

THE ROLE OF BIOENERGY IN THE UK'S ENERGY FUTURE

FORMULATION AND MODELLING OF LONG-TERM UK BIOENERGY SCENARIOS

AUTHORS

Sophie Jablonski^{a,*}, Neil Strachan^b, Christian Brand^c, Ausilio Bauen^a

AFFILIATIONS

^a Imperial College London, Centre for Energy Policy and Technology (ICEPT), Mechanical Engineering Building 3rd Floor, Exhibition Road, London SW7 2AZ, U.K.

^b UCL Energy Institute, University College London, Central House, 14 Upper Woburn Place, London. WC1H 0HY, U.K.

^c Environmental Change Institute, Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, U.K.

* Corresponding author. Tel.: +352 621 36 85 58; *E-mail address*: s.jablonski@eib.org (S. Jablonski)

Note: this is a personal version, created by Christian Brand, of the text of the accepted journal article. It reflects all changes made in the peer review process, but does not incorporate any minor modifications made at the proof stage. The complete citation for the final journal article is:

- Jablonski, S., Strachan, N., Brand, C., Bauen, A., 2010. The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergy scenarios. *Energy Policy* 38, 5799-5816.
- DOI: <http://dx.doi.org/10.1016/j.enpol.2010.05.031>

Copyright © and Moral Rights for this paper are retained by the individual authors and/or other copyright owners

ABSTRACT

This paper explores the prospects and policy implications for bioenergy to contribute to a long-term sustainable UK energy system.

The UK MARKAL technology-focused energy systems dynamic cost optimisation model - which has been used to quantify the costs and benefits of alternative energy strategies in UK policy making - is enhanced with detailed representation of bio-energy chains and end-uses. This provides an important advance in linking bioenergy expert-knowledge with a whole system modelling approach, in order to better understand the potential role of bioenergy in an evolving energy system.

The new BIOSYS-MARKAL model is used to run four scenarios constructed along the pillars of UK energy policy objectives (low carbon and energy security). The results are analysed in terms of bioenergy resources use and bioenergy pathways penetration in different end use sectors.

The main findings suggest that the complexity of different bioenergy pathways may have been overlooked in previous modelling exercises. A range of bioenergy pathways - notably bio-heat and biofuels for transport - may have a much wider potential role to play. The extent to which this potential is fulfilled will be further determined by resources availability, and market segment constraints, as well as policy measures to improve deployment.

ACKNOWLEDGEMENTS

The authors are grateful to the UK Natural Environment Research Council (NERC), the Engineering and Physical Sciences Research Council (EPSRC), and the Biotechnology and Biological Sciences Research Council (BBSRC) for their support for the TSEC-BIOSYS Project: "A whole systems approach to analysing bioenergy demand and supply: Mobilising the long term potential of bioenergy." (Grant reference number: NE/C516279/1). Website: <http://www.tsec-biosys.ac.uk/>.

The authors would also like to thank those who supported this research in providing data and advice: in particular Miles Perry, Bharat Varma and Dr. Giuliano Premier, Marc De Wit and Prof. Andre Faaij, Carly Whittaker, Antonio Pantaleo, and Dr. Calliope Panoutsou

KEYWORDS : Bioenergy; MARKAL; Energy systems modelling;

1. INTRODUCTION

1.1. The objectives

The overall objective of this research is to explore the prospects for bioenergy in the UK energy system in the long-term, and how this is affected by sustainable energy policy objectives. This paper aims to:

- (1) Improve the modelling of bioenergy technologies and pathways in an energy systems model (UK-MARKAL); and
- (2) Provide better quantitative insights on the possible contribution of bioenergy to the future UK energy system under different policy objectives.

This work is of interest as no UK energy systems model (and very few other countries') undertook detailed analysis of the contribution of bioenergy pathways, in particular within integrated scenarios of low carbon and energy security policy objectives.

1.2 MARKAL modelling context

MARKAL is a widely applied, dynamic, technology-rich linear programming (LP) energy systems optimisation model. For full details of the optimization methodology, see Loulou et al. (2004). MARKAL models have a long track record of policy and academic research (e.g. International Energy Agency (2008) and Smekens-Ramirez Morales (2004)). One of the major strengths of this integrated E4 (energy-economic-environmental-engineering) modelling approach is its depiction of the entire energy system¹. This allows for different sectors to compete for finite primary energy resources, for supply vs. demand side energy chain improvements and for distinction between technological vs. behavioural responses.

Despite the large number of analyses using MARKAL models at local, national, regional and global scales, very few have focused on bioenergy, although almost all have included bioenergy in aggregated form (e.g. Chen (2007) and Das (2007)). Other MARKAL modelling exercises have addressed bioenergy as part of a focus on specific renewable energy policy mechanisms (e.g. Contaldi (2007)). However the only dedicated MARKAL bioenergy modelling papers were Schulz (2007), focusing on the specific energy chain of bio-methane, and Gielen (2001), which modelled the contribution of biomass to the Western European energy and materials system. The most relevant study so far (Clarke et al., 2009) used the UK-MARKAL model (prepared for the UKERC 2050 project), to explore the potential contribution of bioenergy technologies to 60% and 80% carbon reductions in the UK energy system by 2050 and outline the potential for accelerated technological development of bioenergy chains. The latter modelling, however, focused only a few bioenergy chains and a limited number of runs². Similarly, despite the existence of numerous sophisticated analyses of bioenergy chains using process or econometric models (see e.g. Jablonski et al. (2008), Junginger et al. (2006), Purohit (2009) and Seiffert et al. (2009)), their integration into larger energy systems has been extremely limited. This is partly due to the computational

complexity and data demands associated with the informed representation of the technological versatility of bioenergy.

Overall there is a lack of appropriate tools connecting bioenergy expert-knowledge with a whole system approach in which all energy supply and use options compete in a systematic, consistent modelling exercise.

1.3. UK bioenergy policy context

The UK has played a leading international role in setting national CO₂ reduction targets, now legislated as -80% by 2050, including international aviation and shipping (Committee on Climate Change, 2008). MARKAL modelling has played a key underpinning analytical role in the adoption of long-term CO₂ reduction targets (Strachan et al., 2009b). In parallel to this the UK has been working on introducing stronger renewable energy targets and policy (strongly driven by the EU), while meeting other energy policy objectives of reliable and affordable energy (DTI, 2007).

Therefore, bioenergy has increasingly been looked at by policy makers as a potential means to meeting climate and renewable energy targets. In the midst of a number of reviews, consultations and strategies related to bioenergy and renewable energy (Slade et al., 2009), one central message has been that bioenergy potentially has an important role to play in fulfilling the UK energy policy goals. Key policy documents over the years have been the UK Biomass Strategy (DEFRA et al., 2007), Renewable Energy Strategy consultation (BERR, 2008b), Heat Call for Evidence (BERR, 2008a), and the Heat and Energy Savings Strategy Consultation (DECC, 2009). The Renewable Energy Strategy consultation (BERR, 2008b) provides an illustrative scenario, indicating that bioenergy could contribute about 30% of the UK's renewable heat and power generation targets in 2020, as well as a significant share of renewable transport fuel (BERR, 2008b). The modelling conducted in this paper provides a more detailed exploration of the potential for diverse bioenergy chains to contribute to the UK energy system in the long-term, putting them in competition among themselves, and with alternative means of producing energy.

2. METHODOLOGY: MARKAL MODELLING OF BIOENERGY

2.1. Summary of the BIOSYS-MARKAL model

UK MARKAL provides a systematic exploration of discounted least system cost configurations across a modelling horizon from 2000-2050 ⁴ to meet exogenous demands for energy services – derived from standard UK forecasts; e.g., for residential buildings (Shorrock and Utley, 2003) and transport (DfT, 2005). Key parameters include resource supply curves (BERR, 2006), an explicit depiction of infrastructures, physical and policy constraints ⁵, dynamically evolving technology costs ⁶, and energy service demands.

Full details of the UK MARKAL energy systems model are given in Strachan (2008a) and Kannan (2007). Prior modelling focused on macro implications (Strachan and Kannan, 2008), international drivers (Strachan et al., 2008b), and - in a comparable study to this paper - enhanced analysis of hydrogen energy chains (Strachan et al., 2009a).

The BIOSYS-MARKAL version of the UK model integrates a comprehensive and up-to-date technological and sectoral representation of bioenergy chains. BIOSYS-MARKAL was developed as follows. First the existing bioenergy representation in UK MARKAL was critically reviewed. Based on the findings of this review, a new structure for bioenergy chains was proposed, with key changes covering the range of biomass resources (both domestic and imported), as well as conversion technologies and pathways, and end-use applications. Finally, the updated structure was populated with data reflecting the state-of-the-art literature and knowledge of bioenergy experts in the UK.

