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Implications of sustainability constraints on UK bioenergy development: Assessing optimistic and precautionary approaches with UK MARKAL

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HIGHLIGHTS

- We assess UK bioenergy resources under optimistic and precautionary approaches.
- Using MARKAL, we find that sustainability constraints add to decarbonisation costs.
- Preferred use of bioenergy is similar in optimistic and precautionary cases.
- Best use of bioenergy is heat and power, not transport, if CCS is available.
- The marginal value of additional land availability to the energy system is high.

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ABSTRACT

Bioenergy is an important renewable energy resource. However, assessments of the future of bioenergy are beset with uncertainty and contested values, suggesting that a precautionary approach to bioenergy resource development may be warranted.

This paper uses UK MARKAL to examine the implications of adopting a precautionary approach to bioenergy development in the UK. The paper reports a detailed review of UK bioenergy resources and sustainability constraints, and develops precautionary and optimistic resource scenarios. The paper then examines the implications of these scenarios using the energy systems model MARKAL, finding that a precautionary approach adds to the cost of decarbonisation, but does not significantly alter the optimal technology mix. In particular, biomass and co-firing CCS emerge as optimal technologies across scenarios.

The question of UK land availability for bioenergy production is highlighted within the paper. With less land available for bioenergy production, the costs of decarbonisation will rise; whereas if more land is available for bioenergy, then less land is available for either food production or ecosystem conservation. This paper quantifies one side of this trade-off, by estimating the additional costs incurred when UK land availability for bioenergy production is constrained.

1. Introduction

Bioenergy is widely seen as an important renewable energy resource, with a potentially significant role in enabling decarbonisation in the UK and globally (Chum et al., 2011). Furthermore, bioenergy has been promoted for its potential role in reducing dependence on imported fossil fuels, and providing a role in meeting renewable energy goals, particularly because bioenergy is dispatchable and storable unlike many other forms of renewable energy. However, the sustainability of bioenergy is also contested, with analysts taking different positions about the likely impacts of significant bioenergy use (Thornley et al., 2009; Upham et al., 2011).

This paper is motivated by two related questions. First, what is the best use of the UK's limited bioenergy resource?[1] The development of a bioenergy supply chain is a long-term commitment that requires a supportive policy framework. It is therefore valuable to examine what the best contribution of bioenergy might be under different assumptions, to help policymakers identify appropriate interventions (Slade et al., 2010). One approach to answering this question is presented in this paper, focusing on the application of the UK MARKAL energy system

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[1] This was the guiding question for the socio-economic work of the Supergen Bioenergy Consortium, under which this work was carried out.

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model, which provides insight into the best use of bioenergy in cost-optimal decarbonisation pathways.

Second, given the concerns about the wider sustainability impacts of bioenergy development, it is helpful to understand the role of bioenergy under different assumptions about the degree to which bioenergy development might be constrained on sustainability grounds. There may be trade-offs between the use of bioenergy in reducing energy system decarbonisation costs and other sustainability concerns. Assessing the energy system implications of sustainability constraints on bioenergy development provides insight into the potential significance of such trade-offs, and this paper examines the energy system implications of a scenario in which a precautionary approach is taken to bioenergy development.

In particular, the question of land availability for bioenergy production raises a clear potential sustainability trade-off: with less land available for bioenergy production, the costs of decarbonisation will rise; whereas if more land is available for bioenergy, then less land is available for other uses such as food production and ecosystem conservation. Here, one side of this trade-off is quantified. That is, the paper estimates the additional energy system costs incurred when UK land availability for bioenergy production is constrained.

The paper first presents the background and conceptual approach, describing the utility of energy systems models and the value in assessing a precautionary approach to bioenergy development. In Section 3, the paper then presents a detailed resource assessment, highlighting uncertainties, and setting out a precautionary and optimistic assessment of the UK's bioenergy resource. The paper then turns to an application of UK MARKAL, setting out the methods and scenario development in Section 4 and results in Section 5. Finally, Section 6 concludes the paper, highlighting key insights and limitations of the analysis.

2. Background and approach: Using energy system models to inform bioenergy technology choice and policy

Energy system models are powerful tools that provide insight into the potential importance of particular technologies or policy options, or the sensitivity or robustness of particular pathways to different assumptions. In particular, energy system models can provide one answer to the question 'what is the best use of the UK's bioenergy resource?'. There are many other ways of addressing this question. Slade et al. (2010) provide a conceptual review of approaches to prioritising bioenergy use, identifying the key performance metrics on which bioenergy pathways are typically compared (such as marginal abatement cost [£/tCO_2]; or energy cost [£/MJ]) and highlighting the challenges of each approach. Using an energy system model overcomes some of these difficulties by incorporating feedbacks and trade-offs between other energy sources and sectors. This is useful for policymakers, including both those who must make regulatory and fiscal decisions that create an investment climate for particular technological options; and those who must determine appropriate levels of R&D investment in particular areas of science and technology, through the process of designing R&D programmes, judging between potential projects and scoping technology deployment and support initiatives.

A dominant frame within the assessment of UK energy policy and technology choice has been cost-effective decarbonisation. In the optimisation framing used in the energy system model MARKAL, 'best use' means the use of bioenergy within an overall cost-optimal decarbonisation solution.

Previous work on bioenergy using the energy systems model UK MARKAL has suggested potentially important roles for bioenergy in heating (Jablonski et al., 2010), and studies that enable the model to invest in biomass carbon capture and storage (CCS) have shown significant uptake of biomass in the power sector (Usher and Strachan, 2010), while those with pessimistic assumptions on biomass CCS show a larger role in transportation (AEA, 2011). However, none of these studies have examined the implications of sustainability constraints for the role of bioenergy in decarbonisation.

2.1. Bioenergy and sustainability: The case for a precautionary approach

The framing above assesses the 'best' use of bioenergy in terms of carbon and cost, in the context of existing UK policy constraints such as the requirement for fuel and electricity suppliers to meet renewable transport fuel and renewable electricity obligations. However, recent studies and policy debates have highlighted a number of other impacts – both positive and negative – associated with the development and use of bioenergy. These issues are typically examined through the broad normative lens of sustainability, referring to environmental, social and economic elements. Impacts associated with the direct, site-specific impacts of bioenergy production, processing and use include: air emissions from biomass or biofuel combustion; extraction and pollution of water resources; life-cycle carbon emissions associated with agricultural inputs, processing and distribution; impacts of biomass cultivation or extraction on biodiversity; carbon and ecosystem impacts of land conversion for biomass cultivation; and impacts on rural development and employment (see for example: RCEP, 2004; Doornbsoch and Steenblik, 2007; Royal Society, 2008; Whittaker et al., 2009; Nuffield Council on Bioethics, 2011). In addition to these direct impacts, the cultivation of bioenergy increases demand for land and other agricultural inputs, leading to indirect effects mediated through prices, including most of the direct impacts above, plus the potential for increased farmer incomes, food price rises and land expropriation from vulnerable populations in response to changing land values (Searchinger et al., 2008; RFA, 2008).

The scale, net effect and likely social and political responses to these issues are all debated vigorously. Analysts and advocates take starkly different positions on both the size and nature of the resource itself, and the best use to which it should be put. At root, these are debates about the sustainability of bioenergy. As Stirling and others have argued (Funtowicz and Ravetz, 1994; Giampietro et al., 2006; Stirling, 1999), attempts to provide a single analytic answer as to which options are 'most sustainable' are doomed to failure where there are both *deep uncertainties* and *plural values*. Both of these conditions apply to the appraisal of bioenergy policy options. First, with regard to uncertainties, Section 3 of this paper demonstrates the very significant uncertainties with respect to bioenergy resources. Many of these uncertainties cannot simply be dealt with using probabilistic methods: Upham et al. (2011) have recently applied a typology of uncertainties (developed by Spiegelhalter and Riesch (2011)) to woody biomass, and illustrate that many issues around woody biomass are beset by indeterminacy and ignorance, as well as analytically tractable uncertainty and risk. The scale of 'incertitude' (i.e., uncertainty and ignorance) with respect to many energy crops, in terms of the life-cycle emissions and overall global potential resource, is very large.

