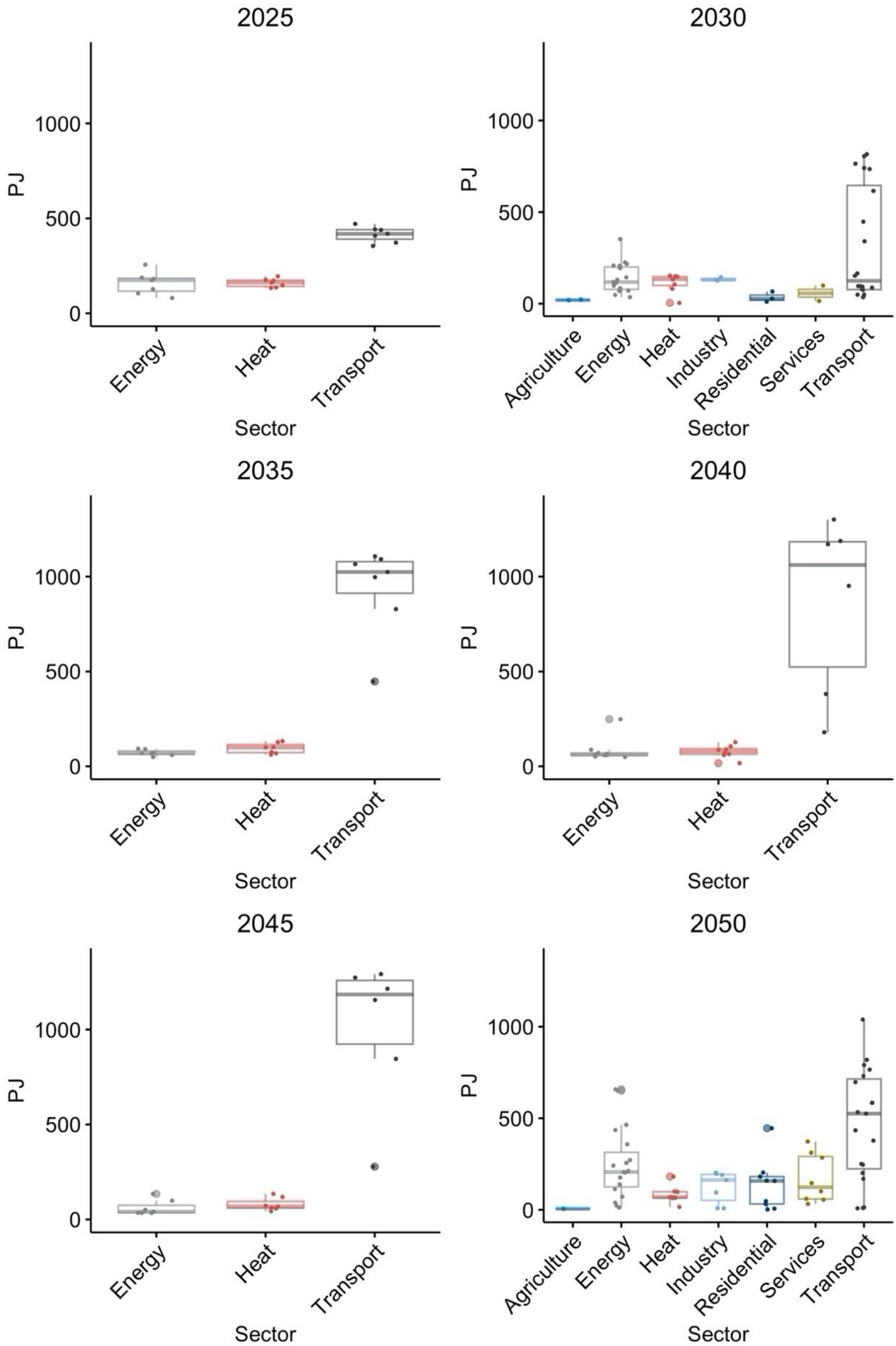


Figure 8: Estimates for UK use (PJ) between 2025 and 2050**.** Boxplots indicate the median (central line), interquartile range (upper and lower edge of box), min and max value (whiskers) and outliers (large dots). Small dots on the figure represent an individual data point from a model output.

5.6. Domestic & Imported Sources of UK Primary Energy

Where stated in model documentation we coded resource availability as either domestic or imports. In the analysis presented in section 6.2 to 6.4 domestic and imports were summed to provide a value for total resource irrespective of provenance. Figure 9 disaggregates sources to provide a breakdown of UK Primary energy across seven vectors indicating the range of values within models for the domestic and imported resource. These results are summarised in Table 10.

Some care must be taken in viewing this figure due to the way that many models represent the imported fraction of the resource. It is common for models to detail specific UK vectors (e.g. crops, waste) and then consider a single vector of “imports” as a catchall. To address this, we categorised data to the highest common level within a specific model. For example, one model considers UK Biomass and Biofuel as a single vector, but disaggregates imports into biomass and biofuel. Here we aggregated this to common categories of domestic bioenergy and imported bioenergy.

With this caveat there are still some useful conclusions that we can draw from the results. Firstly, estimates for the domestic supply of the aggregate “bioenergy” category are circa. 1000 PJ in 2025/2030 rising by around 1000 PJ per decade after that. Central estimates are comparatively tight at around 500 PJ across models. For the imported fraction estimates across this time horizon are usually between 100 PJ and 500 PJ. Taken together this suggest that models predict that the UK will have greater reliance on its domestic bioenergy resource base.

Secondly, many models see a significant role for imported “biomass” with estimate of around 200-300 PJ in 2025/2030, rising to nearer 1000 PJ by 2050. However, for most years there are a limited number of studies. In 2050, where more modelling studies are available, they demonstrate considerable variation with central estimates for imported biomass of between 173 PJ and 891 PJ, and a minimum of 50 PJ to maximum of 1454. Part of the variation in these estimates is undoubtedly due to how imported “biomass” was categorised where it may or may not include forestry, crops or residues. As discussed previously, other sources of variation include assumptions about the future reliance on bioenergy made within the energy systems models, and assumptions about the levels of resource that will be available both domestically and internationally.

Thirdly, for forestry, crops and residues there is broad agreement in the level of these resource across models with central estimates for all years between circa. 50 PJ and circa. 300 PJ. For crops and forestry results suggest a more of less equal balance between the domestic and imported resource base. For residues there is a greater assumption of an imported resource.

Finally, none of the models consider an imported waste stream as being an important vector in the future. This may reflect assumptions around the regulatory framework which would prohibit import of waste as a feedstock or where it would be socially unacceptable.

