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Increasing biomass resource availability through supply chain analysis

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ABSTRACT

Increased inclusion of biomass in energy strategies all over the world means that greater mobilisation of biomass resources will be required to meet demand. Strategies of many EU countries assume the future use of non-EU sourced biomass. An increasing number of studies call for the UK to consider alternative options, principally to better utilise indigenous resources. This research identifies the indigenous biomass resources that demonstrate the greatest promise for the UK bioenergy sector and evaluates the extent that different supply chain drivers influence resource availability.

The analysis finds that the UK's resources with greatest primary bioenergy potential are household wastes (>115 TWh by 2050), energy crops (>100 TWh by 2050) and agricultural residues (>80 TWh by 2050). The availability of biomass waste resources was found to demonstrate great promise for the bioenergy sector, although are highly susceptible to influences, most notably by the focus of adopted waste management strategies. Biomass residue resources were found to be the resource category least susceptible to influence, with relatively high near-term availability that is forecast to increase – therefore representing a potentially robust resource for the bioenergy sector. The near-term availability of UK energy crops was found to be much less significant compared to other resource categories. Energy crops represent long-term potential for the bioenergy sector, although achieving higher limits of availability will be dependent on the successful management of key influencing drivers. The research highlights that the availability of indigenous resources is largely influenced by a few key drivers, this contradicting areas of consensus of current UK bioenergy policy.

1. Introduction

The UK energy sector is facing it's greatest challenges for at least a generation. The sector is expected to renew its energy generation portfolio, whilst providing secure, reliable, affordable and low carbon energy to its customers [1]. Energy from biomass provides options for the energy sector that can provide parts of the solution to each of these challenges.

Despite some concerns over the extent of biofuels deployment, bioenergy is key to many European energy strategies [2]; the European Commission estimates that energy

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from biomass may contribute up to two-thirds of the EU's 2020 target for 20% renewable energy contribution [3]. The UK's Renewable Energy Strategy also confirms that energy from biomass will significantly contribute towards the UK's energy portfolio [4].

Inclusion of energy from biomass pathways in both national and global energy strategies [5] means that increased mobilisation of biomass resource will be required to meet demand. The energy strategies of many EU countries currently assume the extensive use of non-EU sourced biomass [6], which will increase competition for suitable feedstocks [7].

The UK faces urgent choices regarding the future direction of its bioenergy sector. If current plans mature the sector will be increasingly dominated by large scale biopower co-firing systems that will lock the UK into indigenous deficits of the feedstocks required to keep these plants running [8,9]. There are an increasing number of studies and calls [9–13] for the UK to consider alternative biomass options, principally to make better use of the indigenous resources available. Welfle et al. [9] showed, through the development of a series of UK biomass resource scenarios, that the UK could potentially deliver 22% of its primary energy demand in 2050 through indigenously grown biomass and energy crops, 6.5% through the utilisation of indigenous residue resources from ongoing activities and a further 15.4% from waste resources.

The UK has many potential sources of biomass suitable for energy options. If indigenous resources are to be increasingly utilised, it is important that a greater understanding is achieved, of how different influencing drivers determine the extent that biomass resources become available to the bioenergy sector. Assessing the availability of any given resource being a matter of evaluating how much it is realistically, environmentally and economically viable to be made available to the energy market [14]. Some of these key drivers can be categorised as follows [15,16]:

- Policy Drivers – energy and environmental themed policies are particularly important in determining a secure long-term energy strategy. Waste, agricultural and forestry policies have great influence in determining the potential availability of specific resources.
- Market Drivers – biomass is a relatively immature market in the UK. The level of understanding of the UK biomass resource markets, determines the levels of uncertainty and ultimately the likelihood of commitments to long term bioenergy contracts.
- Technical Drivers – are the influences and barriers that may influence the actually processes of energy generation. These may include issues such as the availability of fuel standards or the ability to integrate biomass resources with the existing fossil fuel dominated network.
- Infrastructure Drivers – influences relating to the performance of all facilities required for the bioenergy sector to operate, including the, harvesting, collection, storage and transport of feedstocks.

The aims of this Paper are to identify and evaluate the most significant drivers within supply chains that influence the availability of UK indigenous biomass resources for potential utilisation by the bioenergy sector.

The objective is to inform the developers of bioenergy strategy and policy, and the wider bioenergy sector of opportunities to increase biomass resource availability. This is enabled through: highlighting specific indigenous resources that represent robust and continuous options for the bioenergy sector; identifying specific supply chain drivers that are found to command the greatest influence in determining the availability of biomass resources; identification of the resources whose availabilities are found to be most and least susceptible to variances within supply chains; and highlighting areas where policy measures should potentially focus in order to maximise the availability of indigenous resource.

Although this research is focused on the UK, the analysis is also applicable to similar case studies where a greater understanding of indigenous biomass availability is sought.

The research analysis is undertaking utilising a Biomass Resource Model (BRM), developed to simulate the whole system dynamics of biomass supply chains. The BRM brings together and allows the calibration of a wide range of drivers and variables that collectively determine the potential indigenous resource availability to 2050. Within this research the BRM is utilised in undertaking a sensitivity analysis to evaluate the influence of how supply chain drivers influences the availability of different categories of biomass.

2. Methodology

The following section introduces and discusses the analysis methodologies applied within this Paper. This includes an overview of the methodology developed within the BRM, and also that for measuring the extent that different supply drivers influence indigenous resource availability.

2.1. *The Biomass Resource Model*

The Biomass Resource Model is a resource focused modelling tool that enables the bottom up analysis of the practical potential of indigenous biomass resources, in this case within the UK. The drivers that control the BRM collectively reflect the variances and dynamics that influence biomass supply chains. Calibration of these drivers within the BRM allows the generation of realistic resource availability forecasts up to 2050. These drivers are discussed further and listed in Section 3 of this Paper.

A summary of the BRM's high level design is shown in Fig. 1. This highlights that the BRM's analysis methodology progresses in three distinct stages as described below. A greater depth discussion of the BRM's methodologies including an overview of the key research influences are described by Welfle et al. [9,17].

2.1.1. *BRM analysis stage one: land use & availability analysis*

Analysis stage one evaluates the area of UK land utilised to meet various demands, including; food production, further urban development and forestry to 2050. The remaining UK land area potentially suitable for crop production is then analysed to determine the potential availability for biomass and energy crop growth dedicated for the bioenergy sector.