Second, it is clear that the social priorities and values at stake are contested and are not necessarily commensurable. Key issues include the values that individuals and societies ascribe to particular ecosystems, species or landscapes; their aversion to social inequity; their willingness to accept risks associated with air and water pollution; their concern for future generations and for members of non-human species (Wegner and Pascual, 2011).

This suggests that there is value in analysis that examines the implications of taking a precautionary approach to the development of bioenergy. The current paper presents an assessment, using UK MARKAL, of the implications for the UK energy system of restricting bioenergy availability based on a precautionary view of sustainability. Though partial and limited, this approach provides a powerful lens into some key issues in the bioenergy debate, by highlighting the potential trade-offs between particular aspects of sustainability that are raised in the context of specific resources. It should be clear from both the preceding discussion and the resource assessment set out in the next section that the use of an optimisation model in this work is not intended to suggest that it is possible to identify an uncontested optimum energy system. Rather, the MARKAL framework provides a useful way of exploring the potential system dynamics and implications of the uncertainties that exist, through examining alternative scenarios and sensitivities.

3. Resource assessment: UK bioenergy resources and sustainability constraints

This resource assessment draws on those previously conducted both for UK MARKAL (Jablonski et al., 2010) and within the Supergen Consortium (Thornley et al., 2009), but develops these further, drawing on major recent reviews of bioenergy availability (e.g., (AEA et al., 2011; E4Tech, 2009) to enable the application of sustainability constraints in UK MARKAL, and to highlight the uncertainties in resource availability and sustainability. The resource assessment develops two scenarios of resource availability for the UK: an optimistic and a precautionary assessment.

In this analysis, existing resource estimates and projections were re-assessed to examine whether, under a precautionary approach, they could be considered sustainable. The key sustainability constraints and issues for the UK have been identified by Thornley et al. (2009). For this paper, their work identifying sustainability constraints was supplemented with a literature review, and with interviews with 12 expert stakeholders from government, industry, academia and civil society groups. These were not considered to comprise a representative sample, but rather were used to supplement findings from the literature, to identify sustainability constraints seen as most important by key actors in the UK bioenergy innovation system.

The UK bioenergy resource can be characterised as comprising:

- Domestic energy crops and food crops
- Domestic forestry-related resources
- Domestic wastes (municipal, agricultural, commercial and industrial)

A similar breakdown is used for internationally available resources. Two potentially important resources have not been included, because of the lack of good data and the very significant uncertainties regarding their exploitation. These are grass-clippings from rough pasture, which has been highlighted in some top-down studies (EEA, 2006), and which may have important biodiversity and rural economy co-benefits, particularly in UK uplands (Corton et al., 2011); and marine algal resources, which have been included in other resource assessments (HM Government, 2010) but which are subject to very considerable uncertainty (Ratcliff, 2011).

Note that all costs are expressed in year 2000 pounds sterling (£).

3.1. Domestic energy crops and food crops

Various crops in the UK have been grown for energy purposes, including woody crops (such as short rotation coppice willow and poplar), grassy energy crops (miscanthus) and food crops that have been used for fuel production, particularly oil seed rape, wheat and sugar beet.

Over the long-term, energy crops clearly compete with other uses of land, and the availability of such resources therefore depends principally on the economic decisions of farmers concerning which crops will yield the highest economic return, along with regulatory decisions about conservation of natural habitats and agricultural land.

Pepinster (2008) used an economic approach to develop a supply curve for perennial energy crops in the UK. His work generated supply curves for both woody and grassy energy crops based on the price at which farmers would chose to plant them (i.e., the land rent value, or opportunity cost, plus the estimated production cost of the energy crop). The data used here is based on his work, and on that of E4Tech (2009), who provided data on land conversion rates that would represent a plausible maximum increase in the availability of domestic bioenergy resource. The data presented are those assuming no energy crop subsidies are in place, and prices are £0.6/GJ lower if current crop establishment subsidies are included. The full resource potential is not available in early years, as a time lag is used to represent the process of establishing the crops and building up the capacity of the agricultural system to meet this scale of production. A constraint is applied in the model to represent the overall amount of bioenergy that can be produced in any one period, to ensure that land resources are not double-counted.

Pepinster's work is based on the assumption that land use should be determined through farmers responses to market prices and production costs, and that the question of land 'availability' is overcome by developing a supply curve for bioenergy production. Theoretically, all UK agricultural land should therefore be made available to the model. However, this appears implausible given the fundamental strategic importance of domestic food production. In addition, Pepinster's work (and resource assessments built using it, including E4Tech (2009)) effectively assume no change in average land prices in response to significant additional demand for energy crop production. This assumption results in an understatement of the true costs of biocrop development, which becomes particularly acute when very large portions of UK agricultural land are given over to bioenergy. To minimise the effect of this simplification, a constraint is applied, such that it is assumed that an area equivalent to 50%[2] of the UK's agricultural land could be made available for the development of energy crops, if the economics were favourable. This upper limit is applied across all the energy crops included in the model, equivalent to a maximum bioenergy crop production of 401 PJ in 2030, rising to 489 PJ in 2050 based on a 1% per annum yield improvement. These figures are based on a conservative assessment of average yields (10 oven dried tonnes per hectare) and calorific value of dried biomass (17 GJ per oven-dried tonne), and corresponds well to the range identified in Slade et al. (2011a) (Fig. 1).

Data for annual energy crops (wheat, oil-seed rape, sugar beet) are also included in the resource assessment used in this study, with no changes to the data reported in Jablonski et al. (2010), who provided supply curves for each crop, with assumptions made about the amount available for energy purposes.

3.1.1. Sustainability constraints on perennial energy crops

Many stakeholders have raised concerns about the implications of large areas of the UK being transformed from food

[2] This exact figure is inevitably somewhat arbitrary, given the uncertainties around long-term land prices. The importance of this assumption is tested in sensitivity runs.

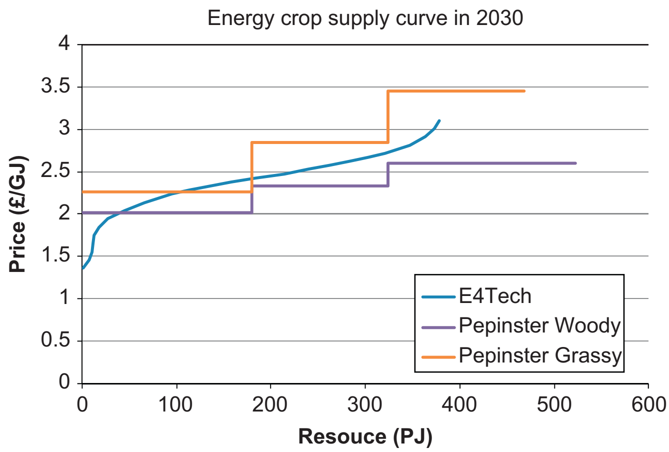

Fig. 1. Supergen supply curves for perennial energy crops, based on Pepinster 2008 and Jablonski et al. 2009, compared with E4tech 2009.

production to energy crop production, because of both direct and indirect impacts. In particular, there is a concern that land taken out of food production results in either land conversion to agricultural uses elsewhere or food price rises with impacts on the poor. This concern has frequently been used to suggest that limits should be placed on the availability of land for bioenergy purposes (RFA, 2008; Malins, 2011).

