Evaluating potential policies for the UK perennial energy crop market to achieve carbon abatement and deliver a source of low carbon electricity

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Abstract

The electricity infrastructure in many developed countries requires significant investment to meet ambitious carbon emissions reduction targets, and to bridge the gap between future supply and demand. Perennial energy crops have the potential to deliver electricity generation capacity while reducing carbon emissions, leading to polices supporting the adoption of these crops. In the UK, for example, support has been in place over the past decade, although uptake and the market development have so far been relatively modest. This paper combines biophysical and socio-economic process representations within an agent-based model (ABM), to offer insights into the dynamics of the development of the perennial energy crop market. Against a changing policy landscape, several potential policy scenarios are developed to evaluate the cost-effectiveness of the market in providing a source of low carbon renewable electricity, and to achieve carbon emissions abatement. The results demonstrate the key role of both energy and agricultural policies in stimulating the rate and level of uptake; consequently influencing the cost-effectiveness of these measures. The UK example shows that energy crops have the potential to deliver significant emissions abatement (up to 24 Mt carbon dioxide equivalent year^{-1}, 4% of 2013 UK total emissions), and renewable electricity (up to 29 TWh year^{-1}, 8% of UK electricity or 3% of primary energy demand), but a holistic assessment of related policies is needed to ensure that support is cost-effective. However, recent policy developments suggest that domestically grown perennial energy crops will only play a niche role (<0.2%) of the UK energy balance.

Keywords

Agent-based model; Energy crops; Energy Policy; Land use; Miscanthus; Short-rotation coppice.

1 Introduction

The world faces the challenge of meeting increasing energy demands while achieving economic, social and environmental sustainability [1]. In the UK, the energy challenge manifests itself through increasing political and public concern about the national energy mix and rising prices [2,3]. The UK's electricity generation sector is based on existing coal and nuclear plants that are reaching the end of their lives, reducing generation capacity [4], while electricity demand is projected to rise gradually [5]. As a result, spare capacity in the UK electricity market is due to reduce in the next few years [6]. New infrastructure to fill the potential gap between future electricity supply and demand, is estimated to require £110 billion of investment over the next 10 years [7]. The UK Government sets the overall framework for investment in energy infrastructure, but the private sector determines where and when this investment will occur.

Biomass is a source of renewable energy that could help to meet these challenges. Globally, it is already the largest source of renewable energy, and is expected to expand to 80-160 EJ year^{-1} in 2050 from 50 EJ year^{-1} today [8,9]. In the UK by 2020, it could provide 8-11% of the UK's total primary energy demand, a substantial increase from 3% in 2012 [10], and contribute to meeting the legally binding target of generating 15% of energy consumption from renewable sources [11]. Agricultural residues and energy crops are expected to have the greatest growth in UK domestic biomass supply [10]. Previous research suggests that the potential energy crop area in the UK will be around 1000 to 2000 kha in 2020 and 2030 [12–17]. It has been suggested that between 930 and 3630 kha of land in England and Wales could be used to grow dedicated perennial energy crops, without impinging on food production [10]. But UK Government policy plays a crucial role in determining the level and rate of adoption of these technologies.

Perennial energy crops, Miscanthus and willow or poplar grown as short-rotation coppice (SRC), have been grown in the UK since around 1996 [18]. Uptake has, however, been limited, with a total area of only 11 kha in 2011, with the planting rate dropping to only 0.5 kha $year^{-1}$ in the period 2008-11 [19]. There is currently no target for areas of these crops, although 350 kha by 2020 was suggested in the Biomass Strategy [13]; it is now expected that the actual figure will be much lower [18]. This low uptake occurs in spite of policies to support the production of energy crops, targeted at both farmers and energy generators. Since 2003, farmers in England have had access to grants to cover a proportion of the establishment costs for Miscanthus or SRC. The support rate was 50% for the last 5 years of the scheme, which closed to new applicants in autumn 2013 [20]. Since 2002 renewable electricity generators have been able to receive support under the Renewable Obligation mechanism [21]; renewable heat technologies have more recently been supported by the Renewable Heat Incentives (RHI) scheme [22]. The RHI scheme when launched in 2011 was initially available only to the industrial sector, but in 2014 expanded to cover domestic usage of renewable heat.

Economic and behavioural factors are implicated in farmers' decisions to adopt energy crops, and therefore potentially to explain the low uptake. Several studies have looked at the economic aspects of energy crops, estimating the annual land rental charge to account for the foregone opportunity to make greater returns from other activities, or opportunity costs [15,16,23]. A similar approach has compared annual gross margins of conventional crops with an equivalent annualised value for perennial energy crops [24–28]. A further method is to use a farm-scale economic model, maximising gross margin, to investigate the potential uptake of perennial energy crops [29]. These studies show that based on the economic case, energy crops should have been adopted more widely, leading to a focus on possible behavioural barriers to adoption. These might include cultural factors, awareness and educational barriers, long-term commitment of land, and perceived risks [18,30–35]. There is heterogeneity in the level of economic and behavioural factors, between farmers and over time, for example in investment return thresholds and risk perceptions [36]. A 'chicken and egg' problem is also an apparent barrier; farmers are unwilling to grow the crops without a more mature market, while potential investors are unwilling to develop the plants and technologies that are required to create the demand and so establish the market [30,37]. The cyclic contingent behaviour between farmers and plant investors increases the complexity of the overall system, complicating analysis of the market.

