Energy Policy 68 (2014) 1–14

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Securing a bioenergy future without imports

Andrew Welfle *, Paul Gilbert, Patricia Thornley

Tyndall Centre for Climate Change Research, School of Mechanical Aerospace & Civil Engineering, University of Manchester, Pariser Building, Sackville Street, Manchester M13 9PL, United Kingdom

HIGHLIGHTS

- Biomass Resource Model & Scenarios reflect biomass supply-chain dynamics to 2050.
- High potential availability of biomass & energy crops without food systems impacts.
- UK Indigenous biomass resource could service up to 44% of UK energy demand by 2050.
- Robust residue resource from ongoing activities and large potential waste resource.
- Indigenous resource abundance and the UK's path towards increased resource deficit.

ARTICLE INFO

Article history:
Received 15 August 2013
Received in revised form
29 October 2013
Accepted 30 November 2013
Available online 31 January 2014

Keywords:
Biomass
Resource
Energy

ABSTRACT

The UK has legally binding renewable energy and greenhouse gas targets. Energy from biomass is anticipated to make major contributions to these. However there are concerns about the availability and sustainability of biomass for the bioenergy sector. A Biomass Resource Model has been developed that reflects the key biomass supply-chain dynamics and interactions determining resource availability, taking into account climate, food, land and other constraints. The model has been applied to the UK, developing four biomass resource scenarios to analyse resource availability and energy generation potential within different contexts. The model shows that indigenous biomass resources and energy crops could service up to 44% of UK energy demand by 2050 without impacting food systems. The scenarios show, residues from agriculture, forestry and industry provide the most robust resource, potentially providing up to 6.5% of primary energy demand by 2050. Waste resources are found to potentially provide up to 15.4% and specifically grown biomass and energy crops up to 22% of demand. The UK is therefore projected to have significant indigenous biomass resources to meet its targets. However the dominant biomass resource opportunities identified in the paper are not consistent with current UK bioenergy strategies, risking biomass deficit despite resource abundance.

1. Introduction

European Governments have greenhouse gas emission and renewable energy targets that are bound by the baseline requirements of the Kyoto Protocol (United Nations, 1998), and the European Commission's (2006, 2008) renewable energy requirements . In addition, the UK is legally bound by the 2008 Climate Change Act (UK Government, 2008), to achieve a mandatory 80% cut in the UK's carbon emissions by 2050 and a benchmark 35% reduction by 2020, below 1990 levels (DECC, 2009). The aim; to encourage a transition towards a low-carbon UK economy through unilateral binding emissions reduction targets (DECC, 2012).

A key route to achieving these targets is to replace fossil fuel based energy with renewable and low carbon energy technologies. It is becoming increasingly accepted that having a broad energy mix is likely to be the best method to achieving energy and climate change targets (IEA, 2013). Biomass as a renewable energy source contributes towards reducing greenhouse gas emissions, decarbonisation of energy systems, diversification of fuel supplies, and the development of long-term replacements for fossil fuels (European Commission, 2006). Despite some concerns over the level of biofuels deployment, bioenergy remains a key component of European energy strategies (Panoutsou et al., 2009). The European Commission estimates that two-thirds of EU's 2020 target for 20% contribution by renewable energy resource may be from biomass (European Commission, 2006). The UK's Renewable Energy Strategy does not propose targets for individual technologies, but

* Corresponding author. Tel.: +44 7554429539.
E-mail address: andrew.welfle@postgrad.manchester.ac.uk (A. Welfle).

0301-4215 © 2014 Published by Elsevier Ltd. Open access under CC BY license.
http://dx.doi.org/10.1016/j.enpol.2013.11.079

confirms that bioenergy systems will likely contribute significantly to the UK's future energy portfolio (DECC, 2009).

However, biomass pathways are being assumed in many national energy strategies globally (Eurelectric, 2011), so critical assessment of the biomass resource availability is essential. Most energy strategies of European States assume the use of non-EU sourced biomass to meet their forecast demands (Upham et al., 2011), so there is likely to be increased demand (competition) for globally traded biomass in the future and there are also concerns about ensuring its sustainability.

The UK provides a case study of a nation with strong bioenergy aspirations but uncertain biomass resource availability. This paper analyses the UK's projected biomass resource availability under different future contexts and constraints. A Biomass Resource Model has been developed that: allows the analysis of forecast scenarios of biomass resource availability to the year 2050; compares indigenous biomass availability against prescribed biomass and renewable energy targets; and enables an evaluation of bioenergy strategies in terms of indigenous resource availability and deficits.

The Model has been developed to reflect a wide range of interacting variables that influence biomass resource availability. The Model can be calibrated to capture the potential range of these variables in different possible futures. This paper explores four forecasts of potential pathways that the UK could take to 2050, and measures the biomass resource availability and potential for the bioenergy sector. The scenarios analysed are:

- *Food focus scenario*—where emphasis on UK food security and productivity is prioritised;
- *Economic focus scenario*—where the UK places future emphasis on economic development and resource competition with the bioenergy sector occurs;
- *Conservation focus scenario*—where the conservation of land, biodiversity and resources are prioritised;
- *Energy focus scenario*—where the UK places future emphasis on developing the bioenergy sector and mobilising biomass resource to meet energy/bioenergy targets.

Within the Energy Focus Scenario different biomass conversion pathways have also been explored via a series of sub-Scenarios. These analyse the bioenergy potential when the biomass resource is converted to power, heat and transport fuels according to their most efficient or 'preferred pathways' (Slade et al., 2010; AEA, 2010, 2011; DEFRA, 2007; NNFCC, 2010). In the Heat Conversion Pathway Scenario, heat energy generation is prioritised where possible; in the Power Conversion Pathway Scenario, electrical energy generation is prioritised where possible; in the Transport Fuel Conversion Pathway Scenario, all suitable resources are utilised to produce biofuels and a hybrid "Balanced Conversion Pathway" is also considered.

2. The Biomass Resource Model—Methodology

2.1. Biomass resource modelling

The vast array of dynamics that impact the availability of any resource means that no set modelling methodology can be universally applied. However, a constant applicable to the modelling of any resource is that it is essentially the science of estimating supply versus demand and attempting to quantify resource reserves (Rowse, 1986). As such biomass resource modelling typically follows one of two pathways, 'Resource Focussed' models aim to quantify the extent of each biomass resource category to determine the resulting energy potential (AEA, 2010; E4tech, 2009), whilst 'Demand Driven' models analyse the bioenergy contribution targeted (DECC, 2010), and measure the resource quantity required to meet this demand (Berndes et al., 2003).

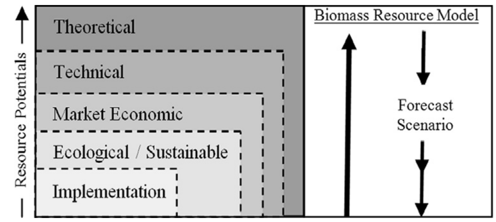

Fig. 1. Biomass modelling potentials.

Furthermore, the outputs from biomass resource models then fall into a series of categories (Fig. 1—adapted from Batidzirai et al. (2012) dependent on the adopted approach and desired output. Theoretical or Ultimate Potentials—represent the biomass resource potentially grown/harvested/collected limited only by physical and biological barriers. Technical/Geographic Potentials—reflect biomass resource extent taking into consideration technical constraints such as land area, ecological impacts and agro-technological constraints. Economic Potentials—demonstrate biomass resource that reflects economic considerations, fundamentally driven by supply-demand curves. Implementation/Realistic Potentials—represent biomass resource availability without inducing detrimental environmental, social or economic impacts (Hoogwijk et al., 2005).

2.2. The UK Biomass Resource Model

The Biomass Resource Model (BRM) is resource focused, analysing the indigenous theoretical potential of each specific biomass resource within the UK. The BRM is then calibrated in line with the scenario assumptions to produce more realistic resource availability forecasts (Fig. 1).

Various previous studies have been undertaken, aimed at analysing biomass resource levels at different geographic and regional levels. Many of these studies were included in a review carried out by the UK Energy Research Centre (Slade et al., 2011). As part of the process when developing the concept design for the BRM, the merits and limitations of each of these previous studies were assessed. A summary of the BRM's high level methodology is shown in Fig. 2. The BRM's analysis methodology progresses in three distinct stages that collectively reflect the dynamics of biomass supply chains. The research influences and descriptions of these analyses stages are provided.

2.2.1. Stage one: Land use and availability analysis

Analysis Stage One calculates the area of UK land utilised to meet various demands, including; food production, further urban development and forestry to the year 2050. The remaining UK land area potentially suitable for crop growth is then analysed to determine the availability for biomass and energy crop growth dedicated for the bioenergy sector. This land-use analysis methodology builds on approaches developed within similar studies (Fischer et al., 2007; Smeets et al., 2004) for wider geographic/regional analysis, and focuses them on the UK in this instance. The BRM goes further than previous studies in that it provides the facility to analyse land for biomass versus land for food dynamics.