Many studies attempt to define a sustainable land area for bioenergy using a 'land release' approach, in which projected gains in crop yields are assumed to 'free up' land for bioenergy (e.g., (EEA, 2006); AEA et al., 2011; Slade et al., 2011a), since this is land that would no longer be required for the cultivation of food. This approach has been used for both UK and global resource assessments. The available areas of land, and resulting yields of bioenergy, depend heavily on assumptions made about agricultural productivity gains, and about global diet, income, population and hence food prices. They also depend on assumptions about alternative competing uses of land, such as urbanisation and leisure-focused green space. In short, there is only rather contested evidence on either the most likely or most desirable use of the land surplus (or decline in land values) arising from assumed agricultural yield improvements. Indeed, some studies suggest that yield improvements are unlikely to keep pace with rising demand, resuling in a global land deficit rather than surplus; see Smith et al., 2010 for a discussion). Assuming that this surplus, if indeed it is realised, is necessarily all available for bioenergy developments does not conform to a strict precautionary approach, since it is quite possible that in many cases other uses will be more desirable from a sustainability perspective[3] .

A precautionary approach to bioenergy development suggests that the area of land dedicated to bioenergy should be limited, and that surplus land created for bioenergy should be prioritised for reversing the already unsustainable intensity of land use. This does not mean that energy crop development necessarily has negative consequences, and indeed there is evidence to suggest that certain perennial bioenergy crops can have positive impacts on soil carbon (CCC, 2011) and biodiversity. Rather, the purpose of the precautionary view taken here is to illustrate the scale of impact on the energy system of taking a cautious approach to the development of the UK's bioenergy resources, given the significant uncertainties that exist.

In our strictly precautionary approach, the analysis in this paper therefore follows the UK government's 2007 Biomass Strategy, which suggested that 350,000 ha could be made available for bioenergy. The origins of this number are somewhat cloudy (Slade et al., 2011a; Slade et al., 2011b), but (Lovett et al., 2009) found that energy crop planting on this scale would entail very minimal negative sustainability impacts.

Food crops (wheat, sugar beet and oil seed rape) are not available as energy resources in the precautionary scenario, as many stakeholders view the direct effect on food prices as unacceptable. This was a key concern raised by stakeholders interviewed. Furthermore, the emissions associated with indirect land-use changes caused by displaced agricultural production are thought to be very significant for oil-seed rape, and non-negligible for wheat (CCC, 2011).[4]

3.2. Domestic forestry resources

MARKAL includes two types of UK forest-derived biomass: forestry residues and wood logs from forestry. As with domestic energy crops, there is significant uncertainty about the future availability of energy resources from forestry. Literature sources use different methodological approaches, and make different assumptions about alternative uses, extraction efficiencies and other important factors. A range of recent estimates is shown in Fig. 2. As noted by Slade et al. (2011a), the resource estimates tend to rely on a small number of original data studies. In this case, the figures from HM Government, E4Tech, and Thornley et al. are all based on differing interpretations of Mckay et al. (2003), with different assumptions made about realistic recovery rates and replanting rates. De Wit and Faaij (2008) adopts a different approach, ultimately relying on year 2000 FAO figures (figure here as cited in Slade et al., 2011a). The resource assessment used for the MARKAL analysis in this paper is based on E4Tech (2009).

3.2.1. Sustainability constraints on domestic forestry resources

From a sustainability perspective, woodland ecosystems rely in the long-term on the cycling of nutrients through decomposition of organic matter. The volume of material that can be sustainably removed from woodland systems is therefore limited. The resource assessment on which the E4Tech data are based (Mckay et al., (2003)) did take into account environmental constraints on resource extraction, and is considered to be a conservative assessment (Mackie, 2011, pers. comm.). Therefore, no changes are made to the resource availability in the precautionary scenario.

3.3. Agricultural wastes

Four types of agricultural residues are included in our model: straw, poultry litter, slurry and 'additional agricultural wastes', which refers largely to wastes arising from vegetable crop harvesting and processing. For the optimistic case, these resources were all based on Jablonski et al. (2010), in which the

[3] In other words, there is a sustainability 'opportunity cost' associated with using land released from food production for bioenergy cultivation: land no longer required for food production can enable a combination of agricultural extensification, reducing material and energy inputs into agriculture, and greater commitment of land to biodiversity conservation, either through the creation of additional nature reserves, or through mechanisms such as field-margin wild-flower schemes. Given continued loss of biodiversity across the developed and developing world, it can be argued that land freed up from food production should be used to improve the sustainability performance of land use, rather than be seen as land that is 'free' for other extractive uses.

[4] Emissions associated with indirect land-use changes are, of course, highly uncertain and contested, and other studies have reached conclusions that differ somewhat from those of the CCC (e.g., E4Tech, 2010b). However, in order to conform to a precautionary approach in the face of these uncertainties, food crops are not made available in the precautionary assessment.

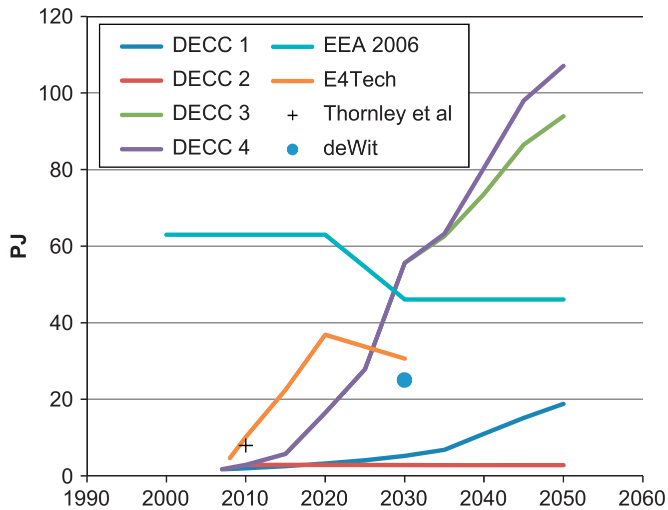

Fig. 2. Resource assessments for forestry-derived energy resources. The four DECC pathways are taken from HM Government (2010).

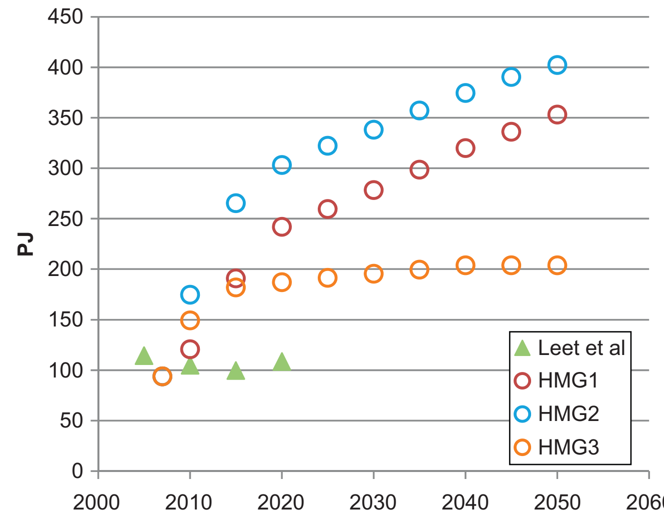

Fig. 3. Assessments of fossil-derived combustible wastes, from Lee et al. (2005) and HM Government (2010).

estimates are based on De Wit and Faaij (2008) and EEA (2006). For the precautionary case, changes were made to the volume of straw available. It was assumed that more straw should be left in situ, due to concerns over soil organic carbon. In the precautionary scenario, this resource is restricted to 18 PJ per year, rather than 95.6 PJ per year in the optimistic scenario, following Thornley et al. (2009).