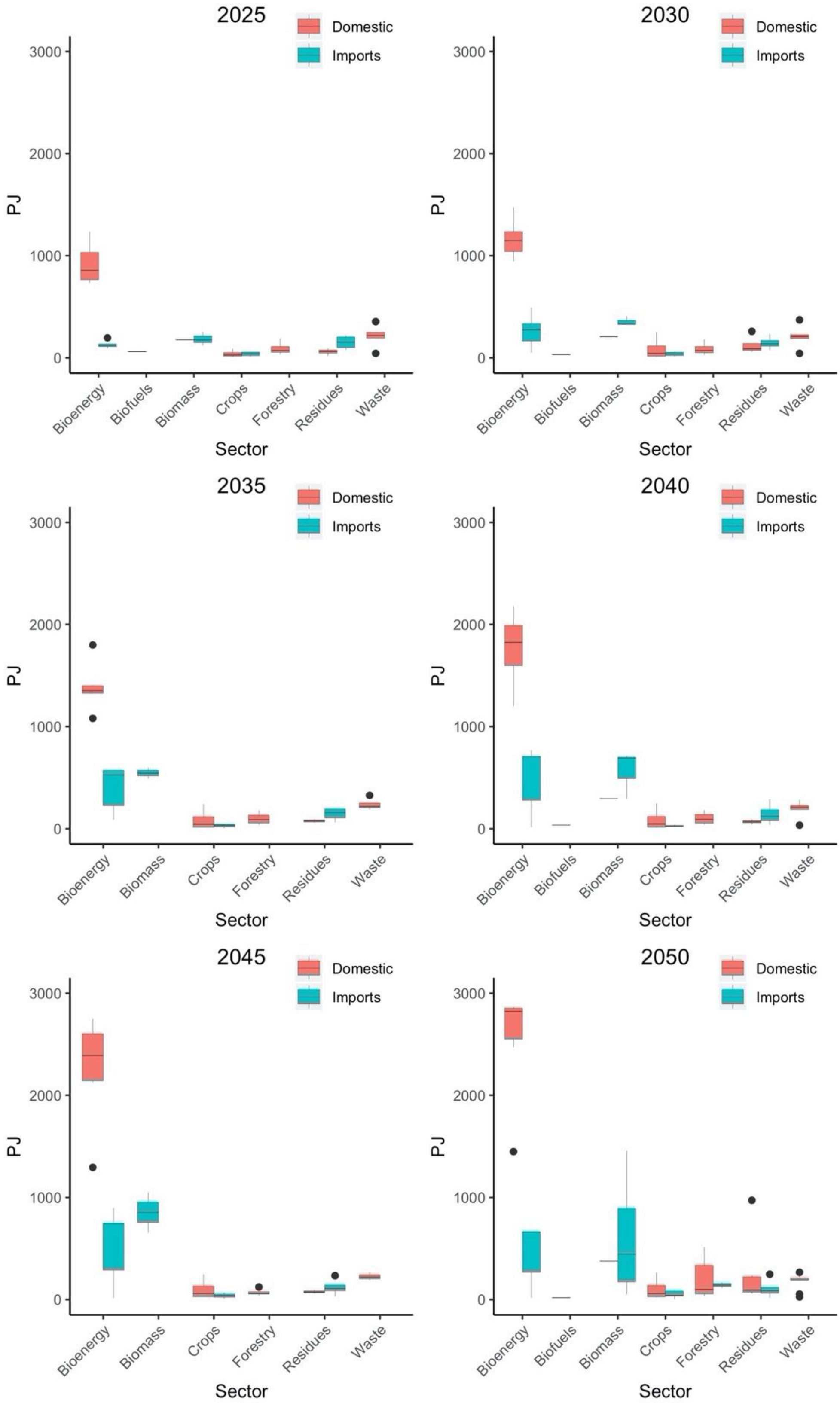


Figure 9: Estimates for UK domestic and imported primary energy (PJ) between 2025 and 2050**.** Boxplots indicate the median (central line), 25th and 75th percentiles (upper and lower edge of box), min and max value (whiskers) and outliers (large dots). Small dots on the figure represent an individual data point from a model output.

Table 10. Summary statistics for models runs of UK use (PJ).

Vector	Source	Min	25th percentile	Median	75th percentile	Max	Count	Year
Bioenergy	Domestic	734	765	855	1032	1237	6	2025
Bioenergy	Imports	92	110	122	136	196	6	2025
Biofuels	Imports	61	61	61	61	61	1	2025
Biomass	Domestic	177	177	177	177	177	1	2025
Biomass	Imports	123	149	176	214	253	3	2025
Crops	Domestic	6	16	29	51	89	4	2025
Crops	Imports	9	21	41	57	57	4	2025
Forestry	Domestic	35	54	71	109	190	4	2025
Residues	Domestic	18	46	63	76	91	4	2025
Residues	Imports	77	99	153	206	220	4	2025
Waste	Domestic	44	193	219	247	354	5	2025
Bioenergy	Domestic	944	1041	1147	1235	1472	6	2030
Bioenergy	Imports	51	164	274	334	493	6	2030
Biofuels	Imports	32	32	32	32	32	1	2030
Biomass	Domestic	209	209	209	209	209	1	2030
Biomass	Imports	328	328	328	367	406	3	2030
Crops	Domestic	10	15	44	116	252	4	2030
Crops	Imports	13	22	38	55	63	4	2030
Forestry	Domestic	31	50	72	110	179	4	2030
Residues	Domestic	59	72	88	139	259	4	2030
Residues	Imports	76	114	138	169	232	4	2030
Waste	Domestic	44	187	209	226	371	5	2030
Bioenergy	Domestic	1081	1325	1353	1398	1800	6	2035
Bioenergy	Imports	88	226	527	572	575	6	2035
Biomass	Imports	491	518	544	571	598	2	2035
Crops	Domestic	11	16	46	115	239	4	2035
Crops	Imports	4	20	33	43	49	4	2035
Forestry	Domestic	39	54	88	132	179	4	2035
Residues	Domestic	58	67	76	85	93	3	2035
Residues	Imports	62	107	156	194	201	4	2035
Waste	Domestic	191	205	218	251	326	4	2035

Table 10. Summary statistics for models runs of UK use (PJ) (continued).

Vector	Source	Min	25th percentile	Median	75th percentile	Max	Count	Year
Bioenergy	Domestic	1201	1596	1826	1987	2177	6	2040
Bioenergy	Imports	16	279	705	705	767	6	2040
Biofuels	Imports	36	36	36	36	36	1	2040
Biomass	Domestic	293	293	293	293	293	1	2040
Biomass	Imports	293	491	690	701	713	3	2040
Crops	Domestic	10	17	48	118	245	4	2040
Crops	Imports	21	22	25	31	42	4	2040
Forestry	Domestic	40	53	90	137	179	4	2040
Residues	Domestic	44	57	68	79	91	4	2040
Residues	Imports	38	79	122	185	288	4	2040
Waste	Domestic	35	187	209	226	284	5	2040
Bioenergy	Domestic	1294	2142	2390	2601	2753	6	2045
Bioenergy	Imports	13	289	743	743	898	6	2045
Biomass	Imports	655	754	853	952	1051	2	2045
Crops	Domestic	25	29	61	131	248	4	2045
Crops	Imports	8	23	38	54	69	3	2045
Forestry	Domestic	39	54	60	77	123	4	2045
Residues	Domestic	59	66	73	85	97	3	2045
Residues	Imports	31	87	107	140	235	4	2045
Waste	Domestic	189	204	221	242	269	4	2045
Bioenergy	Domestic	1449	2551	2823	2852	2866	6	2050
Bioenergy	Imports	19	269	662	662	662	6	2050
Biofuels	Imports	18	18	18	18	18	1	2050
Biomass	Domestic	376	376	376	376	376	1	2050
Biomass	Imports	50	173	446	891	1454	6	2050
Crops	Domestic	22	29	60	137	267	7	2050
Crops	Imports	4	36	39	82	95	5	2050
Forestry	Domestic	35	55	99	335	511	12	2050
Forestry	Imports	113	128	142	156	170	2	2050
Residues	Domestic	59	72	93	222	973	7	2050
Residues	Imports	15	64	88	118	249	6	2050
Waste	Domestic	26	191	191	210	267	13	2050

6. Modelling Biomass Resources Demands & Competition Dynamics

6.1. Existing & Future Competing Uses for Biomass Resources

Biomass resources and the land on which they are produced have many existing uses. The bioenergy sector is going to have to increasingly compete for these resources as the demands of the sector grow as forecast. In many cases this may require competing with other industry sectors on the markets to purchase resources; it will require the bioenergy sector to mature and offer competitive propositions to convince land owners and managers to produce feedstocks for bioenergy rather than products for other end uses, and; it may require the bioenergy sector to purchase lands and develop robust supply chains to ensure supply of feedstocks to fuel their bioenergy projects.

The increased feedstock demands of the bioenergy sector will have impacts on wider industries and sectors, and if not managed appropriately there will be risks of potentially substantial economic, social and environmental impacts. The bioenergy sector should ideally focus on sourcing feedstocks that don't have substantial existing markets, and where there is competition for resources in given regions the local bioenergy sector should ideally focus on deploying technologies fuelled by the local available feedstocks. Lands should be used to produce feedstocks for bioenergy without impacting the wider ability to produce and provide affordable foods for populations, and without risking the threat of direct and indirect land use change that can have potential substantial impacts on ecosystems, biodiversity and GHGs. Table 11 provides a summary of key biomass resource categories in the UK and the existing industries and uses where the bioenergy sector will be competing for resource.

Table 11: Key UK Biomass Resources & their Competing Uses/ Industries

Resource	Competing Uses
Crop Residues:	*Animal Feed / Animal Bedding / Existing Fuels Demands / Compost Industry / Construction Materials / Agricultural Production Processes*
Animal Wastes:	*Agricultural Production Processes*
Forestry Products:	*Competing uses linked to the wood product industry:* *Sawmills / Panel Industry / Pulp & Paper Industry etc.*
Wastes:	*Competing waste management practices along the waste hierarchy:* *Composting / Reuse / Recycling / Existing Energy Applications*
Land:	*Food Production / Conservation / Buildings & Infrastructure / Alternative Uses*

6.2. Competing Demand for Feedstocks across Bioenergy Vectors

There are growing demands for bioenergy for different energy vectors, therefore there is also likely going to be growing competition within the bioenergy sector for feedstock.

