



Alexander, P., Moran, D. and Rounsevell, M.D.A. (2015)  
Evaluating potential policies for the UK perennial energy crop  
market to achieve carbon abatement and deliver a source of low  
carbon electricity. *Biomass and Bioenergy*, 82, pp. 3-12. ISSN  
0961-9534.

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<http://hdl.handle.net/11262/10731>

<http://dx.doi.org/10.1016/j.biombioe.2015.04.025>

Deposited on: 9 May 2016

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

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11        **Abstract**

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

## 33 **Keywords**

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

## 36 **1 Introduction**

37 The world faces the challenge of meeting increasing energy demands while  
38 achieving economic, social and environmental sustainability [1]. In the UK, the  
39 energy challenge manifests itself through increasing political and public concern  
40 about the national energy mix and rising prices [2,3]. The UK's electricity  
41 generation sector is based on existing coal and nuclear plants that are reaching the  
42 end of their lives, reducing generation capacity [4], while electricity demand is  
43 projected to rise gradually [5]. As a result, spare capacity in the UK electricity  
44 market is due to reduce in the next few years [6]. New infrastructure to fill the  
45 potential gap between future electricity supply and demand, is estimated to require  
46 £110 billion of investment over the next 10 years [7]. The UK Government sets the  
47 overall framework for investment in energy infrastructure, but the private sector  
48 determines where and when this investment will occur.

49 Biomass is a source of renewable energy that could help to meet these challenges.  
50 Globally, it is already the largest source of renewable energy, and is expected to  
51 expand to 80-160 EJ year<sup>-1</sup> in 2050 from 50 EJ year<sup>-1</sup> today [8,9]. In the UK by  
52 2020, it could provide 8-11% of the UK's total primary energy demand, a substantial  
53 increase from 3% in 2012 [10], and contribute to meeting the legally binding target  
54 of generating 15% of energy consumption from renewable sources [11]. Agricultural  
55 residues and energy crops are expected to have the greatest growth in UK domestic

56 biomass supply [10]. Previous research suggests that the potential energy crop area  
57 in the UK will be around 1000 to 2000 kha in 2020 and 2030 [12–17]. It has been  
58 suggested that between 930 and 3630 kha of land in England and Wales could be  
59 used to grow dedicated perennial energy crops, without impinging on food  
60 production [10]. But UK Government policy plays a crucial role in determining the  
61 level and rate of adoption of these technologies.

62 Perennial energy crops, Miscanthus and willow or poplar grown as short-rotation  
63 coppice (SRC), have been grown in the UK since around 1996 [18]. Uptake has,  
64 however, been limited, with a total area of only 11 kha in 2011, with the planting rate  
65 dropping to only 0.5 kha year<sup>-1</sup> in the period 2008-11 [19]. There is currently no  
66 target for areas of these crops, although 350 kha by 2020 was suggested in the  
67 Biomass Strategy [13]; it is now expected that the actual figure will be much lower  
68 [18]. This low uptake occurs in spite of policies to support the production of energy  
69 crops, targeted at both farmers and energy generators. Since 2003, farmers in  
70 England have had access to grants to cover a proportion of the establishment costs  
71 for Miscanthus or SRC. The support rate was 50% for the last 5 years of the scheme,  
72 which closed to new applicants in autumn 2013 [20]. Since 2002 renewable  
73 electricity generators have been able to receive support under the Renewable  
74 Obligation mechanism [21]; renewable heat technologies have more recently been  
75 supported by the Renewable Heat Incentives (RHI) scheme [22]. The RHI scheme  
76 when launched in 2011 was initially available only to the industrial sector, but in  
77 2014 expanded to cover domestic usage of renewable heat.

78 Economic and behavioural factors are implicated in farmers' decisions to adopt  
79 energy crops, and therefore potentially to explain the low uptake. Several studies  
80 have looked at the economic aspects of energy crops, estimating the annual land  
81 rental charge to account for the foregone opportunity to make greater returns from  
82 other activities, or opportunity costs [15,16,23]. A similar approach has compared  
83 annual gross margins of conventional crops with an equivalent annualised value for  
84 perennial energy crops [24–28]. A further method is to use a farm-scale economic  
85 model, maximising gross margin, to investigate the potential uptake of perennial  
86 energy crops [29]. These studies show that based on the economic case, energy  
87 crops should have been adopted more widely, leading to a focus on possible  
88 behavioural barriers to adoption. These might include cultural factors, awareness  
89 and educational barriers, long-term commitment of land, and perceived risks [18,30–  
90 35]. There is heterogeneity in the level of economic and behavioural factors,  
91 between farmers and over time, for example in investment return thresholds and risk  
92 perceptions [36]. A 'chicken and egg' problem is also an apparent barrier; farmers  
93 are unwilling to grow the crops without a more mature market, while potential  
94 investors are unwilling to develop the plants and technologies that are required to  
95 create the demand and so establish the market [30,37]. The cyclic contingent  
96 behaviour between farmers and plant investors increases the complexity of the  
97 overall system, complicating analysis of the market.