3.4. Industrial, commercial and residential sector wastes

Any assessment of waste resources is complicated by the heterogeneity of the resource. Waste resources include combustible and non-combustible portions, and the combustible portion is again classified as biogenic waste (paper, food waste, etc), which is considered to be renewable bioenergy since it is derived from the biomass, and fossil-derived waste (plastics), which is not considered renewable[5]. Different parts of the waste stream can be used for different energy purposes, and a wide variety of techniques can be used for separation, processing and recycling. Given significant uncertainties about likely future waste origination rates, recycling rates, and incentive structures for separation, it is difficult to generate good estimates of the future availability of many kinds of waste. Data collection has, historically, been poor. A further complexity arises in consideration of landfill gas. In the short term, the rate of landfill gas production in landfills is dependent on the current stock of decomposing matter in landfills, but future availability will depend on diversion from landfill. Consistent scenarios of long-term waste availability and landfill gas availability are therefore desirable.

Several estimates are available for assessing possible waste futures (Lee et al., 2005; WRAP, 2007; HM Government, 2010; ERM and Golder, 2006; E4Tech, 2009; Penumathsa and Premier, 2008). The resource assessments from these studies are illustrated in Figs. 3–6. HM Government (2010) provides three ‘trajectories’ for the UK’s waste resource, providing a coherent resource assessment for bio and fossil-derived dry waste, waste suitable for anaerobic digestion, and the resulting landfill gas production, and is therefore used in this study. No costs are assumed for waste resources, as the costs of collection and processing waste prior to entry into the energy system are

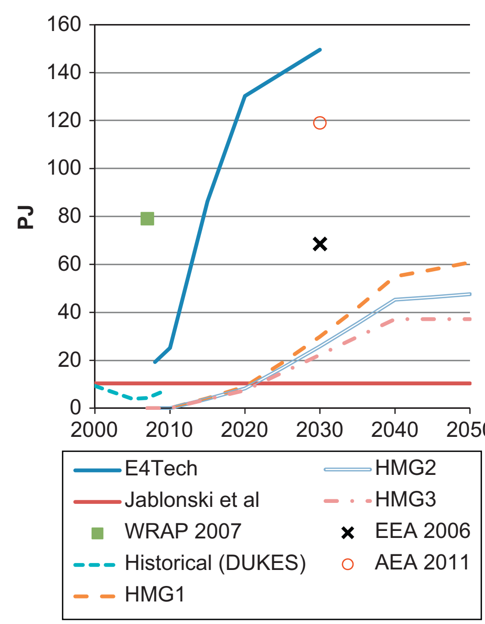

Fig. 4. Assessments of waste wood.

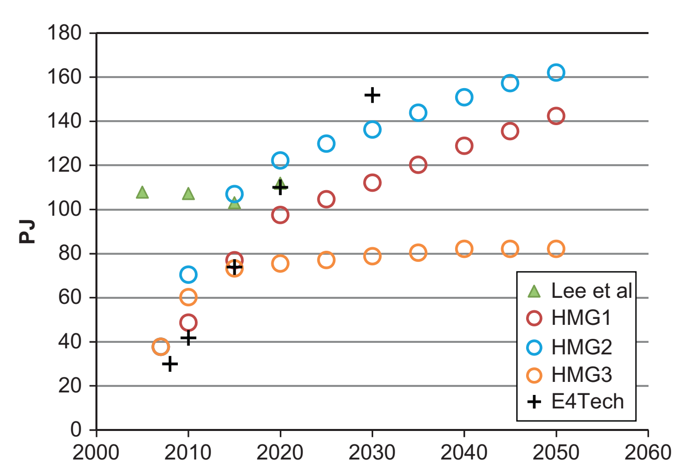

Fig. 5. Assessments of dry bio waste, not suitable for anaerobic digestion.

[5] Fossil-derived waste is not bioenergy. However, the resource is given explicit treatment here to ensure consistent treatment across the energy-from-waste representation in UK MARKAL.

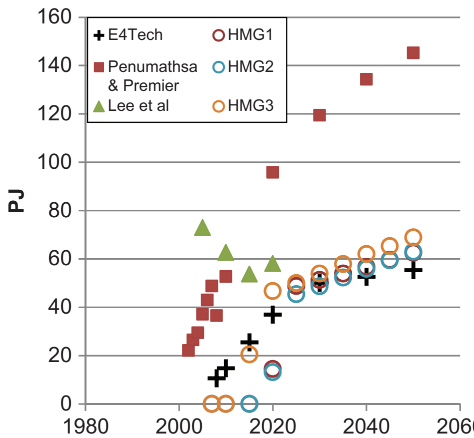

Fig. 6. Assessments of wet bio waste suitable for anaerobic digestion.

assumed to be offset by avoided landfill taxes and tipping fees, in order to simplify the analysis. This assumption is justified currently, given high landfill taxes and low market demand for waste resources, but it is possible that in the longer term further markets will develop for waste resources, which would create higher costs for the use of waste resources for energy purposes. Ideally, the representation of the waste sector would include separation technologies, landfills and explicit representation of the costs and competing uses of waste for energy, but this was judged to be beyond the scope of this work.

3.4.1. *Sustainability constraints on the use of waste resources*

Specifying a precautionary sustainable waste scenario is perhaps even more challenging than for other forms of bioenergy, since energy from waste has been framed by different groups as both deeply unsustainable and as sustainable (e.g., see (Shove and Walker, 2007)). It is possible that a sustainability-oriented scenario sees greater availability of wastes for bioenergy, since it might assume greater effort is put into diverting wastes from landfill. On the other hand, it is equally possible that sustainability concerns limit waste arisings, because further efforts are put into diverting wastes into recycling, or preventing the creation of wastes in the first place. The analysis presented here adopts the 1st and 3rd resource 'trajectories' envisaged by HM Government (2010), since these represent internally consistent scenarios in which priority under sustainable scenarios is given to recycling and the diminution of waste arisings. The 3rd trajectory is treated as a precautionary assessment of the waste resource available for energy purposes.

3.5. *Landfill gas and sewage gas*

Landfill gas is explicitly represented as a resource. Several estimates of landfill gas production have been made (see Fig. 7; (AEA et al., 2011; E4Tech, 2009; ENVIROS, 2005; HM Government, 2010; SKM, 2008)), with variation depending on assumptions made about future landfill diversion rates, and about the availability of the resource in terms of plausible gas capture rates. Only HM Government (2010) and AEA et al. (2011) estimates regarding the landfill gas resource have been developed in a consistent manner alongside the resource assessments for municipal and other wastes. The data used in this study follows the HMG trajectories (HM Government 2010), as these provide consistency of scenarios across the waste resources.

Sewage sludge is also represented in the model. The data are updated based on the figures in HM Government (2010), which fall between the estimates of E4Tech (2009) and (Jablonski et al., 2010).

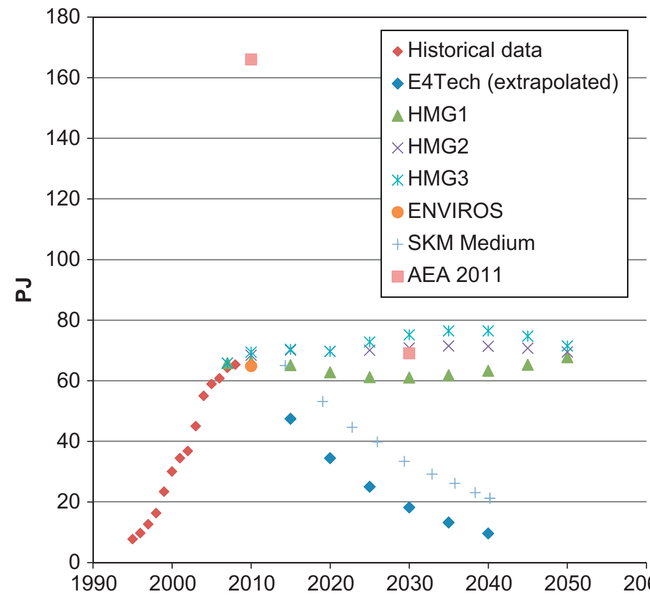

Fig. 7. Historical and estimated future landfill gas resource in the UK.