The UK developed a Bioenergy Strategies in 2012 [56] that signalled the potential future role for bioenergy in the UK and the different directions that the UK bioenergy sector could take over different time horizons. Subsequent sector specific reports, policies and strategies have each built on this over the last 10 years, targeting bioenergy technologies to either kick-start the transition or to become the leading technologies to decarbonise UK heat, transport, power and to fuel the future UK bioeconomy. Each of these bioenergy sectors likely requiring varying forms and levels of biomass feedstocks over a timeline to 2050.

Table 12 has been developed to summarise the potential changing demands for different bioenergy vectors and their potential feedstock demands through time.

Table 12: UK Bioenergy Sector Trends & Potential Resource Demands

UK Bioenergy Sector		2020	2030	2040	2050
		Near-Term	Mid-Term	Long-Term	
Bio-Heat	Trends:	❖ Gradual increase in resource demand for bio-heat generation pathways. Reflecting both increased transitional and specialist roles targeted for bio-heat.	❖ Gradual decline in resource demand for bio-heat generation pathways. Reflecting the targeted focus on emerging alternative low carbon heat technologies in the long term. ❖ Bio-heat continuing within specialist roles such as industry applications.		
	Demand Resources:	Wood based resources (pellets & chip)	Wood based resources (pellets & chips) Feedstocks for biogas production (wastes & residues) Feedstocks for advanced bioenergy technologies		
Bio-Power	Trends:	❖ Sharp increase in resource demand for the bio-power sector, driven by conversion of conventional power plants to allow with biomass conversion.	❖ Gradual decline in resource demand for bio-power sector, as co-firing plants are expected to gradually close. ❖ Continuation of resource demand for dedicated bio-power applications, contributing to balance peak-energy demands. ❖ Potential deployment of BECCS technologies.		
	Demand Resources:	Solid biomass resources (wood, animal, plant, wastes)	Solid biomass resources (wood, animal, plant, wastes)		
Biofuels	Trends:	❖ Sharp increase in resource demand for biofuel production; as biofuels increasingly contribute towards the decarbonisation of the fuel-based transport system.	❖ High uncertainty in the long term biofuel sector, due to the potential emergence of alternative low-carbon transport technologies during this period. ❖ Also new demands potentially emerging for shipping, aviation etc.		
	Demand Resources:	Energy Crops, Wastes	Energy Crops, Lignocellulosic Resources, Wastes		

6.2.1. The UK Bio-Heat Sector

To date the UK's leading renewable heat support scheme has been the Renewable Heat Incentive (RHI), which has enabled the deployment of many bioenergy heat technologies which have been fuelled largely by wood based feedstocks such as chips and pellets. The RHI is likely to be updated/ renewed in the near term. This will further drive the replacements of conventional fossil fuel technologies for both domestics and non-domestics demands - particularly where alternative low carbon technologies are not suitable. There is also expected to be additional focus on deploying biogas technologies where heating could be provided using the UK's existing national grid network. Therefore in the medium term there will be potential growing demand of feedstock to generate biogases such as wastes and agricultural residues, in addition to the continual growth demand for wood based chips and pellets for biomass boiler and CHP systems.

The long term use of bioenergy heat technologies is less certain as there will likely be advancements in alternative heating technologies. However there is expected to be a continued long term role for bioenergy providing heat for high-temperature industrial processes. Bioenergy may also have an increasing role in heating buildings through networks utilising waste heat from biomass based power plants, and bioenergy driven industrial processes. UK bioenergy heat applications may also become increasingly important with the future development and deployment of carbon capture and storage technologies; especially within district heating and industrial applications. Therefore the feedstock demands for the UK bioheat sector are expected to continually grow over the timeframe to 2050.

6.2.2. The UK Bio-Power Sector

In 2011, bio-power generation contributed less than 3% to the total electricity generated in the UK [56]. Although the relative cost-effectiveness of bio-power pathways compared to alternative renewable technologies, has made it a highly attractive option for the UK delivering renewable energy targets. Through deployment of a broad range of dedicated bio-power technologies, up to 11% of the UK's total electricity is currently generated from bioenergy [57] – from anaerobic digestion, direct combustion, and combined heat and power technologies that each require different forms of feedstock. The conversion of large coal fired power stations to either co-fire or use dedicated biomass fuels has driven the exponential rise in UK bio-power generation, also resulting in a sharp rise in demand for solid wood pellet and chip feedstocks.

Bio-power generation will also likely have an important role to play through the medium term, providing cost-effective transitional options towards meeting renewable energy and GHG targets. Although coal power stations are expected to be decommissioned over the coming years, plants that have been converted to be dedicated bio-power means there will likely continue to have steady large feedstocks demands.

In the long term there are high levels of uncertainty as to the extent that bio-power technologies will contribute to the UK's energy system. Alternative low carbon renewable technologies will likely emerge that could potentially reduce the need for large bio-power plants which could reduce the UK's demands for solid biomass feedstocks. However if BECCS technologies are proven and deployed on a large scale there will likely be a further increase in demands for suitable feedstocks.

6.2.3. The UK Bio-Fuel Sector

The Renewable Transport Fuel Obligation (RFTO) is the UK's primary policy for reducing the carbon emissions from the transport sector. Biofuels are at the heart of this policy, and as consequence the demands for biofuels and the feedstocks required to produce different forms of transport fuels has risen sharply over the last 10 years. For as long as the UK utilises liquid fuels to power its transport sector, sustainable first generation biofuels such as biodiesel, bio-ethanol, and bio-methane; may provide a cost-effective contribution option for reducing the carbon emission of UK transport [56]. Imported feedstocks such palm oil or domestically produced oil seed rape represent crops that have been widely used to produce biofuels are subject to the crop cap and therefore their furture contribution will be restricted. The UK policy is instead to increasingly produce advanced biofuels from lignocellulosic feedstocks such as woods and from selected waste resources – these are forecast to play an increasing role in reducing transport emissions through the 2020's and beyond.

Over the timeframe to 2050 alternative renewable fuels and low carbon energy technologies are expected to be developed that may replace biofuels and lead to the fall in demand for the subsequent feedstocks. However over the same timeframe there is expected to be growing demands for biofuels and feedstocks for different transport sectors, including for shipping, aviation and haulage etc.

6.3. Coverage of Changing Demands & Competition for Bioenergy Feedstock within UK Models

When evaluating the availability of different biomass resource through modelling in order to identify opportunities for the bioenergy sector it is crucial that the existing competing uses for resources and lands are accounted. The ability of different types of models to analyse levels of competition is highly variable. It is therefore important when interpreting the outputs on models to understand whether competition is factored into the analyses and whether the model can provide an accurate assessment of this. The section describes how competition for biomass resources is covered within the UK focused models assessed in this scoping report. Table 13 provides a summary of how competition is covered within the key UK models listed within Table 2.

Energy System Models - competition for resources and biomass demand dynamics through time are analysed from the perspective of the whole energy system. Limitations on feedstocks providing a constraint on the extent that bioenergy may be included within the energy systems of a given scenario, and then based on the focus of the specific model this will influence the GHG performances, costs, energy security of the future energy system.

UK Full Biomass Assessment Models - these focus on assessing the availability of specific categories of resources to be potential feedstocks for the bioenergy sector. Therefore these models take account of the different competing uses for resources and lands that may otherwise be applied for bioenergy. Based on the approach of the model competition for biomass resource or lands may be assessed based on a economic cost bases, may be prioritised for use by alternative industries ahead of the bioenergy sector, or may be based on economic forecasts to estimate how demand dynamics may change over a timeline.

UK Environment Assessment Models - the focus of these models is to assess the environmental performances of bioenergy feedstocks and technologies. Assessing the competition and demand dynamics for different resources is not included as an explicit theme within their analyses.

UK Feedstock Specific Models - these models are designed to assess feedstock productivity yields that may be achieved. Assessing the competition and demand dynamics for different resources is not included as an explicit theme within their analyses.

UK Vector Specific Models - assess the potential extent that bioenergy technologies may contribute to the generation of a specific energy vector. Assessing the competition and demand dynamics for different resources is not included as an explicit theme within their analyses. Although they often highlight the various constraints inherent with bioenergy technologies, including issues related to sustainable feedstock supply.

UK Carbon Accounting Models - assess the carbon and GHG performance of different feedstocks and bioenergy technologies. Assessing the competition and demand dynamics for different resources is not included as an explicit theme within their analyses.