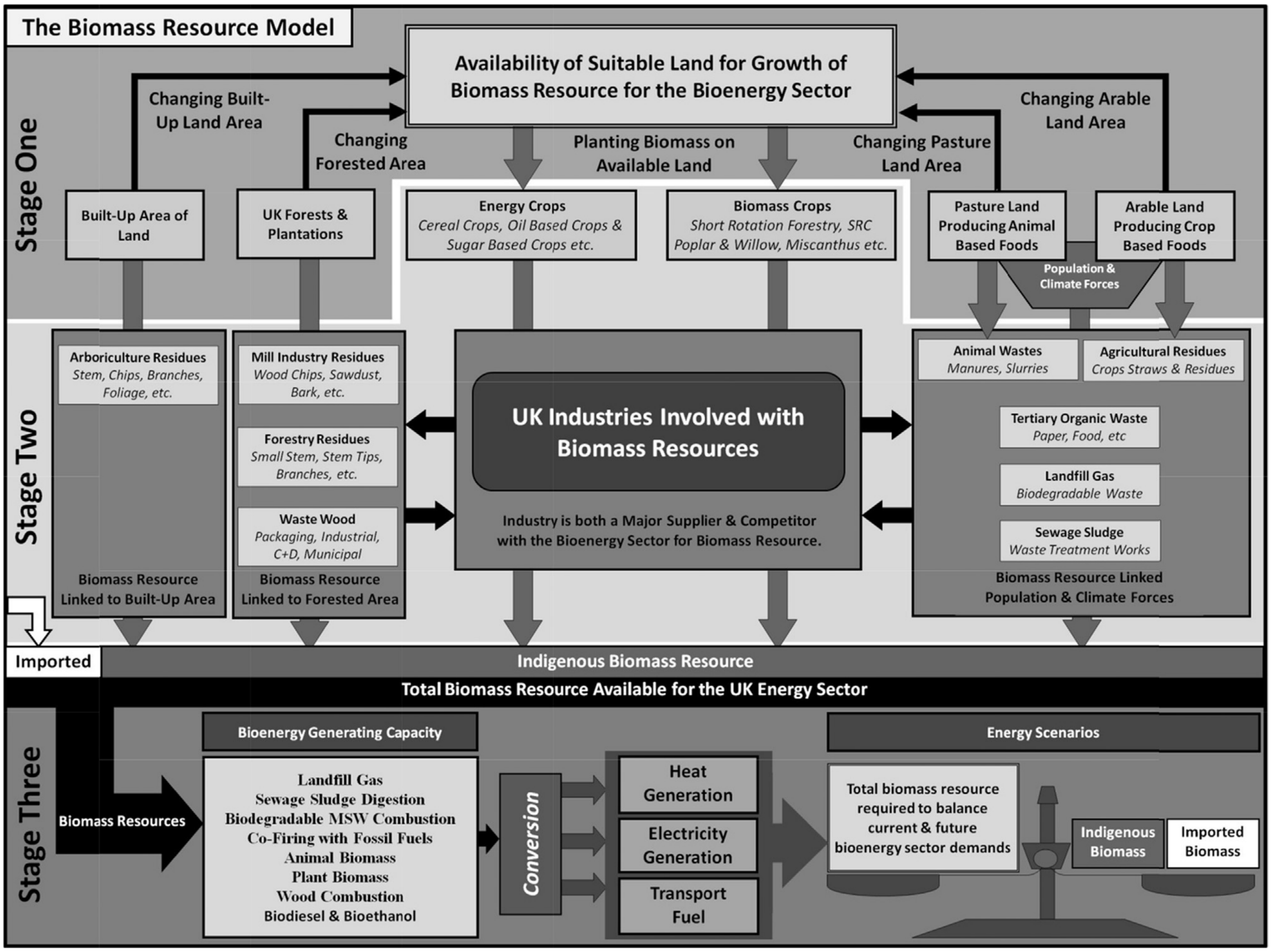

Fig. 1 – The Biomass Resource Model methodology architecture.

2.1.2. BRM analysis stage two: biomass resource availability

The second analysis stage quantifies and forecasts the extent, availability and competing markets for different biomass resources indigenous to the UK. This takes into consideration factors such as the potential for resource collection/harvest, changes in the levels of arisings linked to industrial activity and agricultural residue utilisation. The biomass categories and specific resources analysed within the BRM to reflect the range of UK resources are shown in Table 1. These also represent the biomass categories analysed within this paper.

2.1.3. BRM analysis stage three: indigenous bioenergy potential

The third analysis stage calculates the bioenergy potential of the specific resource quantities calculated within stage two. The range of pre-treatment and energy conversion pathways applicable to different types of biomass are considered. Resource bioenergy potentials are calculated taking account of the resource and energy efficiencies reflective of each bioenergy generation pathway. Once the energy potentials of the available resources have been calculated, these can then be compared against respective renewable energy and bioenergy targets.

In summary the key features of the BRM important to this analysis are the ability to investigate the different supply chain drivers that influence biomass resource availability. Also to evaluate food–fuel interfaces by simultaneously considering the land requirements for food production, biomass production and other uses.

2.2. *Developing a methodology for analysing influences to biomass resource availability*

This section describes the methodology developed for analysing the extent that different drivers influence resource availability. The aim was to undertake an assessment of the maximum practical availability of different indigenous resources to 2050, determine the drivers that most influence resource availability, evaluate the 'availability robustness' of each resource, and identify any notable trends through time.

2.2.1. Developing a baseline

For each of the drivers discussed in Section 3 that control the BRM, a literature review was carried out to analyse how these currently stand in the UK, and to develop an idea of how these may change to 2050. A database was produced that collated

Table 1 – Summary of the analysed biomass Categories & specific resources.

Categories	Biomass resources
Grown Resource *from UK Land*	Energy crops (food species) Cereal crops, oil crops, sugar crops Biomass crops (non-food species) Grasses, short rotation forestry & coppices, other forestry
Residues Resource *from UK Forestry, Industries & Processes*	Forestry residues Crop residues Straws Animal residues Manures & slurries Arboriculture arisings Industry residues Sawmill, pulpmill & industry residues
Waste Resource *from UK Industries & Processes*	Waste wood Packaging, industrial, construction, demolition, municipal Tertiary organic waste Household, commercial, industrial papers, cardboards, textiles, foods, organic & kitchen, garden etc. Sewage – waste treatment

the range of values that literature and studies forecast for these. This database was then analysed to develop a series of average or mean values for each of the drivers to 2050. These values therefore represent a 'literature informed' mean or 'baseline scenario' of how the UK's biomass supply chains may function to 2050. Calibrating the BRM to reflect this baseline enabled an evaluation of the 'average' availability and bioenergy potential of each indigenous resource to 2050. Identifying which resources may be most abundant, and which resources may provide the greatest bioenergy potential being fundamental to this analysis.

2.2.2. *Evaluating how different drivers influence biomass resource availability*

The key element of the Paper's analysis is evaluating the extent that each supply chain driver influences resource availability. A sensitivity analysis methodology was developed so that the influence of each driver could be analysed in isolation of the others. This was achieved through calibrating the BRM to reflect the baseline scenario (discussed in Section 2.2.1). The BRM was then progressively run to reflect the performance range of variances forecast by literature for each individual driver, whilst keeping all the other drivers set at the baseline. Undertaking this methodology for all drivers allowed an assessment to the extent that each influenced the availability of different biomass resource to 2050.

3. Drivers influencing biomass availability

This next section introduces and provides further context to the supply chain drivers that make up the BRM. It also provides a review of selected literature and discussions for how they are deemed to influence the availability of different biomass resources in the UK.

All biomass resource models and assessments revolve around analysing the influence of different drivers. As such the range of drivers listed within literature that are identified as being influential of biomass resource availability is extremely broad. Table 2 presents an overview of many of these and highlights the capabilities and limitations of the BRM in analysing each.

From this list, a series of key supply chain drivers are identified from literature and form the basis of analysis within the BRM and this research. The drivers analysed within this research therefore represent a non-exhaustive reflection of all the drivers that may influence biomass resource within supply chains. These BRM drivers are listed and categorised within Table 3, and their respective influences on biomass resource availability are discussed below.

3.1. *UK development drivers*

3.1.1. *Population change*

Population growth is the fundamental influence for all long term outlooks relating to food and agriculture [30]. The expected large increases in global food demand 2030–2050 are based on forecasts of increasing population [31]. Food and agricultural systems are closely linked to many biomass resource supply chains, therefore population is a driver with likely influence on biomass availability.

Within the BRM population forecasts reflect the United Nations Population Division's forecast variants for the UK [32].

3.1.2. *Built-up land area*

Urbanisation is a further driver that influences food and agriculture systems [33]. Changes in the extent of built-up land area directly influence the potential availability of biomass through reducing the area of land that could otherwise be dedicated for biomass production.

The BRM utilises forecasts of current and future built-up land areas for the UK, as developed within the MOSUS Project (Modelling Opportunities And Limits For Restructuring Europe Towards Sustainability) [34].

3.2. *Food production system drivers*

3.2.1. *Crop and agriculture productivity*

The productivity of land and agricultural yields are important drivers that directly influence the production of biomass. Where crop yields can be increased, agricultural land may be freed for growth of biomass and energy crops [9]. Also where biomass and energy crop yields can be enhanced, more resource can be produced from the land available.