3.6. *Imported bioenergy*

Given the limited bioenergy resources available in the UK, it is very likely that any significant domestic use of bioenergy would involve imports. Developing an appropriate scenario for bioenergy imports is not straightforward, since the availability and costs of particularly kinds of bioenergy feedstock and product depend on profoundly uncertain global trends in food markets, energy markets, and global emissions policies (Slade et al., 2011a). It follows that the resource assessment used here should be seen as one possible illustrative scenario, rather than a robust projection of a likely future resource.

The basic analytic difficulty in specifying a supply curve for imports is that the true supply curve will be generated through patterns of global demand and supply, on which the UK is likely to have only marginal influence. The modelling challenge is to provide a coherent representation of the supply curve as it is likely to be experienced by the UK. If a global supply curve was used without restriction in the model, this would enable the model to select very large volumes of low-cost bioenergy, as the global volume of material at the lower end of the supply curve is enormous. Instead, this paper follow others (e.g., Perry, 2010) in using global supply cost curves assuming that the UK is likely to be on a similar course as other nations, and that the UK would only be able to access a portion of the global resource at any given price. It is assumed that this portion is 2%, i.e., the supply available to the UK at any given price is 2% of the global figure. This 2% figure is chosen as it corresponds to the UK's current share of global primary energy consumption, and it is the same assumption as has been used by Jablonski et al. (2009) and Perry (2010).

Imported bioenergy is associated with a very wide range of potential sustainability concerns, ranging from the food security of the rural poor to concerns over carbon stocks in tropical soils. Translating these into a MARKAL modelling framework is not straightforward, since the only available 'levers' are cost and availability. Jablonski et al. (2010) increased the costs of all imported bioenergy resources by 50% in their 'sustainable and secure' scenario, and by 25% in their 'global sustainability' scenario, to reflect the cost implications of 'strict certification schemes for ensuring sustainability'. Sustainability-certified timber is reported to be around 10% more expensive than non-certified wood (FSC, 2010), and Smeets and Faaij (2010) have estimated the cost increment for compliance with strict sustainability criteria for coppiced energy crops to be around 15–40%. The cost increment used in this analysis is 25% on the cost of imported energy under the 'strict sustainability' criterion, except where otherwise stated. Bioenergy feedstocks derived from food crops are also excluded in the precautionary scenario, for the same reasons as described for domestic resources.

3.6.1. *Imported derived fuels: Ethanol, biodiesel and bio-oil*

A review of projections for biofuel costs and resource availability shows very large discrepancies between estimates (e.g., Perry, 2010; OECD-FAO, 2010; FAPRI, 2010). For most resources the data of Jablonski et al. (2010) is used, with additional sustainability constraints for the precautionary scenario from Thornley et al. (2009). Imported pyrolysis bio-oil resources estimates are based on those in Jablonski et al. (2010), while the cost data for this resource has been updated based on expert input from partners within the Supergen Consortium (with the cost changed from £3.78/GJ to £6.38/GJ (Thornley, 2010). Fischer–Tropsch biodiesel and biokerosene data are taken from Jablonski et al. (2010). However, Perry (2010) provides a more detailed supply curve for first generation biodiesel than is found in Jablonski et al., and his data better reflects current UK imports. Data for first generation biodiesel (i.e., derived from vegetable oils) are thus based on Perry (2010), with sustainability constraints from Thornley et al. (2009).

3.6.2. *Imported feedstocks and raw fuels: Woody biomass, starch, vegetable oil and wastes*

The global forestry industry yields a significant volume of residue material, typically sold as either pellets or chips. There are considerable uncertainties around both the cost of this resource (see, e.g., different cost estimates in Slade et al., 2011a; E4Tech, 2009, 2010; Jablonski et al., 2010) and its sustainability (Upham et al., 2011). Cost data used in this analysis are based on E4Tech (2009) and E4Tech (2010a). Agro-industrial wastes include waste wood and wastes associated with food processing, such as palm kernel expeller and olive cake. The data used in this analysis is based on Thornley et al. (2009). No differences are applied between optimistic and precautionary scenarios for the agro-industrial waste resource.

4. Methods: Examining the best use of bioenergy using UK MARKAL

4.1. *MARKAL and bioenergy*

MARKAL is a bottom-up, perfect-foresight, least-cost energy system optimisation model with a long pedigree (Fishbone and Abilock, 1981; Loulou et al., 2004). It contains a detailed menu of technology options, and optimises the energy system to meet a set of exogenously defined energy service demands, subject to constraints such as total carbon emissions. In the 'elastic demand' version used in this study, the exogenous energy service demands respond to price signals in the model, using functions that value failure to meet energy service demands (such as keeping houses less warm than residents would like). UK MARKAL has been widely used both in academic research projects and as a key analytic tool in UK energy policy-making (Ekins et al., 2011; Strachan and Kannan, 2008; Usher and Strachan, 2010) and is thoroughly documented (Kannan et al., 2007). The model optimises the energy system by maximising the discounted sum of consumer and producer surplus, which is a measure of societal welfare (Loulou et al., 2004), across the full period, using a social discount rate of 3.5% in line with UK government policy appraisal advice (HM Treasury, 2011). However, it should be clear that this framework is only a partial representation of the costs involved in energy transitions, both because it is a partial equilibrium rather than general equilibrium model (i.e., it reaches an equilibrium in energy markets, not in the rest of the economy), and because many non-monetary costs are excluded, such as externalities associated with air pollution and biodiversity loss. Similarly, the framework does not account for distributional impacts.

UK MARKAL includes a detailed representation of the entire UK energy system. Bioenergy is well represented in the UK MARKAL model, which covers biomass resources, process/conversion technologies and end-use devices (see Fig. 8 for a simplified overview). The resource module includes nearly 30 resources, including imported and domestic wastes (including agricultural, municipal, and commercial and industrial wastes), various energy crops and forestry products. It also includes second-generation biofuel production technologies, along with a wide variety of energy process and biomass conversion technologies. Bioenergy products are assumed to be available for meeting a range of heat, power and transportation energy service demands.

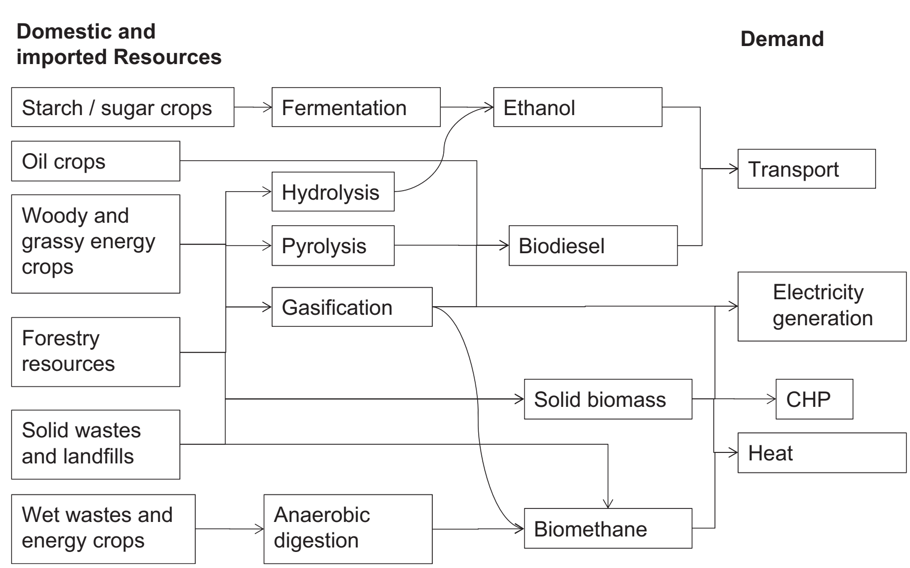

Fig. 8. Simplified representation of bioenergy within MARKAL. CHP=Combined heat and power.