2.2.2. Stage two: Biomass resource availability

Analysis Stage Two quantifies and forecasts the extent, availability and competing markets for different biomass resource categories indigenous to the UK. Taking into consideration factors such as changes in levels of arisings linked to industrial activity or agricultural residues. This analysis stage within the Model has been developed building on the methodologies of a series studies

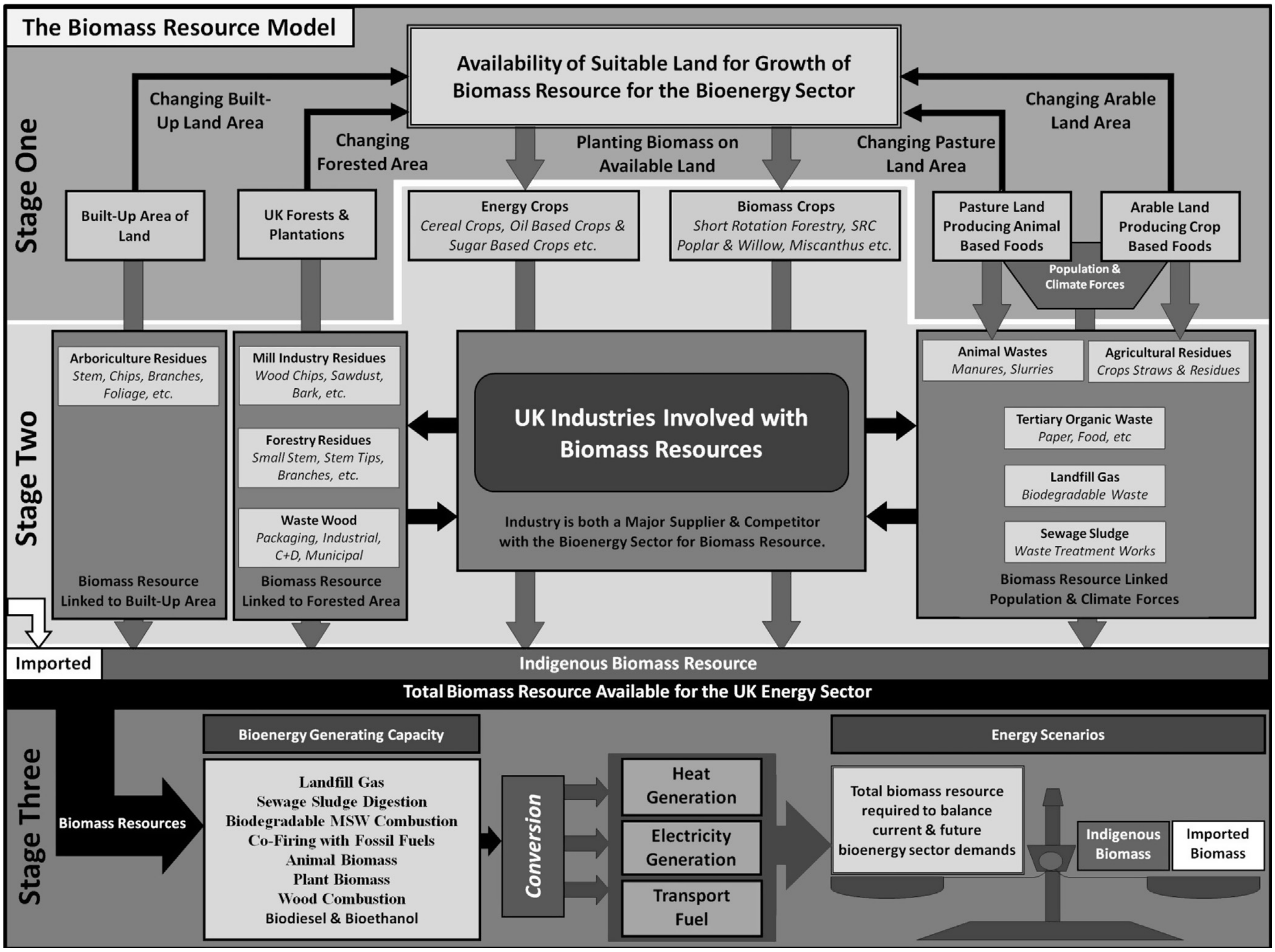

Fig. 2. The Biomass Resource Model methodology architecture.

(AEA, 2010, 2011; E4tech, 2009; DECC, 2010) carried out for the UK's Department for Energy & Climate Change. The analysis within the BRM differs from previous and existing research for the UK in that the resource availabilities analysed are linked to land-use dynamics (Analysis Stage One) and are not driven by economic feasibility bias. Table 1 provides an overview of the specific biomass resources and categories analysed within the Model.

2.2.3. Stage three: Indigenous bioenergy potential

This analysis stage calculates the energy potential of the specific resource quantities calculated within Stage Two. The wide range of pre-treatment and energy conversion pathways applicable to different types of biomass are considered. Within the analysis the resources calculated within Stage Two are 'filtered' through an 'energy pathway' as summarised by Fig. 3. This includes, a potential pre-treatment process where the resource's mass may be reduced and an energy debt incurred (NNFCC, 2010), followed by an energy conversion pathway to produce heat, power or transport fuels energy. The energy generated reflects the resource's calorific value (ECN, 2011) and the energy conversion efficiency (Faaij, 2006; Thornley et al., 2008; IEA, 2006, 2008; DECC, 2011a, 2011b; Twidell and Weir, 1986; Mambre, 2009; Boerrigter, 2006) of the applicable process. The specific pre-treatment and energy conversion pathway applied for each resource are reflective of the desired energy output, as discussed further in the Introduction of this paper. Once the energy potentials of the available resources have been calculated, these are then compared against the UK's renewable energy and bioenergy targets.

In summary, the key features of the BRM are the ability to investigate different variables and drivers that collectively reflect the whole system influences to biomass resource availability. This includes forestry, agriculture and market resource competition, allowing assessment of "land for food" vs. "land for biomass" dynamics. A further discussion of the methodology is described by Welfle et al. (2013).

3. UK biomass resource scenarios

3.1. Scenario analysis

Scenario analysis is the evaluation of potential future events through the consideration of alternative plausible, although not equally likely states of the world (scenarios) (Giljum et al., 2008). Scenarios are a dynamic view of future potential pathways based on the chosen trajectory variables. Scenario analysis provides an advantage of illustrating potential directions and illuminating events that may otherwise be missed. This can be particularly instructive for short and long term coordinated decision making and actions (Means et al., 2005).

3.2. Developing biomass resource scenarios

Many variables influencing the UK's biomass resource availability to 2050 are uncertain and so a scenario approach has been used to explore the potential indigenous resource availability

Table 1
Biomass resource categories and analysis.

Categories	Resources
Grown resource from UK land	Energy crops Cereal crops, oil crops, sugar crops Biomass crops Grasses, short rotation forestry and coppices, other forestry
Residues resource from UK forestry, industries and processes	Forestry residues Crop residues Straws Animal residues Manures and slurries Arboriculture arisings Sawmill, pulpmill and industry residues
Waste resource from UK industries and processes	Waste wood Packaging, industrial, construction, demolition, municipal Tertiary organic waste Household, commercial, industrial papers, cardboards, textiles, foods, organic and kitchen, garden etc Sewage—waste treatment

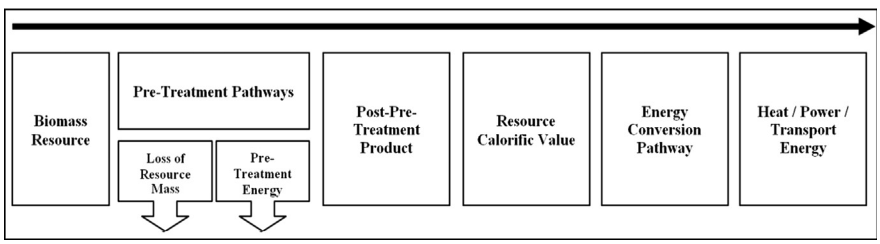

Fig. 3. Biomass Resource Model—energy generation pathways.

under alternative assumptions. Comparative biomass resource scenario approaches have been utilised by existing studies. These develop scenarios that forecast global biomass resource potential (Thran et al., 2010; Kraxner et al., 2013), or specifically focus on the potential of specific resources within a set geography (Larsen et al., 2013; Dam et al., 2007).

The flexibility of the BRM allows scenarios to be analysed that represent realistic future conditions. The chosen scenarios represent different trajectories that are likely to influence biomass availability in the UK and potential contributions to the bioenergy sector. Within each scenario it is also important to highlight that the ability for the UK to continue to meet its food demands are always placed ahead of ability to produce resource for the bioenergy sector. Therefore these scenarios represent potential biomass resource futures that will not conflict with requirements for food production.

The parameters within each scenario are built up through the manipulation of a series of key drivers that collectively control the BRM. These drivers reflect the core dynamics that influence biomass resource availability and potential for the energy sector. The extent and direction in which these drivers are varied within each scenario is reflective of a wide range of previous research and studies that provide forecasts. Table 2 provides an overview of these forecast drivers, and a summary of the literature that has informed how these variables may change to 2050. Table 2 also highlights specific drivers targeted and trade-offs between the scenarios.

In summary the developed research scenarios reflect the collective variations of a series of forecasts. This methodology is designed to be prospective, quantitative and normative as described by Anderson et al. (2008a, 2008b), in that the scenarios explore probable futures through modelling, based on the extension of a number of key drivers. The key themes, assumptions that characterise each scenario are summarised within Table 3.

3.2.1. Food Focus (Foo-F) Scenario

The Foo-F Scenario has been developed to analyse forecasts of biomass resource availability for the energy sector, within a future pathway where prime focus has been placed on improving food security and self-sufficiency.

3.2.1.1. Scenario context. Since World War Two European agricultural policy has focused on enhancing food self-sufficiency for the European population and, as demonstrated by recent overproduction of food, has been highly successful (Ignaciuk et al., 2006). However an enormous future challenge looms—having to feed up to 9–10 billion people by 2050 globally (Godfray et al., 2010). Agricultural systems are highly sensitive to climate fluctuations, and a 2 °C rise in mean global temperature reflecting the Intergovernmental Panel on Climate Change's lowest emission scenarios is predicted to result in widespread destabilization of farming systems across the world (Easterling et al., 2007). In addition to the uncertainty regarding food systems, the large scale production of biofuels is becoming a significant competitor for agricultural land—and whilst energy security concerns may justify the production of biofuels, the proposed scale of production raises questions about the trade-offs between biofuels and food crops (Thomas et al., 2009). The key issue relating to future food systems remains whether they can keep pace with steep growing demand and dietary transitions in an environment of climate change and numerous other drivers (Vermeulen et al., 2012). This strain will put pressure on Europe's future supply chains. Enhancing food security and self-sufficiency may re-emerge as prominent areas of concern for future governments.

3.2.1.2. A future pathway with food focus. Although complete food self-sufficiency is not a current target for the UK, it is important

Table 2
Summary of scenario drivers and forecast assumptions.