98 Energy crops compete with other potential land uses, and so have the potential to  
99 have positive and negative impacts on a range of environmental factors, e.g.  
100 greenhouse gas (GHG) emissions, soil organic carbon (SOC), biodiversity and water  
101 resources [38–41]. Increased uptake of these crops is therefore relevant to other

102 policy objectives for the provision of ecosystem services, including food production  
103 [42]. Biomass energy has on occasions been assumed or stated as having zero net  
104 emissions of carbon dioxide [43,44], or given a zero emissions factor [45].  
105 Although the carbon released during the energy production has been captured during  
106 plant growth, biomass use in energy generation potentially generates direct and  
107 indirect sources of emissions [39,46–50]. Direct emissions can occur in the  
108 production, transport, handling and processing, while indirect emissions are  
109 associated with land use change potentially causing SOC changes. These crops  
110 could, therefore, potentially provide an important source of low carbon energy, and  
111 so help to reduce the carbon intensity of energy production, as well as filling the gap  
112 between future electricity supply and demand. But the relevant economic, social and  
113 environmental trade-offs need to be understood to ensure sustainability.

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

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

## 134 **2 Material and methods**

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

138 ABMs allow the system behaviour to emerge through the dynamic interaction of  
139 agents with one another and the environment [53]. This approach is suitable for the  
140 development of a model of the energy crop market, as ABMs allow the spatial and  
141 dynamic behaviour of complex systems to be investigated [54]. The current model  
142 focuses on farmers and power plant investors as market agents [51]. Agricultural  
143 land is divided into a regular grid of 1km<sup>2</sup> (i.e. 100 ha) areas, each of which is  
144 managed by a separate notional farmer making crop selection decisions based on  
145 their resources (i.e. spatially specific crop yields [55,56]), individual preferences and  
146 market conditions. Farmers determine their willingness to consider adoption, before  
147 examining the economic case, to determine an optimum crop selection given their



148 resources and preferences [57]. Farmers' willingness to consider adoption is  
149 governed by their own previous experience, or when they have none, by the level of  
150 adoption in neighbouring farms in a diffusion of innovation approach [58]. Farmers  
151 are taken as willing to consider energy crops if the proportion of successful local  
152 adoption is greater than a threshold value, which is assigned to each farmer from a  
153 normal distribution [58]. The initial rate of adoption, or proportion of innovators  
154 was taken as 2.5% [58], and represents the fraction of farmers willing to consider  
155 adoption without any previous local adoptions. Areas unsuitable for energy crops for  
156 social or environmental reasons were constrained for selection [59]. Power plant  
157 investor agents control the construction and operation of power plants, which  
158 consume the energy crops. These agents make decisions to invest based on the  
159 expectation of the project achieving an internal rate of return, on their investment,  
160 greater than their hurdle rate [60]. A single delivered market price exists, which was  
161 adjusted exponentially based on the level of market disequilibrium, i.e. if there was  
162 excess demand the price was increased, while if there was excess supply it was  
163 reduced. All monetary values were in 2010 terms, unless otherwise stated.

164 The model was run with annual time-steps, between 2010 and 2050. A detailed  
165 description of the market is produced, including crop selection for each 100 ha farm  
166 and details of the sites, sizes and technologies of the electricity power plants. The  
167 emissions for each lifecycle stage can then be calculated, as the location and yield for  
168 supply, the efficiency of the power plant, and transport distances are known. The  
169 model output was used to determine the carbon dioxide equivalent (CO<sub>2</sub>e) emissions  
170 associated with the production of electricity from the energy crops, the emissions  
171 avoided from displacement of the same amount of conventional electricity

172 generation, and the cost of subsidies provided to support market development.  
173 Details of the GHG balance calculation can be found in Alexander *et al.* [52]. The  
174 total CO<sub>2</sub>e emissions abated and the total cost of subsidy were determined across the  
175 40-year period, to give an average implied cost of carbon abatement.