The improved representation of bioenergy chains and applications, as well as the improved data quality, allows for a whole-energy-system analysis of the contribution of bioenergy in the UK. This is undertaken via consistent “what if” sensitivity analyses in the MARKAL modelling framework for long-term policy insights.

2.2. Key datasets and sources

The data used to populate the bioenergy chains are presented in Annex 1. Sources of data include recent publications on current and future bioenergy options, inputs from TSEC-BIOSYS consortium members, and from interviews with other relevant experts. Further details on the BIOSYS-MARKAL model updated structure and parameters are given in Jablonski et al. (2009a; 2009b).

3. THE BIOSYS SCENARIOS

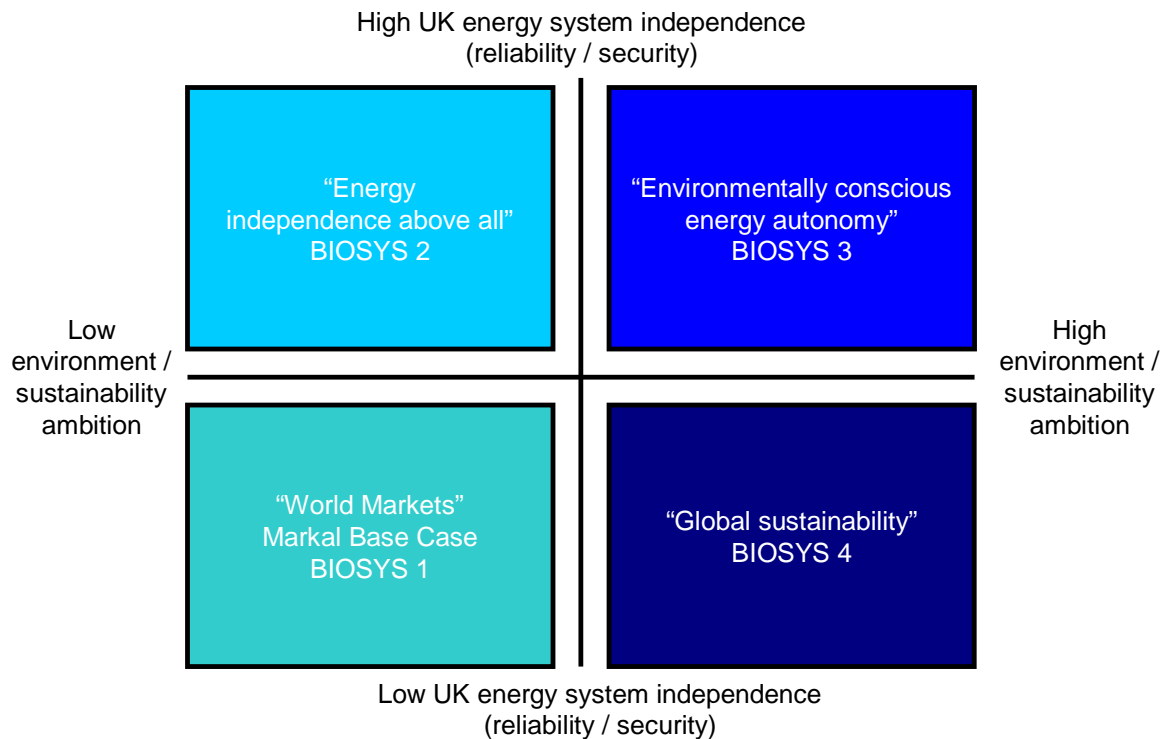
3.1. Approach for BIOSYS scenarios definition

For a consistent approach to addressing multiple uncertainties in long term bioenergy pathways, a scenario framework was used (Grübler et al., 1999). These BIOSYS scenarios include lessons from previous energy scenario exercises in the UK (Hughes, 2008). The BIOSYS scenarios are deliberately constructed to be “*plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions (“scenario logic”) about key relationships and driving forces (e.g., rate of technology changes, prices)*” (Nakicenovic et al., 2000, p.335).

A key point is that the scenarios are built by looking to the long-term future of the UK energy system, and in particular the policy objectives influencing this future. The “pillars” of UK energy policy (DTI, 2007) are (1) the environment and (2) energy

reliability (qualified under the heading “security of supply” and “quality of continuity of supply” (BERR, 2009)). Supplementary government objectives include affordable energy for the poorest and competitive markets for businesses, industry and households. This scenario-policy linkage is crucial to engage UK policy makers and energy system stakeholders (including energy companies, investors, consumers, government) with the possible role of bioenergy. This process was enabled by the TSEC-BIOSYS project, and carried out iteratively through the sharing and discussion of datasets and initial findings.

Therefore the BIOSYS modelling and scenario exercise are characterised by: (a) (environmental) sustainability ambition; and (b) energy system independence (mostly related to energy security of supply – and linked to the balance of imported energy versus domestic sources of energy). Hence, as with many other scenario exercises, these underlying policy objectives are set up in a 2 x 2 matrix of four BIOSYS scenarios (numbered 1 to 4 – see Figure 1). The advantage of such an approach is its effectiveness to produce interesting and contrasting supply-side scenarios (Hughes, 2008), in that case focusing on technology. The combination of the BIOSYS-MARKAL modelling tool and the four visions of the future ensure that the steps between the present (calibrated in the model) and the future (2050) are illustrated, at least in terms of technological choices, in a linear, least-cost optimisation framework.

Figure 1: Simplified representation of BIOSYS scenarios as a futures' matrix

3.2. Overview of the BIOSYS "core" scenarios

The BIOSYS scenarios are first described in a general manner, relying on the two extremes ("high" / "low") of the two driving forces (the policy directions). This is the starting point for the generation of qualitative storylines, focusing on the technological and policy aspects of the energy system.

"World Markets" is the base case BIOSYS 1 scenario. In this scenario, little concern is paid to energy security, energy efficiency or sustainable energy production and climate change. Some renewable technologies are adopted because they are cost-effective. "Energy independence above all" is the BIOSYS 2 scenario, where a supply of cheap and secure energy is the main underlying (policy) objective. Domestic sources of energy are prioritised (both fossil and renewables). The concerns for environmental sustainability (and climate change) come only second to energy security ones. "Environmentally conscious energy autonomy" is the BIOSYS 3 scenario, in which energy systems are restructured around the use of domestic sources of energy but with a priority given to renewables and low carbon sources. Finally, "Global Sustainability" is scenario BIOSYS 4, which involves a drive for sustainability in energy supply, promoted in a globalised manner. This would imply a growth in imported energy sources that are certified as low carbon and / or "sustainable".

3.3. Quantitative modelling of the BIOSYS scenarios in MARKAL

The BIOSYS-MARKAL model finds the least cost energy system configuration under a set of constraints and parameter variations for the different scenarios. The constraints and parameter variations which characterise the different scenarios are provided in Annex 2.

BIOSYS 1 is taken as the base case scenario, and the other scenarios, and data that characterise them, are defined relative to it. In BIOSYS 2, the import of energy sources (both fossil and bioenergy) is limited (in the form of a constraint). The use of domestic bio-energy resources is stimulated, with (1) a larger share of UK agricultural land available for all bioenergy crops; (2) subsidy schemes that encourage bioenergy farming; and (3) R&D schemes that target yield improvements of woody and grassy bioenergy crops. In addition R&D programmes and subsidy schemes target the domestic processing of resources, with the effect that (1) most bioenergy process technologies have lower investment costs in the future; (2) the UK has higher levels of biomass share in co-firing, and (3) transport biofuel blending is allowed at higher levels. Finally, the accessibility of agricultural, forestry and industrial organic residues and waste biomass from Municipal Solid Waste (MSW) is increased.

In BIOSYS 3, the import of energy sources (both fossil and bioenergy) is limited, as in BIOSYS 2. However, in addition, strict certification schemes are in place for ensuring the sustainability of the bioenergy imports, with an impact on costs. The use of domestic bioenergy resources is encouraged under a strong sustainability framework: therefore the planting of bioenergy crops is encouraged, with significant land (potentially) available. However, any increase in domestic bioenergy crops yields is limited by public (non-) acceptability of bio-engineered crops, while food/feed-related crops are not directed to energy purposes in the medium to long term, because of “food versus fuel” concerns. Similarly forestry biomass use is limited to its “environmentally compatible potential” (European Environment Agency, 2006). Moreover similar to BIOSYS 2, the domestic processing of resources is encouraged by R&D programmes and subsidy schemes, though this may not apply to certain technologies considered to pose sustainability risks. In particular there is no support for technologies using food/feed-related biomass sources. Other bioenergy process technologies have lower investment costs, and higher levels of biomass share in co-firing / biofuels blending are still allowed. Finally the overall use of low carbon and renewable energy in the UK energy system is strongly supported by policy. Renewables obligations are set up for all three final end uses (heat, power and transport) in all demand sectors (residential commercial, industrial and transport) in line with EU RE Directive (Commission of the European Communities, 2008) and UK RES consultation (BERR, 2008b), and a CO₂ cap is put on the UK energy system to reach 80% reduction in overall emissions by 2050 (incl.

international aviation and shipping), in line with UK government targets (Committee on Climate Change, 2008).