Energy crops compete with other potential land uses, and so have the potential to have positive and negative impacts on a range of environmental factors, e.g. greenhouse gas (GHG) emissions, soil organic carbon (SOC), biodiversity and water resources [38–41]. Increased uptake of these crops is therefore relevant to other policy objectives for the provision of ecosystem services, including food production [42]. Biomass energy has on occasions been assumed or stated as having zero net emissions of carbon dioxide [43,44], or given a zero emissions factor [45]. Although the carbon released during the energy production has been captured during plant growth, biomass use in energy generation potentially generates direct and indirect sources of emissions [39,46–50]. Direct emissions can occur in the production, transport, handling and processing, while indirect emissions are associated with land use change potentially causing SOC changes. These crops could, therefore, potentially provide an important source of low carbon energy, and so help to reduce the carbon intensity of energy production, as well as filling the gap between future electricity supply and demand. But the relevant economic, social and environmental trade-offs need to be understood to ensure sustainability.

The energy crop market is a complex system involving human decision-making by many individuals, working within an evolving policy context. Moreover, economic, ecological and social aspects of the system are strongly coupled, complicating understanding of any single aspect. The potential benefits and drawbacks of the adoption of these crops at scale requires the coupling to be more fully understood, and to suggest ways that net societal benefits can be maximised. Furthermore, related policies are currently in flux [7], increasing the need for greater scientific understanding of the trade-offs and analysis of which measures are appropriate and cost-effective. The reasons for the lower than anticipated uptake of these crops to date [18] also needs to be understood, and potential measures identified that could help to stimulate the market.

This paper uses representations of biophysical and socio-economic processes in a model of the UK perennial energy crop market. Based on the changing policy landscape, a range of potential policy scenarios is used to evaluate the cost-effectiveness of the market in providing a source of low carbon renewable electricity, and to achieve carbon emissions abatement. The paper outlines the agent-based model (ABM) used to represent the key economic and behavioural aspects of the market, and shows the results of how uptake varies under various policy scenarios. The discussion considers the potential implications for biofuels and the key policy messages, including cost-effectiveness.

2 Material and methods

An agent-based model (ABM) was used to represent the complex social-ecological system of the energy crop market [51,52]. The model is summarised here with a full description provided in Alexander *et al.* [51].

ABMs allow the system behaviour to emerge through the dynamic interaction of agents with one another and the environment [53]. This approach is suitable for the development of a model of the energy crop market, as ABMs allow the spatial and dynamic behaviour of complex systems to be investigated [54]. The current model focuses on farmers and power plant investors as market agents [51]. Agricultural land is divided into a regular grid of $1km^2$ (i.e. 100 ha) areas, each of which is managed by a separate notional farmer making crop selection decisions based on their resources (i.e. spatially specific crop yields [55,56]), individual preferences and market conditions. Farmers determine their willingness to consider adoption, before examining the economic case, to determine an optimum crop selection given their resources and preferences [57]. Farmers' willingness to consider adoption is governed by their own previous experience, or when they have none, by the level of adoption in neighbouring farms in a diffusion of innovation approach [58]. Farmers are taken as willing to consider energy crops if the proportion of successful local adoption is greater than a threshold value, which is assigned to each farmer from a normal distribution [58]. The initial rate of adoption, or proportion of innovators was taken as 2.5% [58], and represents the fraction of farmers willing to consider adoption without any previous local adoptions. Areas unsuitable for energy crops for social or environmental reasons were constrained for selection [59]. Power plant investor agents control the construction and operation of power plants, which consume the energy crops. These agents make decisions to invest based on the expectation of the project achieving an internal rate of return, on their investment, greater than their hurdle rate [60]. A single delivered market price exists, which was adjusted exponentially based on the level of market disequilibrium, i.e. if there was excess demand the price was increased, while if there was excess supply it was reduced. All monetary values were in 2010 terms, unless otherwise stated.

The model was run with annual time-steps, between 2010 and 2050. A detailed description of the market is produced, including crop selection for each 100 ha farm and details of the sites, sizes and technologies of the electricity power plants. The emissions for each lifecycle stage can then be calculated, as the location and yield for supply, the efficiency of the power plant, and transport distances are known. The model output was used to determine the carbon dioxide equivalent (CO_2e) emissions associated with the production of electricity from the energy crops, the emissions avoided from displacement of the same amount of conventional electricity generation, and the cost of subsidies provided to support market development. Details of the GHG balance calculation can be found in Alexander *et al*. [52]. The total CO_2e emissions abated and the total cost of subsidy were determined across the 40-year period, to give an average implied cost of carbon abatement.