Drivers within the biomass resource model		Forecasts informing the scenario characteristics*	Focus placed on the drivers within each scenario: Foo-F	Eco-F	Con-F	Ene-F
UK development	Population	United Nations (2010)	●●	●●	●●	●●
	Changes in built-up land area	Prieler (2011)	●●	●●●	●	●●
Food production systems	Food production yields	AEA (2010, 2011), Smeets et al. (2004), Thornley et al. (2008), FAO (2011), EUROSTAT (2012), DEFRA (2012), Bouwman et al. (2004)	●●●	●●	●●	●●
	Food waste generation	FAO (2011), Foresight (2011), Foresight (2011), Godfray et al. (2010)	●	●●	●	●●
	Food commodity import and exports	Godfray et al. (2010), BIS (2012)	●	●●	●●	●●
	Utilisation of agricultural wastes and residues	DEFRA (2007), E4tech (2009), CSL (2008), DEFRA (2011), DEFRA (2011), Smith et al. (2000), Smith et al. (2000)	●●	●●	●	●●●
Forestry and wood based industries	Forestry expansion and productivity	Forestry Commission (2012a–2012h)	●●	●●●	●●●	●●●
	Wood based industry productivity	BIS (2012), WPIF (2010, 2012)	●●	●●●	●●	●●
	Imports & export of forestry product		●●	●●●	●●	●●
Biomass wastes & residues	Utilisation of forestry residues	E4tech (2009), McKay (2003), Stupak et al. (2011), Ladanai and Vinterback (2009), Lattimore et al. (2009)	●●	●●	●	●●●
	Utilisation of industry residues	BIS (2012), WPIF (2010, 2012)	●●	●●	●●	●●●
	Utilisation of arboriculture arising	E4tech (2009), WPIF (2010)	●●	●●	●●	●●●
	Waste generation forecasts	DEFRA (2011), WRAP (2009), WRAP (2011), DEFRA (2006, 2011)	●●	●●	●	●●
	Waste management strategies		●●	●●	●	●●●
Biomass & energy crop strategy	Land strategies dedicated to crop growth	AEA (2010, 2011), ADAS (2008)	●	●●	●	●●●
	Biomass & energy crop species planting strategies		●●	●●	●●	●●

●●● Future supply chain characteristics within the scenario reflect upper limits of forecasts within the literature*
●● Future supply chain characteristics within the scenario reflect average values forecasts within the literature*
● Future supply chain characteristics within the scenario reflect lower limits of forecasts within the literature*

Table 3
Summary of the key focus areas within each biomass resource scenario.

Scenario	Theme	Future pathway—key focus areas
Food focus scenario	Focus on enhancing food security and increasing self-sufficiency	• Increasing crop yield productivity • Decreasing food waste • Reduced food imports, replaced by domestic growth • Emphasis on agriculture over forestry expansion • Dedication of available land for agriculture ahead of bioenergy crop growth
Economic focus scenario	Economic development is the prime target	• Reduced restrictions on built-up area expansion • Increased focus on forestry expansion and productivity • Utilisation of forestry residues • Increased exportation rates of food commodities and forestry products • Waste generation rates driven by economic growth and technological advancement
Conservation focus scenario	Increased emphasis on conservation & resource protection	• Restricted expansion of built-up land area • Increased focus on forestry expansion and preservation • Lower limit utilisation of forestry & agricultural residues for energy • Decreased levels of waste generation • Waste management strategies focusing on resource recovery • Reduced dedication of available land for bioenergy crop growth
Energy focus scenario	Focus on enhancing and expanding the bioenergy sector	• Increased dedication of available land for bioenergy crop growth • Increasing focus on forestry expansion and productivity • Increased utilisation of forestry residues, agricultural residues and arboriculture arising by the bioenergy sector • Waste management focusing on energy recovery

that food systems adapt so that the UK is able to cope with future stresses in the food system (Foresight, 2011a, 2011b). The UK currently produces about half of the food it consumes, and is ~60% ‘self-sufficient’ (DEFRA, 2012). Recognised strategies to address future food issues include: closing the yield gap—the difference between attainable yields and realised yield; increasing agricultural productivity through technologies, research and investment; reducing wastes from food systems; changing diets; and expanding aquaculture opportunities (Godfray et al., 2010).

UK agricultural productivity has been increasing at a steady trajectory through time, and increased research, development and investment in the sector is likely to see this trend continue (Burgess and Morris, 2009). Estimates also suggest that 30–50% of food grown worldwide may be lost or wasted before and after it reaches the consumer. Therefore future emphasis should be placed on addressing wastes—the UK Government Office for Sciences suggesting that food waste could be realistically halved by 2050, equivalent to as much as 25% of current productivity (Foresight, 2011a, 2011b).

All actions should be realised through coordinated and multi-faceted strategies where sustainability is key. This 'sustainable intensification' involves an enhancement of current business-as-usual trends. Where agricultural systems remain largely unchanged and demands follow current projections, but agricultural productivity becomes increasingly efficient (Smith, 2013).

A summary of the key focus areas and actions within the Foo-F Scenario future pathway are shown in Table 3.

3.2.2. Economic Focus (Eco-F) Scenario

The Eco-F Scenario has been developed to analyse forecasts of biomass resource availability for the energy sector, in a future where emphasis is placed on economic growth over all other considerations.

3.2.2.1. Scenario context. Following the 2008/9 financial problems, an agenda aimed at encouraging economic growth is currently at the forefront driving the majority of UK policy. In the UK, timber and wood based industries are well established and contribute about 1.5% of UK export, equivalent to 2.5% of the global share (BIS, 2012). The flow of materials between the economy and the environment constitutes the physical foundations of economies—this 'economic metabolism' being a key indicator of economic health (Bringezu and Moriguchi, 2002; EUROSTAT, 2001). It is the growth and dynamics associated with the wood based industry that will be a key influence in determining in the availability of biomass resources available for the bioenergy sector within this scenario.

In terms of development of the bioenergy sector, many countries are showing considerable interest in bioenergy from an economic basis because of the value added (income) and employment opportunities that bioenergy can bring, especially in the rural areas where the resources are produced/collected (Steininger and Wojan, 2011). However studies such as Marques and Fuinhas (2012) have concluded that the high costs associated with supporting renewable energy options are actually an economic burden, as polices such as increasing tariffs for electricity results in an economically counterproductive effect and deceleration in economic activity. As things stand European countries have energy systems and infrastructures that are deeply grounded in fossil fuel provision (Marques and Fuinhas, 2012). Therefore if future policy, finance and focus is not directed towards renewable energy pathways, it is unlikely that there will be a widespread move away from conventional fossil fuel generation. A future pathway focused on economic growth may not specifically focus on the development of the bioenergy sector through the mobilisation of resource or building of energy infrastructure. But through increasing the ongoing activities of wood based industries, there will still be opportunities for the bioenergy sector.

3.2.2.2. A pathway with economic focus. A future pathway with economic focus will reflect policies designed to encourage the growth of industry, which in turn may compete for biomass resource but also provide new opportunities for the bioenergy sector. The UK Wood Panel Industry Federation (WPIF) identifies the growth of the bioenergy sector as a major concern for resource, "as subsidised energy generators can afford to out-pay the wood panel industry for primary raw material" (WPIF, 2012). Therefore a future pathway with economic focus would ensure that the wood industry's resource demands are set over those of the bioenergy sector. Industry's future resource demands have been forecast by the WPIF (2010) and forestry expansion and productivity scenarios are forecast by the Forestry Commission (2012a–2012h) to reflect market behaviour, these forecasts are utilised within the Eco-F Scenario.

Meta-analysis of a series of studies (Mookerjee, 2006) concludes that there is statistical significance between economic growth and aggregate export levels, especially relating to both manufactured and energy based export categories. Therefore, it should be expected that a future pathway with economic focus may reflect increases in export levels, particularly wood products with relevance to the bioenergy sector.

Greyson (2007) states that, realising zero waste and sustainability with continued economic growth may not be achievable within the scope of current practices (Greyson, 2007). Therefore the future patterns of waste generation and management within this scenario may reflect variations of continuing trends. To model this the waste strategies within this scenario utilise the UK Department of Environment, Food & Rural Affair's (DEFRA) technologically driven forecasts (DEFRA, 2006, 2011a,b,c,d). These predict that large-scale solutions and technology will be key to dealing with waste continuing issues.

A summary of the key focus areas and actions within the Eco-F Scenario future pathway are shown in Table 3.

3.2.3. Conservation Focus (Con-F) Scenario

The Con-F Scenario has been developed to analyse forecasts of biomass resource availability for the energy sector, within a future pathway where emphasis is placed on a paradigm of enhanced conservation and preservation of biodiversity and resources.

3.2.3.1. Scenario context. A century ago forestry cover in the UK was at an all-time low, although following a series of phases of forestry focus this has increased by two and a half times to the ~13% cover present today. However planting rates in recent years have once again stagnated, leading to recognition that it is time to regain focus and 'up the game', particularly when measured against the context of having to mitigate and adapt to climate change (Woodland Trust, 2011).

The UK's approach to conservation relies on a series of partnerships between statutory, voluntary, academic and business sectors at both the National and local scale. The prime focus being to maintain and create habitats and ecosystems, halt the decline of biodiversity and enhance the robustness of sites to environmental change (DEFRA, 2012). This is backed up by a wide spectrum of legislative requirements that aim at safeguarding forestry, biodiversity and conservation (Shoene and Bernier, 2012).

At the same time: the UK has well established wood based industries that rely on forestry productivity, there is increasing inclusion of forestry resources within renewable energy strategies (Ladanai and Vinterback, 2009), and awareness of forestry resources and ancient woodlands in terms of ecological value is increasing (Goldberg et al., 2007). Collectively these three competing demands and priorities will shape the pathway for utilisation of forestry in the future.

A further increasingly prominent conservation issue is resource availability and scarcity—a theme motivating new waste management strategies at both the European and UK level (Pires et al., 2011). There is great scope for improvement in the UK, where recycling levels stand at about 39% of municipal waste compared to > 60% in leading places such as Austria and Germany (Hill et al., 2006). To help develop innovative and exemplary practices that drive behaviour towards enhanced sustainability, the UK Government has ongoing 'Zero Waste Places' initiatives (Phillips et al., 2011)—"A simple way of encapsulating the aim to go as far as possible in reducing the environmental impact of waste. It is a visionary goal which seeks to prevent waste occurring, conserves resources and recovers all value from materials" (DEFRA, 2008).