Further detail on the representation of bio-energy in UK MARKAL is available in the UK MARKAL documentation (Kannan et al., 2007). Jablonski et al. made considerable improvements to the representation of bioenergy in the UK MARKAL model, through the TSEC-BIOSYS project (see Jablonski et al., 2010), and this paper builds on that work.

4.2. Model improvements: Technology data review

4.2.1. Biomass conversion technologies

The technology data for bioenergy in UK MARKAL was subject to an expert review by the members of the Supergen Bioenergy Consortium. This was supplemented with evidence from the literature. The following changes were made, as reported in McDowall et al. (2010). In summary:

1. Production of biodiesel from lignocellulosic materials via gasification and Fischer-Tropsch was amended to reflect more accurate capital and O&M cost data, with new data based on Bridgwater (2009) and Black and Veatch (2008)
2. Pyrolysis of lignocellulosic biomass data was amended to reflect more accurate cost and efficiency estimates (new data based on (Rogers and Brammer, 2012)).
3. Biomass gasification for electricity was amended to reflect more accurate data on efficiency and annual availability (based on Supergen expert workshop findings; Thornley, 2010).

4.2.2. Representation of waste resources

The work underpinning this paper involved a substantial revision to the representation of waste resources within the MARKAL model, separating resource types (see Table 1):

1. Fossil-derived combustible waste (associated with an emissions factor taken from HM Government (2010))
2. Biogenic wet waste (which is suitable for anaerobic digestion)
3. Biogenic dry waste (which is suitable for combustion or gasification)
4. Wood waste

Table 1
Revised waste resources in UK MARKAL.

Waste fraction	MARKAL identifier	Renewable?	Emissions factor ($ktCO_2e/PJ$)	Available conversion pathways
Wet biowaste (mostly kitchen and food waste)	MINBMSWW	Yes	0	Anaerobic digestion
Dry biowaste (e.g., organic textiles, paper and card)	MINBMSWD	Yes	0	Combustion gasification pyrolysis
Fossil-derived combustible waste (e.g., plastics)	MINFMSW	No	85.56	Combustion gasification pyrolysis
Waste wood	MINWOD	Yes	0	Combustion gasification pyrolysis pelletization

Changes to the structure of waste resources require some changes to energy carriers. A new energy carrier for fossil-derived solid waste 'WSTSNB (Energy carrier 'solid waste-non-bio') has been introduced. WSTS (energy carrier 'Solid Waste') is renamed as WSTSB (energy carrier 'solid waste-bio').

4.3. Defining scenarios for MARKAL

The main scenarios examined in this paper are as follows:

1. **Reference scenario (REF)**. In this scenario, energy service demands are met at least cost, with no carbon constraint. The model is also required to satisfy existing policy measures (such as the Renewables Obligation and Renewable Transport Fuel Obligation).
2. **Low carbon scenario (LCS)**. In this scenario, the model is required to meet the UK's 2050 carbon target, that is, an 80% reduction in carbon emissions from 1990 levels, with an intermediate target of 29% in 2020.
3. **Sustainable bioenergy scenario (SUS)**. This scenario requires the model to meet the 2050 carbon target, and take a precautionary approach to bioenergy development. The precautionary resource assessment is described for each resource in Section 3.

Most of the sustainability constraints applied in the SUS relate to the sustainability of the underlying resources. However, some of the sustainability concerns raised in the literature, and in interviews with stakeholders, concerned the use phase of bioenergy, rather than the cultivation or extraction phase.

First, as noted by Thornley et al. (2009), a key sustainable development constraint on growth in the use of wastes for energy is related to social acceptability of energy-from-waste plant. This conclusion was re-iterated by the stakeholders interviewed for this study. Rather than apply a limit on the overall capacity of energy from waste plant, as suggested by Thornley et al., 10% is added to the capital cost of waste-to-energy plant, in order to represent the costs of additional emissions controls necessary to assuage public concerns. This additional cost is based on a conservative reading of the figures in Stantec (2011), and represents the an estimate of the cost difference between the technology that just meets regulatory requirements and that which provides the most stringent emissions controls considered practical (the Stantec figures suggest a 6% cost increment for the best-available emissions control).

Second, the air quality implications of wood fuel use for heating have been an important restriction on wood fuel in many regions. In the precautionary scenario, the constraint on the use of woodchip and pellet boilers is tightened, such that only 15% of residential heating demand can be delivered using these technologies.

4.4. Examining key sensitivities

Finally, an important, though limited (Saltelli and Annoni, 2010), response to uncertainties is to conduct a sensitivity analysis to examine the robustness of the findings to key parameter uncertainties. This paper therefore also reports on the sensitivity of the results to some key uncertainties highlighted during the analysis.

First, the sensitivity of findings to UK land availability is tested, and the LCS is run with four possible constraints on UK land use. The four scenarios are as follows, each applied to the LCS. Note that the land area is the upper limit, not the area that is necessarily planted in any given scenario.

1. 2.3 million hectares (Mha) available, equivalent to 50% of arable land.
2. 1.58 Mha available. This is the area identified by the EEA (2006) as a likely 'sustainable' level of UK land for bioenergy
3. 1.08 Mha. This is the area identified by E4Tech in their 'high sustainability' scenario (E4Tech, 2009)
4. 0.35 Mha. This is the area identified in the UK Biomass Strategy 2007.

Second, the sensitivity of findings to the availability of CCS for biomass and co-firing is tested. In this sensitivity run, the LCS is run without the possibility of biomass or co-firing with CCS.

5. Results and discussion

Bioenergy plays a significant role even in the Reference Scenario (REF), in which energy service demands are met at the least economic cost, without carbon constraints being applied, although some of this uptake is driven by the representation of existing policy instruments, such as the Renewables Obligation to 2015 and the Renewable Transport Fuel Obligation. In particular, in the reference case, wastes and woody energy crops are used in heating, and in the power sector.

5.1. *"Best use" of bioenergy in decarbonisation: The optimistic case*

The low carbon scenario (LCS) sees a very significant increase in the contribution of bioenergy to the UK's energy demands over the next forty years. Four resources are particularly important (see Fig. 9):

- Wastes, which require the development of significant waste management and sorting infrastructure.
- Domestic energy crops, which require a credible long-term policy signal to encourage farmers to take the significant risks associated with perennial energy crop establishment.
- Imported energy crops, which become cost effective only once marginal abatement costs have risen to £36/tCO_2e.
- Imported bio-pyrolysis oil, which the model selects as a cost-effective option for decarbonising the industrial sector, where it replaces light fuel oil.

The LCS scenario sees considerable uptake of bioenergy in the power sector, with co-firing with CCS a key technology in enabling decarbonisation. As a result, net emissions from the power sector are negative from 2040 onwards. There is also

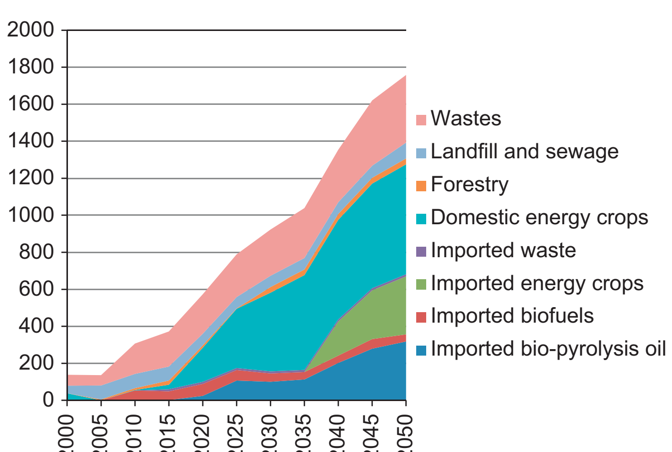

Fig. 9. Bioenergy resources used in the least-cost decarbonisation scenario.