Three policy scenarios for the farmer establishment grant rate were combined with 11 scenarios for renewable energy, to generate the set of policy scenarios tested. The three farmer grants scenario had 0%, 50% and 100% support for establishment costs respectively. The 11 renewable energy policy scenario are each expressed as a trajectory of total revenue, including from wholesale electricity and subsidies, as per the Contract for Difference mechanism, or as the rate of receiving renewable obligation certificates (ROCs). In both cases these are per MWh of electricity generated. It was assumed that support would fall to reflect the expectation of lower costs [61], and the decreases would occur over 10 years and then reach a constant level. The lower level was varied from a total revenue of £124 MWh^{-1} to £50 MWh^{-1}. This could be considered to represent a 0.0 to 2.0 ROC MWh^{-1} minimum support with prices of £37 per ROC [62] and a wholesale electricity price of £50 MWh^{-1} [63], based on the existing support measures. Alternatively, viewed as representing support under Contract for Difference Feed-in Tariff, it is broadly inline with the initial biomass support rate of £125 MWh^{-1}, for the replacement scheme [64].

The model is stochastic in nature, due to probabilistic representations, for example of farmers' resistance to adoption, investors' hurdle discount rate and potential sites. Therefore 20 simulations for each scenario were run to get more data on the results space for that scenario. The mean result for each scenario is presented, unless explicitly stated otherwise.

Insufficient empirical data from the energy crop market is available to allow a direct validation of the model. Therefore, the behaviour of the model was compared against the analogous case of the adoption of oilseed rape in the UK from the 1970s. A substantial rise in the area of oilseed rape cultivation started when the UK entered the European Economic Community in 1973 [65,66], due to price intervention policy. The modelled area of energy crops and the empirical area of oilseed rape in England and Wales for the period 1969-1997 [66–68], followed showed similar behaviour over time [51]. The rate of adoption of both crops follows a typical S-shaped adoption curve [58], and both occur over a similar period of time of approximately 20-years. Furthermore, the modelled and observed geographical spreads both display a spatial diffusion pattern, with adoption tending to spread out from initial selection areas [51,65,67]. There are clearly differences between these crops, including potential behavioural changes between the two time periods; nonetheless the similarity in response builds confidence in the ability of the model to reflect perceptions and communication of farmers in relation to novel crops. The modelled pattern of adoption is further supported by similarities to spatial diffusion observed in the spread of willow SRC in Sweden [37]. Additional validation, sensitivity analysis and comparisons to other published estimates have also been conducted [51,52].

3 Results

The total subsidy, including renewable energy and agricultural subsidies was plotted against the biomass electricity generated, expressed on an annualised basis (Figure 1,A). The cost of supporting the market increases with the size of that market.

The average subsidy cost per unit of electricity generation was determined by dividing the annualised total subsidies by the total emissions abated, and was plotted against the electricity generated, for all policy scenarios (Figure 1,B). The resulting curves display how the level of support available to renewable electricity generators and farmers affects both the level of uptake, and the cost-effectiveness of the subsidy regime. Similarly, an implicit average carbon price was calculated, by dividing the total abatement by the total subsidies. Alexander *et al*. [51] provides a plot of the average carbon price against emissions abatement, showing how the subsidies scenario impacts carbon abatement. Both follow similar patterns, as although the carbon efficiency of the biomass generation supply chain varies, for example larger plants are more efficient, the coal electricity displacement emissions tends to dominates the overall abatement.

The marginal cost of achieving biomass electricity generation and carbon abatement may, in some circumstances, be a more relevant measure for evaluating policy choices, than the average cost (Figure 1,B). If the marginal cost of abatement is rising with higher abatement, then for a given carbon price [69],, the marginal results could be used to determine the most efficient level of abatement (and the associated policy mix). This is where the marginal abatement curve equate to the given carbon price. Any increase in abatement beyond this point would increase costs more than the cost of carbon, and conversely reducing the abatement would mean that the cost of emissions was greater than the cost to abate it. The same argument would apply if there were a desired overall subsidy cost per unit of electricity for achieving biomass generation.

To estimate the marginal costs for each point on a given farmer establishment grant curve, a constant marginal value was assumed between points, i.e. constant gradient of total subsidy against generation or abatement, e.g. the gradient of the line in Figure 1,A. The results were plotted against electricity generation and carbon abatement respectively, see Figure 1,C and Figure 2. The marginal cost results show a greater range of values than the average cost results, and also broadly display a U-shape. The marginal cost of stimulating electricity generation from UK energy crops varies from £37 to £121 per MWh, having an average subsidy cost of £50 to £83 per MWh. The marginal carbon abatement costs are 43 to 141 per tCO_2e, with an average cost of £57 to £97 per tCO_2e. This greater range in the marginal values is to be expected, as they only gradually impact the average figures.

The emissions abatement where the average cost of carbon equals a particular carbon price will be higher than for the marginal cost of carbon. This is because the last abatement has occurred at a higher cost, until the averaged cost has been reduced to the assumed level. Using the carbon price floor, prior to the 2014 budget, of £70 t CO_2^{-1} at 2030 [69], then the marginal abatement cost curve (Figure 2) suggests 8 $MtCO_2$ $year^{-1}$ based on a 100% farmer establishment grant and a biomass generator minimum price of £90 MWh^{-1}. The carbon abatement of the same average prices is 11 $MtCO_2e$ $year^{-1}$, with a higher biomass generator scenario price of £97 MWh^{-1}.