3.2.3.2. A pathway with conservation focus. Trade-offs exist between biodiversity, conservation and optimal biomass resource production for the bioenergy sector. Erb et al. (2012) found that estimates of global biomass crop potential are lowered by 9–32% when land areas of wilderness, biodiversity importance and with protection status are excluded from assessments. The German Advisory Council on Global Change also found that a minimum of 10–20% of global land should be protected if the biosphere's functions such as climate regulation and biodiversity are to be preserved (Schellnuber et al., 1999). Fourteen percent of land is currently protected globally (UNEP, 2009), meaning a further 6% equivalent to 540,000 km² is required (Cornelissen et al., 2012). In summary a future pathway with conservation focus will undoubtedly result in lower levels of biomass resource being available for the bioenergy sector.

In the UK, the Forestry Commission have a wide range of forestry expansion and productivity scenarios that reflect varying levels of forest growth and utilisation (Forestry Commission, 2012a–2012h). A future pathway with conservation focus will reflect the upper projections for forestry expansion. The management of forests including felling is as follows.

The approach of the UK forestry industry has progressively shifted primarily from timber production to increasingly multi-purpose values that include conservation (Cameron, 2011). Forestry industries having an important role to play in conservation, as the industries long-term sustainability depends on the resource (Scottish Forest Industries Cluster, 2013). Therefore industry within a future pathway with conservation focus would therefore continue to utilise forests, albeit strongly abiding to the requirement of the 'UK Forestry Standard' (Forestry Commission, 2011).

Research (Blanco-Canqui and Lal, 2009; Lal, 2006) also highlights that the extraction of residues from both forestry and agricultural systems may pose a risk for the maintenance of soil fertility. It being important that residue removals do not exceed levels required to maintain food and habitats for organisms, provide protection against soil compaction or for maintenance of soil fertility (Stupak et al., 2011; Lattimore et al., 2009). Therefore a future pathway with conservation focus will likely avoid the upper limits utilisation of both forestry and agricultural residues.

Waste generation and management strategies will reflect future pathways of reduced waste generation and increased levels of resource recovery from waste streams. Scenarios reflecting these pathways have been forecast by the DEFRA, 2006, 2011a,b,c,d), and will form the basis of future waste analysis within the Con-F Scenario.

A summary of the key focus areas and actions within the Con-F Scenario future pathway are shown in Table 3.

3.2.4. Energy Focus (Ene-F) Scenario

The Ene-F Scenario has been developed to analyse forecasts of biomass resource availability for the energy sector, in a future

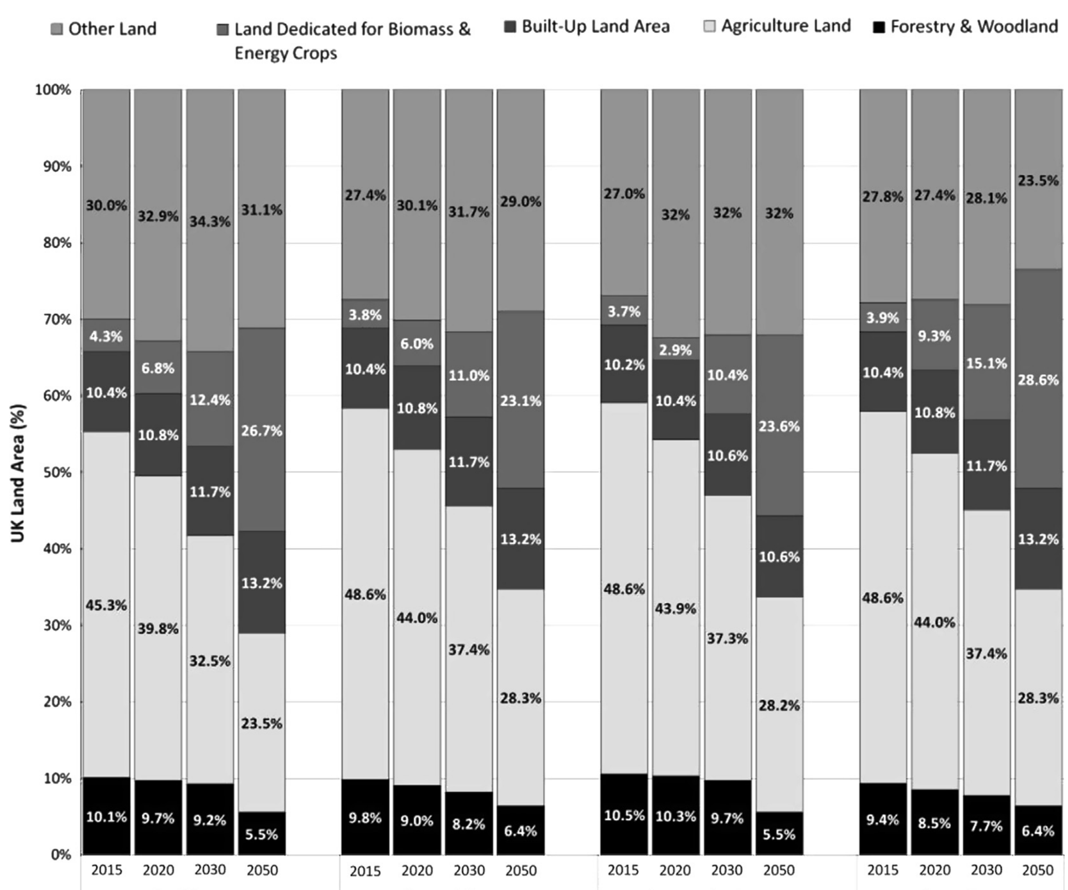

Fig. 4. Utilisation of UK land within the scenarios.

pathway where prime focus has been placed on expanding the UK bioenergy sector.

3.2.4.1. Scenario context. As already discussed the UK has legally binding energy, carbon and renewable energy targets, including a series of bioenergy targets relating to heat, power and transport fuel, and overall generation (DECC, 2012a, 2012b; DfT, 2011). The Energy Focus Scenario sets out a future pathway where the maximum achievable levels of bioenergy are generated from indigenous biomass resources. The strategy being for the UK to maximise it's bioenergy generation potential through the utilisation of indigenous resources, and reduce potential reliance on imported imported resources.

3.2.4.2. A pathway with energy focus. The concept behind this scenario is to explore the upper limits of indigenous biomass resources that could realistically be mobilised for the bioenergy sector to 2050. This involves mobilising and pushing the limits on resource availability across the range of biomass categories.

Within this future pathway the upper limits of available and suitable land (after food demands are met) is dedicated for the potential growth of energy and biomass crops (AEA, 2011; ADAS, 2008). The energy focus scenario will reflect the Forestry Commission's forest expansion and productivity forecasts (Forestry Commission, 2012a–2012h) that provide the greatest resource potential for the bioenergy sector. A further future opportunity explored is highlighted by The Independent Panel on Forestry (DEFRA, 2011), "only 52% of UK forests and woodland are currently actively managed, so major resource use opportunities may exist if progress is made in this area".

There are also notable biomass resource opportunities potentially available for the bioenergy sector in the form of wastes and residues from ongoing activites in the UK (IEEP, 2011). As such a future pathway with energy focus will work towards achieving increased harvest and collection (biological and realistic) limits for biomass residues, from forestry, agricultural and industrial processes. The waste generation and management strategies adopted also reflect DEFRA's forecast pathways where energy recovery is the focus (DEFRA, 2006, 2011a,b,c,d).

A summary of the key focus areas and actions within the Ene-F Scenario future pathway are shown in Table 3.

4. Biomass resource, energy and land use forecasts

The following section provides a series of figures that allow analysis of the biomass resource availability, bioenergy potential and land utilisation within each of the scenarios when calibrated using the UK BRM.

4.1. Land utilisation analysis

Fig. 4 and the data within Appendix A1 summarises how UK land is utilised within each scenario. This is in accordance with the UK meeting it's food production demands, any changes in built-up land area and forestry within each scenario. The output to this analysis is the area of land identified as being potentially available and suitable for biomass and energy crop growth. The extent to which this land is utilised for this purpose differs depending on the focus of each scenario. Areas of land with characteristics unsuitable for crop growth such as, rivers, mountains, coasts and lakes are excluded from the analysis.

The area of land left free and un-utilised within the scenarios is highlighted as 'Other Land' within Fig. 4. The 'Land Dedicated for Biomass & Energy Crops' category reflects the area of land within each scenario that has been specifically dedicated for growth for the bioenergy sector. The 'Built-Up Land Area' category reflects land that is utilised for buildings, roads and infrastructure etc. 'Agriculture Land' represents the land area within each scenario dedicated to both pastoral and arable food productivity. The 'Forestry and Woodland' category reflects the area of both managed and unmanaged forests/woodlands within each scenario.

