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The UK bio-energy resource base to 2050: estimates, assumptions, and uncertainties

Working Paper

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function. The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is useful to policymakers.

This report precedes a TPA study of some of the key issues which face the deployment of bio-energy resources in the period to 2050. The objective of this report was to review existing estimates of the UK resource base and identify the most important assumptions and uncertainties affecting estimates of the domestic resource potential. It was envisaged that this would inform the scope of the subsequent bio-energy TPA. A secondary objective was to assist DECC develop bio-energy route maps, promised under the UK's 2009 Low Carbon Transition Plan.

Acknowledgements

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Contents

Acronyms and abbreviations

BEE	Biomass Energy Europe (an FP7 project)
CAP	Common agricultural policy
CHP	Combined heat and power
FP7	The 7th European framework programme for research and development
GHG	Greenhouse gas
LHV	Lower heating value
MSW	Municipal solid waste
RTFO	Renewable Transport Fuel Obligation
SRC	Short rotation coppice
SRF	Short rotation forestry
WRAP	Waste resource action project

Introduction

The British Government has aspirations to increase the use of renewable energy for the provision of heat, power and transport energy services in the UK. In an effort to realise these aspirations it has included bio-energy in its energy and climate policies, as have the Governments of every other country in Europe (Faaij, 2006). Increasing the use of bio-energy appears to be an attractive option because it has the potential to substitute for fossil fuels, reduce greenhouse gas (GHG) emissions, and contribute to other policy objectives such as rural development. There are also many options for providing high value energy services (and energy vectors) from biomass feedstocks using commercially available technologies.

Biomass, however, is a diverse and complex resource. Potential feedstocks include conventional crops and forestry products, residues, waste materials, and specially cultivated energy crops such as coppiced wood and perennial grasses. The availability of these materials tends to be intertwined with activity in other major economic sectors: agriculture, forestry, food processing, paper and pulp, building materials etc., (Faaij, 2006). They may also be produced domestically or imported. Supply-chains for biomass feedstocks are correspondingly complex. This complexity is accentuated by the fact that the composition of the biomass – its chemical structure, moisture content, etc. – is highly variable, and different grades of biomass may have restricted applications or may need to be blended to meet the specifications of a particular conversion technology.

The role that bio-energy may play in the future energy system is thus fundamentally constrained, not only by the availability of biomass, but by the suitability of the biomass that is available to meet a portfolio of competing demands. If bio-energy is to make a meaningful contribution to the UK energy mix, significant and sustained investment will also be needed. In this context, estimates of the current, and future, biomass resource potential underpin many of the strategic investment and policy decisions that must be made. A project developer, for example, must be able to secure a feedstock supply contracts that are acceptable to financiers; for a large facility, this may mean taking a view on how the demand and availability of feedstocks might change over a twenty year period. From a governmental perspective, knowledge of how much biomass is available might be expected to inform the policy process and the development of appropriate interventions.

Yet, addressing the question "how much biomass is available for bio-energy purposes?" is a challenging task, not least because the definition of *availability* is, itself, somewhat ambiguous. There are also many alternative methodologies that can be applied to the problem. Most have some merit, but all have limitations. This paper aims to review existing estimates of the UK resource base and identify the most important assumptions and uncertainties that affect estimates of resource potential. The focus of the paper is limited to the domestically produced feedstocks expected to make a contribution to the 2050 bio-energy resource base. These are: forest materials, agricultural residues and energy crops. Although not the primary focus of this report, wastes materials are also considered.

The paper is presented in 5 parts:

- An overview of biomass resource assessment
- The current contribution from domestically produced biomass to primary energy supply in the UK
- A review of estimates of the UK biomass resource base
- A review of assumptions, data sources, and uncertainties
- Conclusions and recommendations

Estimating the biomass resource potential – an overview of biomass resource assessment

The availability of biomass for energy purposes has been the subject of a great many studies[1]. Assessments have been undertaken at global, regional, and sub-regional scales, and there is general agreement about the most important parameters affecting the contribution that bio-energy might make to primary energy supply. These are: the availability of land, the productivity of the biomass grown upon it, and competition for alternate uses of the land, the biomass, and for the waste materials derived from the biomass (Berndes, et al., 2003). The range of estimates that can be found in Governmental reports and the academic literature, however, is strikingly diverse. At the global level, for example, estimates for the amount of primary energy that might be provided by biomass in 2050 vary from less than $100EJ.yr^{-1}$, to over $1100EJ.yr^{-1}$(Hoogwijk, et al., 2003, Berndes, et al., 2003). These figures compare with an estimated global primary energy supply of $\sim503EJ.yr^{-1}$ in 2007[2] (IEA, 2009).

Reasons for the large range in estimates include the wide variety of methodologies, datasets, and assumptions used to estimate the availability of land, the yield of biomass, and the availability of residues from existing industries. Generally speaking, existing studies may be classified according to the methodologies they employ. The clearest distinction is between estimates of potential that are *resource focussed*, and those that are *demand driven*. Resource focussed studies seek to compile an inventory of biomass resources, based upon assumptions about the availability of supply side resources (principally land) and competition between different uses and markets. Demand-driven studies, on the other hand, focus on the competitiveness of bio-energy compared to conventional energy sources or estimate the amount of biomass required to meet specific, exogenously imposed, targets (Berndes, et al., 2003); this may be accomplished without necessarily specifying the sources of bio-energy used. A distinction may also be drawn between studies based on their

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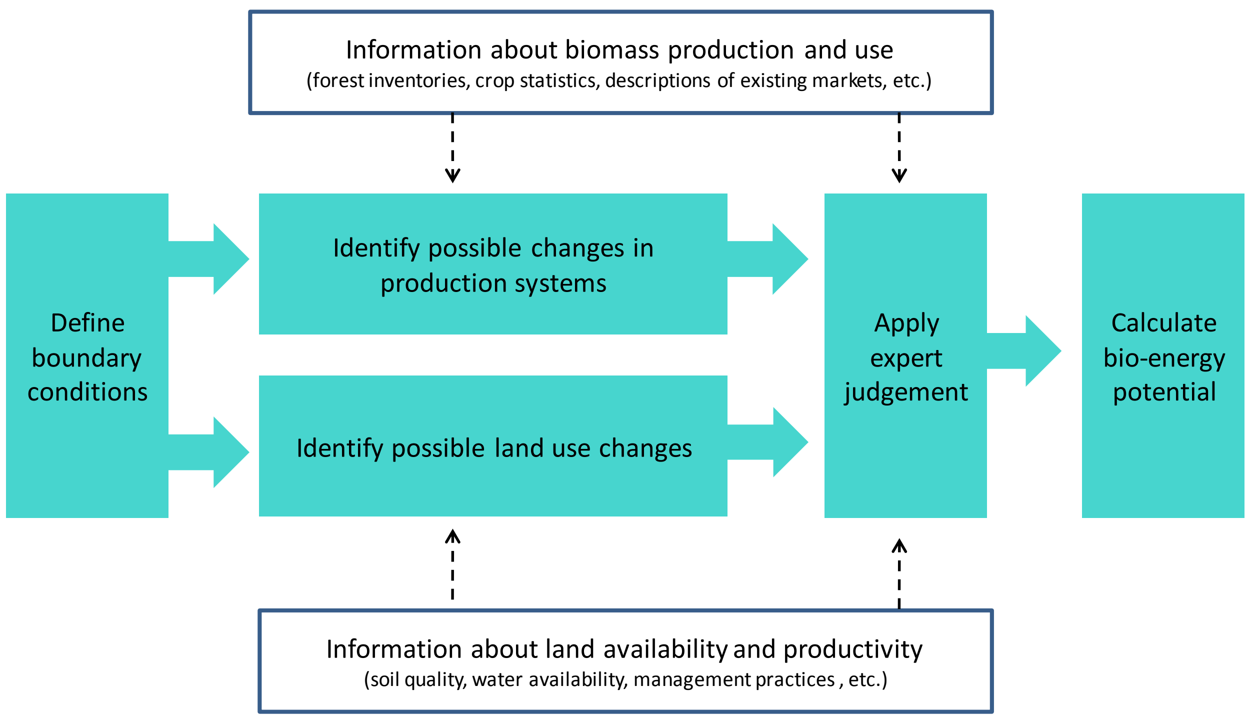
[1] Estimates of potential have been carried out at a global scale by, amongst others, the IPCC, US EPA, World Energy Council, Shell, IASA, and Stockholm Environmental Institute. These reports are reviewed in detail in Berndes et al. (2003).