However, when the marginal costs are dropping, it is more useful to consider the overall average costs, so that the cost impact of stimulating the more expensive early adoption is taken into account. The analogous situation occurs with marginal and average generation subsidy costs (Figure 1).

Iso-carbon price points were calculated for prices at £5 CO_2e^{-1} intervals from £65 to 90 t CO_2e^{-1}, under each of the three rates of establishment grants used, and are plotted in Figure 3. These points are the combination of farmer and renewable energy subsidies that produce a given carbon price from the market. Due to the U-shape curve two points for each establishment grant were possible, corresponding to each side of the U, resulting in two lines for most carbon prices. At each end of the plotted carbon prices, some points were not in the range of the scenarios run, giving rise to fewer points on those lines. The upper sets of lines correspond to the higher emission abatement scenarios, which have higher subsidies, but an equal carbon price.

The subsidy levels that produce iso-carbon emission abatement were determined in the same manner as for the iso-carbon price. These points were determined for emissions abatement from 0.5 Mt CO_2e to 16 CO_2e, doubling the abatement between each value; the figures are plotted in Figure 4. Similar to the iso-carbon price lines, some points of the highest and lowest abatements fall outside of the scenarios tested, and are therefore omitted. Figure 4 shows that a repeated doubling of emissions abatement can be achieved by an approximately constant increase in total subsidy provided, as the lines plotted are broadly parallel and at a constant spacing. This suggests a relatively constant relationship between changes in the subsidy levels and an exponential change in emissions abatement.

Figure 3 and Figure 4 show the relationship between equally desirable points, to achieve the stated carbon price or emission abatement. However, it seems highly likely that both factors would be of relevance to most policy-makers or other stakeholders. Figure 2 shows the relationship between the marginal carbon price and emission abatement over the range of subsidy levels tested.

4 Discussion

To stimulate electricity generation or carbon abatement, the most cost-effective policy scenario tested was with no farmer support and a subsidised biomass electricity minimum price of £94 MWh^{-1}. The results suggest this would achieve an average subsidy cost of £50 MWh^{-1}, although only a small market would be created generating 0.3 TWh $year^{-1}$, and abating 0.3 $MtCO_2e$ $year^{-1}$. However, if the aim is for more substantial electricity generation or carbon abatement, then providing direct farmer support was found to provide the most cost-effective mix of policy measures. The potential for electricity generation and carbon abatement of around 90 times greater than this case, was seen within the policy scenarios tested.

For each level of farmer support, the minimum carbon equivalent abatement and biomass electricity costs are obtained in scenarios with an intermediate subsidy level for electricity generators. That is, the lowest implied carbon prices or biomass support costs are not seen in either the lowest or highest renewable energy subsidy scenarios. For example, with a 50% establishment grant the lowest average carbon price of £57 t CO_2e^{-1} and lowest support of £50 MWh^{-1} were obtained with a minimum subsidised biomass electricity price of £87 MWh^{-1}. This behaviour arises, as there is an interaction between economies of scale, primarily from the electricity generators, and the increasing subsidy costs. Economies of scale occur as larger plants are more efficient and the more developed markets are associated with lower failure rates. The additional costs are initially more than offset by efficiency gains; as the support level raises from the lowest subsidy scenarios, so the carbon price and falls. However, eventually with further increases in the support level, the gains are unable to overcome the escalating cost of the policy measures, and the subsidy costs in terms of electricity generated and carbon abatement rises. This suggests that an intermediate level of support for biomass electricity may be most cost effective at stimulating emission reductions and the generation of biomass electricity from the energy crop market. Nonetheless, the total carbon abatement, electricity generated and subsidy costs all rise with an increases in the rate of subsidy renewable energy subsidy (Figure 1,A).

The results demonstrate the trade-offs between providing subsidies to farmers or renewable electricity generators. The consequence of these trade-offs is that the development or evaluation of energy and agricultural policy must be considered together. Without a coherent set of policies it is unlikely that the desired outcomes will be achieved in the most efficient manner. One example of this is the farmer establishment grant. Providing farmers' establishment grants has been shown to increase both the emissions abatement potential and potentially cost-effectiveness (Figure 1 and Figure 2). However, the Energy Crop Scheme, providing such support, closed for new applications in August 2013. It is unclear whether a replacement will be put in place, although there have been calls for a new scheme

[18,70]. There is an expectation that this will cause the, albeit limited, current market momentum to be lost [70], as occurred during the previous gap in funding in 2006 [18]. There may be alternative mechanisms to support farmers to grow these crops, perhaps through the Common Agricultural Policy, which merits further investigation [70].