4.2. Indigenous biomass resource analysis forecasts

One of the key aims of this research is to analyse the UK's indigenous biomass resource potential to 2050 within each of the analysis scenarios. Fig. 5 and the data within Appendix A2

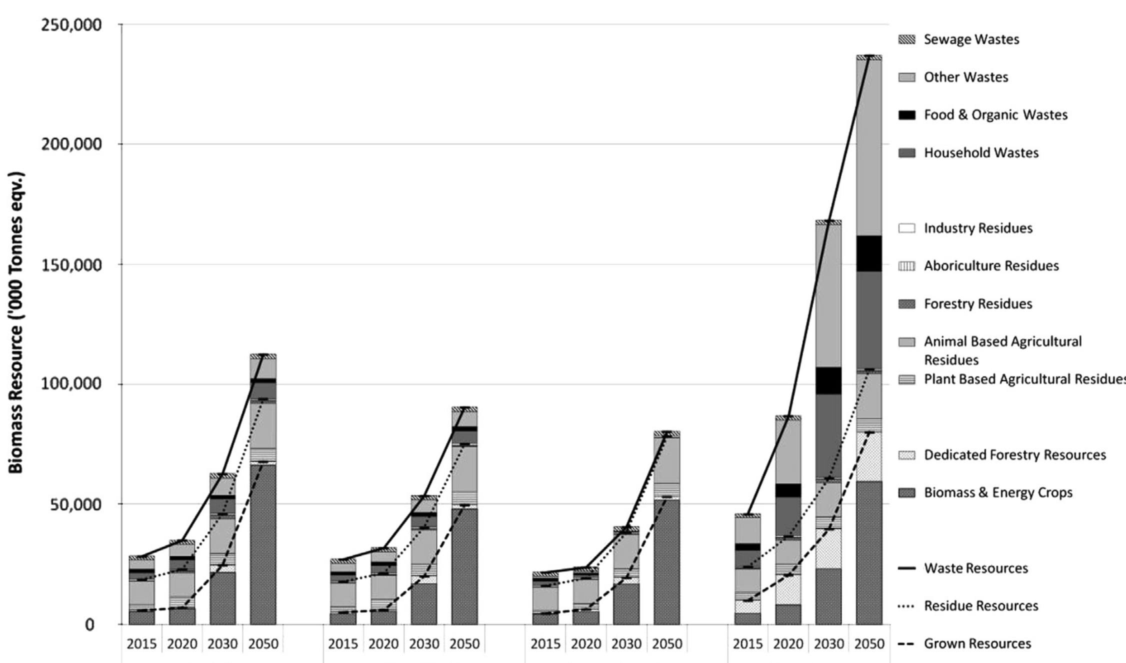

Fig. 5. UK biomass resource scenarios—resource availability analysis.

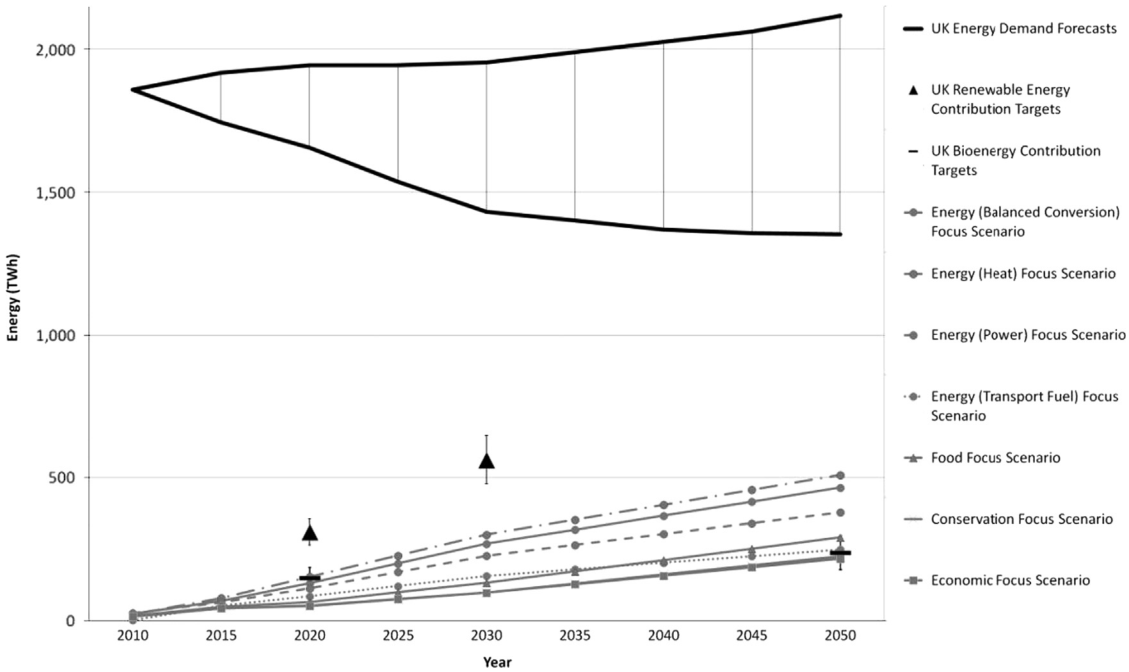

Fig. 6. Scenario bioenergy potentials vs. forecast UK energy demands and targets.

presents this analysis, documenting the potential availability of each resource for the bioenergy sector to 2050. Within Fig. 5 the stacked columns for each scenario reflect the availability of each specific biomass resource. The stacked lines joining the columns within Fig. 5 provide segregation, to highlight the different resources within each of the biomass categories (Table 1)—waste resources, residue resource and grown resources. Grouping the resources into these three categories allows higher level insight into changing trends of resource availability to 2050. To allow ease of comparison and analysis of the data, resource quantities within Fig. 5 have been converted to a single unit (tonnes equivalent).

4.3. *Forecasting the bioenergy potential of the available indigenous resources*

The bioenergy generation potential of the available resources shown in Fig. 5 are analysed and represented in both Fig. 6, and by the data within Appendix A3. Fig. 6 highlights the bioenergy generation potential for each of the scenarios and also for the Energy Focus sub-scenarios. As discussed in Section 1 the Energy Focus sub-scenarios allow an evaluation of strategies that focus on either a balanced, heat, power or transport fuel bioenergy strategy. These are measured against the forecast range (DECC, 2010) of future UK energy demand—shown at the top of Fig. 6. Also the UK's renewable energy and bioenergy targets (DECC 2012a, 2012b; Erb et al., 2012; Schellnuber et al., 1999) represented by the triangle and dash markers within Fig. 6.

4.4. *Biomass import deficit forecasts*

In the UK current and planned biomass projects are focusing predominantly on power bioenergy pathways, and like most European countries the UK will require largely woody biomass (primarily wood pellets and to a lesser extent wood chips) for this energy generation pathway. Liquid biofuels (biodiesel and bioethanol) are also sought for transport (IEA, 2011). The international market for biomass resource is still relatively immature, and therefore projections are uncertain. The UK Department for Transport reported that around 25% of feedstocks purchased for current bioenergy plants was indigenous resource, the remaining imported from the EU, North America, Russia, South Africa and New Zealand (predominantly wood pellets), Brazil (biofuels) and Malaysia and Indonesia (palm oil) (DfT, 2011). Therefore if the UK's bioenergy plans mature, the country could become increasingly dependent on these categories of imported resource (AEA, 2010).

Fig. 7 and the data within Appendix A4 highlights a forecast of the UK's potential wood fibre demand up to 2025 (WPIF, 2010). It also shows the UK's indigenous resource availability within each of the scenarios when restricted to woody and liquid biofuels resources, (the resource categories currently forecast as being required by the UK bioenergy sector if current plans mature). The shaded area under the 'Forecast UK Wood Fibre Demand' line within Fig. 7 represents the UK's potential indigenous resource deficit, of the types of biomass resource that will be required if current UK's bioenergy plans mature and biomass demand forecasts are realised.

5. Discussion

This section discusses the key outputs from the results documented within Section 4, highlighting the importance of the findings in the context of the UK's future energy and bioenergy strategies.

5.1. *Land utilisation forecasts*

The key finding within the land utilisation analysis is that when all the scenarios are compared, the Food Focus Scenario actually has the lowest land area allocation for agricultural productivity over the analysis period. This reflects the key themes reflected within this scenario, where research, development and technology for improving the productivity of agricultural systems are emphasised. Through increasing the productivity of the land, an overall reduction in land area is required to deliver the increased food quantities required to enhance the UK's food security and self-sufficiency. This feedback benefit within the Foo-F Scenario also has a further positive impact since larger areas of the 'freed-up'

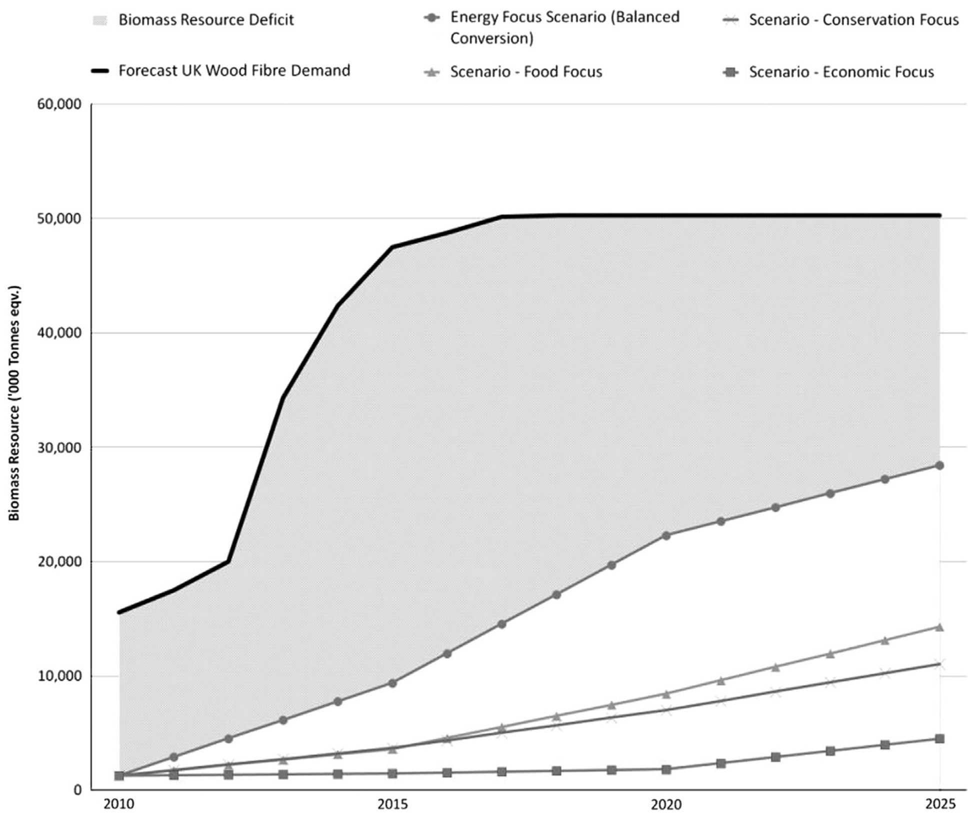

Fig. 7. Analysis of UK indigenous biomass resource availability and future resource deficits.

agricultural land can be dedicated for biomass and energy crop growth, whilst also allowing over 30% of land to be free from use.