[2] Of this 503EJ, the IEA estimate that ~9.8% was provided from combustible renewable energy sources and waste.

complexity (Smeets, et al., 2007). The least complex approaches involve the use of expert judgment to estimate the future share of cropland, grassland, forests, and residue streams available for bio-energy. The most complex involves the use of integrated models which allow multiple variables, trade-offs and scenarios to be analysed[3].

A generic approach to assessing the bio-energy resource potential is shown in Figure 1. Crucially, the results of the assessment are highly dependent on the boundary conditions identified at the outset. One of the most important boundary conditions is the definition used for the *availability* of biomass, and some commonly used definitions are listed in Table 1. Another important boundary condition is the range of biomass materials included in the assessment. A distinction is often made between crops and different types of residues, as outlined in Table 2, but here also, methodologies differ and there is no single classification scheme[4].

Figure 1: A typical workflow for a bio-energy resource-potential assessment



Source: adapted from (Lauer, 2009)

[3] Smeets et al. (2007) identify three integrated models that have been used to estimate the future potential of bioenergy: the Global Land Use and Energy Model (GLUE) (Yamamoto, et al., 1999), the Integrated Model to Assess the Global Environment (IMAGE) (Leemans, et al., 1996) and the Basic-Linked System (BLS) model of the world food system (Fischer and Schrattenholzer, 2001a).

4 Although it should be noted that the European Committee for Standardisation is working on a classification scheme for solid biofuels based on the biomass source (CEN/TC-335) (BEC, 2010).

Table 1: Definitions of biomass resource potential

Name	Definition
Theoretical potential / Ultimate potential	Describes the amount of biomass that could grow annually, limited by fundamental physical and biological barriers. The Theoretical potential may change if conditions change, for example, due to climate change.
Technical potential	All you can collect from the theoretical potential (taking into account ecological constraints, agro technological restraints, topographic problems etc. The technical potential may change as technology advances. The technical potential may also be defined as the proportion of the theoretical potential that is not limited by the demand for land for food, housing, etc.
Economic potential	All biomass available up to a specified price level (taking into account the price elasticity of competitors on the market). I.e. the potential at a given price is determined by where the supply and demand curves intersect. This is highly variable as economic conditions may change dramatically over time. Moreover, markets may not exist for many biomass feedstocks, or they may be imperfect.
Realistic potential / Implementation potential	All biomass available without inducing negative social or social economic impacts and respecting technology and market development issues. May be estimated using *recoverability fraction* or *accessibility factor* multipliers, reflecting what is considered the realistic maximum rates of energy use of biomass residues. Deciding what is the most appropriate multiplier to use in any particular instance is often a matter of expert judgement.

Sources: (Smeets, et al., 2007, Fischer and Schrattenholzer, 2001b) (Lauer, 2009)

Table 2: Classification schemes for biomass feedstocks

Energy crops [a]	Conventional crops		Annual crops: cereals, Oil seed rape, sugar beet
	Perennial energy crops		Short rotation coppice willow or poplar, and miscanthus
	Forestry[f] and forestry residues		Short rotation forestry [h]
Primary residues [b, c]			Wood chips from branches, tips and poor quality stemwood
	Agricultural crop residues		Straw from cereals and oil seed rape
Wastes	Secondary residues [b,d]	Sawmill co-product	Wood chips, sawdust and bark from sawmill operations
		Arboricultural arisings	Stemwood, wood chips, branches and foliage from municipal tree surgery operations
	Tertiary residues [b,e]	Waste wood [g]	Clean and contaminated waste wood
		Organic waste	Paper/card, food/kitchen, garden/plant and textiles wastes
		Sewage sludge	From Waste Water Treatment Works
		Animal manures	Manures and slurries from cattle, pigs, sheep and poultry
		Landfill gas	Captured gases from decomposing biodegradable waste in landfill sites

[a] Availability depends on the amount of land dedicated to the crop, and the crop yield
[b] Availability is dependent on activity in other economic sectors.
[c] Harvest residues: typically available 'in the field' and need to be collected to be available for further use.
[d] Processing residues: produced during production of food or biomass materials; typically available in the food and beverage industry.
[e] Post consumption residues: materials that become available after a biomass derived commodity has been used.
[f] Timber from mature forests is generally considered to be too valuable to use for energy purposes
[g] This category may, or may not, be taken to include a fraction of municipal solid waste (MSW)
[h] short rotation forestry may also be considered an energy crop in some schemes
Source: adapted from (Faaij, 2006, Hoogwijk, et al., 2003, E4tech, 2009)

It is important to recognise that bio-energy potential assessments are only comparable if they are based on the same boundary conditions, and the general lack of consistency between estimates has been identified as a cause for concern. In response, the EU FP7 Research Programme is currently sponsoring two projects that seek to harmonize assessment methods and understand the reasons for discrepancies: *Biomass Energy Europe (BEE)* (www.eu-bee.com), and *Classification of European Biomass Potential for Bioenergy Using Terrestrial and Earth Observations (CEUBIOM)* (www.ceubiom.org). Initial results from the BEE project include a review of studies that have sought to estimate the potential for bio-energy in the EU[5]. Analysing the studies in detail, the BEE project team found that the vast majority (>95%) of assessments could be classified as resource focussed, and that the disparities in estimates could be attributed to four key factors:

- Ambiguous and inconsistent definitions of resource potential.
- A lack of consistent and detailed data on (current) biomass production and land productivity.
- Ambiguous and varying methods for estimating (future) biomass production and availability.
- Ambiguous and varying assumptions used to estimate factors external to the modeled system (such as land use and biomass production for food and fiber purposes) that might influence potentials. (BEE, 2008)

It may be anticipated that these same factors will underlie discrepancies in estimates of the UK resource potential.

The current contribution of domestically produced biomass to primary energy supply in the UK

In order to put estimates of the future UK bio-energy potential in context, it is useful to consider the current contribution of renewable and bio-energy to UK primary energy. UK Government statistics estimate that UK consumption of primary energy was 9805PJ in 2008. Renewables contributed 222PJ to this total, of which ~207PJ were obtained from imported and domestically produced biomass. The contribution from domestically produced biomass is somewhat harder to ascertain, but is estimated to be in the region of ~116-170PJ, depending whether municipal solid waste and tyres are included, see Table 3.

[5] The BEE project identified 136 studies that have sought to estimate the potential for bio-energy, of which 66 were considered to be directly applicable to the EU27 (or a subset of Member States), and 7 considered all biomass categories. Those studies which explicitly identified the resource potential in the UK have been included in this review.

Table 3: The contribution of domestically produced biomass to UK primary energy consumption 2008

Resource	Current Use (PJ)
Landfill methane	65.9
Wood	15.0
Sewage gas	10.2
Poultry litter	5.9 [a]
Other Meat, bone & farm waste	6.5 [b]
Wood waste	4.5
Straw	3.0 [c]
Perennial Energy Crops	2.2 [d]
Biodiesel from oilseed rape, tallow and used cooking oil	2.2 [e]
Bio-ethanol from sugar beet	0.8 [e]
MSW, Tyres and "other" plant based biomass	54.6 [f]
TOTAL	170.0

[a] 670,000t annual consumption from 3 plants operated by EPR Ltd. (EPR, 2009). [b] From UK Energy Statistics, less consumption of poultry litter. [c] Consumption from Ely Power Station (Copeland and Turley, 2008). [d] Based on Booth *et al.* (2009) and Kilpatrick (2008). [e] derived from Renewable Fuels Agency (RFA) Quarterly Report (NB – there is a discrepancy between the RFA figure used here and the figure for domestically produced liquid fuels (12PJ) included in UK energy statistics 2008)(RFA, 2009). [f] Includes MSW, tyres and "plant based biomass" included in 2008 energy statistics, less other categories, assumed to be a waste fraction.
Source: UK Energy Statistics 2008 commodity balances unless otherwise stated (DECC, 2009).