In BIOSYS 4, domestic and imported bioenergy resources are promoted under a strong sustainability framework. The planting of bioenergy crops is encouraged and more land is available for it (principally on idle or marginal lands). But the increase in bioenergy crops yields is limited by public (non-) acceptability of bio-engineered crops. In addition, food/feed-related crops are progressively phased out of the energy system, and are not used for energy purposes from 2020. Again (like in BIOSYS3) forestry biomass use is limited to its “environmentally compatible potential”. Strict certifications schemes are in place for ensuring the sustainability of bioenergy sources, with an impact on costs (assumed less important than in BIOSYS 3). As in BIOSYS 3, the overall use of low carbon and renewable energy in the UK energy system is strongly supported by policy, and renewables obligations are set up for all three final end uses in all demand sectors. Finally, a CO₂ cap is put on the UK energy system to reach 80% reduction in overall emissions by 2050.

4. RESULTS

The results of the BIOSYS-MARKAL runs are analysed with a focus on the bioenergy technologies and pathways, notably biomass resources, the end-use sectoral breakdown of bioenergy, and the bioenergy pathways in each scenario.

The key distinguishing facts about the results of the modelling for different scenarios are highlighted in Annex 3.

4.1. Levels of biomass resources

The UK primary energy demand is estimated to decrease from approximately 9,000 PJ in 2000 to 8,500 PJ in 2050 (in BIOSYS 1 and 2), and 7,000 PJ (in BIOSYS 3 and 4). Over the time horizon 2000-2050, the overall amount of biomass resources supplying the UK energy system to meet various energy service demands (as well as the policy objectives investigated) increases in all scenarios by a significant amount, growing from less than 50PJ to more than 1,200 PJ (and more than 1,600 PJ in BIOSYS 2). The rate of deployment of biomass resources in the short-term is high in all scenarios⁷, and in the medium-term it is the highest for scenario BIOSYS 3, where by 2020 already more than 700 PJ per annum is fed into the system. The deployment is also significant in BIOSYS 2 and 4, with more than 600 PJ of biomass each, while it is slowest for BIOSYS 1 (380 PJ by 2020). Interestingly the overall level of biomass used by the energy system is not that different in the four scenarios tested. What varies is the balance between the biomass types, both regarding their type (wood, grass, wet, liquid) and their origin (domestic or imported), as described below.

Figures 2 to 5 show the different categories of biomass resources composing the mix entering the energy system over time. The most important biomass resources chosen

vary between the scenarios but the lion's share of the total biomass is always a combination of domestic and imported lignocellulosic biomass (mostly wood chips and pellets, but also grass and residues, and wood logs and wood wastes). Domestic "wet biomass" (composed mostly of the organics fraction of municipal solid waste, commercial industrial waste – mostly from the food & drink industry – and sewage sludge) are the most significant resources in the short-term, but only remain a significant part of the biomass resources mix in scenarios BIOSYS 3 and 4.

Liquid biomass (in the form of imported bio-ethanol, bio-diesel or bio-oil) is present in the biomass resources mix of all scenarios, but never reach more than 16% of the mix in the long-term, their biggest share being achieved in scenario BIOSYS 3.

Figure 2: Biomass energy resources entering the UK energy system in scenario BIOSYS 1 (2000 – 2050)

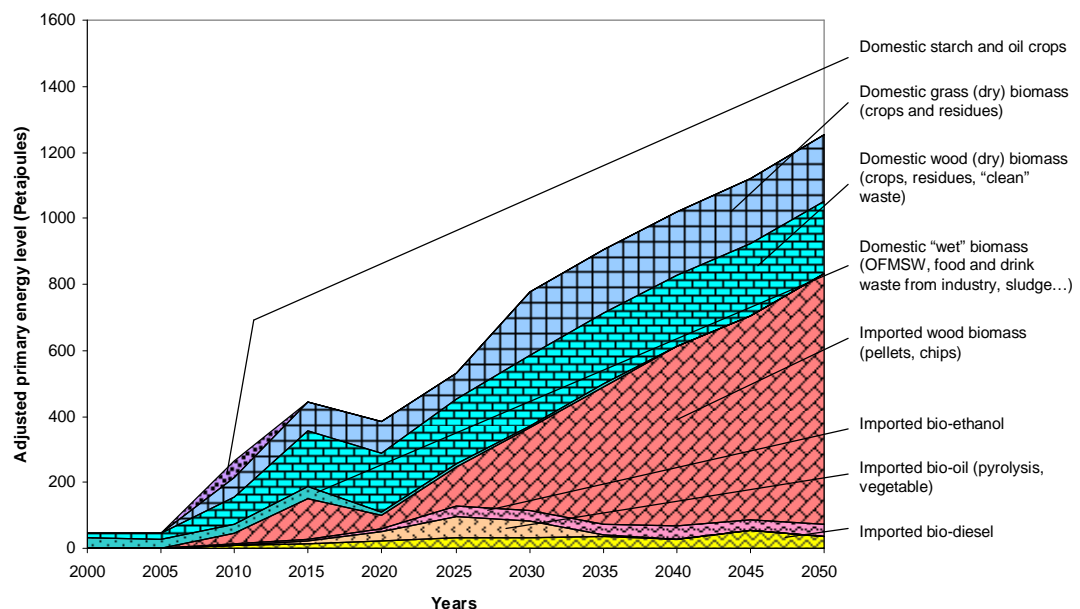


Figure 3: Biomass energy resources entering the UK energy system in scenario BIOSYS 2 (2000 – 2050)

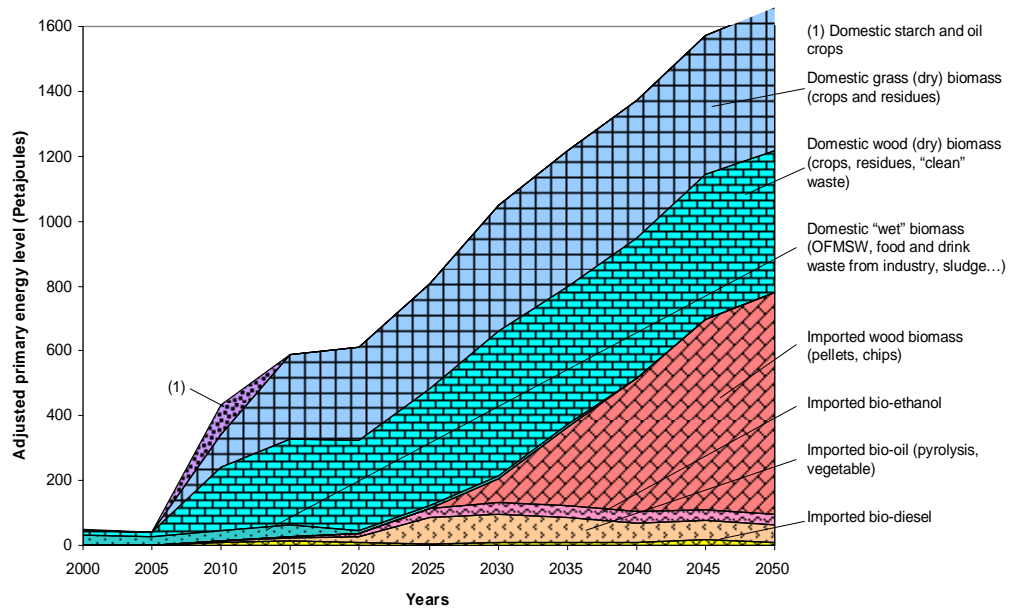


Figure 4: Biomass energy resources entering the UK energy system in scenario BIOSYS 3 (2000 – 2050)