Table 13: Coverage of Changing Demands & Competition within Key UK Models

UK Energy System Models	
ETI's Energy System Modelling Environment (ESME)	• The ESME model includes assessment of UK domestic biomass, imported biomass and imported biofuels, and for each case includes constraints based on the varying availability and competition for these resources. • UK domestic biomass availability is constrained using broad assumptions related to sustainability, economic production limits and the need not to displace land for food production. • The imported biomass analyses within the model is constrained based on assumptions of the resource lime based on the size of the future global market and the proportion of this market that the UK may have access to. The availability of imported biofuels is constrained by assumption of the limits of the 'fair share' of the market the UK may access.
ETM-UCL	• The inclusion of different energy technologies within energy system scenarios developed using ETM-UCL are constrained by resource availabilities. For bioenergy, the model includes external data [58] that forecasts biomass availability at the regional level taking account of competing demands between 2010-2050.
TIAM-UCL	• The TIAM-UCL model has been developed to enable analysis of the trade of both fossil fuels biomass resources across regions, given the specific energy systems within each region. Using IEA Extended Energy Balances data for the baseline year, estimates of future demand dynamics take account of drivers including changing GDP, population, household growth and industry output.
UK MARKAL	• Analysis within UK MARKAL takes account of the 'strong interactions' between biomass demand and supply with food and other industrial sectors. • Constraints on feedstocks such as the competition from other industries has large potential influences on the extent that bioenergy can contribute within future energy system scenarios. • Availability of biomass given variations in constraints are analysed through the design of different scenarios that each draw upon values from built in databases that include resource availability sourced from external literature and reports. Analysis may be undertaken to investigate the extent that competition and constraints may have on limiting the potential of bioenergy deployment scenarios.
UK TIMES	The UK TIMES represents an update of UK MARKAL including: new influences such as tax and policy regimes; updated datasets; inclusion of emissions of all the major GHGs from both energy and non-energy uses, and; new technologies for reducing emissions outside of the energy system.
UK Full Biomass Assessment Models	
ETI's Bioenergy Value Chain Model (BVCM)	• Assessment of land use dynamics is key to the BVCM's analyses and competition for land is well covered – the model able to evaluate scenarios of how much land may be dedicated for biomass production once lands have first been dedicated for alternative uses, based on influences of costs, GHGs, energy and exergy.

	• Future resource demand dynamics are modelled through assessing scenarios with varying yield potentials, climate influences and ramp-up rates that drive the extent that feedstocks are produced and bioenergy technologies are deployed etc. • The model also allows users to vary a series of constraints that would influence the availability of future UK feedstocks.
E4tech's Biomass Supply Curves Analysis	• Competing demands for the resource are assumed to be supplied before any use for bioenergy - meaning the analyses assumes there is no competition between alternative uses on the basis of prices. • Changing dynamics of these competing uses over time are analysed on a scenario basis, with demands over time influenced by projections taken from external literature and reports.
CCC's Biomass in a Low Carbon Economy Analyses	• The CCC acknowledge there is significant uncertainties over the levels of sustainable bioenergy resource that could be available to the UK in 2050, citing the demands from competing uses as a key consideration. • It is unclear how the CCC calculate how the changes in demands and completion for different feedstocks with change over, the accompanying report stating: "demand from competing uses will depend on factors such as levels of timber construction, paper and card usage for packaging, and new products such as bio-based plastics and bio-based chemicals" [33]. • The CCC suggest through their analysis that prioritisation of uses for different categories of feedstocks and choice of bioenergy technologies should also take account of the carbon performances in addition to the costs of different use scenarios.
DECC 2050 Calculator	• Extent that different bioenergy technologies and feedstocks are used within scenarios developed within the DECC 2050 Calculator are determined by the user, therefore the user would determine the extent of overall biomass resource that would be used for bioenergy. • Use of bioenergy within these is based on an assessment of future biomass availability as sourced from a variety of external literature and reports. Competition for biomass and demand dynamics over time are addressed within each of these individual studies, DECC using the 'available UK biomass values' that have already taken account of potential competing uses.

Ricardo's UK and Global Bioenergy Resource Model	• For each of the categories of feedstock analysed within this model, their availability for the bioenergy sector takes into consideration the competing uses for both resources and land. This is achieved through generating a series of 'estimates' of resource that would go to competing non-bioenergy uses based on a series of cost thresholds:
	  ○ where competing use is independent of the price of the feedstock;
	  ○ price dependent competing use at £4/GJ;
	  ○ price dependent competing use at £6/GJ;
	  ○ price dependent competing use at £10/GJ.
	  ○ Price thresholds are maintained over the timeframe of the analysis to 2050.
	• Within the analysis the 'competing use' which is independent of the price of the feedstock is subtracted from the estimate of the potential resource to give an estimate of the 'accessible resource'. Price dependent competing uses are subtracted from this to give the 'unconstrained bioenergy resource' at each of the three price points.

Tyndall Centre's Biomass Resource Model (BRM)	• Coompeting uses for each category of biomass are analysed, including competing land uses for grown feedstocks; the alternative waste management practices for waste feedstocks; alternative agricultural uses for agricultural sourced feedstocks, and; alternative industry sector uses for different categories of feedstocks. • The changing demand and competition for biomass resources is modelled through time based on projections for how the various alternative sectors are expected to develop. For example projections for how the UK wood product sector is predicted to grow, which will drive their future demands for resources that could alternatively be bioenergy feedstock. The future demand dynamics of these competing industries may be designed to reflect different future pathways, reflecting scenarios that may be developed by the model users.
UK Environment Assessment Models	

Biomass Environmental Assessment Tool ($BEAT_2$)	• Designed to assess the GHG and environmental performance of different biomass schemes through apply a LCA analysis methodology. • The model does not assess issues related to the demand or competition for specific bioenergy feedstocks.
JULES land surface model	• This model is designed to evaluate potential biomass production constrained by land and environmental systems. • The model does not assess issues related to the demand or competition for specific bioenergy feedstocks.
The Foreseer Tool	• This model is design to visualise the influence of future demand scenarios on requirements for energy, water and land resources. • Analysis of biomass within The Foreseer Tool is driven by external data and assumptions that influence the land dynamics. • The Foreseer Tool is not designed to assess issues related to competition for specific bioenergy feedstocks.
UK Feedstock Specific Models	
Forest Growth SRC, MISCANFOR, PopFor	• Predict the productivity yield that may be achieved by growing either willow, poplar or miscanthus on specific fields/ sites in the UK. • These models are not designed to assess issues related to the demand or competition for specific bioenergy feedstocks.
UK Vector Specific Models	
DfT's Transport Energy Model (TEM)	• The TEM assesses the GHG and air environmental performance of different transport options and fuels. • The TEM is not is not designed to assess issues related to the demand or competition for specific bioenergy feedstocks. • Although it is acknowledged within the TEM that where biofuels are considered, there is both limited production capacity and availability of sustainable feedstocks which will constrain the extent to which low carbon fuels can meet energy demand across all sectors.
Renewable Heat Incentive Calculator	• This model assesses the specific performance of given bioenergy systems as installed/ operated by the model user. • The Renewable Heat Incentive Calculator is not designed to assess issues related to the demand or competition for specific bioenergy feedstocks.
Whole electricity System Investment Model (WeSIM)	• The WeSIM model is designed to balance future electricity demands through a range of renewable and conventional technologies. • The WeSIM is not designed to assess issues related to the demand or competition for specific bioenergy feedstocks.
UK Carbon Accounting Models	
BioGrace-II	• Allows assessment of the GHG performances of bioenergy electricity, heating and cooling systems using different feedstock and technologies. • BioGrace-II is not designed to allow assessment of demand and competition for biomass resource over time.
CARBINE Forestry Carbon Accounting Model	• Provides an assessment of the potential carbon dynamics that would result from forestry products either being used as a direct source of energy in place of fossil fuels, or where wood is used in place of more energy-intensive materials. • CARBINE is not designed to allow assessment of demand and competition for biomass resource over time.
Ofgem's UK Solid & Gaseous	• Designed to help companies calculate the carbon intensity of the electricity, heat or biomethane produced from solid biomass or biogas for the purpose of reporting under the Renewables Obligation scheme.

Biomass Carbon Calculator	• The UK Solid & Gaseous Biomass Carbon Calculator is not designed to allow assessment of demand and competition for biomass resource over time.

6.4. Assessment of How Changing Demands & Competition for Bioenergy Feedstock is Covered within Models

The inclusion and coverage of changing demands and the competition for biomass resource, and how these may influence bioenergy scenarios varies across the models based on their design and approach. The outputs from most of the models covered in this Scoping Report are presented alongside explanations and caveats that highlight potential constraints around biomass resource availability – these are typically highlighted either within the calculation tools themselves or within the supporting literature.