Estimates of the future contribution of different biomass resources to primary energy supply in the UK

Approach and overview of reviewed studies

A short, systematic review of the literature was undertaken to identify reports and papers that estimated the contribution that biomass may make to UK primary energy, or presented sufficient information to allow the contribution to primary energy to be derived. The search focussed on both the academic and grey literature; the search terms used and databases examined are listed in Appendix 1. As discussed above, biomass can sub divided into many different categories each of which could be the subject of a systematic review in its own right. To prevent the number of reports from becoming unmanageable, reports that sought to estimate the potential for a single biomass category were not included in this first phase of the analysis, (key reports are discussed in the following section). Reports more than 10 years old were also excluded. Each report was then examined to in detail to identify the following attributes:

- Scope
- Definition of bio-energy potential used
- Results given for future UK bio-energy potential
- Methodology and assumptions
- Main input data

The review identified 14 reports which met the criteria outlined above; these are listed in Table 4. Where estimates were quantified in terms of delivered electricity or heat, these figures were converted back to primary energy using the conversion ratios used in the original report, or 30% for electricity if no conversion ratio was stated (as noted in the text). For liquid biofuels the contribution to primary energy was taken to be the energy content (lower heating value[6] (LHV)) of the liquid fuel. For anaerobic digestion, the contribution to primary energy was taken to be the LHV value of the gas. For reports where figures were given in oven dry tonnes of biomass an average calorific value of $17GJ.odt^{-1}$ was used unless otherwise stated. Following the classification scheme presented in Table 2, the categories used to describe biomass resources in this report are: conventional crops, perennial energy crops, forestry residues, agricultural crop residues, and wastes. Short rotation forestry (SRF) has been grouped with perennial energy crops. Where reports provided sufficient detail, the biomass potential for each resource category is described.

[6] The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C; i.e. the latent heat of vaporization of water in the reaction products is not recovered.

Table 4: Studies included in this review

Study Label	Title	Geographic focus	Main reference
Oxera02	Regional renewable energy assessments: a report to the DTI and DTLR	UK	(Oxera, 2002)
E4Tech03	Biomass for heat and power in the UK: a technoeconomic assessment of long term potential - a report to the renewables innovation review	UK	(E4Tech, 2003)
RCEP04	Royal Commission for Environmental Pollution: Biomass as a renewable resource	UK	(RCEP, 2004)
CT05	Biomass sector review for the Carbon Trust	UK	(Carbon Trust, 2005)
Taskforce05	Biomass Taskforce 2005	UK	(Biomass Taskforce, 2005)
AEA05	Renewable heat and heat from combined heat and power plant - study and analysis	UK	(AEA, 2005)
EEA07	How much bioenergy can Europe produce without harming the environment	EU	(EEA, 2007)
UKBioStrat07	UK Biomass strategy 2007	UK	(DEFRA, 2007)
E&Y07	Renewable heat initial business case	UK	(Ernst & Young, 2007)
Fischer07	Assessment of biomass potentials for biofuel feedstock production in Europe: Methodology and results	EU	(Fischer, et al., 2007)
Kilpatrick08	Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities.	UK	(Kilpatrick, 2008)
E4tech09	Biomass supply curves for the UK: a report for DECC	UK	(E4tech, 2009)
Thornley09	Sustainability constraints on UK bioenergy development	UK	(Thornley, et al., 2009)
deWit09	European biomass resource potential and costs	EU	(de Wit and Faaij, 2009)

Estimates of future bio-energy potential

The approach, timeframe, and definition of potential used in each study is summarised in Appendix 2, along with a summary of the estimates obtained. The focus of the reports ranges from studies that have sought to address the potential of biomass in a particular UK sector – e.g. electricity or heat – to studies that consider the aggregate UK potential in comparison with other EU Member States. It is important to note that although all the reports contain estimates for the UK bio-energy potential, calculating this potential was not necessarily the main objective of each report. The Carbon Trust report (CT05), for example, sought to examine which supply-chains would deliver the most cost effective carbon savings primarily as a means of directing its own research and investment strategy. The report by Ernst and Young (2007) provides another example: here the main objective was to examine the business case for renewable for heat; biomass was just one of the options considered.

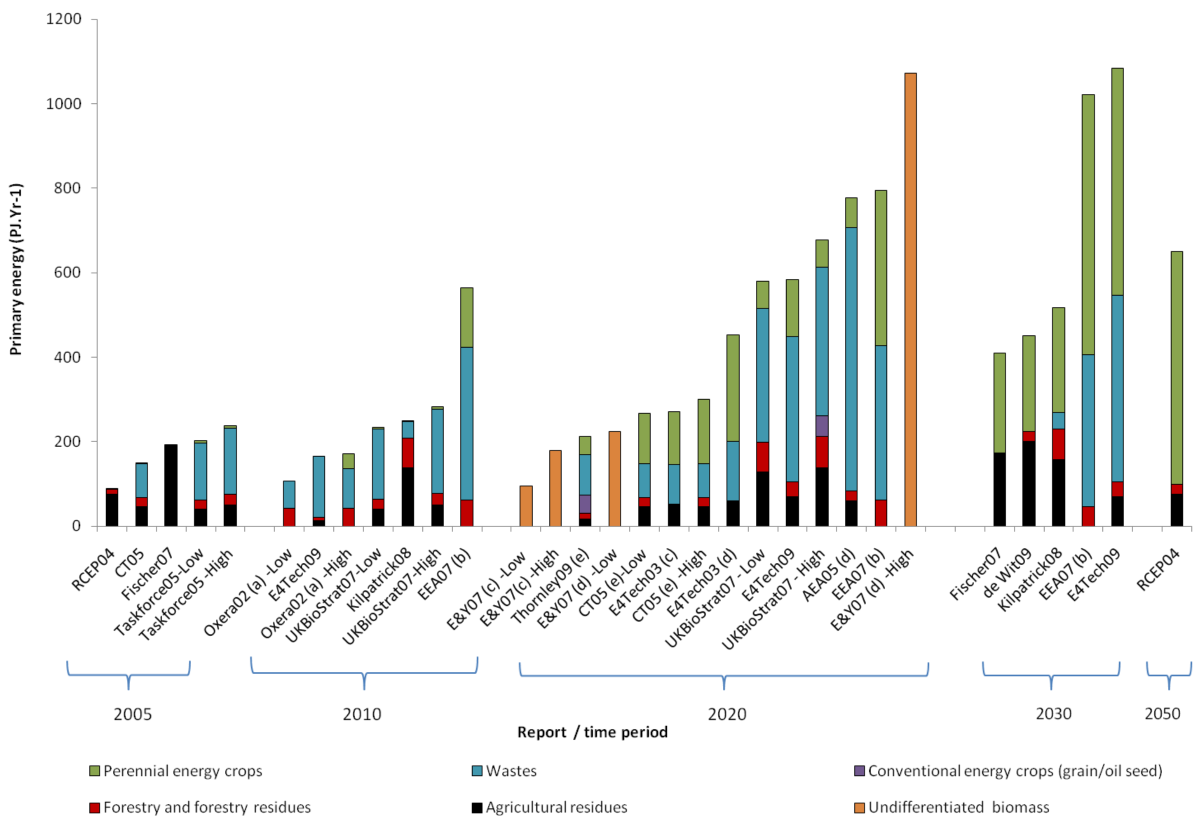
All the reports can be considered to be resource focussed, rather than demand driven. They either compile resource inventories from land availability projections and existing statistics, or re-interpret earlier resource inventories with additional assumptions and scenarios. Direct comparison between estimates is hindered by the use of different boundary conditions, the inclusion of different resource categories, and consideration of different time periods. Definitions of potential also range from illustrative scenarios and estimates of the un-constrained technical potential to assessments of realistic and market potential. Yet the overlap between reports is also considerable in terms of data sources used. The estimated resource potentials described in the Ernst and Young (2007) report, for example, are derived from the report by AEA (2005). Likewise, the data, underpinning the UK Biomass Strategy (DEFRA, 2007) appears more-or-less identical to the data collated by the Biomass Taskforce two years earlier (Biomass Taskforce, 2005). (Interestingly, in this last case, the main change appears to be the re-definition of municipal solid waste (MSW) as *paper and card* and *waste wood*. It may be speculated that this change was made because the use of MSW for energy purposes is controversial.)