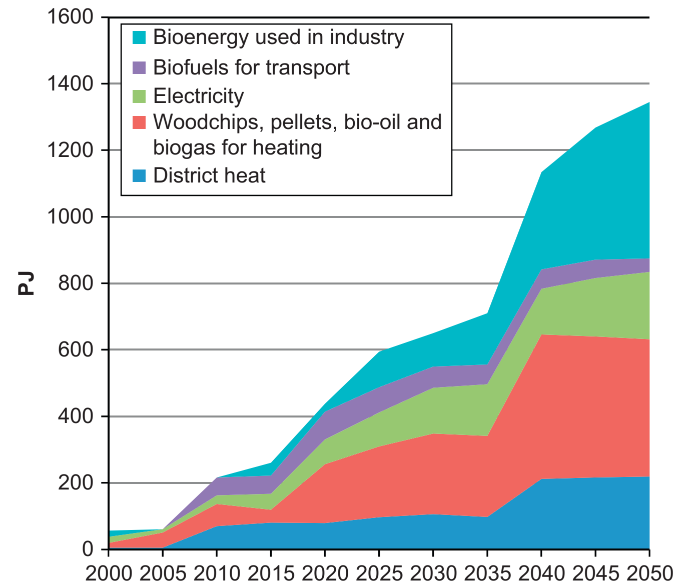

Fig. 10. Bioenergy use, by final fuel.

considerable uptake of bioenergy in residential and service sector heating, both in biomass boilers and through use in district heating. Bioenergy is not selected as a least cost technology for decarbonising the road transport sector. This is in part because deep decarbonisation of the power sector, partly enabled through co-firing of biomass with CCS, reduces the pressure on other sectors, and enables the road transport sector to achieve decarbonisation through fuel switching to low-carbon electricity, through deployment of plug-in hybrids and battery electric vehicles.

Fig. 10 shows the use of bioenergy in the LCS. The rapid growth between 2035 and 2040 reflects both increased use of primary bioenergy, and a shift towards using bioenergy feedstocks (particularly wood chips) as a final energy fuel, rather than as a feedstock for the production of other fuels such as electricity or biofuels.

5.2. *Impact of the precautionary approach on energy system choices and costs*

5.2.1. *Changing energy choices*

Despite the very significant changes to the treatment of bioenergy in the precautionary Sustainable Bioenergy Scenario (SUS), the model follows an overall pathway to 2050 that is similar to the optimistic scenario. Bioenergy is largely used in the power sector, with CCS as a key technology, and in residential and service sector heating, both in biomass boilers and in district heating. Rather than significantly alter the shape of the optimal energy system, the model responds to the precautionary constraints by reducing energy demands. One notable difference is a fall in the proportion of bioenergy used as a final fuel for residential and service sector heating (see Fig. 11).

The precautionary approach in the SUS scenario reduces the availability of low-cost biomass, thus raising the cost of meeting energy service demands. In response to higher costs, the model selects further demand reductions to meet the carbon target. These demand reductions have real costs, albeit non-monetary costs. For example, energy service demands associated with residential heating are reduced in this scenario, which can be understood as a continuation of the plight of many low-income people who cannot afford to keep their homes as warm as they would like.

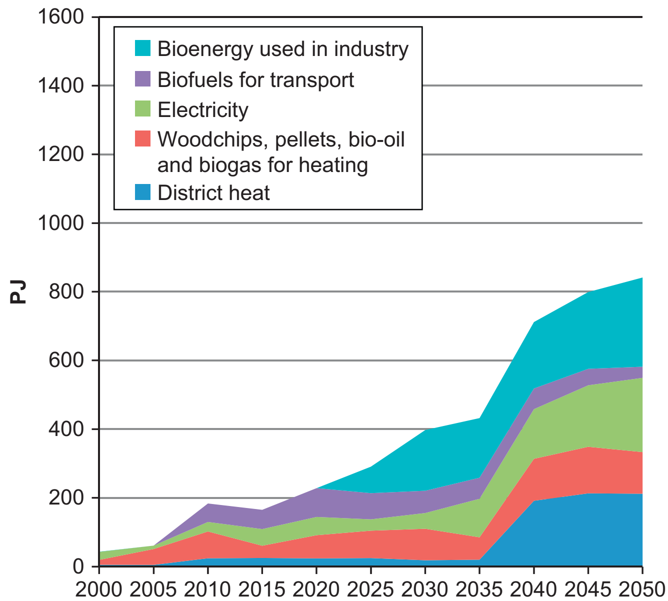

Fig. 11. Bioenergy use by final fuel in the SUS scenario, for comparison with Fig. 10.

There are some small changes to the energy system in addition to these changes in energy demand. For example, the model suggests that earlier deployment of some decarbonisation technologies, such as plug-in hybrid electric vehicles, becomes cost effective in the precautionary scenario.

5.2.2. Impacts of the precautionary case on system costs

The major effect of the precautionary constraints of the SUS scenario is to raise the marginal cost of meeting energy service demands, leading to significant demand reductions, and associated welfare costs. When compared to the total surplus of the energy system (i.e., total consumer plus producer surplus), the effect appears small, with a decrease in discounted total surplus against the reference case of 1.9%, compared to 1.4% in the LCS). However, when expressed as a cost increase relative to the least-cost decarbonisation pathway (LCS), the costs of precaution appear higher (see Fig. 12). The additional total discounted costs of the optimistic LCS decarbonisation pathway compared to the reference case are £40bn, compared with £56bn for the SUS scenario, an increase of over 35%.

The precautionary case necessarily increases the costs of decarbonisation in the MARKAL framework, because the scenario adds costs and constraints to the model. This does not mean that the precautionary approach is more costly to society overall, because the benefits associated with the precautionary approach are not valued within MARKAL. For example, the air quality benefits associated with further limiting residential heating using woodchips are likely to yield significant and highly valued health benefits, and no account is taken on the effects on food prices of limiting land available for energy crops or of benefits to ecosystems.

5.3. Sensitivity to constraints on the availability of land

A particular sustainability concern is the area of land that might be given over to bioenergy production. Four scenarios were developed, each with different levels of constraint on the availability of UK agricultural land for energy crop production, holding other scenario variables constant.

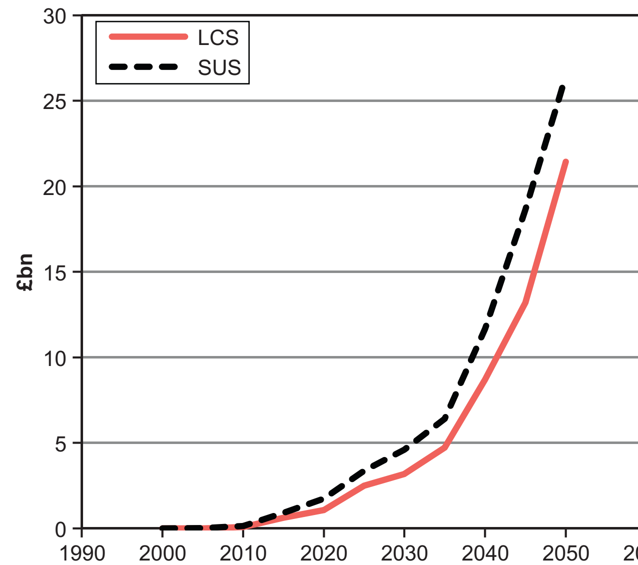

Fig. 12. Shows the increase in cost (losses of consumer plus producer surplus) of LCS and SUS compared to the reference scenario, where LCS is the least cost path to meeting carbon targets, and SUS meets targets while taking a precautionary approach to bioenergy development.