Only the models categorised as 'UK Full Biomass Assessment Models' within this Scoping Report carry out specific analyses aimed at assessing the competing industries and alternative uses for biomass. These models typically first calculate the levels of resource required by competing markets, and then exclude this resource quantity from the proportion available for the bioenergy sector. Assessments of resource quantities required by competing markets are calculated either based on: an economic costs assessment where resources is available for bioenergy given economic constraints (e.g. £/GJ), or; based on an assessment of the current proportion (%) or quantities (t) of resources required for a competing use, this value either remaining constant over the analysis timeframe or changing in line with external forecast data reflecting future economic growth in the sector.

When assessing land availability for potential bioenergy feedstock production, the models all typically carry out calculations to calculate available land areas based on the assumption that 'food production won't be impacted', i.e. the models set aside land for food production alongside other key uses such as for conservation, buildings, infrastructure, and unsuitable lands before carrying out an assessment of what lands could be used to produce feedstocks.

6.4.1. Gaps and Weaknesses in the Current Models

Gaps and weaknesses in how the models included within this Scoping Report assess changing demands and competition for resources include:

- Many of the models do not specify which industries/ sectors they do and do not include in their analyses.
- The assumption data and references for assessing competing demands these are often well hidden or not available for scrutiny.
- The models do not have dynamic coverage of how the demands from different sectors may change over time, and have no means of assessing the emergence of new demand sectors; for example the potential for growing demands from competing vectors within the bioenergy sector.
- The models assume that land owners and managers are open to shifting towards production of biomass feedstocks over food products. Modelling assessments of UK 'grown biomass resource' potentials based on 'available land' are consistently many magnitudes higher than real production values. The bioenergy sector is in great competition with alternative sectors to 'convince' land owners and managers to produce feedstock over food. This constraint is not covered in any of the models.
- Very few of the models cover changing food habits such as diet change that may have large influences on available lands in the future that could be utilised.

7. Modelling & the Sustainability Criteria for Biomass Supply Chains & Bioenergy Technologies

This section provides an overview of sustainability within existing biomass resource models. We consider the indicators used and how they are integrated within modelling frameworks. Over the last decades controversies such as the food vs. fuels debate have resulted in greater interest in the sustainability of feedstocks beyond the contribution that they can make to climate targets. In examining how a broader set of sustainability targets are considered in biomass resource models we question how such models deal with the wider policy context in which they are operating. Models that incorporate understanding of the economic, social and environmental consequences of biomass resources will be able to better inform the development of policy that delivers benefits for society across these three pillars of sustainability. Models with a narrower focus, for example just on GHG benefits, are likely to produce results that have a higher risk of producing perverse outcomes in other areas. Below we discuss one example of this whereby *post hoc* analysis of pathways to achieve the UK's ambitions aligned with the Paris Agreement would require 61% of UK agricultural land being used for bioenergy production.

7.1. Approach

To examine how sustainability criteria have been incorporated into modelling frameworks we brought together the major global initiatives around sustainable biomass production (Table 14).

Based on reviews by Scarlet and Dallemand (2011) [59] and Cucuzzella et al (2020) [60] eight major categories and 37 sub-categories relating to sustainability were identified. We accessed documentation (where available) for each of the models assessed in section 6, and scored consideration of criteria across the eight major categories. The use of these broad headings recognises that there are very specific indicators used in detailed sustainability assessments which could never be captured in systems models (e.g. Forced Labour; Working conditions). However, identifying pathways that minimise impacts, or deliver benefits, for the environment (GHGs, soil, water, air, biodiversity, natural capital), society (employment) and the economy (increased income) could be seen as a prerequisites for consideration in order to avoid unintended consequences arising from adoption of a particular energy pathway.

We must also recognise that there will be difference between models in the specifics of what they examine. So for example under "Carbon Conservation" some models may simply assume an emissions factor, others may consider changes in carbon stocks associated with direct conversion of land use from agricultural production to biomass production, others may incorporate an indirect land use change factor to account for emissions resulting from displaced food production. In presenting these results we are interested in the broad picture of what is considered. Specific indicators may need to be developed in future work to reflect policy drivers. This is discussed in further detail in the Section 8 – Current Knowledge Gaps.

Table 14: Sustainability criteria used in biomass certification schemes. Adapted from Scarlet and Dallemand (2011) and Cucuzzella et al (2020).

	Renewable Energy Directive 2009/28/EC of the European Union EU-RED	Council on Sustainable Biomass Production CSBP	Global Bioenergy Partnership GBEP	Roundtable for sustainable biofuels RSB	International sustainability and carbon certification ISCC	Certification sheme for sustainably produced biomass for energy NTA 8080	Renewable transport fuels obligation RTFO	Better Sugarcan Initiative BSI	Roundtable for responsible soy production RTRS	Roundtable on sustainable Palm oil RSPO	Forest Stewardship Council FSC	Programme for the Endorsement of Forest Certification schemes PEFC	Global Partnership for Good Agricultural Practice Global GAP	Sustainable Agriculture Network/Rainforest Alliance SAN	Fairtrade Labelling Organisations International Fair Trade	Social Accountability International SAI	International Federation of Organic Agriculture Movements IFOAM	Sustainable biomass program SBP
Carbon conservation																		
Preservation of above/below ground carbon	+	+			+	+	+	+	-	+								+
Land use change	+	+	+	+	+	+			+	+	+				+			+
GHG emissions	+	+	+	+	+	+	+	+	+	+				+				+
Biodiversity and Natural Capital																		
Biodiversity	+	+	+	+	+	+	+	+			+	+	+	+	+		+	+
Natural habitats, ecosystems	+	+	+	+		+	+	+	+	+	+	+	+	+			+	+
High conservation value areas	+			+	+		+	+	+	+	+		+		+			+
Native, endangered and invasive species	+	+	+	+			+	+	+	+	+	+		+	+		+	+
GMO				+							+		+		+			+
Soil conservation																		
Soil management, soil protection		+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	
Residues, wastes, by-products		+		+						+				+			+	+
Use of agrochemicals		+		+	+		+		+	+		+	+	+	+		+	+
Waste management				+	+	+	+	+	+	+	+		+	+	+		+	
Sustainable water use																		
Water rights				+	+									+			+	+
water quality	+	+	+	+		+	+	+	+	+			+	+			+	+
Water management, conservation		+		+	+	+	+	+		+				+				
Efficient water use		+	+	+														

Table 14 (continued): Sustainability criteria used in biomass certification schemes.

	EU-RED	CSBP	GBEP	RSB	ISCC	NTA 8080	RTFO	BSI	RTRS	RSPO	FSC	PEFC	Global GAP	SAN	Fair Trade	SAI	IFOAM	SBP
Air quality																		
Air pollution	+		+	+	+	+	+	+	+					+				+
No burning for land clearing/waste disposal						+	+	+		+					+		+	
No burning residues, waste, by products.			+	+			+	+					+	+				
Economic development																		
Economic benefits to community			+	+		+			+	+	+							+
Economic performance			+	+				+		+	+				+			+
Energy efficiency			+		+			+		+				+				
Energy balance			+	+				+										
Social Aspects	+																	
Social impact assessment			+	+				+	+	+	+			+				
Social benefits to community			+	+	+	+								+				
Human rights				+	+	+		+						+			+	+
Land right issues			+	+	+	+	+		+	+	+	+		+			+	+
Labour conditions																		
Working conditions		+	+	+		+	+	+	+		+		+	+	+	+		+
Contracts		+			+		+		+		+			+		+		
Health and safety		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Freedom of association, bargaining			+	+	+	+	+	+	+	+	+	+		+	+	+	+	+
Discrimination		+	+	+	+	+	+	+	+	+	+	+		+	+	+	+	+
Wages		+	+	+	+		+	+	+	+	+	+	+	+	+	+		+
Working hours		+		+	+		+	+			+		+	+	+	+		+
Child Labour			+	+	+	+	+	+	+	+	+	+		+	+	+	+	+
Forced labour			+	+	+	+	+	+	+		+	+		+	+	+	+	+
Training, capacity building		+	+		+			+	+	+	+		+	+	+			+

7.2. Sustainability within Reviewed Models

Each of the models examined in section 6 were scored as to which environmental, social or economic impacts of the energy system they considered. Impacts were based on the broad headings relating to criteria identified in Table 15.

Table 15. Incorporation of sustainability criteria in reviewed models.