With the exception of the paper by Thornley (2009) and the two academic papers that consider the EU biomass potential (Fischer, et al., 2007) (de Wit and Faaij, 2009), the reports which provide aggregate estimates of UK bio-energy potential take the form of consultancy reports, or reports to Government. It is unsurprising, therefore, that the focus of these reports has changed as policy has evolved. The earliest studies (Oxera02 and E4Tech03) – which were conducted around the time that the Renewables Obligation for electricity was introduced – focus exclusively on biomass (and other renewables) for electricity. Later studies consider biomass for heat and biofuel applications. It is reasonable to assume that this shift in focus follows the introduction of EU directives on transport fuels (the biofuels directive, (2003/30/EC)) and renewable energy more generally (the renewable energy directive, (COM(2008)19) PROV(2008)0609)). Another reason for the shift, worth considering, is the continued refinement of the tools and methods used to assess bio-energy pathways over the last decade. Refinements include improved methodologies to deal with co-products and the selection of appropriate reference systems, refinement of basic data, and an improved understanding of consequential impacts (Turley, 2010).

Figure 2 illustrates that diversity of estimates contained in (or readily derived from) the reports, grouped by time period. Again, it needs to be emphasised that because the boundary conditions and definitions of potential used in each of the report differ, the estimates cannot be compared directly. With this caveat in mind, a number of observations can be made:

- Estimates of the future potential are greater than estimates of the existing potential
- All estimates include a contribution from agricultural residues, and (with one exception) from forestry residues
- Only two reports include a contribution from conventional energy crops
- All estimates from 2020 onwards include contributions from perennial energy crops and wastes

Figure 2: Estimates for the potential contribution from biomass to UK primary energy derived from individual studies. *Estimates have been grouped by time period. Studies include different resources categories and encompass many definitions of the potential.*



(a) Electricity only – Agricultural residues and forestry not differentiated; (b) wastes and agricultural residues not differentiated; (c) Market potential / Constrained potential; (d) Technical potential / unconstrained potential; (e) No date for future forecast - assumed to be 2020

For 2005, the most significant outlier is the Fischer07 estimate for agricultural residues. This can be attributed to the top-down methodology used by Fischer and in particular the assumption that 50% of residues could be available without considering other markets. It is also notable that the Carbon Trust's estimate excludes municipal solid waste (MSW) whereas the Taskforce05 report includes a modest contribution from this source.

For 2010, all estimates include contributions from forestry, agricultural residues and wastes, but these are not presented as distinct categories in all the reports. Kilpatrick's estimate for agricultural residues (~8Modt.yr^{-1} / 138PJ.yr^{-1}) is notably higher than the UK Biomass Strategy, but this estimate is an upper limit that assumes all *harvestable* straw is collected. The Biomass Strategy in contrast assumes that only ~3Modt.yr^{-1} tonnes (52PJ.yr^{-1}) could be made available without disrupting livestock use/buying costs. The difference between the Kilpatrick08 estimate and the earlier Fischer07 estimate appears to be due to different assumptions about the fraction of straw available: Fischer assumes *total straw*, whereas Kilpatrick assumes that only 60% of total straw would actually be *harvestable*. Other discrepancies seem likely to be attributable to differences in the databases used.

Five of the seven estimates for this period include a contribution from energy crops, but the only sizable contributions appear in the Oxera02-high estimate, and the EEA07 report. It is worth considering that in 2002, when the Oxera report was finalised, 2010 was sufficiently distant that the development of an energy crops sector was at least feasible. The EEA07 report considers land availability only, and does not take into account the time taken to establish perennial crops. The difference between estimates for wastes can be attributed to the inclusion of MSW in some reports but not others, and also to some reports being more ambitious about the fraction of total waste that can be converted to energy.

For 2020, in comparison with earlier years, the greatest change envisaged is the growth in dedicated energy crops and the proportion of wastes materials that are diverted to energy use. The EEA07 estimate for 2020, for example, considers that all growth compared to 2010 comes from increase deployment of perennial energy crops. Looking at waste materials, the CT05 report excludes MSW, and hence gives a far lower contribution from wastes that the AEA05, E4tech09, and EEA07 reports. The estimates for the use of agricultural and forest residues are comparable with estimates for the earlier periods.

Two estimates for 2020 consider the contribution from conventional crops to liquid biofuels:

- The UK Biomass Strategy assumes that 0.74Mha *might* be made available, and if it is assumed that this area is used to grow wheat which is then used to produce ethanol, then this area translates to roughly 50PJ.yr^{-1} of liquid fuel[7]
- Thornley09 identifies a proportion of the UK's surplus 2.4Mt of wheat as suitable for conversion to transport fuels and proposes that the existing rape crop (400-600kha ~ 27PJ) represents the upper bound on the available resource

For 2030, the three estimates clustered around 400PJ exclude MSW. (The Kilpatrick08 estimate includes residues from verges and urban green areas, here classified as waste.) The two high estimates, E4tech09 and EEA07, both include MSW and represent the unconstrained technical potential. It is notable that none of the estimates for 2030 include

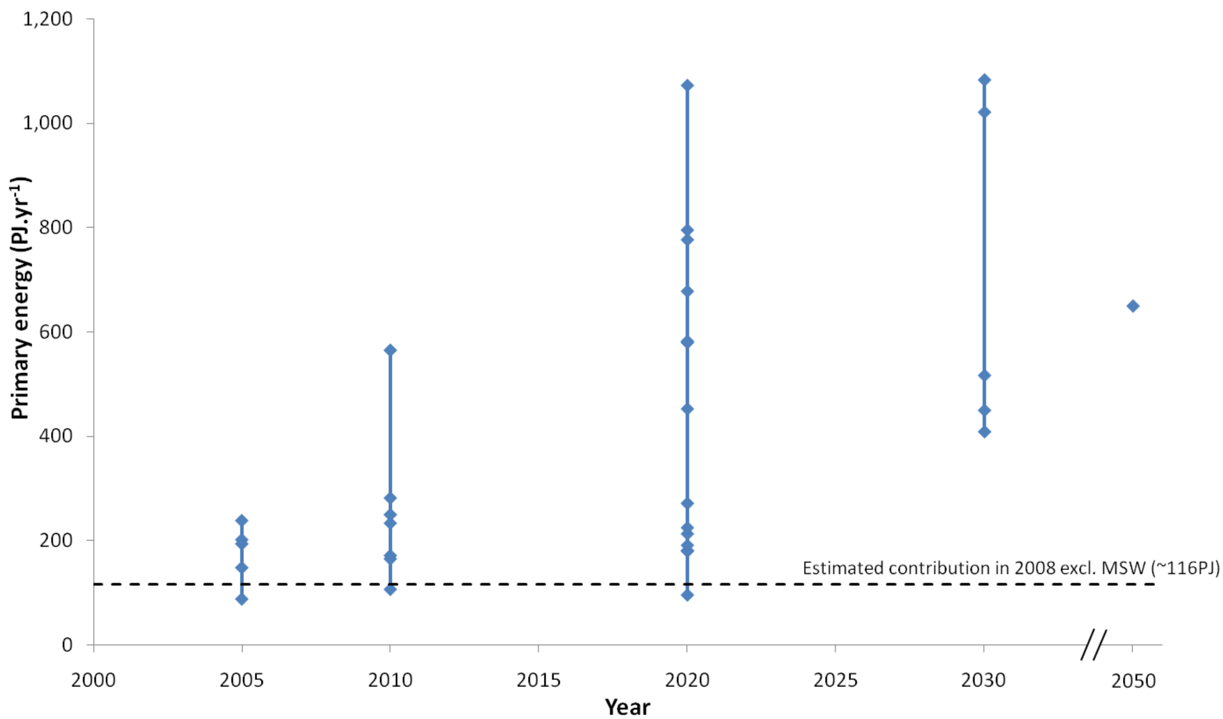
[7] This estimate only considers ethanol produced from the grain, and ignores the possible use of the straw for energy purposes; our calculation assumes a wheat yield of 8tonnes.ha^{-1}, an ethanol yield of 400l.$tonne^{-1}$, and a calorific value of ethanol of 21MJ.l^{-1}

transport fuels produced from conventional crops, but this appears to be because transport fuels were defined out of scope, rather than because they were considered and rejected.