4.1 Adoption time lags and path dependence

The important role of farmers' networks and communication on the rate of adoption of new crops or technologies, such as energy crops, is suggested by the results. Significant time lags in adoption arise from the diffusion of innovation and the consequential spatial diffusion process [51]. The model simulates time lags of around 20 years, which is supported by empirical data from an analogous oilseed rape adoption in the UK from the 1970s [66–68]. This implies the need to account for time lags arising from spatial diffusion when developing policy or market targets for the development of such novel crops, and has potential implications for the adoption of other new crops and agricultural technologies. The behavioural barriers and time lags help to explain the low levels of adoption seen to date. It also implies that to reduce the adoption time lags there should be more focus on raising farmers' awareness of new policies and crops; providing enhanced knowledge transfer between farmers; and lowering perceived barriers to adoption.

The energy crop market displays path dependence, arising from the reinforcement of the location of plant construction and energy crop selection, based on the locations of the previous plants and energy crops. Once a plant has been built at a location, and a number of farmers have adopted to produce supply for that plant, that area is more likely to be selected for further plant development, and associated energy crop growth. The existence of farmers already growing energy crops increases the number of farmers who are willing to consider growing them. The increased pool of farmers potentially increases the availability of supply, which in turn increases the likelihood, and the potential size, of further plants in that proximity. The spatial reinforcement, or agglomeration, means that initial plant locations can create a significant influence on the overall outcome. The significance of this effect is supported by the adoption patterns and locations observed in Swedish SRC market [37] and is also a part of a proposed conceptual framework for the introduction of energy crops [71].

4.2 Implication for biofuels

The production of second-generation biofuels, produced from a ligno-cellulosic feedstock, potentially provides a new market for perennial energy crops. Despite the slower than anticipated development to commercial scale, there are now a number of pilot second-generation biofuel plants operating globally [72]. This provides the realistic prospect that such plants will be built in the UK in the near future. The ligno-cellulose bio-refineries have different economic and emission abatement characteristics from the biomass power plants represented in the model presented here. These differences will alter the energy crop market's potential for emissions abatement and response to policy incentives. Nonetheless, there are some implications from the results that are likely to remain, and conclusions that can be drawn, that are relevant to the production of second-generation biofuels in the UK.

The addition of a new source of demand is unlikely to alter the process of farmers' adoption of novel crops, based on the spatial diffusion of uptake, resulting in long time lags. Claims have been made that second-generation biofuels will form a significant component of the UK's least cost energy system to 2050 [73]. Therefore, if biofuel production from energy crops is important in the UK's future energy mix, an additional justification can be made for currently supporting electricity production from energy crops. The long time lags in achieving adoption from farmers can be overcome by establishing a market as early as possible, so that when additional demand is required (for example, for biofuel production), further and more rapid expansion is easier to achieve. The greater the size and geographic spread of the existing market, the quicker the market should be able to respond to provide additional supply. Although this is likely to be an upper limit when a high proportion of the suitable land has been established. However, even with the highest levels of subsidy, the maximum energy crop area obtained was 2900 kha, less than the published upper estimate of 3630 kha for land available without impinging of food production [10].

4.3 Policy developments

The existing subsidy arrangements influencing the energy crop market in the UK are currently in flux. The RO scheme, supporting renewable electricity generators, ends in 2017, and the energy crops establishment grant, supporting farmers, closed for applications in August 2013. The Electricity Market Reform proposals [7], which are effectively the replacement for the previous Renewable Obligation scheme, received Royal Assent in December 2013 [74]. The stated aim of the Electricity Market Reform proposals is to decarbonise energy generation in a cost-effective manner, while maintaining security of supply. It contains three main elements; a feed-in tariff using the Contract for Difference mechanism, a carbon price floor, and a capacity market. Under Contract for Difference contracts, a single fixed price level known as the 'strike price' replaces generators revenues, from electricity and Renewable Obligations. The draft Contract for Difference strike prices are claimed to have been set to be consistent with the total revenue under this previous scheme [7]. The initial strike price is £125 MWh^{-1} [64], inline with the policy scenarios tested.

There are several specific elements of the proposed policy changes that have the potential to radically alter the development of the UK energy crop market. Firstly, the technologies that are eligible for support are proposed to change. New build electricity only plants would not receive support; new plants would be required to be combined heat and power (CHP) facilities to be eligible. Also, co-firing, using a proportion of biomass in existing coal fired power station, would no longer be supported, and only complete conversion to biomass from these facilities would be accepted. Secondly, the energy crop premium would be removed, this currently pays an additional 0.5 ROC MWh^{-1} (or around £18-20 MWh^{-1}) for producing electricity from energy crops, in comparison to other sources of biomass. Thirdly the terms of the support contracts are being changed. Perhaps most importantly, the contract length with RO was 20 years, but with the Contract for Difference scheme it would be reduced to 15 years in general, but with a cap, specifically for biomass contacts, to cease paying in 2027. After these contracts end, the support for renewable projects will be indirectly through the climate change levy. The climate change levy is a tax applied to the fossil fuels used to generate electricity, with a minimum level via the carbon price floor. The carbon price floor is due to be £70 Mt CO_2e^{-1} in 2030, which is expected to increase the wholesale electricity price from £50 MWh^{-1} to £70 MWh^{-1} by 2030 [75], in 2012 terms. However, the 2014 budget saw the planned increases in the carbon price floor being stopped in 2016, by the imposition of a £18 t CO_2e^{-1} cap [76]. Fourthly, and finally, as already mentioned the Energy Crop Scheme, supporting farmers with establishment grants, closed to applications in August 2013.