Sustainability Criteria	DECC Calculator	Energy System Modelling Environment	ETM-UCL	UK MARKAL	TIAM-UCL	Biomass Resource Model (BRM)	Bioenergy Value Chain Model (BVCM)	Transport Energy Model (TEM)	UK and Global Bioenergy Resource Model	Biomass Environmental Assessment Tool	UK TIMES	Whole electricity System Investment Model
Carbon conservation	+	+	+	+	+	+	+	+	+	+	+	+
Biodiversity/Natural capital		+				+	+			+		
Soil conservation		+					+			+		
Sustainable water use										+		
Air quality	+		+					+		+		
Economic development	+	+	+	+	+	+	+	+	+	+	+	+
Social Aspects								+		+		
Labour conditions												
Land Use	+	+				+	+			+		

Given the framing of the debate around future energy pathways in terms of the energy trilemma (decarbonisation, energy security, investment requirements and affordability) it is not surprising that all models consider carbon conservation and economic development. Of the twelve models that we examined five considered no other criteria directly.

Of the models that consider a broader range of sustainability criteria the ESME model has underpinning data from the ETI's Biomass Value Chain Model and so these two can be seen to be linked. Use of the ETI BVCM data within ESME is based on a series of model runs that serve to define the maximum UK production that is economic and "sustainable". This data incorporates a series of constraints based on Lovett et al. taken to act as proxys for factors such as biodiversity by restricting deployment within areas such as national parks or sites of special scientific interest. As such we score both ESME and the BVCM as considering biodiversity conservation, soil conservation and land use in addition to carbon conservation and economic development. This proxy based approach simply restricts deployment strategies, but it does not, and cannot, consider how deployment strategies could be used to enhance biodiversity or natural capital by optimising for these targets as well. We would also note that although BVCM does incorporate data at 1km × 1km grid scale to be tractable it operates at 50 km × 50 km grid resolution. At this scale it is questionable how well consideration of biodiversity and land use impacts could be considered within model runs.

To illustrate the value of incorporating a broader set of criteria into energy system models we can consider outputs from the Transport Energy Model which we score as considering Air Quality and Social Aspects in addition to measures relevant for the energy trilemma. The Transport Energy Model was designed to identify pathways to cut air pollution by 2035 as detailed in the Road to Zero. The driver for this was estimates by Public Health England that failure to improve air quality could lead to cumulative health and social care costs of between £5.3 billion to £18.6 billion by 2035 depending on assumptions about the links between specific conditions and poor air quality. Factoring in this externality drives models solutions to reduce this cost.

The best performing model in terms of the sustainability criteria covered is the Biomass Environmental Assessment Tool. This examined all the sustainability criteria identified, with the exception of Labour Conditions (a category relevant to supply chains overseas and so outside the scope of the BEAT2 tool). As detailed in Section 4.3.1 this is an environmental assessment model that uses attributional life cycle assessment to examine different bioenergy resources, and as such differs substantially from the other models examined here.

The importance of incorporating a broader set of sustainability criteria into future model development can be illustrated by examples of *post hoc* analysis, an increasingly common follow on to energy system modelling exercises. The Clean Growth Strategy, published by the UK Government, considered the implications of actions taken to meet our carbon budgets. This included consideration of the benefits of increasing forest cover, and how conversion of the transport sector towards ultra-low emission vehicles could improve air quality. Work by Konadu et al. (2015) [61] on the land use implication of the UK 2050 Carbon plan, provides a compelling example of the need to incorporate sustainability criteria within energy system models. Taking scenarios developed with the MARKAL model, Konadu et al. (2015) demonstrated that depending on the characteristics of the scenarios in terms of energy efficiency, crop yields and feedstock sources, between 7% and 61% of UK's agricultural land would need to be appropriated for bioenergy production to meet targets for an 80% GHG reduction by 2050. What is interesting about this analysis is that it demonstrates that by not incorporating broader measures of sustainability within the modelling framework, the model may solve itself in such a way as to produce extreme future energy pathways (i.e. 61% of UK agricultural land used for bioenergy production). This is also noted in the Bioenergy Strategy in a discussion of uncertainties where it is noted that external policy drivers, such as air quality objectives, might drive the adoption of technologies in a way that the energy system model used would consider suboptimal.

7.3. Conclusion

Results presented in Table 15 support findings in recent reviews of the link between energy and environmental scenarios at global [62] and UK [63] scales. These studies demonstrate that energy scenarios and the models that underpin them consider a relatively narrow set of environmental and social consequences. These typically focus on decarbonisation, energy security, investment requirements and affordability, the pillars of the energy trilemma. Such limited consideration on the energy trilemma seems short-sighted given that the UK has a range of national and international commitments relating to the environment (e.g. the Strategic Plan for Biodiversity; UN SDGs) that can be negatively impacted by the choice of energy pathways.

As detailed in the Government's 25-year Environment Plan, the coming decade will see an increasing focus on the value of public goods such as clean air and water. This shift will be concurrent with the UK's energy system undergoing a period of rapid transformation to meet targets to reduce greenhouse gas emissions. As discussed in the previous section, the current approach to considering the implications of energy pathways based on the use of constraints acting as proxies for public goods, and the use of *post hoc* analysis to examine the implications of energy pathways may not deliver optimised solutions across all the policy commitments that we face. Section 8 considers the implications of this finding in detail within a natural capital framework and suggest a way forward for future model development.

8. Scoping for Next Steps

The Supergen Bioenergy Hub has identified four broad areas that should be considered to further develop the scope and performances of UK biomass resource models and to provide a policy framework that supports development of the bioenergy sector. In line with the aim of this Scoping Study the we highlight areas for development to inform the design of future policy. We do not make technical recommendations around the design of future modelling frameworks. However, we would note that there are substantial opportunities for developing modelling frameworks that would not have been feasible even a decade ago due to the increasing availability of data and computing resources. For example, representing bioenergy deployment strategies and their influence on natural capital (see 1. below) presents a substantial challenge due to the complexity of the environmental models needed to understand interactions between the feedstock and environmental processes. The use of model emulators, which build a statistical model of a more complex process based model, can cut down processing times from days/hours to seconds allowing realtime exploration of policy options.

One of the most notable developments in this arena over the last decade has been the move towards "open source" modelling. This has many benefits including increased transparency, improving access to resources to aid decision making, and the involvement of a wide community to drive forward development. An example of such an approach is provided by the Joint UK Land Environment Simulator (JULES - https://jules.jchmr.org/), and this could represent a model for similar development relating to bioenergy modelling going forward.

1. Natural Capital within Bioenergy Resource Models

There is a need to incorporate natural capital and ecosystem services within bioenergy resource models. This relates directly to the discussion of sustainability presented in Section 7 (above). Below we provide an introduction to natural capital and ecosystem services, and provide the rationale for the areas of work that we identify across three broad areas;

1) Work should be carried out to improve our understanding of the role that bioenergy feedstocks can play in the provision of ecosystem goods and services recognising that natural capital is central to human wellbeing, and that there are significant policy drivers in this area.
2) We must recognise that natural capital and the provision of ecosystem goods and services has a significant spatial element. Analysis must be conducted at appropriate spatial scales to capture spatial heterogeneity in the distribution of natural capital and the goods and services that flow from it.
3) Implement values for natural capital and ecosystem goods and services aligned to those measured by the ONS within energy system models. In doing so optimisation within models can identify deployment patterns that address targets around the energy trilemma, benefit land managers through PES schemes, and society through the delivery of public goods.

Background

The Natural Capital Committee (NCC), a body established to provide advice to government in this area, defines natural capital as "those elements of the natural environment which provide valuable goods and services to people, such as the stock of forests, water, land, minerals and oceans". From these natural capital stocks flow ecosystem goods such as food, timber and fuels, together with ecosystem services including climate regulation, soil formation, and water and air purification. This flow of ecosystem goods and services from natural capital stocks is critical for human wellbeing, and has a substantial economic value to the UK. The Office for National Statistics estimates that the value of goods and services derived from the UK's natural capital stocks was in the region of £1 trillion in 2017. This valuation is likely an underestimate as it focuses primarily on those goods and services that have a market value such as agriculture, timber, minerals and fish. Many of the benefits that society derives from natural capital are not supplied through markets, and so they lack market prices or have prices derived through alternate methods that may poorly reflect their true value to society.

Since the publication in 2011 of its White Paper "The Natural Choice" the Government has repeatedly stated an ambition to be "the first generation to leave the natural environment of England in a better state than it inherited...". This ambition was reiterated in "A Green Future: Our 25 Year Plan to Improve the Environment" that sets out a blueprint for environmental policy following the UK's exit from the European Union. Most recently, HM Treasury commissioned the "Dasgupta review" that sets out the economic benefits of biodiversity, a key component of natural capital, and considers the consequences of its loss. Together these reports give a clear direction of travel indicating that natural capital thinking must be included in future planning decisions across all sectors of society.