For 2050 there is only one estimate, provided in the RCEP report. This estimate is an illustrative scenario that considers the how much land might be required to meet a target of 16GW electrical and thermal capacity from biomass combined heat and power (CHP).

The ranges of predictions for the total contribution to UK primary energy are summarised in Figure 3 and compared with the estimated contribution from biomass in 2008. The conservative estimate is that the contribution of biomass will quadruple by 2030 to around 400PJ.yr^{-1} (about 4% of UK primary energy in 2008). It can also be seen that no studies consider that the contribution will exceed 1100PJ.yr^{-1} even with all constraints removed (about 11% of UK primary energy in 2008). It is also notable that the progress that the UK is predicted to make by 2020 varies from none, to the maximum conceivable 1100PJ.yr^{-1}.

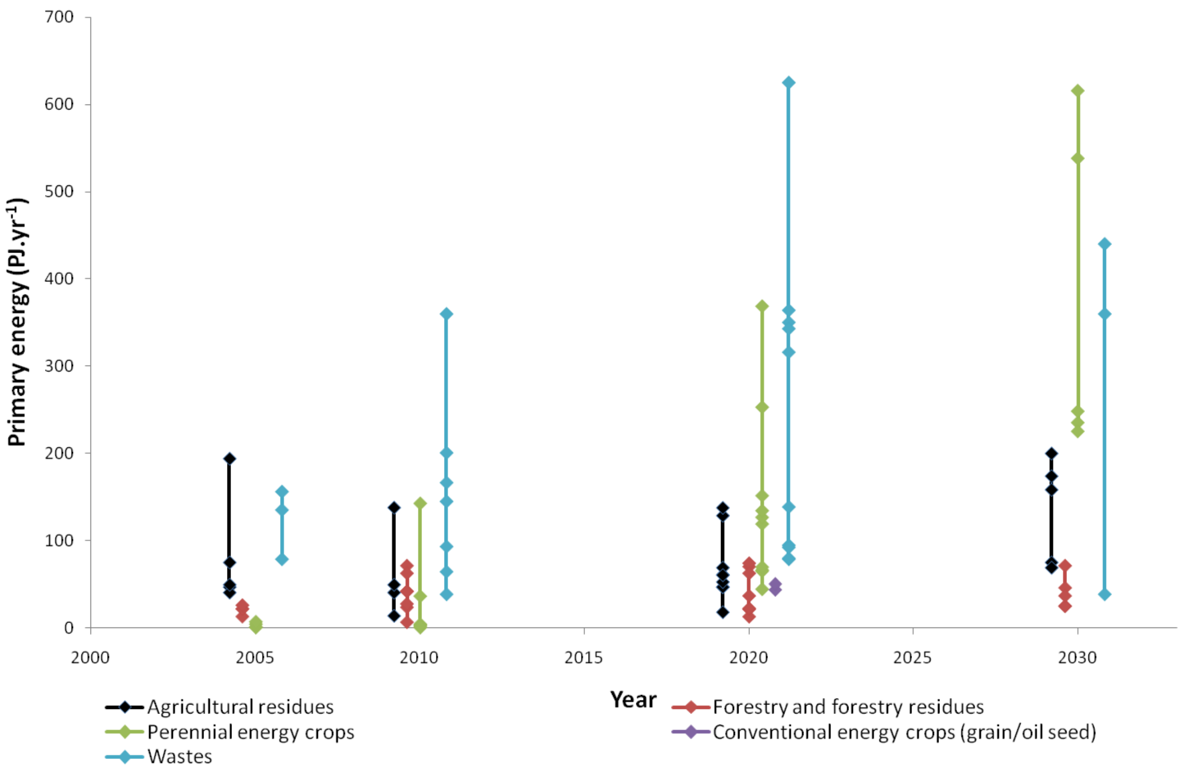
Figure 3: Range of predictions for the total contribution to UK primary energy from domestically sourced biomass feedstocks. *Estimates have been grouped by time period. Studies include different resources categories and encompass many definitions of resource potential.*



Review of assumptions, methods and data sources

The range of predictions for each of the biomass categories is shown in Figure 4. It can be seen that the categories predicted to experience the greatest growth are perennial energy crops and wastes. The nature of the growth envisaged, however, is quite different. For wastes, growth comes from diverting existing material streams (e.g. MSW) to energy purposes and collecting and utilising a wide range of residual waste streams (e.g. arboricultual arisings). For energy crops, growth comes from the allocation of land to a variety of perennial crops. In the case of forest residues, growth comes from collecting and utilising the existing resource more effectively but no increase in the fundamental resource is envisaged. Lastly, for agricultural residues, growth comes from increased utilisation, but the fundamental resource does not change markedly; interestingly, Fischer07 predicts that the total for this resource will decrease as perennial crops encroach onto agricultural land. The remainder of this section looks at each of the categories in turn, examining the key methodologies and assumptions. The section ends with a summary of the overarching assumptions.

Figure 4: Range of predictions for the contribution to UK primary energy from domestically sourced biomass feedstocks



Agricultural residues

Good data about the production of crops in the UK exist and is published regularly in UK Government statistics. From this data it is possible to estimate the total amount of straw produced annually for different crops, and this represents almost the entirety of agricultural residues. For each of the main combinable crops, the basic calculation is:

*Resource = Total crop * Harvest index * Recoverability – Straw dedicated to existing uses*

This basic method is the same for all reports, although there are differences in the databases used: deWit09, Fischer07 and EEA07 use FAO statistics, whereas the other reports use UK Government statistics. The greatest variation comes in deciding what proportion of the total straw produced is *recoverable* and how much should be dedicated to existing uses. Fischer07 assumes 100 % of the straw is recoverable and that half of the total is dedicated to existing uses. Kilpatrick08 assumes that 60% is recoverable and that half of this lower figure is dedicated to animal bedding and other markets. The UK Biomass Strategy assumes a greater proportion is dedicated to existing uses.

The harvest index is the fraction of the above ground biomass that is the primary crop. In the case of wheat and barley this is ~51%, and for rapeseed it is about 30% (Kilpatrick, 2008). It is worth considering that past genetic improvements in the major food crop species have largely resulted from increases in the harvest index, with more biomass partitioned to the harvested product and less to vegetative parts of the plant, rather than increases in the total biomass produced by each plant (Hay, 1995). Following this logic, it cannot be taken for granted that future increases in grain yield will simultaneously increase the yield of straw[8].

Forestry and forestry residues

With one exception, all estimates of the UK forestry and forest residue resource base can be traced back to Forestry Commission statistics and in particular a 2003 report: Woodfuel Resource in Britain (McKay, 2003). The source data for this report is the National Inventory of Woodland and Trees – a periodic survey undertaken by the UK Forestry Commission (Forestry Commission, 2001) – and a database held by the Commission that describes the forested areas they manage. The latest inventory (conducted from 1994 – 2000) can be considered the definitive dataset for estimates of the forested area in the UK. The exceptional report, which does not directly or indirectly reference Forestry Commission statistics, is deWit09. This report has a European focus and extrapolates data from Poland, Finland, France and Netherlands to the UK; interestingly, the estimate arrived at from this extrapolation (25PJ.yr^{-1} in 2030) is similar to the value estimated in the UK Biomass Strategy for 2010 (23-27 PJ.yr^{-1}).