Improvements and variances in food and crop systems productivity result from the collective influence of a range of manageable and external inputs. The UK has great strength in crop science, including increasing understanding of responses to global climate change [35]. Mueller et al. [36] suggest that the 'yield gap' – the difference between attainable & actual yields, will continue to be reduced. Other forecasts suggest that yield increases of 70% by 2050 are possible for most crops through improved nutrient management, irrigation and productivity techniques [36,37].

Table 2 – Summary of supply chain drivers that influence biomass resource availability.

Categories	Supply chain drivers	References	BRM analysis capability
Economic & Development Drivers	▪ Population change	[18–25]	✔
	▪ Resource import/export	[18,23]	✔
	▪ Economic & technical development	[20,26]	–
	▪ Industry productivity	[20,23,26]	✔
	▪ Gross domestic product	[19,24,25]	–
	▪ Rural economy development	[27,28]	X
Infrastructure Targets	▪ Energy system structure	[23,27–29]	✔
	▪ Energy generation plant	[27,28]	✔
	▪ Supply chain development	[27,28]	✔
Physical & Climate Drivers	▪ Land use change	[20,22–25]	✔
	▪ Water availability	[21,25]	X
	▪ Climate change	[18,20,21,25]	–
	▪ Flood protection land requirements	[18]	X
	▪ Nature conservation land requirements	[18,21]	–
	▪ Soil degradation	[18,21]	X
Food Drivers	▪ Per-capita food demand & consumption	[18,19,21]	✔
	▪ Calorie consumption	[19]	X
	▪ Diet change	[19]	X
	▪ Agriculture productivity yields	[18,19,21,22]	✔
Resource Mobilisation Technical Drivers	▪ Technological advances	[22–26,29]	✔
	▪ Forest system productivity	[22–26,29]	✔
	▪ Industry & process residue generation	[22–26,29]	✔
	▪ Forestry residues collection	[22–26,29]	✔
Resource Demand Drivers	▪ Resource use by industry	[18,19,22,24–26,29]	✔
	▪ Demand for round wood	[19,22,24,25,29]	✔
	▪ Demand for wood fuel	[22,24–26,29]	✔
	▪ Demand for other resources	[19,22,24,25,29]	✔
Policy Drivers	▪ Greenhouse gas emission targets	[23,25,27,29]	–
	▪ Energy efficiency & consumption targets	[23–25,27,29]	✔
	▪ Renewable & bioenergy targets	[23–25,27,29]	✔
	▪ Fuel security drivers	[23,27]	✔
	▪ Support policies & mechanisms	[23–25,27–29]	X

Key	✔	The BRM allows the analysis of these drivers in terms of their influence on biomass resource availability and bioenergy potential.
	–	The BRM allows the analysis of partial aspects of these drivers. Or can provide an indirect evaluation the drivers influence on biomass resource availability and bioenergy potential.
	X	The BRM current design and outputs do not allow the analysis of these drivers.

Haberl et al. [30] found that Western European yields could experience further mean increases of >16% from CO_2 fertilisation by 2050, resulting from climate change forces (>2% without CO_2 fertilisation).

Although whilst the main northern hemisphere producers may experience favourable conditions from climate change in the next 40 years, regions where rising food demand is most pronounced will likely see production hindered. This may lead to a greater number of countries relying on fewer high latitude producers – increasing vulnerability to extreme weather events in these regions [38].

Current and forecast crop and agricultural yields analysed within the BRM reflects those documented in a wide range of studies and literature, including predicted climate change impacts [15,16,38–44].

3.2.2. *Food waste generation*

Food waste influences the availability of biomass resource in multiple ways. Food waste itself is a plausible resource for bioenergy generation pathways. At the same time food waste is a factor that reduces the supply chain efficiency – the greater waste from the system, the more land is required to produce food commodity quantities to meet demand.

Research estimates that 25–50% of food produced is wasted along the supply chain [45–47]. 50% of the UK's food waste comes from households, where at some point at least 60% of this waste could have been consumed [48]. The European Commission is targeting a 50% reduction in food wastes by 2020 [49], and the UK Government Office for Science suggests that halving food waste by 2050 may be equivalent to 25% of current productivity [50,51].

Table 3 – Summary of key supply chain drivers analysed within the BRM.

Category	Drivers
UK Development Drivers	1) Population change 2) Changes in built-up land area
Food Production System Drivers	3) Crop & agriculture productivity 4) Food waste generation 5) Food commodity imports 6) Food commodity exports 7) Utilisation of agricultural wastes & residues
Forestry & Wood-based Industry Drivers	8) Forestry expansion & productivity 9) Wood-based industry productivity 10) Imports of forestry product 11) Exports of forestry product
Biomass Residue & Waste Utilisation Drivers	12) Utilisation of forestry residues 13) Utilisation of industrial residues 14) Utilisation of arboriculture arisings 15) Waste generation trends 16) Waste management strategies
Biomass & Energy Crop Strategy Drivers	17) Land dedicated for energy crop growth

These waste reduction targets are considered in the analysis, through the BRM utilising a series of forecasts [39,50–53], to quantify UK food waste trends.

3.2.3. *Food commodity imports and exports*

Food commodity import and export trends are drivers that can influence biomass availability, as they contribute towards determining the area of UK land that is required to produce the food quantities to meet demand. Any land dedicated for food production is therefore unavailable for biomass or energy crop growth.

The majority of the UK's imports come from the EU, with the Common Agricultural Policy and EU Directives strongly influencing the shape of the UK food system [54]. The UK currently produces about half of the food it consumes, and is ~60% 'self-sufficient' [55]. The UK Government's stance is that it "sees no economic or environmental rationale for Government to set targets to raise UK output of particular food products in step with changes in global food demand" [54].

The analysis takes into consideration these stances of future food import/export trends, the BRM utilising data from a series of studies [39,52,56] to reflect the UK's path.

3.2.4. *Utilisation of agricultural wastes and residues*

Agricultural wastes and residues reflect a resource category with sizeable potential for the bioenergy sector [10]. Welfle et al. [9] found that this category of biomass resource could deliver up to 80 TWh of bioenergy by 2050.

The key drivers determining the availability of this resource for the bioenergy sector are the extent to which it is harvested/collected and the competition for the resource. The BRM analysis reflects the wide range of research and studies that forecast the extent and timeframes to which these resources could be utilised for energy generation: 20%–100% of total resource could be utilised, with typically half of this being available for the energy sector [57–65]. The UK Department for Food & Rural Affairs (DEFRA) provides sustainability guidance on the extent that agricultural residues should be returned to the soil to protect and enhance soil and biodiversity (10% Lower Limit, 50% Higher Limit) [66].

3.3. *Forestry and wood-based industry drivers*

3.3.1. *Forestry expansion and productivity*

The extent and productivity of forestry systems directly influences the availability of resources for the bioenergy sector. Forests provide energy generation opportunities either through specifically harvested resources, or via the collection of residues. Forests also provide indirect opportunities for the bioenergy sector through supplying resource to wood-based industries, that in turn produce wastes and residues that can be utilised by the bioenergy sector.

The BRM utilises the UK Forestry Commission's expansion and productivity forecasts [67–74].

3.3.2. *Wood-based industry productivity*

The ongoing activities of wood-based industries produce wastes and residues that provide an opportunity for the bioenergy sector. At the same time wood-based industries require raw forestry products, of which it competes directly with the bioenergy sector for the lower grades of resource.

The BRM utilises existing data [56,75,76] and forecasts [76] that predict the trends and directions that UK wood industries may take.