Most of these policy developments can be seen as negative for the potential for the energy crop market. Consequentially, in the short term the market expansion may be restricted. Evidence of this can be seen from the pulling out of some large biomass projects, for example a proposed 300 MW plant at Blyth, and a further three 120 MW plants in Scotland [77,78]. The results also support this view, suggesting the market would generate 1 TWh $year^{-1}$ of electricity (0.3% of UK electricity and 0.1% of primary energy demand) and abate 1 Mt CO_2e $year^{-1}$, assuming the current lack of farmer subsidy and subsidised renewable electricity revenue reducing to £100 MWh^{-1} by 2024. Despite this outlook, longer-term the need for a source of feedstock for second-generation biofuels may increase the significance of the energy crop market.

5 Conclusions

Energy crop markets operate within a policy environment that is shaped by both energy policy and agricultural policy. This analysis shows the inter-dependency between these policy areas, in determining the rate and level of adoption, and the cost-effectiveness of carbon abatement. Unfortunately, responsibility for these areas often lies in separate government departments; e.g. in the UK the Department of Energy & Climate Change and the Department for Environment Food & Rural

Affairs, potentially making coordinated policy decision-making more difficult. An illustration of this can be seen in the ending of the establishment grant scheme for farmers, just as some evidence emerged suggesting the important role that it plays in the uptake and efficiency of the market. Overall, the results and recent policy developments appear to suggest that domestically grown perennial energy crops in the UK will only play a niche role, in the short term. A coherent and stable set of related policies is needed to ensure that the potential for the energy crop market to deliver significant emissions abatement, and to provide a source of renewable electricity is achieved, and in a cost-effective manner.

Supporting energy crop markets for electricity generation provides an additional benefit of increasing future supply capacity, if the production of second-generation biofuel from energy crops is envisioned to expand rapidly in the future. Long time lags (up to 20 years) for farmers to adopt of novel crops, such as energy crops, are seen both in the modelled results and in empirical data. These time lags arise from the behavioural aspects of farmers' decision-making, and imply that it may be problematic to rapidly achieve a large quantity of energy crop production. Currently, supporting biomass electricity generation could therefore be viewed as creating 'option value' for future ligno-cellulosic biofuel feedstock supply.

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7 References

[1] IEA. World Energy Outlook 2012. International Energy Agency, Paris, France: 2012.

[2] Sandle P, Holton K. UK energy firm stokes growing political row with price hike. Reuters, 10 Oct 2013 2013.

[3] BBC News. Ed Miliband: Labour would freeze energy prices. BBC News, 24 Sept 2013 2013.

[4] Ofgem. Electricity Capacity Assessment Report 2013. Ofgem, London, UK: 2013.

[5] National Grid. UK Future Energy Scenarios. National Grid, Warwick, UK: 2012.

[6] Ofgem. Electricity Capacity Assessment. Ofgem, London, UK: 2012.

[7] DECC. Implementing Electricity Market Reform (EMR). Department of Energy & Climate Change, London, UK: 2014.

[8] IEA. Technology Roadmap Bioenergy for Heat and Power. International Energy Agency, Paris, France: 2012.

[9] Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L, Arent DJ, Banerjee R, et al. Global Energy Assessment: Toward a Sustainable Future. Cambridge University Press, Cambridge, UK: 2012.

[10] DfT, DECC, DEFRA. UK Bioenergy Strategy. Department of Energy & Climate Change, London, UK: 2012.

[11] DECC. UK Renewable Energy Roadmap. Department of Energy & Climate Change, London, UK: 2011.

[12] Aylott MJ, Casella E, Tubby I, Street NR, Smith P, Taylor G. Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. New Phytol 2008;178:358–70.

[13] DEFRA. UK Biomass Strategy. Department for Environment Food and Rural Affairs, London, UK: 2007.

[14] Gill B, MacLeod N, Clayton D, Cowburn R, Roberts J, Hartley N. Biomass Task Force Report to Government. Department for Environment Food and Rural Affairs, London, UK: 2005.

[15] Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Aylott MJ, Casella E, et al. Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. Bioresour Technol 2010;101:8132–43.

[16] E4tech. Biomass supply curves for the UK. E4tech, London, UK: 2009.

[17] Thomas A, Bond A, Hiscock K. A GIS based assessment of bioenergy potential in England within existing energy systems. Biomass and Bioenergy 2013;55:107–21.

[18] Aylott M, McDermott F. Domestic Energy Crops; Potential and Constraints Review: A report for DECC. The National Non-Food Crops Centre, York, UK: 2012.

[19] DEFRA, Government Statistical Service. Area of Crops Grown For Bioenergy in England and the UK: 2008-2011. Department for Environment Food and Rural Affairs, London, UK: 2013.

[20] Natural England. Establishment Grants Handbook, 3rd Edition. Natural England, Sheffield, UK: 2009.