Given the limited underlying dataset, it is unsurprising that estimates for this resource category are similar. The variation in estimates can be attributed to the fraction of the existing resource that is considered to be available, and this is most often determined by

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[8] Empirical functions to describe straw yields as a function of grain yield have also been developed and applied to GIS land cover maps by (Edwards, et al., 2006, Edwards, et al., 2005). Using this methodology, Edwards et al. estimate that up to 51PJ of energy might be obtained from straw in the UK, comparable with the CT05 and UKBioStrat07 reports.

expert judgement. The E4tech09 report, for example, considers a range of scenarios where use of the forest resource increases on the following trajectory: 10% in 2010, 50-75% in 2015 and 100% in 2020. Other more general assumptions that appear to guide estimates of potential include:

- That the long growth times in the forest sector effectively mean that the maximum available resource in the forest sector is static
- Mature stem wood is too valuable to be used for energy purposes.
- Stumps and roots are not harvested[9]

Only the Kilpatrick08 report considers an increase in the forest resource: this comprises short rotation forestry[10] (SRF) on 586kha and 1230kha of permanent pasture and rough grazing respectively. Some variation also occurs because categories are merged. The UK Biomass Strategy, for example, combines forestry residues with arboricultural arisings.

Perennial energy crops

Energy crops require land. How much land is needed to meet renewable energy goals depends upon the quality of the land used and the crop yields that can be achieved. How much land is available depends upon competing uses.

The greatest competing use for land arises from the demand for food, feed and pasture. If technological improvements increased crop yields, or population decreased, or diets changed and the consumption of meat was reduced, then at least in theory, surplus land would become available. How much land is released can be determined by models or judgement. Here there is a clear distinction between the studies with a European focus and those with a UK focus. The EU focussed studies (deWit09, EEA07, Fischer07) all use top-down models to estimate the availability of land, whereas the UK focussed studies all use expert judgement. The EEA07 report evaluates land availability using a partial equilibrium land-use model (CAPSIM[11]) to derive an estimate that between 0.824Mha in 2010 to 3.4Mha[12] in 2030 could be released as a result of reform to the common agricultural policy (CAP). Approximately half of the land released would be former grassland. The Fischer07 report uses assumptions about the rate of *technical advances in crop yields*, *food demand* (considered to be a function of *population* and *diet)* and *livestock intensity* to estimate land available for energy crops in Member States. Stipulating that maintaining the current level of self-sufficiency for food should be a fundamental constraint, this report estimates that up to 1.1Mha could be made available for energy crops, split between different land classes. The deWit09 report adopts a similar approach, calculating that the area freed up in the UK will be 0-6.5% in East England, 6.5-17% across most of the rest of the UK, and up to 31%

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[9] This contrasts with the situation in Scandinavia where a proportion of stumps are now harvested for energy purposes.

[10] In this review SRF is categorised as a perennial energy crop.

[11] CAPSIM is an established model for projecting agricultural activity in the EU.

[12] Around 1.5Mha of which would be arable, the remainder would be grassland.

in South West England. From the data given in the report it is not possible to translate these proportions into estimates of the actual area (although the authors must have done so).

In the UK focussed reports, consideration of the amount of land available for energy crops has been dominated by the existence of *set aside*, a feature of the CAP that has been a part of UK agriculture since the early 1990s (Kilpatrick, 2008). The Carbon Trust report, for example, roughly equates its estimation of available land (680k ha) with the area of set-aside available in 2003. The UK biomass strategy also considers that up to 350kha of perennial energy crops could be grown "on arable and set aside [...] and used for energy purposes without affecting existing markets". This 350kha figure can be traced back to a submission to the 2004 Department of Trade and Industry (DTI) Renewables Innovation Review by the consultancy LEK (DTI, 2004) (LEK, 2004). Although not entirely transparent, it appears that this estimate is also based on the 2003 set-aside area, but this time with the assumption that ~50% could be economically developed. The 350kHa figure is also remarkably close to a ballpark estimate of 300kha proposed in the Oxera02 report, although there is no evidence that the estimates are related. Most recently, retrospective analysis of the 350kHa estimate by Lovett et al. (2009) concluded that UK food security would not be greatly impacted if this area comprised grade 3/4 agricultural land and was planted with miscanthus.

Although this review is limited to the last ten years, attempts to predict the proportion of agricultural land that could be dedicated to energy crops go back much further than this. In 1999, for example, analysis conducted by the Energy Technology Support Unit (ETSU) for the DTI, included an analysis of land availability[13] (ETSU, 1999). This report observed that *"early predictions"*[14] that 1.0 to 1.5 Mha of land may become surplus to requirements for food production by year 2000 (rising to 5.5 Mha by 2010) were *"proving to be an overestimate"*, and concluded that a more realistic figure might be closer to a maximum of 1Mha by 2010. To put these figures in context, it is useful to bear in mind that the total agricultural area of the UK is in the region of ~18.6Mha[15], that set-aside was withdrawn in 2008 (IATC, 2009), and that in 2009 the deployment of energy crops in the UK was negligible.

The amount of land required to grow energy crops can be reduced if yields can be increased. Crop yields are a function of the incident solar radiation, the proportion of that radiation intercepted by the crop, the efficiency with which the intercepted radiation is converted to biomass by photosynthesis and the proportion of that biomass partitioned to the harvested product (Monteith, 1977, Hay and Walker, 1989). At any given location, the yield achieved will be determined by complex interactions between plant physiology, local

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[13] This analysis was a contribution to the public consultation for the Renewables Obligation introduced in 2002. ETSU was subsequently incorporated into the consultancy AEA technology.

[14] Attributed to the Department of Land Economy at the University of Cambridge.

[15] All in all, the total area of the United Kingdom of Great Britain and Northern Ireland covers some 24.5 million hectares, divided as follows: grazing land (14 Mha); arable land (4.6 Mha); forest and woodland (2.5 Mha); buildings/roads etc. (2.4 Mha) (IATC, 2009). Maximum set-aside was in 2001 when ~800kha was withdrawn from production (www.ukagriculture.com).

ecology and climate, and management practices. Yields that can be achieved on poor quality soil, or in areas where water is scarce, may be far less than those achieved under optimum conditions. For the purposes of estimating the future contribution from energy crops, there are two approaches to estimating the productive yield:

- Model based yields – where empirical crop models are developed to predict crop growth on different soils, and using different agronomic practice etc
- Extrapolation from case-studies and sample plots

It is important to recognise that uncertainty about how model parameters will change, and limitations on the number of sample plots available means that both methods are ultimately speculative (Berndes, et al., 2003).

The approach to yield estimates used in the reviewed reports ranges from assuming conservative average yields (~10odt.ha^{-1}.yr^{-1}; Oxera02, RCEP04) to modelling yields according to crop, land class and location (Fischer07, deWit09). One recent advance in UK research has been the combination of simulation models with experimental data to generate spatially resolved yield maps. Such maps are better able to predict the productive yield of perennial species in different areas, on different soils, and in different ecological zones (G. M. Richter, et al., 2008, Aylott, 2008). This modelling suggests spatial distribution preferences for different perennial crop species in order to achieve maximum yields. Generally, willow is the preferred crop in the wetter western climate and Miscanthus is preferred in the dryer eastern climate. In closely related work, and applying an arable land availability constraint of up to about 1.5 million hectares (the EEA07 estimate for 2030), Bauen et al. (In press) estimate that SRC and miscanthus could contribute around 270PJ.yr^{-1}.

Conventional energy crops (grain/oil seed)

Only two of the reviewed reports include estimates for the production of transport fuels from conventional crops (cereals, oil seed rape and sugar beet), and, analogous to the case of perennial energy crops, estimates of the domestic resource based cannot be divorced from land availability considerations. The estimate included in the UK Biomass Strategy, for example, is simply an illustration that around half the renewable transport fuel obligation (RTFO) target (5% of transport fuels biofuels by 2010) could be met from 0.74 Mha (~12%) of arable land. The estimate included in the Thornley09 paper is similar, equating to around 0.15Mha of wheat and 0.60Mha of rapeseed. Thornley et al. justify the sustainable use of cereals on the basis that the UK has produced an annual wheat surplus of 2.4Mtonnes.yr^{-1} in recent years. Converting cereals to ethanol also gives rise to co-products which can displace existing demand for cereals (e.g. protein rich co-products may be used for animal feed instead of wheat). The rule of thumb used by the ethanol analyst group F.O Licht's is that converting 1tonne of cereals to ethanol translates into only ~0.66tonnes of additional demand for cereals when co-products are taken into account (Keller, 2010). Other interpretations are also possible. For example, Ensus, a project development company building a wheat-to-ethanol plant in Wilton, UK, estimate that converting 1.2Mtonnes of wheat to ethanol will result in the co-production of 350Ktonnes of animal feed. They assert that this feed will displace imports of Brazilian soy, thereby leading to minimal additional demand overall.