3.3.3. *Imports and exports of forestry product*

Forestry product import and export trends can influence the availability of biomass resource through determining the extent that the indigenous forestry systems are utilised. Where imports are increased and exports are reduced, there will be less strain on indigenous forestry systems to produce the wood resource required to meet demand. This may in turn provide increased opportunities for the bioenergy sector. Likewise reduced imports and increased exports would have the counter influence, putting greater strain on indigenous forests.

The BRM again utilises existing data [56,75,76] and forecasts [76] that predict the trends and directions that UK forestry products imports/exports may follow.

3.4. *Biomass residue & waste utilisation drivers*

3.4.1. *Utilisation of forestry residues*

Forestry residues represent an opportunity for the bioenergy sector that is currently un-utilised in the UK [58]. The availability extent of this resource is dependent on the proportion extracted from forestry systems and the proportions left in-situ to maintain the health of the habitat.

The BRM reflects the full range of residue extraction levels recommended by research and studies [29,58,77–79], from 10% to as much as 100% by 2020 [58].

Forest certification standards set by the Forestry Stewardship Commission (FSC Criterion 5.3 & 6.3), Ministerial Conference on the Protection of Forests in Europe (MCPFE

Criterion 2 & 3) and Programme for the Endorsement of Forest Certification (PEFC Criterion 4) all provide details for the minimisation of on-site harvesting and residue processing, maintenance of ecosystem health and function and protection of biodiversity [78].

3.4.2. *Utilisation of industrial residues*

Biomass residues from ongoing industrial processes represent a potential opportunity for the bioenergy sector [9]. The key drivers influencing the availability of this resource category are the extent to which it can be collected/processed, and productivity of the UK wood-based industry.

The BRM utilises data that reflects current and forecast productivity trends for the UK's wood-based industries [56,75,76], and also forecasts of potential industry residue utilisation for energy [58,80,81].

3.4.3. *Utilisation of arboricultural arisings*

UK Local Authorities and tree surgeons produce thousands of tonnes of arboriculture arisings. The majority of this is currently land-filled, stored for landscaping applications or burnt onsite. Although with correct processing, handling, grading and storing, these residues provide an opportunity for the bioenergy sector [82]. The key drivers determining resource availability are the extent to which the resource is harvested/collected and the competition for the resource.

The BRM utilises forecasts from a series of research and studies that forecast that up to 100% of arboriculture arising could be utilised by the bioenergy sector [58,76,77].

3.4.4. *Waste generation trends & waste management strategies*

The potential availability of waste resources for the bioenergy sector is influenced by two key drivers: The amount of waste being generated, and the strategy implemented for how the waste is managed. Welfle et al. [9] found that there is both potentially high variability and availability of this resource, forecasts ranging from 1.8 to 130.7 Mt by 2050 dependent on the waste generation and management strategies.

The BRM utilises a series of data sets [48,61,83–86] that reflect the UK's current waste system, and applies DEFRA forecast scenarios [61,85] to analyse how the implementation of alternative waste strategies may influence potential availability for the bioenergy sector.

3.5. *Biomass & energy crop strategy drivers*

3.5.1. *Land dedicated for energy crop growth*

The area of land dedicated for biomass and energy crop growth is a fundamental driver in determining the potential availability of grown resource. Energy crops have an important role to play in helping to achieve the UK's renewable energy targets [66,87]. The UK Department for Energy & Climate Change (DECC) estimate that for the UK to meet these targets, approximately 3500 km^2 of land needs to be dedicated for energy crops – a large increase from the current 250 km^2 utilised. Although 3500 km^2 seems large it currently reflects <2% of UK agricultural land – an area that could be easily realised through farmers utilising un-used/marginal lands [66,87].

A large number of reports and studies estimate that varying amounts of the UK's >170,000 km^2 of agriculture land could be dedicated for biomass resource growth [88,89]. Potential land dedication estimates range from 3,500 to 10,000 km^2 [15,16,35,59,90–93], whilst the theoretical maximum available land for short rotation coppices and Miscanthus without impacting food systems have been estimated to be between 9,300 and 36,300 km^2 [66,87].

The European Environment Agency (EEA) also reported that between 8,000 and 34,000 km^2 of land could be released in the UK by 2030 by reform of the Common Agricultural Policy [92]. Fischer et al. [65] estimating that half of this released land would be former grassland.

The BRM takes into consideration these estimates when determining the proportion of free land to be dedicated for biomass resource growth.

4. Results–UK biomass availability & supply chain influences

The following section provides the results, presented in the form of figures and Supplementary tables. These document the availability and bioenergy potential of different biomass resources to 2050. They also outline the results of the sensitivity analysis that evaluates the extent that different supply chain drivers influence biomass resource availability.

4.1. *The potential availability of UK biomass for the bioenergy sector*

Fig. 2 documents the results of the analysis undertaken to determine the maximum availability of each category of UK biomass (Table 1), when the BRM is calibrated to reflect the literature informed baseline scenario to 2050. The resources availabilities in the research are presented in million tonnes (Mt) of dry basis biomass resource. This analysis reflects the range of forecast supply chain characteristics for each driver (Table 3) as informed by literature. The trends represented document the resource potential if the most influential drivers are managed so that maximum levels of resource availability are achieved. Through highlighting the range in resource availability between 2015 and 2050, Fig. 2 also provides an indication of the extent of actions that may be required to achieve the higher level forecasts.

- UK 'Grown Resources' are shown to have relatively low availability in 2015 (>1.9 Mt), but this potentially increases by >1503% by 2050 (to >31 Mt).
- UK 'Residue Resources' in 2015 are shown to have availability of >11.7 Mt, potentially increasing by >152% by 2050 (to >29.7 Mt).
- UK 'Waste Resources' in 2015 are shown to have availability of >15.2 Mt, potentially increasing by >491% by 2050 (to >90.0 Mt).