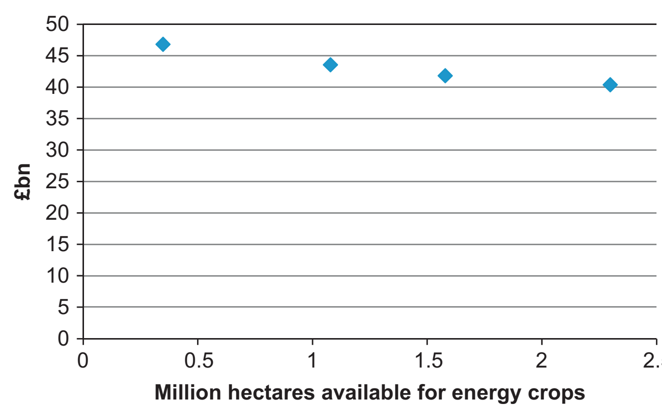

Fig. 13. Relationship of land availability and total discounted welfare cost of meeting the 2050 carbon target (i.e., change from the reference case).

Reducing the area of land available for bioenergy increases the costs of meeting carbon targets while satisfying energy service demands. Fig. 13 shows the relationship between land availability for bioenergy and the overall discounted cost of meeting the 2050 carbon target (i.e., the additional costs as a result of forcing the model to meet carbon targets, for the entire period 2000–2050). Limiting the amount of land available for energy crops increases the overall cost of decarbonisation, but not dramatically. The additional costs of constraining the area of UK land made available to energy crops should be weighed against the alternative, which envisages up to 50% of the UK arable land area could be planted with perennial energy crops. The impacts associated with such a change would be significant, though not all would be negative, and would encompass impacts on food and land prices, biodiversity, rural employment, and other environmental and social impacts. Given the very significant difference in terms of the UK's rural landscape between the scenarios, it is perhaps surprising that the overall difference in cost between the most and least restrictive scenario is only 16%.

Fig. 14 shows the marginal value (i.e., the marginal change in total surplus) of allowing use of additional agricultural land by relaxing the land use constraint. The figure shows that by 2050,

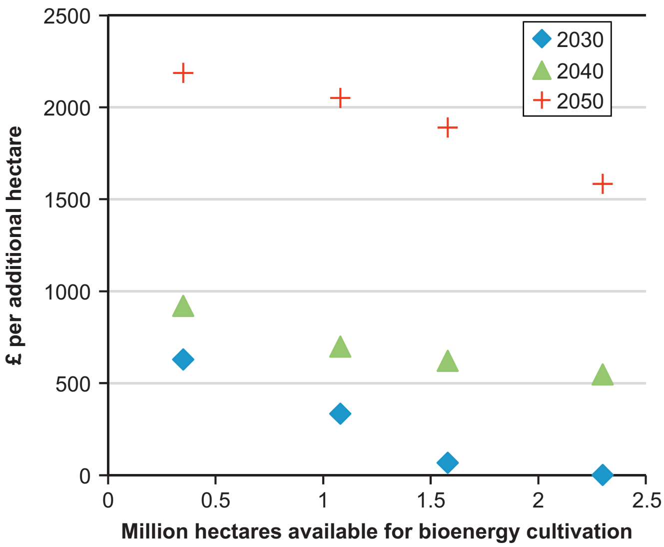

Fig. 14. Marginal system value of additional agricultural land, 2030–2050.

farmers would have a strong incentive to plant more area with energy crops than is allowed by any of the land use constraints (current agricultural land rental prices are around £180 per hectare, (Defra, 2011)). This figure emphasises that, under the assumptions used in the model, there would be significant additional demand for land for bioenergy production by mid-century under a decarbonisation trajectory, with implications for food prices and pressure on land for conservation purposes.

However, it is important to note that the approach used in the paper likely underestimates the future cost of energy crops and thus overestimates their value to the energy system, since it assumes that land prices remain constant (see Section 3.1), and are independent of land use for bioenergy. These conditions are least likely to hold for the scenarios in which significant land take for bioenergy is allowed, which suggests that the relative costs between the 0.35 Mha and 2.3 Mha scenarios are overstated here.

5.4. Sensitivity to the availability of biomass or co-firing CCS

The results discussed so far emphasise the importance of CCS technologies, which when used in combination with biomass (either alone or co-fired) enable negative emissions, with significant implications for the decarbonisation trajectories in other sectors. However, progress in developing CCS demonstration projects has been disappointing in recent years, and the future availability of biomass CCS technologies must be regarded as very uncertain.

In a scenario in which no bio-CCS (or co-firing CCS) is available, the costs of emissions reductions are substantially increased, and the energy system responds by redeploying bioenergy away from the power sector, and to heating, industry and transport. The higher costs lead to more significant demand reductions. This finding, which has also been reported by others (Usher and Strachan, 2010; CCC, 2011) emphasises the potential importance of biomass CCS technology, and suggests that greater research efforts should be placed on assessing and improving the potential for biomass CCS technology.

6. Conclusions

Energy system models provide insights into the role of bioenergy within the context of the UK energy system as a whole. This paper reports on results of MARKAL modelling undertaken as part of the SUPERGEN Bioenergy Consortium, and finds that bioenergy is an important option for heat and power in a least-cost, low-carbon energy system. It appears from these results that bioenergy is less cost-effective as a decarbonisation option in transport. The model instead decarbonises transport by deploying plug-in hybrid vehicles from 2035 onwards, such that around half of all cars are plug-in hybrids by 2050.

It should also be clear that the results are derived from estimates about the future availability and costs of various resources and technologies, all of which are inherently uncertain and many of which are contested, and that the model is an abstracted representation of the way in which energy systems operate, not a 'truth machine'. Given those caveats, three conclusions emerge from the analysis:

- Adopting a strictly precautionary approach to the development of UK bioenergy resources does have impacts on our assessment of the overall costs of UK decarbonisation, increasing costs by around 35% in terms of present value. This cost should be weighed against the benefits associated with the precautionary approach. Importantly, the precautionary approach does not significantly change the overall decarbonisation pathway in terms of the most promising technological options, implying that this pathway, while rather sensitive to other uncertainties (such as the availability of CCS), is robust to a precautionary approach to bioenergy development.
- Turning over large portions of the UK to energy crops does have benefits in terms of reducing the overall costs of decarbonisation, but these benefits are relatively small. The reduction in cost as one moves from the most restrictive land-use scenario (350,000 ha) to the most generous (in which up to 50% of the UK's arable land is available for bioenergy) is only 16%. The difference between the most generous scenario and other scenarios that have been presented in the literature as 'sustainable' is less than 11%. The energy system benefits of making large areas of land available should be weighed against the potentially large impacts of transforming significant parts of the UK to the cultivation of energy crops. In particular, better understanding of the likely biodiversity and other impacts of such development, both positive and negative, is needed.
- CCS with biomass emerges as a key technology for power sector decarbonisation (with biomass contributing up to 25% of the fuel mix in co-firing with CCS). This technology enables negative emissions from the power sector, and allows other parts of the economy to decarbonise less steeply. Removing this technology leads to significant changes in the optimal energy mix, with much more biomass uptake in heating in the medium term and transport in the longer term, and much greater demand reductions necessary to 2050. This suggests both that further efforts to understand the likelihood of CCS availability, and to bring forward CCS technologies, are important research and policy priorities.

There are two important limitations to the present work:

- The modelling framework used is not able to represent interactions of land use, bioenergy prices and food prices, which are mediated through global food and bioenergy markets.
- The work follows energy modelling convention in assuming that bioenergy emissions are offset by the carbon sequestered, without taking into account any emissions associated with land use change.

Insights into these global level interactions – both of which are mediated through food and land prices – are important for policy decisions about the long-term role of bioenergy. Increasingly, researchers are now focusing on the global scale modelling of these interactions, and this is to be welcomed.

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