[21] Ofgem. Renewables Obligation : Guidance for Generators. Ofgem, London, UK: 2013.

[22] DECC. Renewable Heat Incentive. Department of Energy & Climate Change, London, UK: 2011.

[23] Monti A, Fazio S, Lychnaras V, Soldatos P, Venturi G. A full economic analysis of switchgrass under different scenarios in Italy estimated by BEE model. Biomass and Bioenergy 2007;31:177–85.

[24] Bell J, Booth E, Ballingall M. Commercial viability of alternative non food crops and biomass on Scottish Farms. A special study supported under SEERAD Advisory Activity 211. SAC, Rural Business Unit, Bush Estate, Penicuik, UK: 2007.

[25] Styles D, Thorne F, Jones M. Energy crops in Ireland: An economic comparison of willow and Miscanthus production with conventional farming systems. Biomass and Bioenergy 2008;32:407–21.

[26] Turley D, Liddle N. Analysis of the economic competitiveness of perennial energy crops on arable farms. The National Non-Food Crops Centre, York, UK: 2008.

[27] Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 4.4. Energy Technologies Institute, London, UK: 2013.

[28] Clancy D, Breen JP, Thorne F, Wallace M. The influence of a Renewable Energy Feed in Tariff on the decision to produce biomass crops in Ireland. Energy Policy 2012;41:412–21.

[29] Sherrington C, Moran D. Modelling farmer uptake of perennial energy crops in the UK. Energy Policy 2010;38:3567–78.

[30] Sherrington C, Bartley J, Moran D. Farm-level constraints on the domestic supply of perennial energy crops in the UK. Energy Policy 2008;36:2504–12.

[31] Glithero NJ, Wilson P, Ramsden SJ. Prospects for arable farm uptake of Short Rotation Coppice willow and miscanthus in England. Appl Energy 2013;107:209–18.

[32] Gedikoglu H. Impact of Off-Farm Employment on Farmers' Willingness to Grow Switchgrass and Miscanthus. South. Agric. Econ. Assoc. Annu. Meet. Febr. 4-7, 2012, Birmingham, AL, 2012.

[33] Bocquého G, Jacquet F. The adoption of switchgrass and miscanthus by farmers: Impact of liquidity constraints and risk preferences. Energy Policy 2010;38:2598–607.

[34] Qualls DJ, Jensen KL, Clark CD, English BC, Larson J a., Yen ST. Analysis of factors affecting willingness to produce switchgrass in the southeastern United States. Biomass and Bioenergy 2012;39:159–67.

[35] Paulrud S, Laitila T. Farmers' attitudes about growing energy crops: A choice experiment approach. Biomass and Bioenergy 2010;34:1770–9.

[36] Reise C, Musshoff O, Granoszewski K, Spiller A. Which factors influence the expansion of bioenergy? An empirical study of the investment behaviours of german farmers. Ecol Econ 2012;73:133–41.

[37] Mola-Yudego B, González-Olabarria JR. Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: Lessons to be

learned about the spread of energy crops. Biomass and Bioenergy 2010;34:442–8.

[38] Thomas ARC, Bond AJ, Hiscock KM. A multi-criteria based review of models that predict environmental impacts of land use-change for perennial energy crops on water, carbon and nitrogen cycling. GCB Bioenergy 2013;5:227–42.

[39] St. Clair S, Hillier J, Smith P. Estimating the pre-harvest greenhouse gas costs of energy crop production. Biomass and Bioenergy 2008;32:442–52.

[40] Hillier J, Whittaker C, Dailey G, Aylott M, Casella E, Richter GM, et al. Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. GCB Bioenergy 2009;1:267–81.

[41] Rowe RL, Hanley ME, Goulson D, Clarke DJ, Doncaster CP, Taylor G. Potential benefits of commercial willow Short Rotation Coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment. Biomass and Bioenergy 2010.

[42] Watson R, Albon S, Aspinall R, Austen M, Bardgett R, Berry P, et al. UK National Ecosystem Assessment: Synthesis of the Key Findings. UNEP-WCMC, Cambridge: 2011.

[43] Al-Mansour F, Zuwala J. An evaluation of biomass co-firing in Europe. Biomass and Bioenergy 2010;34:620–9.

[44] Bertrand V. Switching to biomass co-firing in European coal power plants : Estimating the biomass and CO 2 breakeven prices. Les Cahiers de La Chaire Economie Du Climat, Paris, France: 2013.

[45] HM Treasury, HM Revenue & Customs. Carbon price floor: support and certainty for low-carbon investment. HM Treasury, London, UK: 2010.

[46] Cherubini F, Jungmeier G. LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass. Int J Life Cycle Assess 2009;15:53–66.

[47] Perilhon C, Alkadee D, Descombes G, Lacour S. Life Cycle Assessment Applied to Electricity Generation from Renewable Biomass. Energy Procedia 2012;18:165–76.

[48] Bullard M, Metcalfe P. Estimating the energy requirements and CO2 emissions from production of the perennial grass miscanthus, switchgrass and reed canary grass. Energy Technology Support Unit, London, UK: 2001.