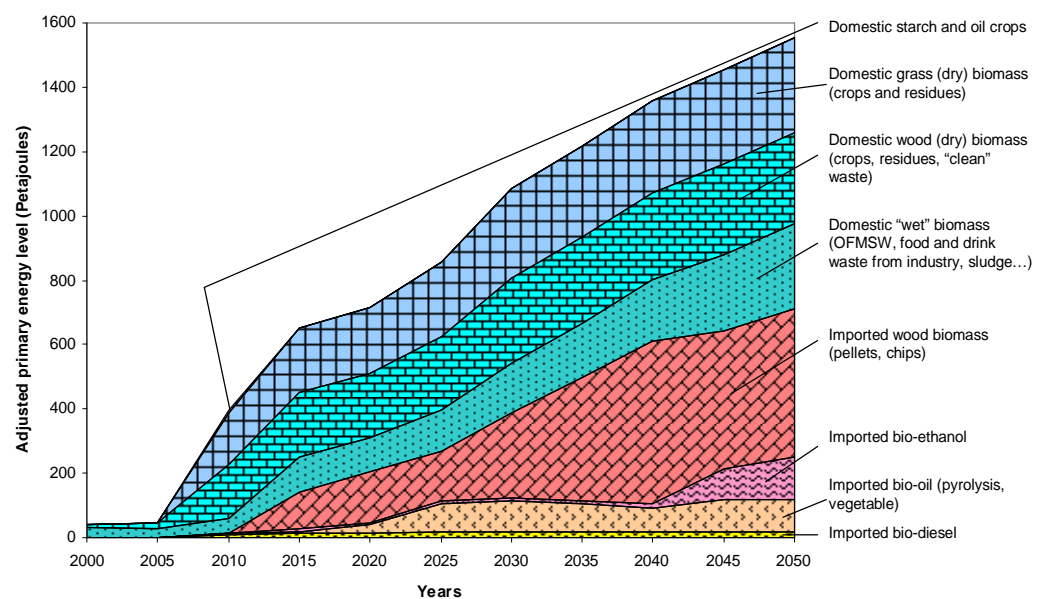
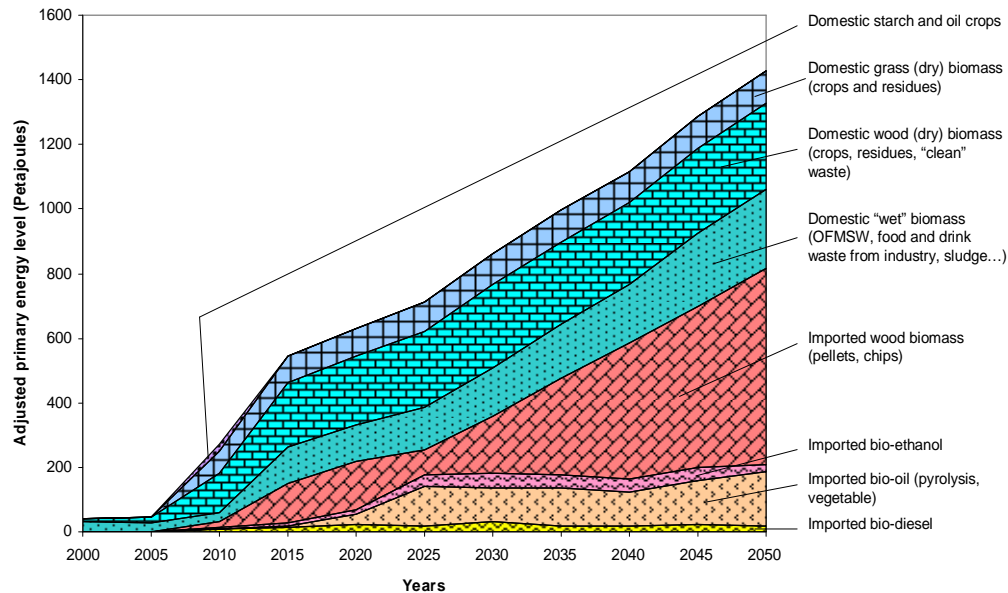


Figure 5: Biomass energy resources entering the UK energy system in scenario BIOSYS 4 (2000 – 2050)



4.2. Use of bioenergy in different sectors of the UK energy system

The overall (long-term) level of final (bio-) energy ranges between about 1,200 PJ (for BIOSYS 1, 3 and 4) to about 1,500 PJ in BIOSYS 2 (see Figures 6 to 9). Like for biomass resources this level increases significantly in all scenarios from about 30 PJ to more than 400 PJ in the short- to medium-term (2020); the fastest overall uptake in bioenergy use occurs in BIOSYS 3 (about 750 PJ by 2020), and slowest in BIOSYS 1 (close to 400 PJ in 2020).

The main bioenergy use in all scenarios is heat, representing more than 50% of the bioenergy use in the long-term (in BIOSYS 1, 2 and 4 it is more than 90%). The balance between heat sectors varies between scenarios, with residential heat dominating (reaching about 60% of the bioenergy use mix by 2050 - followed by industrial heat and service heat) in BIOSYS 1 and 2; whereas the dominance of residential bio-heat is less in the medium- and long-term in scenarios BIOSYS 3 and 4 (and industrial and service heat take over, reaching respectively 53% and 69% of the bioenergy use mix by 2050). In particular in BIOSYS 3 residential bio-heat penetration is extremely eroded in the medium-to long term, as other renewable or low carbon heat options become widely available in the residential sector (in the form of low carbon electric heating). As a result pellets and woodchips are not cost effective for residential heat anymore (although wood logs keep their market share).

Biofuels for transportation are the second biggest use of bioenergy in the energy system in the longer term: their share of the bioenergy use mix varies widely between scenarios,

only taking 6% to 10% in BIOSYS 1, 2 and 4, but reaching 46% in BIOSYS 3 (partly as a result of the drop in bio-heat contribution, but also because of a much larger uptake in the medium- to long-term in absolute terms – 575 PJ by 2050). Interestingly biofuels for transportation represent a larger share of final bioenergy use than the share of the biomass resources mix (which oscillates between 0% and 12% depending on the scenarios throughout the time horizon): this is partly due to the significant role of domestic biofuels processing (especially for bio-diesel and bio-kerosene - more details on this are provided in section 4.2).

Finally, bio-electricity contribution is the lowest in the bioenergy use mix: in scenarios BIOSYS 1 and 2 its absolute contribution decreases over time (from about 15 PJ in 2000 to less than 2 PJ by 2050); in scenarios BIOSYS 3 and 4 it increases in the short to medium-term (reaching almost 30 PJ) but then drops to even lower long-term levels than in BIOSYS 1 and 2 (less than 1 PJ by 2050). In terms of the share of the bioenergy use mix, bio-electricity contribution decreases from a relative dominance (around 60% in the short-term) to less than 1% in the long-term in all scenarios (maximum 2020 share is 6% in BIOSYS 3).

Figure 6: Evolution of the use of bioenergy in different end-use sectors (heat, power, transport fuel) in scenario BIOSYS 1 (2000 - 2050)>>

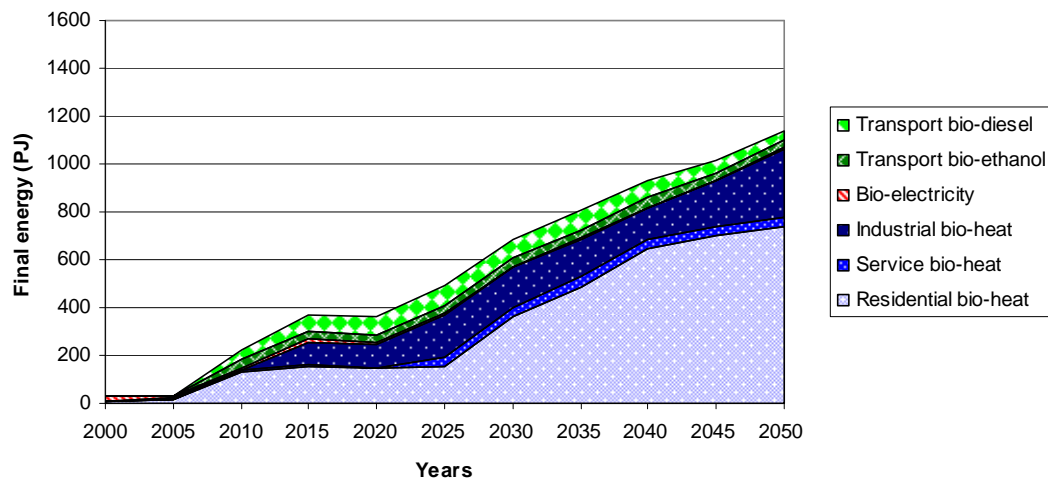


Figure 7: Evolution of the use of bioenergy in different end-use sectors (heat, power, transport fuel) in scenario BIOSYS 2 (2000 - 2050)