5.2. *Indigenous biomass resource availability forecasts*

The 'Grown Resource' category within this analysis includes both biomass and energy crops and also dedicated resource from forests that are available to the bioenergy sector. These are represented at the bottom of the graphs within Fig. 5. Overall, grown resources represent a potentially large opportunity for the bioenergy sector. Especially towards the latter stages of the analysis where by 2050 in the Foo-F, Eco-F and Con-F Scenarios, they represent over half of the total resources potentially available to the bioenergy sector. Further analysis of the Grown Resource category within Fig. 5 highlights that the available resource direct from forestry is relatively small compared to that from dedicated biomass and energy crops. Although, the Ene-F Scenario does highlight that resources available direct from forestry when mobilised represent a relatively constant and significant resource opportunity for the bioenergy sector to 2050.

All scenarios assume that an increasing proportion of un-utilised land will be set aside for growth of biomass and energy crops. The overall proportion of land dedicated being dependent on the focus of the particular scenario. The analysis highlights that regardless of scenario, UK grown biomass and energy crops are shown to represent significant potential for the UK bioenergy sector.

As documented in Section 5.1, a positive feedback effect can be seen within the Foo-F Scenario. Towards the end of the analysis period shown in Fig. 5, areas of agricultural land are 'freed-up' as a result of sustainable intensification and improved production yields. This allows larger areas of land to be utilised for the growth of dedicated biomass and energy crops for the bioenergy sector.

The 'Residue Resource' category represents resources from ongoing activities such as agriculture, forestry and industrial processes. Within Fig. 5 these represent the middle analysis band of the columns. Fig. 5 demonstrates that the resources within this category have relatively continuous and stable availability for all scenarios and throughout the analysis period to 2050. The resource potential of both plant (straw) and animal (slurry) based agricultural residues is shown to have significant availability for bioenergy. Even within the Con-F Scenario where the lower limits of agricultural residues are collected/harvested, the collective availability of this resource is still significant.

Residue resource from industrial processes are also documented as having relatively constant availability regardless of scenario or progress of time—slight increases are documented within the Eco-Focus Scenario where industrial activities are increased.

The 'Waste Resource' category represents the broad range of waste streams that may be utilised by the bioenergy sector (Table 1). These are represented by the top segment of resources highlighted within Fig. 5. Significant potential from the waste category resources is highlighted. While the availability of the waste resources varies substantially across the scenarios, the Ene-F Scenario highlights the maximum realistic potential for the bioenergy sector. Household, food and organic wastes represent a large portion of the available waste resources in this scenario, while other waste streams including woods, textiles, sludge's and oils (represented as 'Other Wastes' within Fig. 5) also highlight significant potential.

5.3. *Bioenergy potential forecasts*

This analysis highlights that if any of the developed scenarios and forecasts of future UK energy demand were realised, between 19 and 44% of the UK's primary energy demand could be delivered from indigenous biomass resources. Within the Foo-F and Ene-F

Table A1
Utilisation of UK land within the scenarios (‘000 ha).

	Food focus				Economic focus				Conservation focus				Energy focus			
	2015	**2020**	**2030**	**2050**	**2015**	**2020**	**2030**	**2050**	**2015**	**2020**	**2030**	**2050**	**2015**	**2020**	**2030**	**2050**
Total UK land area	24,193				24,193				24,193				24,193			
Forestry & woodland	2,439	2357	2236	1340	2,375	2,188	1985	1553	2,548	2,490	2354	1340	2,265	2,057	1867	1553
Agriculture land	10,952	9626	7851	5683	11,756	10,648	9045	6850	11,748	10,628	9017	6820	11,756	10,648	9045	6850
Built-up land area	2,512	2612	2821	3188	2,512	2,612	2821	3188	2,463	2,514	2562	2562	2,512	2,612	2821	3188
Land dedicated for biomass & energy crops	1,031	1642	2991	6448	917	1,461	2671	5581	900	711	2514	5714	937	2,246	3657	6909
Other land area	7,259	7956	8295	7534	6,634	7,284	7671	7021	6,535	7,851	7747	7756	6,724	6,630	6802	5693

Table A2
UK biomass resource scenarios—resource availability analysis (‘000 t Eqv.).

	Food focus				Economic focus				Conservation focus				Energy focus			
	2015	**2020**	**2030**	**2050**	**2015**	**2020**	**2030**	**2050**	**2015**	**2020**	**2030**	**2050**	**2015**	**2020**	**2030**	**2050**
Grown resources																
Biomass & energy crops	5148	6422	21,479	66,137	4303	5208	16,793	47,965	4220	5080	16,641	51,697	4397	8007	22,994	59,378
Dedicated forestry resources	676	521	3117	1586	744	689	3285	1753	248	1217	2765	1523	5537	12,489	16,677	20,656
Biomass residues																
Plant agricultural	2152	4290	4839	5439	2144	4290	4805	5346	1072	2145	3602	5392	3218	4290	4911	5488
Animal agricultural	9846	10,133	14,379	18,937	9846	10,133	14,379	18,937	9846	10,133	14,379	18,937	9846	10,133	14,379	18,937
Forestry	152	736	1396	837	19	86	156	122	17	79	143	121	283	963	1166	970
Arboriculture	126	151	270	308	127	154	283	346	124	148	257	278	126	278	293	308
Industry	591	603	603	603	645	690	725	761	565	565	565	565	565	565	565	565
Biomass wastes																
Household	2737	3855	6042	6786	2515	3153	4419	5193	1770	1171	211	0	6780	16,149	34,848	40,716
Food & organic	1367	1404	1408	1625	1366	1405	1491	1799	1145	816	153	0	2626	5379	11,188	14,700
Other	3900	5080	7335	8299	3635	4244	5440	6382	963	686	128	0	10,945	26,857	59,472	73,421
Sewage	1649	1697	1788	1878	1649	1697	1788	1878	1649	1697	1788	1878	1649	1697	1788	1878
Totals																
Grown resources	5824	6943	24,596	67,723	5047	5897	20,078	49,718	4468	6297	19,405	53,220	9934	20,496	39,671	80,035
Residue resources	12,867	15,913	21,488	26,124	12,781	15,353	20,348	25,512	11,607	12,991	18,802	25,172	14,038	16,229	21,313	26,267
Waste resources	9653	12,036	16,572	18,589	9165	10,499	13,137	15,253	5526	4370	2279	1878	22,000	50,082	107,295	130,716

Table A3
Scenario bioenergy potentials vs. forecast UK energy demands and targets (TW h).

Year	Scenarios						
	Food focus	**Economic focus**	**Conservation focus**	**Energy focus (balanced conversion)**	**Energy focus (heat prioritised)**	**Energy focus (power prioritised)**	**Energy focus (transport fuel prioritised)**
2015	54.66	49.09	49.51	79.31	91.45	72.53	59.70
2020	75.36	58.83	59.87	151.59	178.27	131.00	98.25
2030	154.20	113.25	114.10	312.62	349.90	263.30	181.63
2050	338.18	251.25	261.15	541.48	593.00	440.74	289.06

Table A4
UK indigenous biomass resource availability and future resource deficits (‘000 t Eqv.).

Year	Forecast UK wood fibre demand	Scenarios			
		Food focus	**Economic focus**	**Conservation focus**	**Energy focus (balanced conversion)**
2010	15,542	1,276	1,276	1,276	1,276
2015	47,508	3,593	1,475	3,690	9,378
2020	50,263	8,433	1,828	7,009	22,302
2025	50,263	14,307	4,504	11,042	28,439

Scenarios, the UK could potentially meet it's 2050 bioenergy targets and a large portion of it's 2050 renewable energy targets from indigenous biomass resource (Fig. 6). Also if the UK were to pursue a pathway that focused on developing it's bioenergy sector, the ‘Heat Prioritised’ Energy Focus Sub-Scenario demonstrates that heat conversion pathways will likely provide the highest energy generation for the resources available. Even if future scenarios prioritised conservation or economic themes as much as 19% of the UK energy demand could still be met from indigenous resources, as long as there is some focus on increasing resource mobilisation.

5.4. *Indigenous resource deficits and imports*

Fig. 7 shows the results in the context of the UK's renewable energy and bioenergy strategies. Even though the UK has potentially large indigenous biomass resource availability (Fig. 5) and a large portion of the UK's energy targets could be met through the utilisation of these indigenous resources (Fig. 6), the UK does not have an abundance of the ‘woody’ and transport fuel compatible biomass resources required to meet future demand, if the UK's current bioenergy plans mature. Fig. 7 shows that even within the Ene-F Scenario where the upper limits of indigenous biomass resource are mobilised, a large resource deficit will still exist when compared to the forecast resource demand. In summary this analysis describes an uncomfortable nexus between the high potential availability of various indigenous resource categories, and the current and future bioenergy strategies that are potentially steering the UK towards reliance on biomass resource imports. Highlighting the concept that the UK is not potentially investing in the appropriate biomass technologies and infrastructure to match the indigenous opportunities.

6. Conclusions—Scenario lessons

The scenarios developed in this study were designed to represent four potential pathways that could be realised in the UK, in order to determine the biomass resource potentials and implications for the bioenergy sector. They allow an assessment of the potential impacts of different variables and contexts on potential biomass resource supply. The key policy conclusions arising from the analysis are highlighted below.