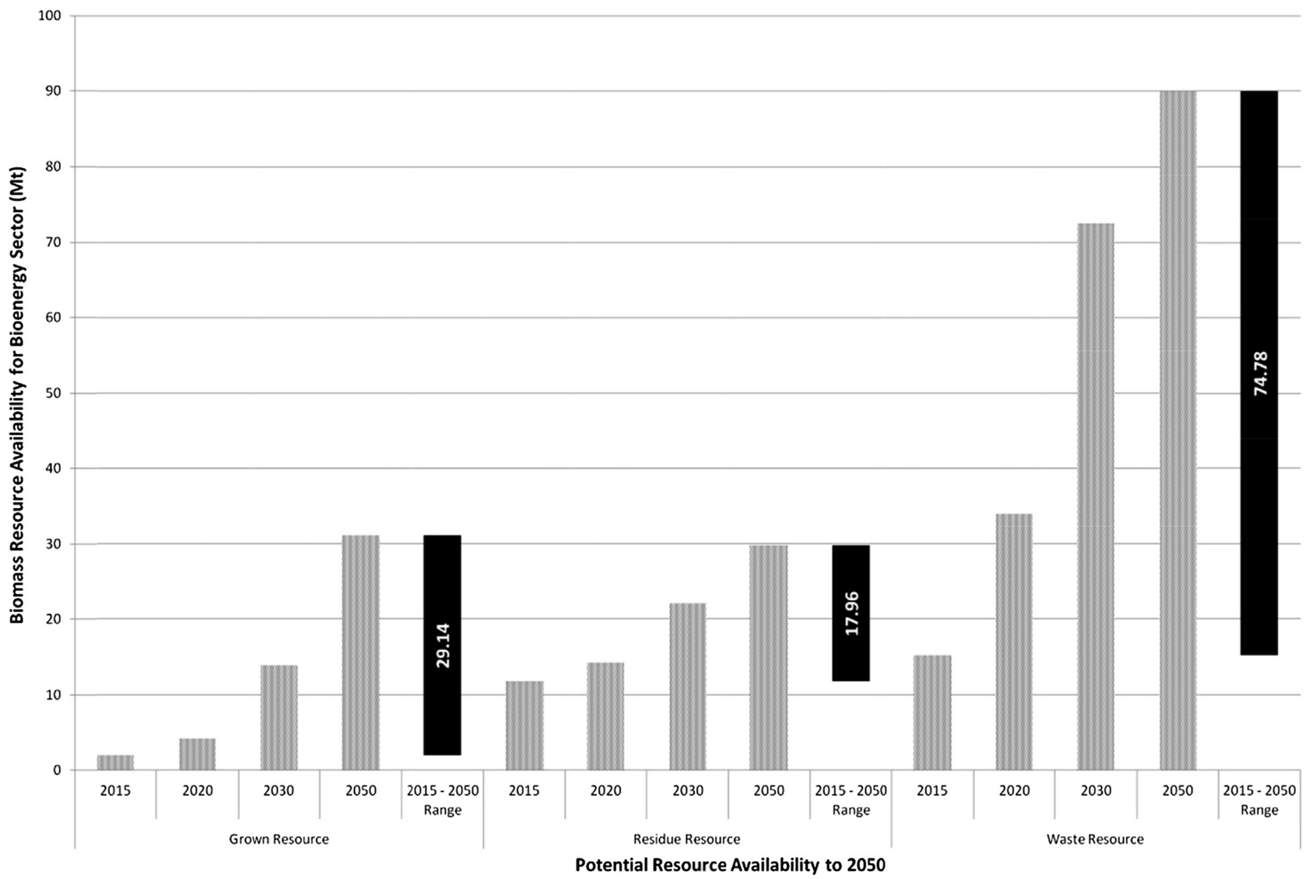

Fig. 2 – The potential availability of biomass resources for the bioenergy sector.

4.2. *Analysing the influence of supply chain drivers on biomass resource availability*

Figs. 3–5 present radar graphs that document the results of the supply chain driver sensitivity analyses. These show the extent that the different drivers influence resource availability, with each numbered spoke of the radar graphs reflecting the corresponding analysis for each of the numbered supply chain drivers (Table 3). The figures highlight the maximum availability of the each respective category of biomass resource to 2050 when the characteristics of each driver reflect the ranges informed by literature.

- Fig. 3 highlights that the key supply chain drivers influencing the availability of UK 'Grown Biomass Resources' are 'Population Change' (Driver 1), 'Crop & Agriculture Productivity' (Driver 3), 'Forestry Expansion & Productivity' (Driver 8) and 'Land Dedicated for Energy Crop Growth' (Driver 17).
- Fig. 4 highlights that the key supply chain drivers influencing the availability of UK 'Residue Biomass Resources' are 'Population Change' (Driver 1), 'Utilisation of Agricultural Wastes & Residues' (Driver 7) and the 'Forestry Expansion & Productivity' (Driver 8).
- Fig. 5 highlights that the key supply chain drivers influencing the availability of UK 'Waste Biomass Resources' are 'Waste Generation Trends' (Driver 15), and most notably by 'Waste Management Strategies' (Driver 16).

4.3. *UK resources demonstrating the greatest potential for the bioenergy sector*

Further analysis was carried out to determine which specific biomass resources may demonstrate the greatest potential for the bioenergy sector. The data from this analysis is documented within Appendix A1. This highlights the availability and bioenergy potential of different biomass resources, when supply chain characteristics reflect the literature informed baseline scenario to 2050. Further details describing the methodology for calculating bioenergy potential, including the applied conversion and pre-treatment pathways and efficiencies can be found in Welfle et al. [9,17]. From this analysis the following UK resources are shown to demonstrate particular availability for the bioenergy sector:

- UK 'Biomass & Energy Crops' from the Grown Resources Category (>31.2 Mt resource, equivalent to >104 TWh by 2050),
- UK 'Agricultural Residues' from the Residue Resources Category (>26.2 Mt resource, equivalent to >83 TWh by 2050),
- UK 'Household Wastes' from the Waste Resources Category (>40.7 Mt resource, equivalent to >117 TWh by 2050),
- UK 'Other Wastes' from the Waste Resources Category (>32.7 Mt resource, equivalent to >75 TWh by 2050).

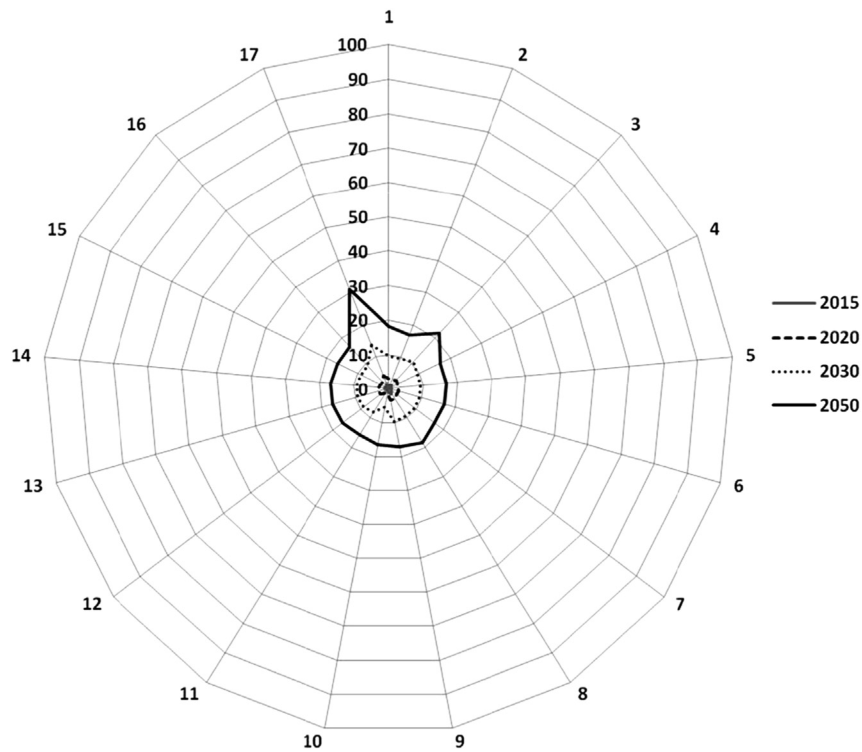

Fig. 3 – Analysis of drivers influencing the availability of grown biomass resources (Mt).

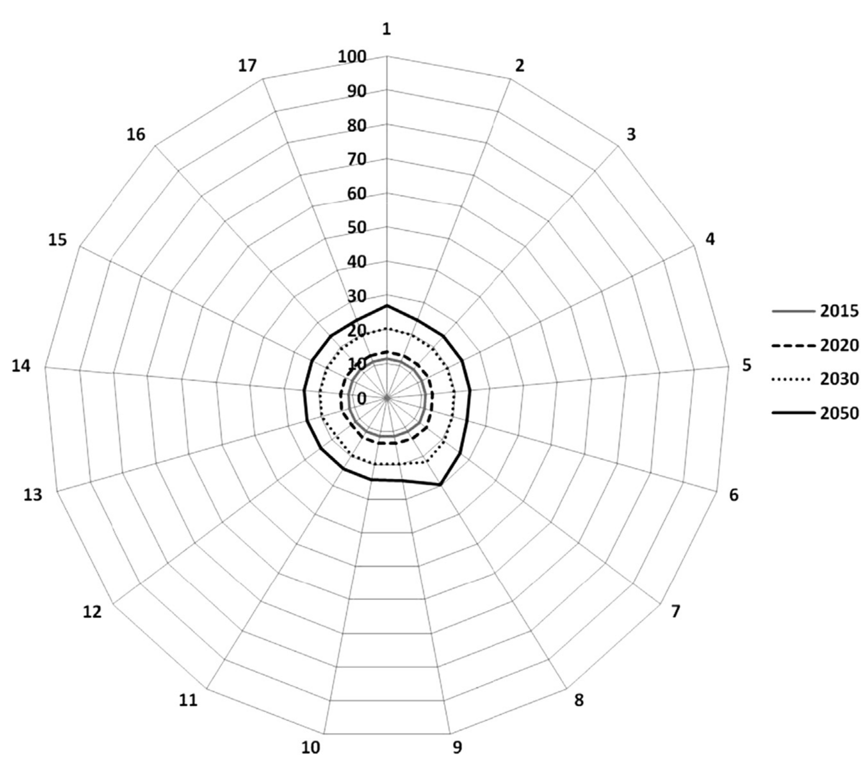

Fig. 4 – Analysis of drivers influencing the availability of residue biomass resources (Mt).