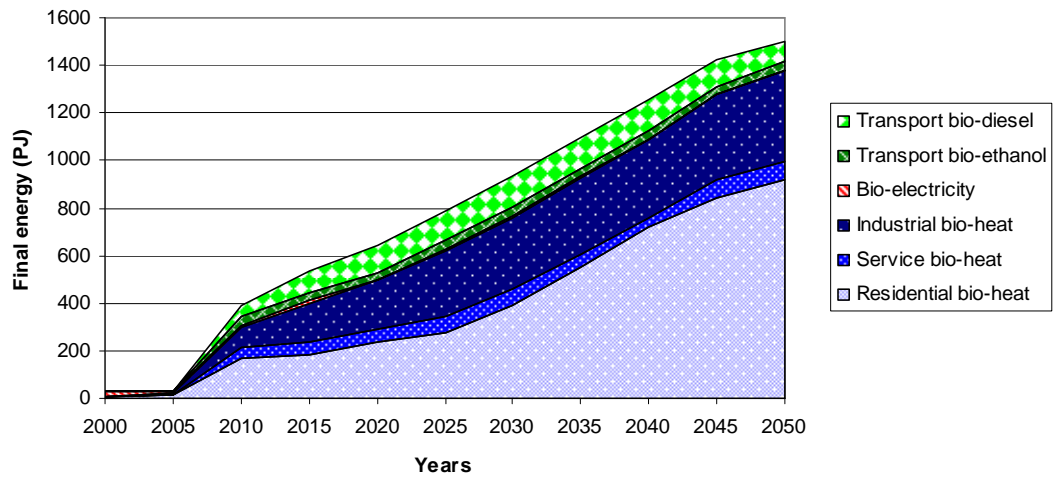


Figure 8: Evolution of the use of bioenergy in different end-use sectors (heat, power, transport fuel) in scenario BIOSYS 3 (2000 - 2050)

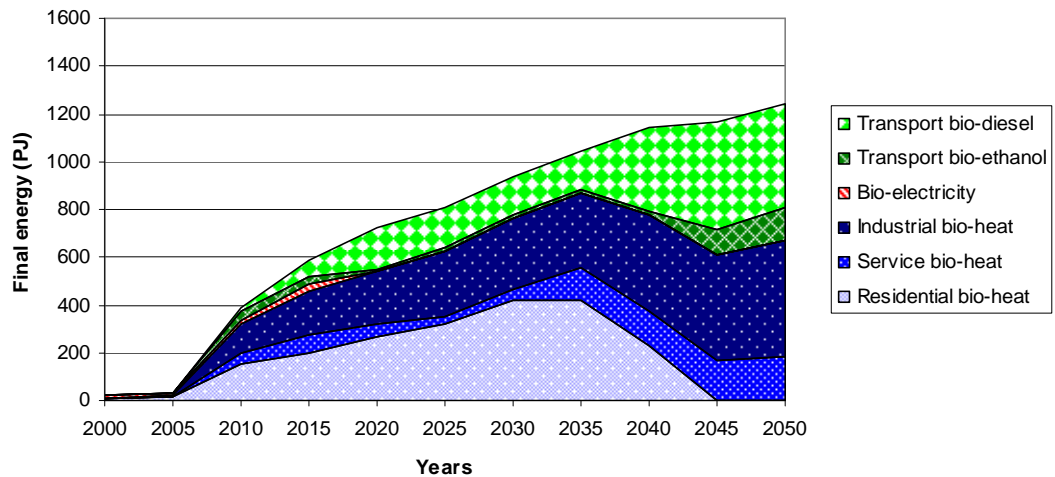
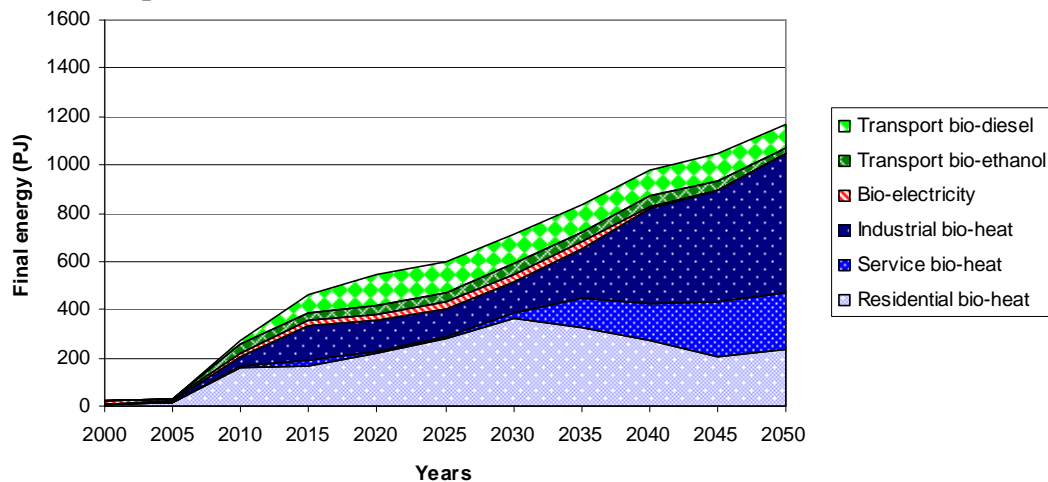


Figure 9: Evolution of the use of bioenergy in different end-use sectors (heat, power, transport fuel) in scenario BIOSYS 4 (2000 - 2050)



4.3. Overall energy resources and technology pathways

Annex 4 presents a synthetic view of the dominant bio-energy pathways, the options not selected, and which other energy pathways are dominating the UK energy system throughout the modelled time horizon (2000-2050) for all four scenarios.

The use of wood biomass (from imported or domestic woodchips or pellets) to produce heat in different end-use sectors is the most dominant pathway in all scenarios, especially in BIOSYS 1 and 2.

Wood resources selected for different scenarios come in order of costs: “cheaper” feedstock like forestry residues or clean wood waste are always used first, then complemented by other sources like wood bioenergy crops (willow, poplar) or imported woodchips / pellets. In all scenarios imported wood biomass plays a key role in supplying wood biomass to the energy system in the medium- and long-term. In scenarios with constrained imports of energy there is an earlier development of domestic wood biomass supply (from crops).

Wood is used to produce heat in different end-use sectors (residential, service, industrial, and district heating). The most dominating pathways go to the residential and the service sectors, which are activated in all scenarios. In scenarios with high environmental sustainability ambition the wood-heat pathways become more diversified, including the industrial sector, and some district heating for service and residential sectors.

In addition to direct heat production, wood is also used in transportation, processed into 2nd generation biofuel (FT bio-diesel and bio-kerosene). This pathway is only significant as all other cheaper feedstock to process into biofuels have been already used: this is the case in BIOSYS 3 (longer term) and 4 (both in the short and long-term).

Associated with the use of wood for bio-heat is the deployment of pelletisation pathways. The production of wood pellets domestically (for use in residential and service sector heat boilers) is in competition with imported pellets, and is a significant pathway only when wood crops feedstock can be produced at lower costs, assumed achievable where energy security is a stringent policy objective, i.e. in BIOSYS 2 and 3.

Another significant lignocellulosic pathway corresponds to using grass crops (produced domestically, e.g. miscanthus) or agricultural residues (mostly straw) for the production of industrial heat, and /or 2nd generation biofuels.

The production of transportation biofuels from grass biomass and (in particular) agricultural residues is a key pathway in the BIOSYS scenarios. This is due to the combined effect of the renewable transport fuel obligations in place, in all scenarios (with higher blending levels in BIOSYS 3 and 4), and the limited availability of other pathways (using imports, or 1st generation feedstock), especially in the short- to medium-term. Agricultural residues are significantly processed into 2nd generation biofuels (notably bio-diesel and bio-kerosene) in BIOSYS 1 and 2 early on, whereas in BIOSYS 3 and 4 this occurs later (in the medium- to long-term).

Where other resources are available for obtaining transportation biofuels (notably imports) low quality pellets are a cost-attractive vector for penetration of the industrial heat sector. Grass crops complement when no more residues are available (in BIOSYS 2 and 3). Other pathways for agricultural residues go to power and district heating (but minor) for BIOSYS 3 & 4.

Wet biomass to energy via anaerobic digestion is another significant pathway, as biogas is used for power production and / or injected in the natural gas grid depending on the scenarios, its largest contribution being in BIOSYS 3.

The main resources of biomass selected in the BIOSYS scenarios (for these pathways) are the Organic Fraction of Municipal Solid Waste (OFMSW), commercial industrial waste (mostly from the food and drink industry), and sewage sludge.

The most noticeable difference between scenarios relate to the use of biogas once it is produced. In BIOSYS 1 and 2 the production of power from biogas (in internal combustion engines, and CHP units in the longer term) is the major bio-electricity pathway for the UK energy system. In BIOSYS 3 and 4 the biogas resource is compressed and injected in the gas grid in the longer-term, and then used in natural gas boilers of the industrial (mostly) and service (in BIOSYS 3) heat sectors.

Some bioenergy pathways correspond to the production of energy from already “refined” liquid biomass sources imported into the energy system (such as pyrolysis bio-oil, bio-ethanol or bio-diesel). These pathways are present in all BIOSYS scenarios, but play a larger role in BIOSYS 3 and 4.

Liquid transportation biofuels (bio-ethanol and bio-diesel) are consistently imported to the UK energy system in all four scenarios but emerge strongly in BIOSYS 3 in the longer term, as the demand for biofuels as low carbon transport options is the highest of all scenarios. The import of vegetable oil (then processed to 1st generation bio-diesel) is another pathway (although of less importance ⁸) in the short to medium-term, or in the longer-term for BIOSYS 4.