The use of food crops to produce transport fuels is controversial, and a detailed examination of the many reports which seek to influence the debate falls outside the scope of this review. Nevertheless, it seems inescapable that producing biofuels from conventional crops will require a significant area of land.

Wastes

Sources of waste biomass that may be used for energy purposes include a diverse assortment of materials ranging from livestock manure to municipal solid waste. Data about the fate of individual waste streams is patchy[16] but Government statistics provide good data about the economic activity of the principle sectors that are responsible for producing the waste. From this data, top-down estimates of the quantity of waste likely to be produced per unit of existing activity may be derived. These estimates may then be projected into the future, moderated by judgements about the effect of new legislation or other anticipated changes. This approach is generic to all the reviewed reports, although the details of the calculation change for each waste sub-category. The EEA07 report, for example, assumes that the production of MSW will be driven by GDP growth at national and sectoral level[17], moderated by the anticipated impact of household waste reduction measures (estimated to be 25% in 2030). Similarly, the E4tech09 report calculates the MSW resource as a function of the *existing resource*, moderated by *growth rates*, *recycling rates*, and *availability fractions*, but derives values for each of these values from the literature.

One of the principal sources of variation between reports is the inclusion / exclusion of waste sub-categories in the resource inventory. Differences occur because certain categories are merged or defined out of scope (e.g. Fischer07 and deWit09 consider agricultural residues as waste) or for other reasons: the CT05 report, for example, excluded MSW because the Carbon Trust had no remit in this area. More detailed inventories will also obtain higher figures than less detailed inventories. An example of this is identified in the E4Tech09 report, which observes that the UK Biomass strategy obtains a lower estimate for the resource potential of livestock manures because fewer categories of animals are included in the inventory.

Other assumptions / cross-cutting issues

Looking across all the reports, the following assumptions and issues stand out.

Competition. It is universally assumed that expanding the use of biomass will have no impact, or negligible impact, on other economic sectors. Different reports express this in different ways: deWit09 describes this constraint as a “food first paradigm”, the UK Biomass

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[16] Like the forestry sector, there appear to be relatively few source documents for detailed information about the waste sector in the UK. Notable reports that are directly or indirectly cited in multiple reports include: (Biffa, 2002) (ERM, 2006) (DETR, 2000) (WRAP, 2005)

[17] Estimated using PRIMES, an established partial equilibrium model of energy supply and demand in EU member states.

Strategy asserts that the development of bio-energy should have "no effect on existing markets", and the EEA07 study explicitly disregards the effect of competition between bio-energy and food production for domestic supply. This assumption greatly simplifies the analysis, effectively limiting the area of land available for energy crop production to the un-used agricultural area. More generally, limited consideration has been given to possible competition for biomass resources between energy and other markets (e.g. biomaterials), for providing environmental services such as soil organic carbon (Wilhelm, et al., 2007) (Watts, et al., 2006), and between alternative energy uses (heat, power, transport fuels). The anticipated profitability of bio-energy crops relative to conventional crops has, however, been considered as a constraint to development.

Scheduling. Little consideration is given to the time taken to ramp up production of the different biomass resources. Kilpatrick08 considers that it would take ~10 years to bring SRC and miscanthus production on stream and around 20 years for short rotation forestry. E4Tech09 uses expert judgement to develop ramp-up scenarios for different resources.

Improvements in yields. It is assumed that increasing yields in conventional crops will free up agricultural land for perennial energy crops. Only two of the studies consider potential increases in perennial crop yields: EEA07 and E4Tech09. Although it should be noted that potential increases in crop yields has been considered elsewhere in the academic literature (Tuck, et al., 2006) (Aylott, et al., 2008).

Conclusions

From the studies reviewed, and the analysis presented in this report, the following insights can be drawn.

- Forecasts for the total contribution of bio-energy to UK primary energy in ~2030 range from 400 to 1100 $PJ.yr^{-1}$ (4-11% of UK primary energy cf. 2008). It is important to note that the higher estimates require that all constraints are removed or overcome.

- All assessments adopt a resource focused approach, either compiling an inventory of existing feedstocks and rationalising about how that inventory may change over time or overlaying an existing inventory with combinations of cost and sustainability constraints.

- Consistent with the findings of reviews undertaken at EU level (the BEE project), differences between estimates can be ascribed to:
    - Varying definitions of resource potential
    - Differences in the scope of, and extent of, resource inventories
    - Varying assumptions about the proportion of existing resources that may be captured

- High level assumptions are remarkably consistent, conservative, and normative. In summary these are:
  - That expanding the use of bio-energy should not impinge upon other resource or land uses
  - That protected forest areas should be excluded from wood production and deforestation for bio-energy production should not be allowed
  - That competition between the use of forest biomass for energy production and wood-fuel or industrial round-wood production should be avoided (Thornley, et al., 2009).

- There is considerable overlap between reports. Later reports are often derivative of earlier work. Estimates of the land available for energy crops, in particular, have remarkable longevity: early estimates are quoted and re-quoted without the original assumptions necessarily being revisited or stated.

- There is also considerable overlap between reports in terms of the data sources on which they draw. Ultimately, resource inventories are dependent upon a restricted dataset: for wastes, residues and forestry resources there are a small number of key documents and custodians of statistical data. Prominent custodians include the UK Government, the Forestry Commission, and the Waste Resource Action Project (WRAP). Although reliance on a limited number of data sources is not inherently problematic. It is clearly preferable that the data be of high quality, publically available, and open to scrutiny.

Recommendations

The following recommendations are proposed for future work:

- Existing studies of UK energy potential are imperfect, but they pretty much exhaust the availability, and the quality, of the underlying data sets. Efforts are being made to harmonise assessment methods at a European level and in the future this may have an impact on consistency, but while it is laudable to have a consistent basis for speculation, it remains speculation. Irrespective of methodological consistency, there is a clear need for open assessments with well documented data sources and assumptions.

- Estimating the bio-energy resource potential is a highly interdisciplinary task. A mix of approaches needs to be applied to different biomass resources in order to tease out the interactions with existing markets, the technical and agronomic constraints and the potential opportunities. There is also a need for expert judgement when compiling and combining multiple biomass resource estimates as no one organisation is likely to have the necessary breadth of expertise in all sectors.

- The dominant assumption that bio-energy can only proceed with negligible impact on other markets seems untenable and is worthy of further investigation. If this assumption proves not to be the case, what sort of impacts and interactions might occur as the resource base is expanded? Which existing sectors would suffer most? This is touched upon in the reports which postulate sustainability constraints, but otherwise is given limited consideration. In this context the role of biomass imports might also be investigated.

- The need for precision in resource estimates needs to be considered in relation to the policy decisions that they are intended to inform. If a high level of precision is required then need a fundamental reassessment of methodologies and datasets is needed and this would be no small undertaking. Given the rapid expansion in the use of biomass envisaged, a pragmatic course of action might be to start developing the most attractive supply-chains, carefully monitor how they perform, and then revise estimates of future potential accordingly.