4.4. *Supply chain drivers with the greatest influence on biomass resource availability*

This section provides further discussion of the results of the sensitivity analysis. Evaluating the extent that the different drivers (Table 2) influence the biomass resources found to demonstrate the greatest potential availability in the UK: 'Biomass & Energy Crops', 'Agricultural Residues' and 'Household Wastes'. 'Other Wastes' are excluded from this further analysis, as this resource category represents a collection of all other wastes that are not classified as either 'Household' or 'Food or Organic' (Table 1). The data reflecting this analysis is included in Appendix A2.

4.4.1. *Drivers influencing the availability of UK biomass & energy crop resources*

Three drivers are shown to have significant influence in determining the availability of Biomass & Energy Crop resources. 'Population Change' (Driver 1) and 'Crop & Agricultural Productivity' (Driver 3) demonstrate marginal influence in determining the potential availability of this resource. However the 'Land Dedicated for Energy Crop Growth' (Driver 17) is shown to be the key influence. The results show that if the upper limits of land are made available for biomass and energy crop growth (Driver 17) as forecast by literature, the availability of this resource may be >87% greater in 2050 compared to scenarios where lower limits of land are utilised.

4.4.2. *Drivers influencing the availability of UK agricultural residue resources*

The availability of agricultural residue resources is demonstrated to be influenced by 'Population Change' (Driver 1) and the 'Utilisation of Agricultural Residues' (Driver 7). The analysis shows that realisation of higher population forecasts (Driver 1) may potentially increase the availability of this resource in 2050 by >12.6%. Whilst realising upper limits of agricultural residue collection/harvests and utilisation (Driver 7) as forecast by literature, may result in >11.6% greater resource availability by 2050.

4.4.3. *Drivers influencing the availability of UK household waste resources*

The potential availability of household waste resources for the bioenergy sector is demonstrated to be influenced by both 'Waste Generation Trends' (Driver 15) and 'Waste Management Strategies' (Driver 16). Forecast trends of waste generation (Driver 15) are shown to have a minor influence on the availability of this resource. In contrast the results confirm that the waste management strategy adopted (Driver 16) represents a major influence. A waste management strategy complementing the bioenergy sector as forecast by literature may increase the availability of this resource: >318% by 2020, >476% by 2030 and >500% by 2050, compared to forecasts where waste is less utilised by the bioenergy sector.

5. Discussion–maximising the potential of UK biomass

This next section provides a discussion of the results highlighted within Section 4. Identifying which of the UK's indigenous biomass resources may provide the best opportunities for the bioenergy sector, and how these relate to current UK policy.

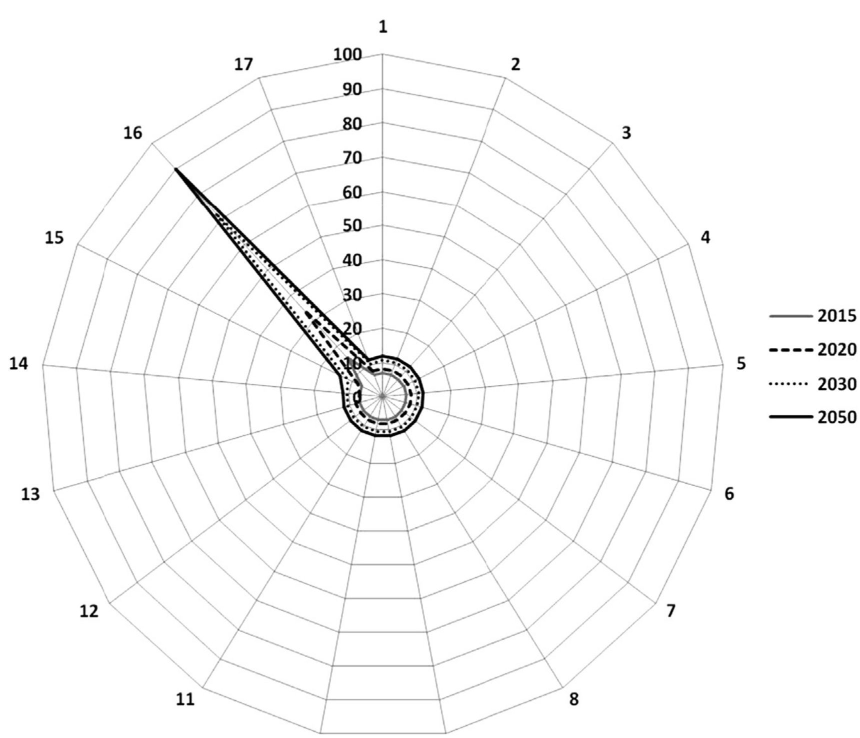

Fig. 5 – Analysis of drivers influencing the availability of waste biomass resources (Mt).

5.1. The potential of UK biomass resources for the bioenergy sector to 2050

For UK resources to substantially contribute towards meeting bioenergy targets, it is important to highlight which of the broad range of resources may provide the greatest potential and opportunities for the bioenergy sector.

The results presented within Fig. 2 represent three levels of analysis: the maximum potential availability of different categories of UK biomass; the extent that each resource category may be available in the near-term (by 2015); and also the range in potential resource increment between 2015 and 2050. The maximum availability potential is important, as it identifies how much resource could be mobilised for the bioenergy sector if influencing supply chain drivers are effectively managed. The near-term forecast and 2015–2050 increment ranges are important as they provide an insight into how much resource may be available without extensive further actions and management of drivers, and likewise provide an indication of the effort that may be required to achieve the higher levels of forecast availability.

Using this premise to evaluate the result for the three analysed biomass categories: Fig. 2 shows that UK 'Grown Biomass Resources' are forecast to have relatively low near-term availability, but large potential by 2050. This suggests that these resources may be highly influenced by supply chain drivers, and substantial effort may be required to manage these in order to increase the resource availability from the low base. Fig. 3 confirms that the availability of land dedicated for the growth of these resources is the key driver requiring appropriate management if higher levels of resource availability are to be realised.

The research highlights that UK agricultural residues represent large resource opportunities for the bioenergy sector. Fig. 2 demonstrates that UK's 'Residue Biomass Resources' are shown to have 'medium' near-term availability compared to the other two resource categories. This increases at a steady rate to 2050 suggesting that residue resources are relatively robust to supply chain influences and less effort may be required to increase residue availability in comparison to the other resources categories. The relatively continuous increment in resource availability demonstrated by the spacing of the analysis time-lines within Fig. 4 also highlights that the availability of residue resources shows robustness to supply chain influences.

Household wastes are also found to represent large resource opportunities for the bioenergy sector. Fig. 2 shows that UK 'Waste Biomass Resources' have near-term availability that exceeds the other two categories and the potential maximum increase in waste resource availability to 2050 is significant. This large increment suggests that waste resources are highly susceptible to supply chain influences, and significant effort may be required to manage these if the higher forecasts of resource availability are to be realised. This is reaffirmed within Fig. 5 where the influence of implemented waste management strategies is shown to be key. This research therefore highlights that in the long-term, wastes may represent resource options with significant potential for the bioenergy sector, albeit reliant on the implementation of complementary waste management strategies.