Bio-oil from pyrolysis can be upgraded into light fuel oil (LFO), and then be used for heat production in stationary applications. This pathway is a significant one for the industrial sector, and especially so in BIOSYS 2, 3 and 4; but it is not cost-effective enough for the residential or the service sector. In addition, the fast pyrolysis processing of lignocellulosic biomass resources into bio-oil does not appear to be cost effective enough to be done in the UK: as a result pyrolysis oil is only used from imports, and this occurs even in the futures where overall energy imports are constrained.

Finally other “non-bioenergy pathways” (fossil fuels - coal, natural gas and oil – nuclear power or other electric and renewable technologies) play significant roles in the futures modelled.

Electricity production from coal is very dominant in BIOSYS1 and 2, with the shares of other power pathways decreasing in time. Natural gas to heat is the most dominant heat pathway until bio-heat takes the lead in the residential sector. Oil is the main fuel for the transportation sector, but also plays a significant role producing heat and power in the short- to medium-term. In these two BIOSYS scenarios nuclear power is phased out of the power mix around 2030, as fossil fuels remain largely unconstrained.

In BIOSYS 3 and 4 the energy system's dominant pathways change significantly in the medium- to long-term. In the power sector, renewables (dominated by off- and on-shore wind) become the main energy resource, and nuclear power remains a major player in the power mix, and increasing significantly its share in BIOSYS 4. Fossil fuels go from being major resources for all types of end-use sectors and services to mostly service and industrial heat, and a fair share of the transportation fuel in the longer term. (Decarbonised) electricity becomes a key player in all end-use sectors, is used to produce a large amount of heat, and a significant share of transportation fuel in the longer term.

5. DISCUSSION

The modelling exercise has focused on consistent scenarios of long-term deployment of bioenergy under the twin drivers of sustainable energy (low carbon and sustainable land-use) and energy security (imported vs. domestic fuel shares). The scenarios were implemented via enhanced bioenergy pathway representation in a UK energy systems optimisation model. This twin focus represents an innovative and powerful approach to understand the potential role of bioenergy in long-term system evolution. The results of

the BIOSYS-MARKAL modelling confirmed some insights from earlier studies (notably the short to medium-term market penetration of transport biofuels, and the low long-term penetration of bio-electricity). But, the BIOSYS-MARKAL modelling exercise provides novel insights on a range of bioenergy technologies and pathways, notably related to the bio-heat market, as well as the infrastructure underpinning domestic processing of transport and heat biofuels. If the bio-heat potential is to be developed, the stimulation of domestic bioenergy farming, and the logistics and infrastructure implications of managing increased quantities of biomass would need to be carefully considered.

In terms of resources, all scenarios suggest a very large increase in the demand for both domestic energy crops, residues and imported lignocellulosic biomass (between 18 and 43 million ODT depending on the scenarios in 2020, reaching 54-88 million ODT in 2050). Especially notable are the levels of agricultural land uptake for bioenergy crops projected for a largely energy independent future (BIOSYS 2), which we estimated equivalent to more than 1.5 million hectares by 2020 (stabilised until 2050 as yield improvements materialise). Such a figure is substantially higher than the “optimistic” RCEP scenario where the land required for energy crops reaches 1 million hectares in 2020 (RCEP, 2004). But longer-term results suggest lower land uptake than the 5.5 million hectares envisaged by 2050 in that same RCEP scenario (RCEP, 2004). It is likely that the actual medium-term uptake will be limited by a number of constraints, including farmers perceptions, and the competition from other markets (Sherrington et al., 2008). Nevertheless our results suggest that aiming for more than the UK Biomass Strategy goal of 350,000 hectares by 2020 (DEFRA et al., 2007) could be cost-effective. In the long term, other infrastructure constraints are likely to dominate, including cargo requirements in UK harbours for imports of woodchips and wood pellets in BIOSYS 3 and 4. Similarly the transportation of this favoured bio-pathway to final end-use is likely to be a challenge. In addition the bio-pathway using biogas (injected into the gas grid) is not a dominant one in the least-cost modelling undertaken here, suggesting that planning and expectation over this bioenergy pathway may be misplaced. Adding to this planning uncertainty is the balance between bio-heat penetration in end-use sectors (residential, service, industrial), which varies importantly between scenarios.

With regards to transport biofuels and their use in transportation our modelling results highlight that at present biofuels are relatively expensive to be produced and supplied. In the short- to medium-term they are only taken up as a result of the renewable transport fuel obligation (RTFO). Any further stimulus has to come from additional policy incentives⁹. In the longer term, biofuels can be cost effective low-carbon fuels (we estimated this happens with CO₂ price levels above 250 GBP / ton¹⁰ in BIOSYS 3), in competition with electricity.

Imported fuels appear the most cost-effective way to deploy transportation biofuels in the UK. However the use of imported biofuels is highly limited by their availability in the short- to medium-term. As mentioned in the UK biomass strategy biofuels imports play an important role in meeting the RTFO targets (DEFRA et al., 2007). Their balance in our results (in terms of type) is what is not in line with trends until now: in the BIOSYS scenarios very little vegetable oil is imported (notably palm oil, soya oil and oilseed rape) to be upgraded into 1st generation bio-diesel, while this has been the preferred pathway to bio-diesel until now (DEFRA et al., 2007). The fact that bio-ethanol has been imported directly as “refined” fuel (mainly from Brazil (DEFRA et al., 2007)) is reflected in the BIOSYS scenarios results.

Furthermore, the results of the BIOSYS scenario runs suggest that the domestic processing of biofuels (notably 2nd generation) would be needed, already from the short- to medium-term in complement to imported biofuels. In the modelled scenarios the combined production of bio-diesel and bio-kerosene appears particularly attractive in this respect, as they address strong carbon targets including in the international aviation sector. Such levels of deployment, however, would crucially depend on the ability of research and development to deliver efficient FT technologies and other 2nd generation technologies before the medium-term. If not, it is likely that most of the demand for biofuels would need to be fulfilled via 1st generation fuel, even if this does not appear like the most “cost effective” option (from the modelling perspective).

With regards to bio-electricity, BIOSYS scenarios results are all lower, in terms of uptake, than the comparative modelling exercises and relevant studies. In the short to medium term the maximum penetration does not go beyond 2%, where the Renewable Energy Strategy consultation (BERR, 2008b) indicates 5.3% by 2020. In the longer term, even less penetration of bio-electricity occurs for all scenarios. In BIOSYS 3 and 4, bio-electricity is phased out of the mix. This suggests that cheaper alternative technologies / pathways (especially using wind and / or tidal power) are available to produce renewable and / or low carbon power. Such results are also somewhat lower than in the UKERC 2050 low carbon futures where bioenergy plays a minor role (in most scenarios producing between 50 and 150 PJ electricity – or 4-10% of the power mix - by 2050 (UKERC, 2009).

Our modelling further suggests that from an “overall system cost minimisation” perspective the co-firing of biomass is not competitive with other ways of providing cheap, low carbon and / or renewable energy. One of the reasons for this result is the constraint on co-firing pathways to use only wood chips or low quality pellets, thereby limiting the feedstock to the most expensive biomass. It is possible to imagine that other types of less “refined” biomass (e.g. agricultural residues) would drive the use of co-firing if it was modelled. In addition, other factors influence the uptake of co-firing in practice, probably the most notable being financial, existing infrastructure and logistics

aspects. In the case of heavy discounting of the future (representing e.g. a focus on the short-term or a strong uncertainty regarding emerging and future technology options which will be available to fulfil the policy objectives), biomass co-firing could in fact appear very cost effective (by increasing the lifetime of existing power plants – and keeping options open for future investments). Finally, there could be values for some investors in developing a portfolio of power options, even including some with higher "overall lifetime costs", and co-firing being one of them.

Biogas is the main bioenergy source for the production of electricity in all BIOSYS scenarios. However, in low carbon futures, its contribution is lower in the longer term (and even phases out in BIOSYS 4), assuming that the wet biomass can be directed towards other disposal routes (e.g. agricultural spreading). Medium term contribution is in line, however, with what is envisaged in the Renewable Energy Strategy consultation scenario, which looks at 1.2% of power coming from biogas CHP technologies (BERR, 2008b).