- *High potential availability of biomass & energy crops without impacting food systems*—The analysis shows that the potential availability of biomass and energy crops for the bioenergy sector remains high, even when land is 'ring-fenced' for the UK to maintain it is food production requirements (and even enhanced food production within the Food Focus Scenario).
- *Robust and continuous resource availability from ongoing UK activities*—Biomass residue resources, including agricultural, forestry, industrial and arboriculture residues were found to represent a continuous and robust resource that maintained a high availability regardless of the scenario or time within the analysis. Agricultural residues, particularly both straw and slurry resources represent a major opportunity for the bioenergy sector due to their high abundance, availability robustness and current under-utilisation (DECC, 2011a, 2011b).
- *Large potential from waste resources*—Within the Energy Focus Scenario where the adopted waste management strategy emphasised energy recovery, the potential waste resource availability for the bioenergy sector was shown to be substantial (> 1308 million tonnes equivalent per year in 2050). Likewise within the Conservation Focus Scenario where a strategy of reduced waste generation and resource recovery was adopted, the potential for the bioenergy sector was much less attractive (> 1.8 million tonnes equivalent per year in 2050). The abundance of both household and food/plant based waste streams were identified as showing particular potential for the bioenergy sector.
- *A food focus positive feedback benefit*—Analysis within the Food Focus Scenario found that a future pathway that emphasised increasing the productivity and reduction of wastes from food systems, resulted in future benefits for the bioenergy sector. Increasing the productivity of the land not only resulted in increased food security and self-sufficiency, but ultimately resulted in less land being required to produce more food—freeing up additional land for biomass growth.
- *Heat conversion pathways providing most energy efficient use of resources*—The analysis of the energy conversion sub-scenarios (Fig. 6), highlighted that the prioritisation of heat energy conversion pathways with suitable resources, resulted in the greatest levels of bioenergy generation. This suggests that the best option for the UK to make the most of its indigenous biomass resource is potentially for, selected resources to be utilised by the industries in bio-refineries with all remaining suitable resources being dedicated for heat generation pathways. The generation of renewable electricity being achieved through alternative technologies.
- *Indigenous resource abundance and our pathway towards increased resource deficit*—Overall the results identified the high potential availability of indigenous resources for the bioenergy sector (Fig. 5), the large contributions that indigenous resource could make towards the UK achieving it is energy targets (Fig. 6), but the forecasts deficits in biomass resources that the UK will need to import in order to supply the current and planned bioenergy sector (Fig. 7). In summary this analysis highlights the non and under-utilisation of indigenous biomass resources in the UK, and the major currently missed opportunities that are contrary to the current direction of the UK bioenergy sector.

Appendix A

See Tables A1–A4 here.

References

ADAS, 2008, Addressing the Land Use Issues for Non-Food Crops, in Response to Increasing Fuel and Energy Generation Opportunities, NNFCC Project 08-004, National Non-Food Crops Centre.

AEA, 2010, UK and Global Bioenergy Resource—Annex 1 Report: Details of Analysis, Oxford Economics, Biomass Energy Centre, Forest Research, Department for Energy & Climate Change.

AEA, 2011, UK and Global Bioenergy Resource—Final Report, Oxford Economics, Biomass Energy Centre, Forest Research, Department for Energy & Climate Change.

Anderson, K., Bowes, A., Mander, S., Shackley, S., Agnolucci, P., Ekins, P., 2008a. Tyndall decarbonisation scenarios—Part 1: Development of a backcasting methodology with stakeholder participation. Energy Policy 36, 3754–3763.

Anderson, K., Bowes, A., Mander, S., Shackley, S., Agnolucci, P., Ekins, P., 2008b. Tyndall decarbonisation scenarios—Part 2: Scenarios for a 60% CO_2 reduction in the UK. Energy Policy 36, 3764–3773.

BIS, 2012, Industrial Strategy: UK Sector Analysis, Department for Business Innovation & Skills, BIS Economics Paper No. 18, September 2012.

Batidzirai, B., Smeets, E., Faaij, A., 2012. Harmonising bioenergy resource potentials—methodological lessons from review of state of the art bioenergy potential assessments. Renewable Sustainable Energy Rev. 16, 6598–6630.

Berndes, G., Hoogwijk, M., Van Den Broek, R., 2003. The contribution of biomass in future global energy supply. Biomass Bioenergy 25 (1), 1–28.

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity & environmental quality. Crit. Rev. Plant Sci. 28, 139–163.

Boerrigter, H., 2006. Economy of Biomass to Liquid (BTL) Plants—An Engineering Assessment. Energy Centre of the Netherlands.

Bouwman, A., Van der Hoek, W., Eickhout, B., Soenario, I., 2004. Exploring changes in world ruminant production systems. Agric. Syst. 84 (2), 121–153.

Bringezu, S., Moriguchi, Y., 2002. In: Ayres, R.U., Ayres, L (Eds.), Material Flow Analysis Handbook. Edward Elgar Publishers, pp. 79–90.

Burgess, P., Morris, J., 2009. Agricultural technology & land use futures: the UK case. Land Use Policy 26S, S222–S229.

CSL, 2008, National & Regional Supply/Demand Balance for Agricultural Straw in Great Britain, Central Science Laboratory, Department for Environment, Food & Rural Affairs.

Cameron, A., 2011. Has commercial timber production become an inconvenient truth? Commer. Timber, RSFS Scot. For. 65 (2), 12–16.

Cornelissen, S., Koper, M., Deng, Y., 2012. The role of bioenergy in a fully sustainable global energy system. Biomass Bioenergy 41, 21–33.

DECC, 2009. The UK Renewable Energy Strategy. Department for Energy & Climate Change, London.

DECC, 2010. 2050 Pathways Analysis. Department of Energy & Climate Change, London.

DECC, 2011a. 2050 Pathways Analysis: Response to the Call for Evidence—Part 2. Department for Energy & Climate Change, London.

DECC, 2011b. Digest of United Kingdom Energy Statistics 2011. Department of Energy & Climate Change, London.

DECC, 2012a. The Future of Heating: A Strategic Framework for Low Carbon Heat in the UK. Department of Energy & Climate Change, London.

DECC, 2012b. UK Bioenergy Strategy. Department for Energy & Climate Change, London.

DEFRA, 2006. Carbon Balances and Energy Impacts of the Management of UK Wastes. Department for Environment, Food & Rural Affairs, London.

DEFRA, 2007, UK Biomass Strategy, Department of Trade & Industry, Department for Transport, Department for Environment, Food and Rural Affairs, London.

DEFRA, 2008. Criteria & Guidance for Zero Waste Place Proposals. Department for Environment, Food & Rural Affairs, London.

DEFRA, 2011a, Consultation on Recovery & Recycling Targets for Packaging Waste for 2013–2017—A Consultation on Proposed Changes to the Producer Responsibility Obligations (Packaging Waste) Regulations 2007 (as amended) and the Producer Responsibility Obligations (Packaging Waste) Regulations (Northern Ireland) 2007 (as amended)', Department of the Environment, The Scottish Government, Welsh Government, Department for Environment, Food & Rural Affairs.

DEFRA, 2011b, The Economics of Waste & Waste Policy, Environment and Growth Economics, Department for Environment, Food & Rural Affairs, London.

DEFRA, 2011c, Independent Panel on Forestry—Progress Report, Department for Environment, Food & Rural Affairs, London.

DEFRA, 2011d. Farm Practices Survey. Department for Environment, Food & Rural Affairs, London.

DEFRA, 2012. UK Conservation Strategies. Department for Environment, Food & Rural Affairs, London..

DEFRA, 2012. Farming Statistics. Department for Environment, Food & Rural Affairs, London.

Dam. J., Faaij. A., Lewandowski. I., Fischer. G., 2007, Biomass Production Potentials in Central & Eastern Europe under Different Scenarios', Biomass & Bioenergy, vol. 31, No. 6, pp. 345–366 United Nations, 2010, 'World Population Prospects', found on at: 〈http://esa.un.org/unpd/wpp/index.htm〉.

DfT, 2011, Renewable Transport Fuel Obligation: Quarterly Report, Department for Transport, London.

E4tech, 2009. Biomass Supply Curves for the UK. Department for Energy & Climate Change.

ECN, 2011. ECN PHYLLIS Database—The Composition of Biomass & Waste. Energy Centre of the Netherlands.

EUROSTAT, 2001. Economywide Material Flow Accounts & Derived Indicators: A Methodological Guide. European Commission, Luxembourg.

EUROSTAT, 2012. EuroStat—Forestry Statistics Database. European Commission, Luxembourg.

Easterling. W., Aggarwal. P., Batima. P., Brander. K., Erda. L., Howden. S., Kirilenko. A., Morton. J., Soussana. J., Schmidhuber. J., Tubiello. F., 2007, Food, Fibre & Forest Products. In: Parry. M., Canziani. O., Palutikof. J., van der Linden. P., Hanson. C., (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmen, Cambridge, Cambridge University Press, pp. 273–313.

Erb, K., Haberl, H., Plutzar, C., 2012. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation & political stability. Energy Policy 47, 260–269.

Eurelectric, 2011, Biomass 2020: Opportunities, Challenges & Solutions, Found Online at: 〈http://www.eurelectric.org/media/26720/resap_biomass_2020_8-11-11_prefinal-2011-113-0004-01-e.pdf〉.

European Commission, 2006, The Promotion of the Use of Energy from Renewable Sources, Brussels.

European Commission, 2006, Renewable Energy Roadmap: Renewable Energies in the 21st Century, Brussels.

European Commission, 2006, Communication from the Commission—An EU Strategy for Biofuels, Brussels.

European Commission, 2008, 20 by 2020, Europe's Climate Change Opportunity, Brussels.

FAO, 2011. FAO Statistics Food Commodity Datasets. Food & Agriculture Organization.

Faaij, A., 2006. Bio-energy in Europe: changing technology choices. Energy Policy 34 (3), 322–342.

Fischer, G., Hizsnyik, E., Prieler, S., Van Velthuizen, H., 2007. Assessment of Biomass Potentials for Biofuel Feedstock Production in Europe: Methodology & Results. European Union Refuel Program.

Foresight, 2011a, Foresight Project on Global Food & Farming Futures—Synthesis Report C4: Food System Scenarios & Modelling, Department for Business Innovation & Skills, London.

Foresight, 2011b. The Future of Food & Farming: Challenges & Choices for Global Sustainability. Department for Business Innovation & Skills, London.

Forestry Commission, 2011. The UK Forestry Standard: The Government's Approach to Sustainable Forestry'.