Within this context, future policy around bioenergy resources must be informed by detailed understanding of the implications for natural capital stocks. Bioenergy feedstock production can have both positive and negative implications for naturals capital stocks and the ecosystem goods and services that flow from them. These implications are contingent on spatial context, mediated primarily through land use and land use change. For example, a review of the implication of second-generation (2G) bioenergy feedstock production by Holland et al (2015) [64] demonstrated that conversion of arable land to 2G feedstock production could deliver substantial benefits for a number of ecosystem services including hazard regulation, disease and pest control, water and soil quality. Conversely, conversion of existing forest would likely lead to a reduction in these self-same services (see Figure 10). We would note that that despite a number of studies that have examined the role that bioenergy feedstock production can play in the delivery of ecosystem goods and services there are still knowledge gaps in this area.

From a policy perspective, the importance of considering the influence of bioenergy feedstock production on natural capital stocks relates to the concept of payment for ecosystem services (PES). This concept recognises that there will often be a manager of a natural capital asset, and that these managers should be paid for the provision of the goods or services that arise from it. The most famous example of a PES scheme is probably the management of New York City's water supply through a programme of measures to maintain water quality in the Catskills and Delaware catchments. Components of this PES scheme include land acquisition at market values, payment and tax relief to relinquish development rights, and assistance to farmers to implement pollution prevention plans. The programme costs US$1.5 billion, compared to an estimated cost of US$8-10 billion for water treatment. Further examples of PES schemes can be found in a best practice guide to Payment for Ecosystem Services produced by DEFRA available here. The most immediate way that such PES schemes will be implemented in the UK is through the Environmental Land Management Scheme (ELMS) that was mandated in the 2019 Agriculture Bill. ELMS make management of natural capital explicit, and rewarded on the principle of public money for public goods.

As discussed in Section 8 of this report, few energy system models consider natural capital beyond climate regulation. Those that do consider natural capital typically either; (i) apply constraints to limit deployment of bioenergy crops to areas assumed to be of limited value for natural capital, or (ii) conduct post hoc analysis to examine the implications of "optimal" solutions for natural capital assets. As PES schemes become more widespread, energy system models that seek to optimise strategies for bioenergy resource feedstock production without incorporating the value of natural capital may arrive at solutions that diverge from the wider policy context in which they are operating. For example the use of constraint maps may exclude bioenergy production from areas where deployment could deliver wider environmental benefits of economic value to society (i.e. flood mitigation). Future models must balance climate targets, energy security, and the protection of natural capital assets for future generations.

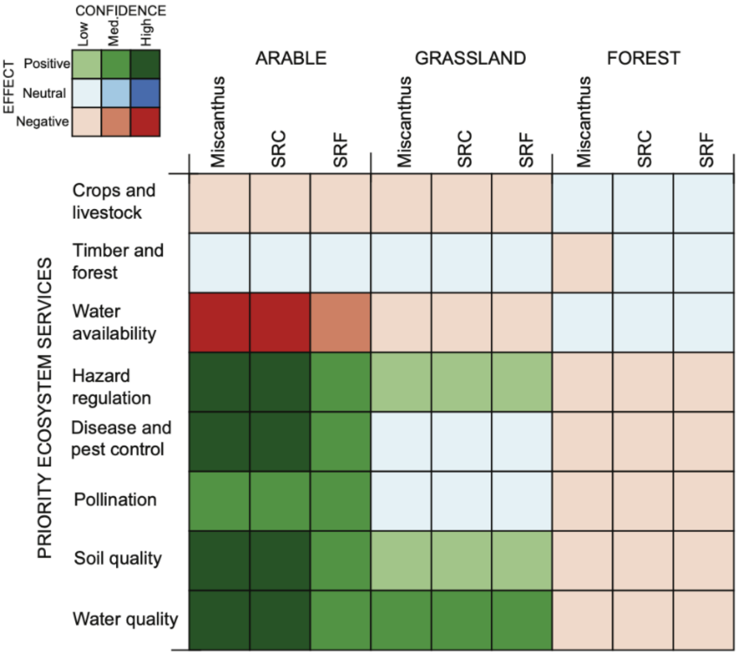


Figure 10: Impact matrix of effects on priority ecosystem services of land use transitions to second generation feedstocks based on literature review of 61 unique studies reporting 179 ecosystem service effects. Impacts are scored positive where there is an increase in the services, negative with a decrease, and neutral where there is no significant effect reported. Confidence is based on the number of studies and agreement on direction of impact.

In part, failure to incorporate natural capital within existing energy system models can be attributed to a paucity of data and methodological challenges in valuing natural capital and the ecosystem goods and services. However, the last decade has seen a substantial acceleration of understanding and the development of methods in this area. At the global level, the United Nations (UN) System of Environmental-Economic Accounting Central Framework and System of Environmental-Economic Accounting Experimental Ecosystem Accounting principles (see here) provide an agreed standard for capturing the value of a countries natural capital assets through time. Based on this standard, the Office for National Statistics (ONS) and DEFRA have established a set of Principles of Natural Capital Accounting. These provide a structured set of information relating to stocks of natural capital and the flows of goods and services arising from them based on two measures. Firstly, physical accounts that classify and record measures of extent, condition and annual service flow. Secondly, monetary accounts that assign a monetary valuation to limited set of services annually, and record an overall valuation of the natural asset's ability to generate flows of the service in the future. The ongoing development of methods in this area provides a clear way forward to incorporate the value of natural capital and ecosystem goods and services within energy system models, in a way that is consistent with UK policy drivers.

Given that natural capital and ecosystem goods and services exhibit complex spatial patterns, energy system models must also better incorporate spatial data within their frameworks. Most existing energy system models operate at relatively coarse scales such as regions or 50km^2 grid cells. Work conducted through the Addressing the Valuation of Energy & Nature Together (ADVENT) programme, of the UK Energy Research Centre (https://ukerc.ac.uk/research/advent/), has demonstrated that optimisation of bioenergy feedstock deployment strategies based on data at such coarse scales can lead to significant error in our understanding of the implications for natural capital assets. Choice of the appropriate scale at which to conduct analysis will need further investigation. A balance will need to be struck between the increasing availability of high-resolution data, and the feasibility of incorporating data that could be smaller than field scale. For tractability within modelling frameworks, and recognising that energy system models are not designed to be prescriptive of exact deployment strategies as these are also determined by socioeconomic factors, spatial scales of around 1-2 km^2 may represent a good compromise. Such scales would capture heterogeneity within the data identifying potential areas for feedstock production, while allowing flexibility in exact deployment strategies.

Finally, we must recognise that demand for bioenergy resources in the UK has a significant global component, and that this has important policy implications. The UK's 25 Year Environment Plan states that "[a]s a developed country, the UK should drive progress on certain SDGs where domestic consumption has an impact on other countries" to "avoid[...] improving our domestic environment at the expense of the environment globally". Biomass resource models will often include an international component as "imports" to meet the demands in the model without specifying where these imports come from. The discussion above relating to protection of the UK's natural capital assets and the ecosystem goods and services that flow from them also applies to this international component of UK biomass resource demand and so more specificity is needed. Failure to consider this component of UK resource demand could undermine internationally agreed targets around sustainability such as those in the UN Sustainable Development Goals. Addressing this represent a substantial challenge.

Although the United Nations (UN) System of Environmental-Economic Accounting Central Framework and System of Environmental-Economic Accounting Experimental Ecosystem Accounting principles provide an international standard for measuring and monitoring natural capital assets, globally the coverage is patchy. In the short term it is unlikely that data on natural capital assets comparable to that available in the UK will be available globally. However, alternate metrics are available through techniques such as Environmentally Extended Multiregion Input Output Analysis that could provide an interim set of indicators on which to assess the implications of UK biomass resource demand internationally.

2. Human Actors within Biomass Resource Models

A substantial challenge exists in translating results from bioresource modelling into the real world. While bioenergy plays a critical role in many future scenarios that meet climate ambitions, deployment of dedicated bioenergy crops in the UK has so far been slow. This section provides a brief discussion of this issue, mainly taken from two academic papers that have examined this question. We would suggest that future work should:

1) Examine how farm scale dynamics that influence uptake of dedicated bioenergy crops are currently represented in models.
2) Examine methods that could be employed to capture these farm scale dynamics to understand the influence of different policy options.
3) Consider how "constraints" of bioenergy deployment might be more dynamically modelled.

Background

Production of dedicated 2G energy crops such as miscanthus or short rotation coppice on marginal lands is consistently identified as playing an important role in the UK's future energy mix. However, predicted rapid expansions has not materialised. Within the context of this report this raises an interesting question of whether there is a disconnect between the outputs of bioenergy resource models and what is achievable on the ground, why such a disconnect exists, and what steps could be taken to address it. The resolution of these questions will be critical if bioenergy is to play an important role in future UK energy strategy.