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Appendix 1

Table A1.1: Search terms included in the systematic review

• Bioenergy • Biomass • Short rotation coppice • Energy crops • Miscanthus • Energy from waste	• Resource assessment • Potential • Resource potential • How much • Land availability • Supply • Production	• Methods • Yield • Constraints • Estimates	• UK • World • Europe

Table A1.2: Databases and other information sources included in the search

Databases / search engines

Elsevier 'Science Direct'
Google Scholar

Ongoing research projects

TSEC Biosys
Supergen Bioenergy
RELU
Foresight Land Use Futures
Foresight Global Food and Farming Futures
Biomass Bioenergy Europe
Biomass futures

Governmental and related organisations

DECC
BERR
DEFRA
DTI archive
Carbon Trust
WRAP
EEA
NNFCC
Biomass Energy Centre
Forestry commission

Appendix 2

Table A.2.1: Approach, timeframe and definition of potential used in the reviewed studies

Label	Definition of potential	Focus and approach	Time-frame
Oxera02	Constrained technical potential	UK electricity only - a summary of regional assessments. Biomass figures estimated using a bottom up resource inventory informed by GIS mapping	2010
E4 Tech03[a]	Technical potential (constrained / unconstrained)	UK electricity only - bioenergy fuel chain analysis. Report develops fuel chains populated with literature data, these are used to estimate the % contribution to UK electricity	2020
RCEP04	Theoretical potential based on land use scenarios	UK electricity and heat. Resource inventory combined with a top down estimate of land requirement for energy crops to meet a 16GW by 2050 target.	2005 and 2050
CT05	Existing potential plus estimate of land availability	Inventory of all major UK biomass sources excluding MSW. Resource inventory from literature sources. Top down estimates for each resource type moderated by expert judgement	2005 and "future"
Taskforce05	Existing potential	UK biomass for energy (excl. biofuels). Resource inventory with simple availability assumptions, includes MSW	2005
AEA05	Technical potential	UK biomass for heat. Resource inventory based on previous literature, includes MSW	2020
UKBioStrat07	Technical potential	UK Biomass. Resource inventory estimate assuming no impact on existing markets. Based on same dataset as Taskforce05, MSW included but not explicit.	2010 and "future"
E&Y07	Technical and market potential	Renewables for heat, including UK biomass. Biomass figures are derivative of AEA05 and CT05. I.e. a resource inventory based on previous literature. Inventory includes MSW.	2020
EEA07	Potential not leading to environmental harm	EU Focus, UK is included as one datapoint. Resource focussed assessment predicated on modelled land availability and top-down estimates of residue availability overlaid with sustainability criteria	2010, 2020, 2030

Label	Definition of potential	Focus and approach	Time-frame
Fischer07 [b]	Technical potential based on land use scenarios	EU Focus, report estimates bio-mass for biofuels potential. Resource focussed assessment, land availability and productivity estimated using GIS databases. Self sufficiency ratios used to subtract land required for food and fodder crops. Inventory includes woody crops and residues.	2000, 2030
Kilpatrick08[c]	Existing potential plus future land use scenarios	UK Biomass for energy. Detailed UK resource inventory. Estimates of Land availability and the potential availability of materials from existing sectors based on expert judgement	2010, 2030
E4tech09	Market potential and technical potential	UK biomass supply curves. Supply curves estimated using existing resource inventory literature and scenarios. Notable inputs include EEA07, Kilpatrick08.	2010, 2020, 2030
Thornley09	Sustainable potential	Sustainable UK bio-energy resource potential. Literature based resource inventory overlaid with sustainability criteria and constraints. Includes MSW	No date
deWit09	Technical potential based on land availability scenarios	EU cost and supply potential, UK included as a single data point. Bottom up cost and resource assessment from detailed spatial yield modelling driven by top-down estimations of land availability assuming productivity gains and a "food first" paradigm.	2030

[a] To derive a figure for total UK biomass potential it was assumed that that total UK electricity use was 234 TWh.yr-1 The conversion efficiency to electricity given in the report was 40%.

[b] 2030 figure is a rough estimate for the UK based on Fischer's land suitability distribution, suggested average yield for biofuel crops and assumed planted area of 1.1Mha

[c] Results converted from oven dry tonnes to PJ using a conversion factor of $17GJ.odt^{-1}$.

Table A.2.2: Summary of estimates of potential included in the reviewed studies. *Estimates are grouped into five categories: agricultural residues, forestry and forest residues, perennial energy crops, conventional energy crops and wastes.*

Report	Year of estimate	Agricultural residues $PJ.yr^{-1}$	Forestry and forestry residues $PJ.yr^{-1}$	Perennial energy crops $PJ.yr^{-1}$	Conventional energy crops (grain/oil seed) $PJ.yr^{-1}$	Wastes $PJ.yr^{-1}$	Total - Primary energy $PJ.yr^{-1}$	Notes
Oxera02	2010		42.0			64.8	106.8	2010 low - electricity only - Agricultural residues and forestry not differentiated
Oxera02	2010		42.0	36.0		93.6	171.6	2010 high - electricity only - Agricultural residues and forestry not differentiated
E4Tech03[a]	2020	52.7	0.0	126.4	0.0	92.7	271.7	Constrained potential - figure shown here is derived from % contribution of biomass to UK electricity supply presented in original report
E4Tech03[a]	2020	61.1	0.0	252.7	0.0	139.0	452.8	Future unconstrained tech potential
RCEP04	2005	75.0	13.0	0.2			88.2	
RCEP04	2050	75.0	25.0	550.0			650.0	
CT05	2005	46.8	21.6	0.7		79.2	266.4	2005
CT05	2020	46.8	21.6	118.8		79.2	299.8	Future Low (no date - assumed 2020)
CT05	2020	46.8	21.6	151.2		80.2	191.3	Future High (no date

Report	Year of estimate	Agricultural residues $PJ.yr^{-1}$	Forestry and forestry residues $PJ.yr^{-1}$	Perennial energy crops $PJ.yr^{-1}$	Conventional energy crops (grain/oil seed) $PJ.yr^{-1}$	Wastes $PJ.yr^{-1}$	Total - Primary energy $PJ.yr^{-1}$	Notes
								- assumed 2020)
Taskforce05	2005	40.5	21.9	3.9	0.0	135.5	201.8	
Taskforce05	2005	49.5	26.0	6.7	0.0	156.5	238.7	
AEA05	2020	60.5	22.2	69.4		625.0	777.0	Technical potential - assumes Calorific value of AD gas is primary energy
UKBioStrat07	2010	40.5	23.6	2.8		166.8	233.7	2010 low
UKBioStrat07	2010	49.5	27.6	4.0		201.0	282.0	2010 high
UKBioStrat07	2020	128.7	70.4	64.7	0.0	316.2	580.0	Future Low (no date - assumed 2020)
UKBioStrat07	2030	137.7	74.4	65.9	50.0	350.4	678.3	Future High (no date - assumed 2030)
E&Y07	2020						225.0	Technical potential - low
E&Y07	2020						1073.0	Technical potential - high
E&Y07	2020						96.0	Market potential - low
E&Y07	2020						180.0	Market potential - High
EEA07	2010		62.8	142.4		360.1	565.2	Wastes includes agricultural residues
EEA07	2020		62.8	368.5		364.3	795.5	Wastes includes agricultural residues
EEA07	2030		46.1	615.5		360.1	1021.6	Wastes includes agricultural residues

Report	Year of estimate	Agricultural residues $PJ.yr^{-1}$	Forestry and forestry residues $PJ.yr^{-1}$	Perennial energy crops $PJ.yr^{-1}$	Conventional energy crops (grain/oil seed) $PJ.yr^{-1}$	Wastes $PJ.yr^{-1}$	Total - Primary energy $PJ.yr^{-1}$	Notes
Fischer07	2000	194.0					194.0	
Fischer07[b]	2030	174.0		235.0			409.0	
Kilpatrick08[c]	2010	137.9	71.5	1.5		39.0	250.0	
Kilpatrick08[c]	2030	158.4	71.5	248.0		39.0	516.9	
E4Tech09	2010	13.8	6.4	0.0		145.3	165.5	Constrained
E4Tech09	2020	69.0	36.8	134.0		343.2	583.0	
E4Tech09	2030	69.0	36.8	538.0		440.2	1084.0	Unconstrained - effectively the same as the technical potential
Thornley 2009	2020	18.0	12.8	44.0	43.3	95.1	213.2	Sustainable potential (not date - assumed 2020)
de Wit09	2030	200.0	25.0	225.0			450.0	

[a] To derive a figure for total UK biomass potential it was assumed that that total UK electricity use was 234 TWh.yr-1 The conversion efficiency to electricity given in the report was 40%.

[b] 2030 figure is a rough estimate for the UK based on Fischer's land suitability distribution, suggested average yield for biofuel crops and assumed planted area of 1.1Mha

[c] Results converted from oven dry tonnes to PJ using a conversion factor of $17GJ.odt^{-1}$.

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