5.2. Increasing the focus of bioenergy strategies

The UK Bioenergy Strategy aims to maximise the opportunities for improving the availability of all biomass resources through policies aimed at managing a broad range of supply chain drivers [87].

This research has analysed a wide range of supply chain drivers, finding large variances in their influence in determining biomass availability for the bioenergy sector. The research also highlights that particular resources demonstrate significantly greater availability and bioenergy potential than others. Therefore if the contribution of UK resources is to be maximised, the research suggests that bioenergy policies and strategies should become increasingly focused and targeted.

Table 4 summarises the research findings: ranking the UK's biomass resources based on their availability and bioenergy potential; also ranking the analysed supply chain drivers based on their influence in increasing UK biomass availability for the bioenergy sector.

5.3. Potential strategies for increasing UK resource availability for the bioenergy sector

The following section discusses the current UK context, barriers and potential strategies for increasing the availability of the UK's resources in the context of the research findings.

5.3.1. Strategies for increasing the availability of UK resources grown for the bioenergy sector

5.3.1.1. Research outputs. The research identifies 'Crop and Agricultural Productivity' and the area of 'Land Dedicated for Energy Crop Growth' as the drivers that most significantly influence the availability of UK grown biomass resources such as energy crops.

The influence of realising higher limits of crop and agricultural productivity is shown to potentially increase the availability of this resource by >30% by 2050. This is an unsurprising trend, as greater crop yields will also benefit the production of crops dedicated for the energy sector. Although the standout driver with key influence on this resource is utilisation of available land dedicated for growth. Realising maximum levels of available land utilisation demonstrates a potential >87% improvement in resource availability in 2050, compared to conditions with reduced land use. Highlighting that if the UK wants to increase its biomass and energy crop resource, focussing on anything other than increasing land availability is unlikely to deliver the same scale of results.

5.3.1.2. Current UK policy & strategy context. The UK Bioenergy Strategy [87] states that the increased growth of resources on unused or low ecosystem value lands is essential for producing resources for the bioenergy sector. Although the area of available land dedicated to grow these resources is essentially reliant on UK farmers utilising their lands to grow crops for the energy sector. To promote this the UK's primary

Table 4 – Analysis summary ranking UK biomass availability, bioenergy potential & supply chain influences.

Ranking	Influencing drivers	Resource availability & bioenergy potential for bioenergy sector
High Ranking *Drivers & resources with the greatest influence/potential*	▪ Waste management strategies ▪ Land dedicated for energy crop growth	▪ Agricultural residues ▪ Household wastes ▪ Biomass & energy crops ▪ Other wastes
Medium Ranking *Drivers & resources with medium influence/potential*	▪ Crop & agriculture productivity ▪ Population change ▪ Changes in built-up land area ▪ Food waste generation ▪ Utilisation of agricultural wastes & residues ▪ Forestry expansion & productivity ▪ Waste generation trends	▪ Dedicated forestry resources ▪ Forestry residues ▪ Food & organic wastes
Low Ranking *Drivers & resources with the least influence/potential*	▪ Food commodity imports ▪ Food commodity exports ▪ Wood-based industry productivity ▪ Imports of forestry product ▪ Exports of forestry product ▪ Utilisation of forestry residues ▪ Utilisation of industrial residues ▪ Utilisation of arboriculture arisings	▪ Sewage wastes ▪ Industry residues ▪ Arboricultural residues

incentive mechanism to promote farmers to grow biomass and energy crops has been the ‘Energy Crops Scheme’. Although over the lifetime of the scheme widespread dedication of lands to grow biomass and energy crops has not materialised [94]. A summary of key barriers preventing land owner from producing resources for the bioenergy sector are presented in Table 5.

5.3.1.3. *Pathways for increasing resource availability*. The demand for biomass and energy crops is growing fast [95], whilst their production offers environmental and economic benefits much wider than for just the energy sector [96]. Thus developing a policy framework and financial packages especially with respect to the Renewable Heat Incentive, Feed-in-Tariffs and a reworked Energy Crop Scheme are essential to reduce barriers and allow markets to drive progress [91].

The UK's already has good comparative examples of policies and incentives in the form of the Forestry Commission's ‘Woodfuel Strategy’ [97], where a roadmap and framework of targets backed by incentives are increasing the availability and use of woodfuels. There are also many examples of leading incentive schemes currently being applied across the EU to promote the bioenergy sector and incentivise the growth of resources [98]. These provide insights into further potential directions that the Government could go in developing UK policies.

5.3.2. *Strategies for increasing the utilisation of agricultural residues by the bioenergy sector*

5.3.2.1. *Research outputs*. ‘Population Change’ and the ‘Utilisation of Agricultural Residues’ are the two drivers identified by the research as providing the greatest influencing the availability of this resource. These linkages appear to be self evident, higher levels of population growth means that more food will need to be produced, resulting in greater availability of agricultural residues. At the same time the greater extent that agricultural residues are collected/harvested, the greater availability for the bioenergy sector.

However the more valuable analysis highlighted by Fig. 2 and also reflected within Fig. 4, is the near-term and continuous availability of agricultural residues – shown to be relatively constant and robust to major fluctuations caused by supply chain influences. The resource availability in 2015 is also forecast to exceed 10.3 Mt and steadily increase by >109% by 2050. Based on this analysis, agricultural residues should be highlighted and targeted within bioenergy strategies as reliable and robust opportunities for the bioenergy sector.

5.3.2.2. *Current UK policy & strategy policy context*. There are currently comparatively low levels of agricultural residues utilisation by the bioenergy sector in the UK. This trend is reflected in UK farming statistics [99] documenting that: <5% of the UK's livestock focused farms generate renewable energy, and of these <50% utilise manures and slurry feedstocks. Whilst <6% of arable agriculture focused farms generate renewable energy, and of these <45% utilise feedstocks such as straws. The UK Bioenergy Strategy [87] recognises the need to work to improve the economics of respective supply chains and bioenergy pathways, although many barriers remain as summarised in Table 5.

5.3.2.3. *Potential mechanisms for increasing resource availability*. There are many case studies that the UK could consider where agricultural residues are widely utilised by the bioenergy sector. Within Europe, Denmark represents the leading example of straw residue utilisation. Denmark's established harvesting infrastructure and market development is the consequence of targeted policy driven initiatives, such as: mandates requiring that higher prices are paid for energy from straws; collaborations between the bioenergy sector, individual farmer and specialised contractors enabling the shared utilisation of high specification harvesting and processing equipment; and a market structure that provides farmers with enhanced controls over their pricing demands, and standard contracts between produces and generators regardless of resource scale [100].

The utilisation of slurries and manures within anaerobic digestion bioenergy systems from large scale farms or localised farming cooperatives, represents key opportunities for the UK bioenergy sector. Raising awareness [101] and financial support [102] for these systems is key. The UK has an array of existing financial mechanisms and incentives [103,104] designed to promote this sector, although it remains highly undeveloped [105]. Again the UK could learn from successful policy case studies from across the EU, such as the German Renewable Energy Act [102] and related policies [105,106] that reduce the financial barriers of AD development schemes through directing increased financial responsibilities onto grid operators.

The European Common Agricultural Policy (CAP) is also widely identified as potential mechanism for increasing the utilisation of agricultural residues by the bioenergy sector. Potential reform areas being: further guidance of the quantities of resources to be returned to soils; initiatives to support residue supply chains; and the broadening of existing institutional and local partnerships to support the bioenergy sector [107].

5.3.3. *Strategies for increasing the utilisation of household waste resources by the bioenergy sector*

5.3.3.1. *Research outputs*. The research finds that ‘Waste Generation Trends’ and ‘Waste Management Strategies’ are the key drivers determining the availability of household wastes. The analysis highlights that implementation of a waste management strategy that focuses on energy from waste pathways could provide over 40 Mt of household waste resource for the bioenergy sector by 2050. Household wastes therefore representing a substantial opportunity for the bioenergy sector, albeit highly reliant on the development of complementary waste management strategies.