In terms of other energy system technologies and pathways, the BIOSYS scenarios results resonate well with other studies and modelling exercises. In BIOSYS 1 ("World Markets") the energy system stays largely dominated by fossil fuels, with an increasing dependency on imported energy sources (in line with projection shown in BERR (2008b). Nuclear power is not a cost-effective pathway, and is phased out of the energy system by 2030 (in line with the expected closures of existing stations (DTI, 2007)). In BIOSYS 2 ("Energy Independence") concerns over energy security help the "cheapest" renewables to emerge in the longer term (notably wind on-shore reaches 2GW of installed capacity by 2020 – in fact in line with estimated potential (BERR, 2008b)). The biggest changes occur under strong carbon reduction constraints. As mentioned in the Committee on Climate Change's report (Committee on Climate Change, 2008) the energy system is expected to change configuration in the future, including a much larger role of decarbonised electricity (notably from renewables and some nuclear power), used also for heat and transport fuel purposes, and of low carbon heat (including heat pumps). The role of nuclear power is much larger in BIOSYS 4 (reaching 35% by 2050) than in BIOSYS 3 (16% by 2050).¹¹ With regards to renewables deployment, again our estimates are higher than other studies, looking at the medium-term in particular: whilst the Renewable Energy Strategy scenario looks at about 20% of on-shore and off-shore wind by 2020 (BERR, 2008b), BIOSYS 3 and 4 show higher penetration levels (respectively 39% and 32% by 2020) in the medium term, and very high levels by 2050 (80% and 60%). For the modelled deployment levels to be technically achieved implies that high care is given to (among other things) power system balancing and intermittency issues.

Finally, the approach and results as discussed previously also have some limitations. First we assume – as part of the hypotheses of our “integrated” scenarios – some significant cost reductions for some pathways, caused by R&D investments (and additional learning by working with early-stage technologies in commercial niche markets). In reality, however, invested (time and) capital into new technologies does not always lead to improvements in costs and / or performance. Similarly, changes in costs of some biomass resources, assumed caused by the certification process or by subsidy programmes (and which have some impact on the penetration of bioenergy), could not materialise, therefore changing the actual use of biomass and bioenergy in different sectors.

Additional limitations arise from the focused modelling of the UK “energy system”: indeed bioenergy is linked to the wider availability of biomass, not just as an energy source, but as a feedstock for many industries and processes currently not modelled (including waste management, food and feed, chemicals, wood industries etc.). In fact we only partially modelled these interactions (included as constraints) which ultimately determine the achievable level of bioenergy in the system. In a forthcoming paper we will address in more detail the considerations affecting bioenergy deployment, and develop storylines, including RD&D, industrial and policy aspects, to put a perspective on the modelling results implications.

6. CONCLUSIONS

Although views on bioenergy may vary, one is shared: bioenergy is extremely versatile and can contribute in many ways to the future UK energy system. Examining the potential sources, technologies and overall role of bioenergy, and analysing the impact of potential policies requires coherent concepts, integrated datasets and policy-relevant system models. This paper has explored the possible contribution of bioenergy to the UK energy system in the long-term, with an updated MARKAL model following these guidelines, and including more detailed bioenergy chains.

From the practical point of view, our results suggest that a combination of existing bioenergy technologies, and those currently under development could contribute significantly to meeting current UK energy policy objectives. The UK could significantly increase its use of bioenergy in all three main end use sectors (heat, power and transport), providing between 16% and 23% of final energy demand by 2050. Bio-heat seems a cost effective option even in the base scenario, suggesting that uptake is hindered by non-economic factors, such as securing feedstock quantity and quality (e.g. from farmers willing to grow energy crops), the availability of infrastructure required to support the growth in biomass use, or local and regional market dynamics. Competition for biomass resources is limiting bio-heat uptake especially in the residential sector, as the medium-term bio-electricity market penetration, as well as the longer term transport biofuel deployment are strongly driven by the renewable (electricity) targets, as well as

the RTFO legislation and EU renewable transport fuel targets. In the longer term, bioenergy is in competition with (decarbonised) electricity, which unlocks the potential for a wider range of energy end uses (especially transport and heat). It is likely that international bioenergy trade will play an increasing role in the UK energy system (as it emerges in all scenarios, even the ones with high energy independence). Domestic biomass will also need to play a key role to achieve significant penetration levels, especially in the short to medium-term. In addition, trading standards will need to be in place and effective to ensure that domestic and imported biomass is sustainable (land use, competition with food crops, transport to the UK, etc.).

From a methodological point of view, we have demonstrated it is possible to have a more realistic and stylised representation of bioenergy chains – from sources to uses – and technological specification in energy systems models such as MARKAL that are widely used in policy making. Doing so (notably) requires the coupling of “traditional” energy systems model with more detailed representation of bioenergy chains, the competition between them for the same feedstock, the competition between end-use sectors for the same biofuel, and constraints of market penetration that are often not related to price. Failure to do so implies that modellers use only aggregate bioenergy chains and patterns of technological adoption. Thus previous versions of the UK-MARKAL model, whose ensuing scenarios are employed for policy analysis, typically focused on the role of bioenergy in fairly aggregated power production and transport fuel sectors. Our results suggest that bioenergy has an important role to play in achieving long term policy objectives mainly in the heat and transport sector. In addition the approach used here for the definition and development of the BIOSYS scenarios can inform further work that uses similar energy policy pillars (carbon reduction, energy security), for instance in other EU countries or the US.

Overall, and despite the (acknowledged) high levels of uncertainty associated with the modelling and results of the BIOSYS scenarios, the insights provided are useful to the future energy system debate, especially raising questions about the kind of energy system that could emerge, the contribution of bioenergy to different end uses, and the implications this has for resource, technology and infrastructure deployment.

In a forthcoming paper, the results of the modelling exercise will be put in perspective considering the implications which could drive or hinder the energy system representations shown in the BIOSYS scenarios. In so doing, the research can ultimately provide a holistic representation of the bioenergy system which could effectively guide policy makers as they contemplate energy policy trade-offs.

FOOTNOTES

¹ Imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers

(including electricity, heat and hydrogen), end-use technologies and energy service demands in the industrial, commercial, residential, transport and agricultural sectors.

² Due to the number and complexity of bioenergy pathways and technologies in the model, three chains and two underpinning technologies were selected for detailed investigation: (1) lignocellulosic hydrolysis for the production of bioethanol, (2) gasification technologies for heat and power, (3) fast pyrolysis of biomass for bio-oil production, (4) biotechnological advances for second generation bioenergy crops, and (5) the development of agro-machinery for growing and harvesting bioenergy crops. Detailed literature searches and expert consultations (looking inter alia at research and development needs and economic projections) led to the development of an 'accelerated' dataset of modelling parameters for each of the selected bioenergy pathways, which were included in five different scenario runs with UK-MARKAL (MED).

³ Additional UK energy policy goals included affordable energy for the most vulnerable, and a commitment to competitive markets.

⁴ The model operates with perfect foresight across the model horizon to enable inter-temporal trade-offs between investments in, and operation of, energy system components.

⁵ For example, all currently legislated major UK environmental and relevant tax policies as of 2007 are included.

⁶ Via vintages of future energy chain options, and - for less mature renewable electricity and H₂ technologies - exogenously calculated learning rates (McDonald and Schrattenholzer, 2002) together with global technology uptake forecasts (European Commission, 2005).

⁷ The observed rapid ramp-up of bioenergy resources and penetration in the short term (2010-2015) can be explained in modelling terms, as the model gets free of the calibration constraints (set up for the 2000 and 2005 time steps) useful to represent the UK energy system at present. In reality there is maximum rate of deployment which could be achieved, especially in the in the short term. Such a rate is however difficult to implement without affecting the ability of the model to provide "new insights", since the results would then simply reflect an additional constraint on the deployment. The levels of uptake envisaged by the modelling results are further discussed in section 5 of this paper.

⁸ The graphs of biomass resources entering the UK energy system do not present the data for imported vegetable oil separately but as an aggregated value with imported pyrolysis oil.

⁹ This version of MARKAL uses historic and current fuel duties for road transport fuels, expressed in GBP.GJ⁻¹. For example, petro-diesel attracts a duty of 11.8 GBP. GJ⁻¹, while bio-diesel only about half of this at 6.1 GBP.GJ⁻¹.

¹⁰ The price of 250 GBP / ton CO₂ may appear unlikely based on present price levels on existing carbon markets. However in a long term future where overall CO₂ emissions

need be reduced by 80% when compared to 2050, this may be need to be the type of price that are reached if no other technologies than those modelled were to be chosen from.

¹¹ This may seem surprising as nuclear is often assimilated as a potential solution for higher “energy security”. In the context of the modelling exercise, however, the geopolitical advantages of using nuclear to enhance energy security are not accounted for, and the uranium needs be imported, increasing the share of energy supply coming from imports.

REFERENCES

BERR, 2006. Updated Energy Projections (updated from EP-68). Department for Business, Enterprise and Regulatory Reform (BERR), London. [Available online] <http://www.berr.gov.uk/energy/environment/projections/index.html> (accessed on: 27 May 2009).

BERR, 2008a. Heat Call for Evidence. Department for Business Enterprise & Regulatory Reform (BERR), London. [Available online] <http://www.berr.gov.uk/files/file43609.pdf> (accessed on: 20 February 2008).