Forestry Commission, 2012a, Forestry Statistics: A Compendium of Statistics about Woodland, Forestry & Primary Wood Processing in the UK, Bristol.

Forestry Commission, 2012b, Restocking in the Forecast, Forecast Technical Document, Bristol.

Forestry Commission, 2012c, GB 25 Year Forecast of Standing Coniferous Volume & Increment, National Forest Inventory Report, Bristol.

Forestry Commission, 2012d, Forecast Types, Forecast Technical Document, Bristol.

Forestry Commission, 2012e, Growing Stock Volume Forecasts, Forecast Technical Document, Bristol.

Forestry Commission, 2012f, 25 Year Forecast of Softwood Timber Availability, National Forest Inventory Report, Bristol.

Forestry Commission, 2012g, Volume Increment Forecasts, Forecast Technical Document, Bristol.

Forestry Commission, 2012h, Felling & Removals Forecast, Forecast Technical Document, Bristol.

Giljum, S., Behrens, A., Hinterberger, Lutz, C., Meyer, B., 2008. Modelling scenarios towards a sustainable use of natural resources in Europe. Environ. Sci. Policy 11 (3), 204–216.

Godfray, H., Beddington, J., Crute, I., Haddad, L., Lawrence, L., Muir, J., Pretty, J., Robinson, S., Thomas, S., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

Goldberg, E., Kirby, K., Hall, J., Latham, J., 2007. The ancient woodland concept as a practical conservation tool in Great Britain. J. Nat. Conserv. 15, 109–119.

Greyson, J., 2007. An economic instrument for zero waste, economic growth & sustainability. J. Cleaner Prod. 15 (13–14), 1382–1390.

Hill, J., Shaw, B., Hislop, H., 2006. A Zero Waste UK. Green Alliance, London.

Hoogwijk, M., Faaij, A., Eickhout, B., 2005. Potentials of biomass energy out to 2100 for four IPCC SRES land-use scenarios. Biomass Bioenergy 29, 225–257.

IEA, 2006. Energy Technology Perspectives: Scenarios & Strategies to 2050. International Energy Agency.

IEA, 2008. Energy Technology Perspectives: Scenarios & Strategies to 2050. International Energy Agency.

IEA, 2011. Sustainable International BioEnergy Trade: Securing Supply & Demand. International Energy Agency.

IEA, 2013, Redrawing The Energy-Climate Map, International Energy Agency.

IEEP, 2011. Securing Biomass for Energy—Developing an Environmentally Responsible Industry for the UK Now & into the Future. Institute for European Environmental Policy.

Ignaciuk, A., Vohringer, F., Ruijs, A., Ierland, E., 2006. Competition between biomass & food production in the presence of energy policies: a partial equilibrium analysis. Energy Policy 34, 1127–1138.

Kraxner, F., Norstom, E., Havlik, P., Gusti, M., Mosnier, A., Frank, S., Valin, H., Fritz, S., Fuss, S., Kindermann, G., McCallum, I., Khabarov, N., Bottcher, H., See, L., Aoki, K., Schmid, E., Laszlo, M., Obersteiner, M., 2013. Global bioenergy scenarios—future forest development, land-use implications, & trade-offs. Biomass Bioenergy TBC (TBC), pp. TBC.

Ladanai, S., Vinterback, J., 2009. Global Potential of Sustainable Biomass for Energy. Department of Energy & Technology, Uppsala.

Lal, R., 2006. Soil & environmental implications of using crop residues as biofuel feedstock. Int. Sugar J. 108, 161–167.

Larsen, L., Jepsen, M., Frederiksen, P., 2013. Scenarios for biofuel demands, biomass production & land use—the case of Denmark. Biomass Bioenergy 55, 27–40.

Lattimore, B., Smith, C., Titus, B., Stupak, I., Egnell, G., 2009. Environmental factors in woodfuel production: opportunities, risks, & criteria & indicators for sustainable practices. Biomass Bioenergy 33 (10), 1321–1342.

Mambre. V., 2009, Biomass gasification for production of "green energy". In: 24th World Gas Conference 2009, Argentina.

Marques, A., Fuinhas, J., 2012. Is renewable energy effective in promoting growth? Energy Policy 46, 434–442.

McKay. J., 2003, Woodfuel Resource in Britain, DTI, Scottish Enterprise, Welsh Assemble, Forestry Commission.

Means, E., Patrick, R., Ospina, L., West, N., 2005. Scenario planning: a tool to manage future water utility uncertainty. J. Am. Water Works Assn. 97 (10), 68–75.

Mookerjee, R., 2006. A meta-analysis of the export growth hypothesis. Econ. Lett. 91 (3), 395–401.

NNFCC, 2010. Techno-Economic Assessment of Biomass 'Densification'. Technologies, National Non-Food Crops Centre, York.

Panoutsou, C., Eleftheriadis, J., Nikolaou, A., 2009. Biomass supply in EU27 from 2010 to 2030. Energy Policy 37 (12), 5675–5686.

Phillips, P., Tudor, T., Bird, H., Bates, M., 2011. A critical review of a key waste strategy initiative in England: zero waste places projects 2008–2009. Resour. Conserv. Recycl. 55, 335–343.

Pires, A., Martinho, G., Chang, N., 2011. Solid waste management in European countries: a review of systems analysis techniques. J. Environ. Manage. 92, 1033–1050.

Prieler. S., 2011, Built-Up and Associated Land Area Increases in Europe, MOSUS Model: WP3—Environmental Evaluation, International Institute for Applied Systems Analysis, Luxemburg.

Rowse, J., 1986. Constructing a supply function for a depletable resource. Resour. Energy 10, 15–29.

Schellnuber. H., Kokott. J., Beeses. F., Fraedrich. K., Klemmer. P., 1999, Conservation & Sustainable Use of the Biosphere, Bremerhaven.

Scottish Forest Industries Cluster, 2013, Scotland's Forest Industries, Forest Industries Development Council & Scottish Enterprise.

Shoene, D., Bernier, P., 2012. Adapting forestry & forests to climate change: a challenge to change the paradigm. For. Policy Econ. 24, 12–19.

Slade, R., Bauen, A., Gross, R., 2010. Prioritising the Best Use of Biomass Resources: Conceptualising Trade-Offs. UK Energy Research Centre, London.

Slade. R., Saunders. R., Gross. R., Bauen. A., 2011, Energy from Biomass: the Size of the Global Resource, Imperial College Centre for Energy Policy & Technology, UK Energy Research Centre, London.

Smeets, E., Faaij, A., Lewandowski, I., 2004. A Quickscan of Global Bio-Energy Potentials to 2050. Copernicus Institute, Utrecht.

Smith, K., Charles, D., Moorhouse, D., 2000. Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground surface waters—Part 2: Pigs & poultry. Bioresour. Technol. 71, 183–194.

Smith, K., Charles, D., Moorhouse, D., 2000. Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground surface waters—Part 1: Cattle & sheep. Bioresour. Technol. 71, 173–181.

Smith, P., 2013. Delivering food security without increasing pressure on land. Global Food Secur. 2 (1), 18–23.

Steininger, K., Wojan, T., 2011. Economic impact of bioenergy development—some evidence from Europe and the US. EuroChoices 10 (3), 31–37.

Stupak, I., Lattimore, B., Titus, B., Smith, T., 2011. Criteria & indicators for sustainable forest fuel production & harvesting: a review of current standards for sustainable forest management. Biomass Bioenergy 35 (8), 3287–3308.
Thomas, V., Choi, D., Luo, D., Okwo, A., Wang, J., 2009. Relation of biofuel to bioelectricity & agriculture: food security, fuel security, & reducing greenhouse emissions. Chem. Eng. Res. Des. 87, 1140–1146.
Thornley, P., Tomei, J., Upham, P., et al., 2008. Supergen Biomass & Bioenergy Consortium: Theme 6 Resource Assessment Feedstock Properties. Supergen, Tyndall Centre Manchester, Kings College, London.
Thran, D., Seidenberger, T., Zeddies, J., Offermann, R., 2010. Global biomass potentials—resources, drivers & scenario results. Energy Sustainable Dev. 14 (3), 200–205.
Twidell, J., Weir, A., 1986. Renewable Energy Resources, second ed. Taylor & Francis Publishing.
UK Government, 2008, UK Climate Change Act, Chapter 27, London.
UNEP, 2009. World Database on Protected Areas. United Nations Environment Programme.
United Nations, 1998, Kyoto Protocol to the United Nations Framework Convention on Climate Change, Found Online at: ⟨http://unfccc.int/resource/docs/convkp/kpeng.pdf⟩.
United Nations, 2010, World Population Prospects, Found on at: ⟨http://esa.un.org/unpd/wpp/index.htm⟩.
Upham, P., Riesch, H., Tomei, J., Thornley, P., 2011. The sustainability of forestry biomass supply for EU bioenergy: a post-normal approach to environmental risk and uncertainty. Environ. Sci. Policy 14 (6), 510–518.
Vermeulen, S., Aggarwal, P., Ainslie, A., Angelone, C., Campbell, B., Challinor, A., Hansen, J., Ingram, J., Jarvis, A., Kristjanson, P., Lau, C., Nelson, G., Thornton, P., Wollenberg, E., 2012. Options for support to agriculture & food security under climate change. Environ. Sci. Policy 15, 136–144.
WPIF, 2010. Wood Fibre Availability & Demand in Britain 2007 to 2025. Wood Panel Industries Federation.
WPIF, 2012, Make Wood Work, Wood Panel Industries Federation.
WRAP, 2009, Wood Waste Market in the UK—Summary Report, Waste & Resources Action Programme.
WRAP, 2011. Wood Waste Market Situation Report—April 2011. Waste & Resources Action Programme.
Welfle. A, Gilbert. P, Thornley. P, 2013, Meeting Bioenergy Targets with Reduced Imports. In: 21st European Biomass Conference & Exhibition, Denmark, Proceedings, pp. 21–29.
Woodland Trust, 2011, The State of the UK's Forests, Woods and Trees, found online at: ⟨http://www.woodlandtrust.org.uk/en/about-us/publications/Documents/state-of-the-uks-forest-report-4865.pdf⟩.