5.3.3.2. *Current UK policy & strategy policy context*. Energy from waste in the UK has historically had a poor image with landfill distribution and early incinerators favoured. However the introduction of landfill diversion targets and the development of new technologies have placed energy from waste back on the UK's agenda. Although the prime focus of the UK's waste management strategies is to reduce and recycle, efficient energy recovery remains an important element of the strategy to both generate energy and reduce land-filled waste volumes [108]. A summary of key barriers preventing the wider utilisation of wastes and growth of the sector are presented in Table 5.

5.3.3.3. *Potential mechanisms for increasing resource availability*. The UK's scope for developing waste management strategies is highly restricted and defined by EU Directives [109]. However when adapting applicable EU Directives into national laws there is room for manoeuvre, with the definitions of wastes in the context of bioenergy being a key variable differing between Member States. Adjusting these categorisation parameters allows varying subsidisation and favourability of energy from waste pathways [109]. Reviewing these key policy variances between Member States presents a series of case studies for the UK to potentially consider if aiming to support the energy from waste sector.

With respect to addressing the large barriers associated with the social opposition to energy from waste technologies, the UK could draw influence from scenarios around the world and specifically other EU Member States, where public opinions are far less hostile. A review undertaken by WMW (2014) [110] found that: educating local populations of benefits, linking arguments to climate change, reassuring communities of air pollutant regulations and providing direct local energy benefits such as cheap district heat can vastly soften opposition. Also being mindful in planning processes that the voices of minority groups opposing energy from waste plant, often overshadow the opinions of the majority [111].

Table 5 – Key barriers to the greater production & utilisation of UK resources by the bioenergy sector.

Biomass resources	Barriers to increasing resource availability for the bioenergy sector
Grown Biomass & Energy Crops [91,94,112]	▪ **Educational** – awareness to incentive schemes, reluctance to move away from producing traditional agricultural crops, and poor understanding of energy crop establishment and management best practice. ▪ **Economic** – cash flow problems between planting and harvests, current margins associated with small scale productions, and the lack of links between biomass producers and markets. ▪ **Legislative** – lack of recognition of certain ‘innovative’ crops by inventive schemes. ▪ **Technical** – specific fuel requirements of bioenergy systems place increased demands on resources produced, and lack of processing infrastructure that would increase the economic viabilities.
Plant Based Agricultural Residues (straws) [100]	▪ **Underdeveloped Markets** – the lack of established supply chains for straw for bioenergy purposes. ▪ **Competing Uses** – straws are extensively used by existing markets with which the bioenergy sector will compete for resource. ▪ **Inaccurate Guidance** – overuse of the resource beyond best practice to maintain soil health can lead to large unnecessary impacts on resource availability. ▪ **Undeveloped Infrastructure** – the inaccessibility and lack of appropriate machinery

(*continued on next page*)

Table 5 – (continued)

Biomass resources	Barriers to increasing resource availability for the bioenergy sector
	and infrastructure for the handling and processing of straw residues. ▪ **Resource Variability** – due to varying climatic conditions and fluctuating harvest yields, the variability in the quantity and quality of straws has large implications for the bioenergy sector that typically requires specific fuel specifications.
Animal Based Agricultural Residues (slurries & manures) [101,113]	▪ **Transportation** – The nature and bioenergy characteristics of slurries and manures makes them impractical, uneconomical and energy inefficient to be transported any great distance. ▪ **Resource Availability** – as a result of UK farming practices, slurry and manure can only typically by collected for a limited number of months, reflecting livestock housing regimes. ▪ **Spatial Constraint** – anaerobic digestion (AD) systems, the most suitable bioenergy systems for the use of manure and slurry resources require physical space. The economics of AD systems are also largely improved through the addition of energy crops feedstocks, which may require additional (potentially large) planting areas that are typically incompatible with the nature of the farms with the large animal based biomass resources. ▪ **Capital Costs** – the capital costs of digesters and associated infrastructure is high and are unlikely to fall significantly in the near-term. ▪ **Collaboration Complexity** – The time and costs associated with developing large community or district systems that pool resources from a number of local sites can be highly complex and costly.
Waste Resources [112,114,115]	▪ **Incentive** – the cost comparison of energy from waste systems compared to landfill represents a strong barrier against the further development of this sector. ▪ **Waste Hierarchy** – the supply of the specific waste feedstocks required by bioenergy systems is restricted by the waste hierarchy and the UK's waste policies primary focus to reduce and recycle. ▪ **Opposition** – social opposition led by local communities and the lobbying of environmental action groups are by far the greatest barrier to the development of the UK energy from waste sector. ▪ **Finances** – the varying definitions of biomass wastes and their respective subsidy regimes can prevent developers from accessing the finances required to grow the sector.

6. Conclusions

A Biomass Resource Model (BRM) was developed reflecting the UK's indigenous biomass supply chains. The drivers controlling the BRM were calibrated to 2050 to analyse current and forecast parameters in reflection of a wide literature review. The analysis focused on the development of a baseline scenario to determine the specific indigenous biomass resources that demonstrate the greatest potential for the UK bioenergy sector. Systematic analysis of the BRM's drivers allowed the evaluation of the extent that they influence indigenous resource availability to 2050. Key policy conclusions for increasing the availability of UK indigenous resource for the bioenergy sector are highlighted below.

- Biomass and Energy Crops, Agricultural Residues and Household Wastes – are identified as the biomass resources that demonstrate the greatest promise for the UK bioenergy sector, in terms of their availability quantity and bioenergy potential.
- Potential and Mobilisation of Grown Biomass Resource – UK grown biomass and energy crop resources have been identified as potentially providing >31 Mt for the bioenergy sector by 2050. The standout driver influencing the availability of these resources was identified as the uptake of available land dedicated for its growth. However the analysis also highlighted that this resource currently has a relatively low starting base, with >1.9 Mt forecast by 2015. Therefore concerted efforts will be required in managing the drivers that influence availability, if anywhere near the upper levels of resource forecasts are to be realised. These should include the implementation of policies that encourage/incentivise the utilisation of available land for the growth of resource dedicated for the bioenergy sector.
- Potential and Mobilisation of Biomass Residue Resource – Residue biomass resources were identified as potentially providing upto >29.8 Mt of resource for the bioenergy sector by 2050. Agricultural residues (straws & slurries) make up the majority of this quantity, whilst also continuing to be utilised to maintain soil systems. The availability of residues was forecast to steadily increase and be comparatively robust to supply chain influences. Biomass residues therefore representing a potentially continuous and reliable near and long-term indigenous resource option for the bioenergy sector.
- Potential and Mobilisation of Biomass Waste Resource – Waste biomass in the UK was identified as potentially providing up to >89 Mt of resource for the bioenergy sector by 2050. Household wastes being the largest waste contributor. Wastes were found to be highly influenced by one key driver, the waste management system adopted. The

availability of waste resources was found to be much diminished when the adopted waste management strategy was uncomplimentary to the bioenergy sector. Therefore if wastes are to be increasingly utilised by the bioenergy sector, the analysis confirms the importance of implementing policies for effective development of waste management strategies.

- Refocusing Bioenergy Strategies to Increase the Availability of Indigenous Resources – The paper highlights the importance of applying a targeted approach for increasing the potential of indigenous resources. This is contrary to the broad policy focus approach currently being implemented in the UK. The analysis has identified that there are multiple biomass resource opportunities in the UK, but realisation of the upper levels of resource availability forecasts is highly dependent on the implementation of effective policies that target and manage the specific supply chain drivers most influential for each respective biomass resources.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2014.08.001.

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