BERR, 2008b. UK Renewable Energy Strategy - Consultation. BERR, London. [Available online] <http://www.berr.gov.uk/consultations/page46797.html> (accessed on: 12 August 2009).

BERR, 2009. Energy Reliability. [Electronic source] <http://www.berr.gov.uk/energy/reliability/index.html> (accessed on: 24 March 2009). Department for Business Enterprises and Regulatory Reform (BERR).

Chen, W., Wu, Z., He, J., Gao, P., Xu, S., 2007. Carbon emission control strategies for China: A comparative study with partial and general equilibrium versions of the China MARKAL model. *Energy* 32, 59-72.

Clarke, D., Jablonski, S., Moran, B., Anandarajah, G., Taylor, G., 2009. How can accelerated development of bioenergy contribute to the future UK energy mix? Insights from a MARKAL modelling exercise. *Biotechnology for Biofuels* 2.

Commission of the European Communities, 2008. Proposal for a Directive of the European Parliament and the Council on the Promotion of the Use of Energy from Renewable Sources. COM(2008) 19 final. European Commission, Brussels. [Available online] http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf (accessed on: 10 June 2008).

Committee on Climate Change, 2008. Chapter 2 - Meeting a 2050 Target, Building a Low-Carbon Economy – The UK's Contribution to Tackling Climate Change. The Stationary Office (TSO), London.

Contaldi, M., Gracceva, F., Tosato, G., 2007. Evaluation of green-certificates policies using the MARKAL-MACRO-Italy model. *Energy Policy* 35, 797-808.

Das, A., Rossetti di Valdalbero, D., Viridis, M.R., 2007. ACROPOLIS: An example of international collaboration in the field of energy modelling to support greenhouse gases mitigation policies. *Energy Policy* 35, 763-771.

DECC, 2009. Heat and Energy Saving Strategy - Consultation. Department for Energy and Climate Change (DECC), London. [Available online] <http://hes.decc.gov.uk/> (accessed on: 07 May 2009).

DEFRA, DfT, DTI, 2007. UK Biomass Strategy. Department for Environment, Food and Rural Affairs, [Available online] <http://www.defra.gov.uk> (accessed on: 25 June 2007).

DfT, 2005. National Transport Model - Working Paper 2. Department for Transport, London. [Available online] <http://www.dft.gov.uk/pgr/economics/ntm/pdfnatransmodwp2.pdf> (accessed on: 27 May 2009).

DTI, 2007. Meeting the Energy Challenge - A White Paper on Energy. URN 07/1006. Department of Trade and Industry, [Available online] <http://www.berr.gov.uk/energy/whitepaper/page39534.html> (accessed on: 29 May 2007).

European Commission, 2005. World Energy Technology Outlook - 2050 (WETO-H2). EUR 22038. European Commission, Luxembourg. [Available online] http://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf (accessed on: 15 July 2009).

European Environment Agency, 2006. How Much Bioenergy Can Europe Produce without Harming the Environment? European Environment Agency, Copenhagen. [Available online] http://reports.eea.europa.eu/eea_report_2006_7/en (accessed on: 27 June 2007).

Gielen, D.J., de Feber, M.A.P.C., Bos, A.J.M., Gerlagh, T., 2001. Biomass for energy or materials?: A Western European systems engineering perspective. *Energy Policy* 29, 291-302.

Grübler, A., Nakicenovic, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. *Energy Policy* 27, 247-280.

Hughes, N., 2008. The Use of Scenario Planning in Sustainable Energy Policy. Sustainable Energy UK - Meeting the Science and Engineering Challenge. Oxford, UK, 13-14 May 2008.

International Energy Agency, 2008. Energy Technology Perspectives 2008: Scenarios and Strategies to 2050. International Energy Agency, Paris.

Jablonski, S., Brand, C., Pantaleo, A.M., Perry, M., Bauen, A., Panoutsou, C., Strachan, N., 2009a. Selection of Proposed Improvements for UK-MARKAL with Regards to Bioenergy Chains - MARKAL Working Paper 2. TSEC-BIOSYS Project & Imperial Centre for Energy Policy and Technology (ICEPT), London.

Jablonski, S., Brand, C., Pantaleo, A.M., Perry, M., Pepinster, M., Bauen, A., Panoutsou, C., Varma, B., Premier, G., De Wit, M., 2009b. Proposed dataset for improved UK-MARKAL bioenergy structure - MARKAL Working Paper 2bis. TSEC-BIOSYS Project & Imperial Centre for Energy Policy and Technology (ICEPT), London.

Jablonski, S., Pantaleo, A.M., Bauen, A., Pearson, P.J., Panoutsou, C., Slade, R., 2008. The Potential Demand for Bioenergy in Residential Heating Applications (Bio-heat) in the UK based on a Market Segment Analysis. *Biomass and Bioenergy* 32, 635-653.

Junginger, M., de Visser, E., Hjort-Gregersen, K., Koornneef, J., Raven, R., Faaij, A., Turkenburg, W.C., 2006. Technological learning in bioenergy systems. *Energy Policy* 34, 4024-4041.

Kannan, R., Balta-Ozkan, N., Pye, S., 2007. UK MARKAL Model Documentation - UKERC Working Paper. UK Energy Research Centre (UKERC), London. [Available online] <http://www.ukerc.ac.uk/Home.aspx> (accessed on: 27 May 2009).

Loulou, R., Goldstein, G., Noble, K., 2004. Part I : The Standard MARKAL Model, Documentation for the MARKAL Family of Models. Energy Technology Systems Analysis Programme, p. 386.

McDonald, A., Schrattenholzer, L., 2002. Learning curves and technology assessment. *International Journal of Technology Management* 23, 718.

Nakicenovic, N., Kram, T., Makarov, A., Sorensen, B., Yokobori, K., Fengqi, Z., 2000. Chapter 9 - Energy Scenarios, in: United Nations Development Programme, United

Nations Department of Economic and Social Affairs, the World Energy Council (Eds.), World Energy Assessment - Energy and the Challenge of Sustainability. United Nations Development Programme, New York, pp. 334-366.

Purohit, P., 2009. Economic potential of biomass gasification projects under clean development mechanism in India. *Journal of Cleaner Production* 17, 181-193.

RCEP, 2004. Biomass as a Renewable Energy Source. Royal Commission on Environmental Pollution, [Available online] <http://www.rcep.org.uk/bioreport.htm> (accessed on).

Schulz, T.F., Barreto, L., Kypreos, S., Stucki, S., 2007. Assessing wood-based synthetic natural gas technologies using the SWISS-MARKAL model. *Energy* 32, 1948-1959.

Seiffert, M., Kaltschmitt, M., Miranda, J.A., 2009. The biomethane potential in Chile. *Biomass and Bioenergy* 33, 564-572.

Sherrington, C., Bartley, J., Moran, D., 2008. Farm-level Constraints on the Domestic Supply of Perennial Energy Crops in the UK. *Energy Policy* 36, 2504-2512.

Shorrock, L.D., Utley, J.I., 2003. Domestic Energy Fact File 2003. BRE Bookshop.

Slade, R., Panoutsou, C., Bauen, A., 2009. Reconciling bio-energy policy and delivery in the UK: Will UK policy initiatives lead to increased deployment? *Biomass and Bioenergy* 33, 679-688.

Smekens-Ramirez Morales, K.E.L., 2004. Response from a MARKAL technology model to the EMF scenario assumptions. *Energy Economics* 26, 655-674.

Strachan, N., Balta-Ozkan, N., Joffe, D., McGeevor, K., Hughes, N., 2009a. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. *International Journal of Hydrogen Energy* 34, 642-657.

Strachan, N., Kannan, R., 2008. Hybrid modelling of long-term carbon reduction scenarios for the UK. *Energy Economics* 30, 2947-2963.

Strachan, N., Kannan, R., Pye, S., 2008a. Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models. UK Energy Research Centre (UKERC), London. [Available online] <http://www.law.monash.edu.au/regstudies/synopsis.scenarios-sensitivities-on-long-term->

[carbon-reductions-using-the-uk-markal-and-markalmacro-energy-system-models.pdf](#)

(accessed on: 27 May 2009).

Strachan, N., Pye, S., Hughes, N., 2008b. The Role of International Drivers on UK Scenarios of a Low-Carbon Society. *Climate Policy* 8, S125-139.

Strachan, N., Pye, S., Kannan, R., 2009b. The iterative contribution and relevance of modelling to UK energy policy. *Energy Policy* 37, 850-860.

UKERC, 2009. Accelerated Development of Low Carbon Energy Supply Technologies - UKERC Energy 2050 Research Report No. 2 - Version 2. UK Energy Research Centre (UKERC), London. [Available online] http://www.ukerc.ac.uk/Downloads/PDF/U/UKERCEnergy2050/TAcceleration_Draft.pdf (accessed on: 05 June 2009).