To examine possible reasons for a disconnect between energy models and farmers action we draw heavily on work carried out by Richard Helliwell at the University of Nottingham, published in Energy Policy in 2018 [65]. Helliwell interviewed 32 farmers across the north of England about their view of marginal land and production of dedicated bioenergy crops. Helliwell's primary conclusion is that there is a disconnect between the key assumptions that are made when designing and modelling policy, and the views of farmers. The key policy modelling assumptions that he identifies are:

1) That the marginality of land is characterised by a set of biophysical properties. An example of these would be the constraint maps produced by Lovett et al. that have been used extensively in modelling exercises in the UK such as the ETIs Biomass Value Chain.
2) The quality of the land is benchmarked against arable production. This ignores the many other uses that land can be put to.
3) Logistic and economic constraints are the primary on-farm drivers. Here examples of logistic constraints again relate to those identified in Lovett et al. such as access for machinery to harvest. Economic constraint relate to such things as the price of the bioenergy crop vs. alternate crops.
4) Again relating to Lovett et al. cultural and heritage features are assumed to act as a constraint. For example, conversion of land in a national park to 2G crop is assumed to have a negative impact on the landscape.

Helliwell's principal finding is that these static definitions of marginal land based do not reflect real world management options for farmers. Factors such as the availability or size of machinery or opportunities to improve land mean that the definition of marginal land is fluid. Energy crops exist as just one of a range of options available to farmers, and so policy must be designed to reflect this.

Capturing such dynamics within bioenergy resource models is challenging. A key knowledge gap would be addresseed if existing "constraint" maps could be developed that are more fluid to reflect changing policy. As discussed in the Recommendations relating to natural capital, the introduction of ELMS and the adoption of policies that reward public money for public goods could have a profound influence on the desirability of bioenergy crops within farm settings. Here techniques such as Agent Based Modelling, that allow the integration of biophysical, economic and social processes in modelling frameworks, may present a way forward. An example of such an approach is provided by Brown et al. (2016) [66] who used an agent-based modelling framework in Scotland to assess adoption of bioenergy crops based on different representation of farmers types and enterprises. Such a tool allows the exploration of different policy options to incentivise production of dedicated bioenergy crops.

3. Dynamic Competition & Demands within Biomass Resource Models

Bioenergy is a key renewable energy technology targeted to provide options for decarbonising heat, power and transport energy in the UK. In addition, development of the bio-economy is a core element of the UK's industrial strategy. As discussed within section 6, to deliver these strategies the UK's demands for feedstocks is likely to increase accordingly and therefore there will be growing competition for resources as demands change. This scoping study has highlighted how competition and changing demands are analysed within many of the UK's existing models and has identified gaps and weaknesses. For example the supply and demands for different feedstocks is likely to be highly dynamic over the short medium and long terms; current models fail to capture the many interactions that will influence the extent that feedstocks may be available for different end uses. The Supergen Bioenergy Hub recommends that further work is undertaken to investigate the future dynamics of biomass resource demands and competition and specifically how this may potential impact development of the UK bioenergy sector and bio-economy. Such work could focus in the following areas:

1) Undertake analyses to build a better understanding of the current competing uses for the major categories of biomass and lands. This would be enhanced by also mapping locations of key resources and that of competing industries.
2) Firmer evidence is required that characterises the UK resource availability and demand in order to aid long term decision making. The lack of a solid evidence base represents a knowledge gap that will need to be addressed to allow comprehensive evaluation of the future changing resource demands of key sectors including that of the future bioenergy sector. This could be achieved through scenarios analyses to highlight future resource availability risks and opportunities.
3) There is a knowledge gap of what the best uses of different categories of biomass are, when considering the wider economic, environmental and social performance indicators. This is required in order to allow the prioritised/ incentivisation of the use of specific biomass resources

for bioenergy. Where potential impacts from increased competition for resources have been identified, it would be useful identify whether alternative resource solutions are available.

Background

Analysing the current and future potential competition for resources will require consideration of many multi-disciplinary factors, for example: Economics dynamics including consideration of supply and demand curves for different feedstocks and sections, and the impacts and benefits of emerging factors such as a carbon prices and the changing prices of energy. Many of these issues are widely analysed through models developed for wider disciplines, so collaborations would be beneficial.

Social dynamics such as considerations of how behaviours impacts decision making, assessing the likelihood that markets will develop and the level of uptake of new technologies, and the acceptance of new technologies. Analysis methods such as agent based modelling and broad reaching stakeholder engagement covering whole supply chains may provide options for investigating the social dynamics influencing the future demands and competitions for different resources.

4. The Policy Factor

The development of the UK bioenergy sector and bio-economy will be limited by or will flourish upon a secure sustainable supply of feedstocks. The UK's future supply of feedstocks will be dependent upon the extents that resources are grown, produced and mobilised. Establishing robust supply chains will be aided or restricted by the design of policy framework – policies ideally being developed to require or incentivise the use of targeted biomass resources for energy end uses. To ensure policies are developed that support the bioenergy sector, the Supergen Bioenergy Hub strongly recommend that the following work is undertaken to provide a firmer understanding of biomass and bioenergy in the UK:

1) Bioenergy is different to other renewable energy options in that it is linked directly to the land, people, industry and the many processes and interactions between these. As a result all bioenergy schemes will likely be influenced by many broad ranging policies and strategies coming from both the central and local Government. We recommend work is undertaken to identify the contributions and remit of different sectors and Government Departments that forms the current policy landscape influencing bioenergy.
2) We recommend that work is undertaken to identify and start to analyse the many policies that currently influence bioenergy, highlighting the most influential. Individually these policies may promote or restrict bioenergy schemes, but collectively there is the risk of potential contradictions and a barrier to new developments in the sector, since bioenergy is so inextricably linked to land, people, industry processes and interactions between these as well as energy.
3) We recommend work is undertaken to build cross sector/ Department working groups to work towards developing a new UK Bioenergy Strategy.

Background

The 'burden' of developing policies to help build the UK bioenergy sector has historically been placed in the sphere of energy policy. However bioenergy is different from other renewable technologies in that it is intrinsically linked to activities and processes that come under the remit of many government departments. Current examples where bioenergy has a footprint across many central Government Departments include:

- Development of biofuels as an option to decarbonise UK transport – managed by the DfT;
- Promotion of bioenergy as an option to decarbonise UK heat and power – managed by BEIS;
- Classification of waste materials to determine their potential use within energy technologies choices about use of lands for energy – managed by DEFRA, and;
- Department such as the FCO, DTI and the Treasury also controlling and influencing wider elements of the UK bioenergy sector.

Going forward a policy framework needs to be developed to promote the UK bioenergy sector that cuts across these departmental divides.

The UK's current policy framework in some cases also works against the bioenergy sector. There are a number of key policy areas that should be re-analysed and consideration given as to whether changed could be made to better support the UK. Examples include:

Waste are increasingly targeted as a key resource opportunity for the UK, that could be used to recover heat and power, or through matching with advanced technologies could be used to produce alternative fuels for aviation, shipping or road transport. The UK's current targets for waste reduction and recycling when linked to the waste management guidance provided by the waste hierarchy will potentially result in ever decreasing volumes of wastes available for energy in the future. This may provide feedstock supply problems in the future if the UK was to target the production of advanced biofuels from wastes. Could some of the restrictions of the waste hierarchy be rethought so the prioritisation of specific waste streams for the production biofuels would be regarded with equivalency with other 'reuse' waste management activities?

There has been a long standing disconnect models and reality, in the levels of energy crops and biomass resources that the UK could grow for the bioenergy sector. Historically there has been problems in convincing land owners and managers to produce resource for energy rather than for food. Many of those that have ventured into energy crop production have also had mixed experiences. A new UK energy crop strategy and potential support policies should be considered to incentivise production for the bioenergy sector. The current rethinking of the Common Agriculture Policy could provide a mechanism to restart this process?

Many stakeholders and actors that should/ could be central to bioenergy schemes are simply not interested within energy. For example: the waste management sector's primary business is not the generation of energy or biofuels to decarbonise the UK, and; the majority of farmers primary businesses are to produce livestock or food crops, not to manage agricultural wastes and residues to provide alternative feedstock for bioenergy. However if the UK bioenergy sector is to develop using UK biomass resource, each of these actors will need to be engaged. A challenge for policy makers is to develop a strong formula of incentives and requirements that could stimulate the growth of feedstock supply chains and new markets.

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