[49] Bauer C. Life Cycle Assessment of Fossil and Biomass Power Generation Chains: An analysis carried out for ALSTOM Power Services. Paul Scherrer Institut, Villigen, Switzerland: 2008.

[50] Wiltshire J, Hughes R. Carbon impacts of using biomass in bio-energy and other sectors: energy crops. ADAS UK, Cambridge, UK: 2011.

[51] Alexander P, Moran D, Rounsevell M, Smith P. Modelling the perennial energy crop market: the role of spatial diffusion. J R Soc Interface 2013;10.

[52] Alexander P, Moran D, Rounsevell M, Hillier J, Smith P. Cost and potential of carbon abatement from the UK perennial energy crop market. Glob Chang Biol Bioenergy 2014;6:156–68.

[53] Rounsevell MD a, Robinson DT, Murray-Rust D. From actors to agents in socio-ecological systems models. Philos Trans R Soc Lond B Biol Sci 2012;367:259–69.

[54] Zimmermann A, Heckelei T, Domínguez IP. Modelling farm structural change for integrated ex-ante assessment: review of methods and determinants. Environ Sci Policy 2009;12:601–18.

[55] Tallis MJ, Casella E, Henshall PA, Aylott MJ, Randle TJ, Morison JIL, et al. Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. GCB Bioenergy 2012;5:52–66.

[56] Hastings A, Tallis M, Casella E, Matthews R, Hensall P, Milner S, et al. The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. Glob Chang Biol Bioenergy 2014;6:108–22.

[57] Alexander P, Moran D. Impact of perennial energy crops income variability on the crop selection of risk averse farmers. Energy Policy 2013;52:587–96.

[58] Rogers EM. Diffusion of innovations (4th ed.). Free Press, New York, USA; 1995.

[59] Lovett AA, Sünnenberg GM, Dockerty TL. The availability of land for perennial energy crops in Great Britain. Glob Chang Biol Bioenergy 2014;6:99–107.

[60] Oxera Consulting. Discount rates for low-carbon and renewable generation technologies. Committee on Climate Change, London, UK: 2011.

[61] DECC. Consultation on proposals for the levels of banded support under the Renewables Obligation for the period 2013-17 and the Renewables Obligation Order 2012. Department of Energy & Climate Change, London, UK: 2011.

[62] Ofgem. The renewables obligation buy-out fund 2011-12. Ofgem, London, UK: 2012.

[63] DECC. Energy and emissions projections. Annex F: Price and growth assumptions. Department of Energy & Climate Change, London, UK: 2012.

[64] DECC. Investing in renewable technologies – CfD contract terms and strike prices. Department of Energy & Climate Change, London, UK: 2013.

[65] Lane AB. Benefits and hazards of new crops: Oilseed rape in the U.K. Agric Ecosyst Environ 1983;10:299–309.

[66] Wrathall J. The oilseed rape revolution in England and Wales. Geography 1978;63:42–5.

[67] Allanson P. A Structural Account of the Diffusion of Oilseed Rape in England and Wales. Econ Innov New Technol 1994;3:31–47.

[68] EDINA. Agcenus data for England and Wales. EDINA, Edinburgh, UK: 2012.

[69] HM Treasury, HM Revenue & Customs. Carbon price floor consultation: the Government response. HM Treasury, London, UK: 2011.

[70] Lindegaard K. Why we need an Energy Crops Scheme 3. Crops for Energy, Bristol, UK: 2013.

[71] Mola-Yudego B, Dimitriou I, Gonzalez-Garcia S, Gritten D, Aronsson P. A conceptual framework for the introduction of energy crops. Renew Energy 2014;72:29–38.

[72] HLPE. Biofuels and food security. High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome, Italy: 2013.

[73] Jablonski S, Strachan N, Brand C, Bauen A. The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergy scenarios. Energy Policy 2010;38:5799–816.

[74] DECC. Energy Act. Department of Energy & Climate Change, London, UK: 2013.

[75] National Grid. National Grid EMR Analytical Report. National Grid, Warwick, UK: 2013.

[76] HM Revenue & Customs. Carbon price floor : reform and other technical amendments Operative date. HM Revenue & Customs, London, UK: 2014.

[77] BBC News. RES “ceases work” on £300m Blyth biomass power station. BBC News, 6 March 2014 2014.

[78] BBC News. Forth Energy pulls out of Scottish biomass projects. BBC News, 27 March 2014 2014.

Figure captions

Figure 1: Cost of subsidy to stimulate electricity generation from UK energy crops under a range of policy scenarios. Figure *A* shows the annualised support total cost, while figures *B* and *C* respectively show the average and marginal subsidy per unit of electricity generated, each plotted against the annualised generation.

Figure 2: Marginal carbon abatement price against annual emission reduction under a range of subsidy policy scenarios, assuming displacement of coal generation.

Figure 3: Iso-carbon price curves for carbon prices in the range £65-90 tCO_2e^{-1}, assuming displacement of coal generation.

Figure 4: Iso-carbon emission abatement curves for carbon abatement in the range 0.5-16 Mt CO_2e^{-1}, assuming displacement of coal generation.