176 Three policy scenarios for the farmer establishment grant rate were combined with  
177 11 scenarios for renewable energy, to generate the set of policy scenarios tested. The  
178 three farmer grants scenario had 0%, 50% and 100% support for establishment costs  
179 respectively. The 11 renewable energy policy scenario are each expressed as a  
180 trajectory of total revenue, including from wholesale electricity and subsidies, as per  
181 the Contract for Difference mechanism, or as the rate of receiving renewable  
182 obligation certificates (ROCs). In both cases these are per MWh of electricity  
183 generated. It was assumed that support would fall to reflect the expectation of lower  
184 costs [61], and the decreases would occur over 10 years and then reach a constant  
185 level. The lower level was varied from a total revenue of £124 MWh<sup>-1</sup> to £50 MWh<sup>-1</sup>  
186 <sup>1</sup>. This could be considered to represent a 0.0 to 2.0 ROC MWh<sup>-1</sup> minimum support  
187 with prices of £37 per ROC [62] and a wholesale electricity price of £50 MWh<sup>-1</sup> [63],  
188 based on the existing support measures. Alternatively, viewed as representing  
189 support under Contract for Difference Feed-in Tariff, it is broadly inline with the  
190 initial biomass support rate of £125 MWh<sup>-1</sup>, for the replacement scheme [64].

191 The model is stochastic in nature, due to probabilistic representations, for example of  
192 farmers' resistance to adoption, investors' hurdle discount rate and potential sites.

193 Therefore 20 simulations for each scenario were run to get more data on the results

194 space for that scenario. The mean result for each scenario is presented, unless  
195 explicitly stated otherwise.

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

### 215           **3 Results**

216           The total subsidy, including renewable energy and agricultural subsidies was plotted  
217           against the biomass electricity generated, expressed on an annualised basis (Figure  
218           1,A). The cost of supporting the market increases with the size of that market.

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

231           The marginal cost of achieving biomass electricity generation and carbon abatement  
232           may, in some circumstances, be a more relevant measure for evaluating policy  
233           choices, than the average cost (Figure 1,B). If the marginal cost of abatement is  
234           rising with higher abatement, then for a given carbon price [69], the marginal results  
235           could be used to determine the most efficient level of abatement (and the associated  
236           policy mix). This is where the marginal abatement curve equate to the given carbon  
237           price. Any increase in abatement beyond this point would increase costs more than

238 the cost of carbon, and conversely reducing the abatement would mean that the cost  
239 of emissions was greater than the cost to abate it. The same argument would apply if  
240 there were a desired overall subsidy cost per unit of electricity for achieving biomass  
241 generation.

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

253 The emissions abatement where the average cost of carbon equals a particular carbon  
254 price will be higher than for the marginal cost of carbon. This is because the last  
255 abatement has occurred at a higher cost, until the averaged cost has been reduced to  
256 the assumed level. Using the carbon price floor, prior to the 2014 budget, of £70 t  
257 CO<sub>2</sub><sup>-1</sup> at 2030 [69], then the marginal abatement cost curve (Figure 2) suggests 8  
258 MtCO<sub>2</sub> year<sup>-1</sup> based on a 100% farmer establishment grant and a biomass generator  
259 minimum price of £90 MWh<sup>-1</sup>. The carbon abatement of the same average prices is  
260 11 MtCO<sub>2</sub>e year<sup>-1</sup>, with a higher biomass generator scenario price of £97 MWh<sup>-1</sup>.

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

265 Iso-carbon price points were calculated for prices at £5 CO<sub>2</sub>e<sup>-1</sup> intervals from £65 to  
266 90 t CO<sub>2</sub>e<sup>-1</sup>, under each of the three rates of establishment grants used, and are  
267 plotted in Figure 3. These points are the combination of farmer and renewable  
268 energy subsidies that produce a given carbon price from the market. Due to the U-  
269 shape curve two points for each establishment grant were possible, corresponding to  
270 each side of the U, resulting in two lines for most carbon prices. At each end of the  
271 plotted carbon prices, some points were not in the range of the scenarios run, giving  
272 rise to fewer points on those lines. The upper sets of lines correspond to the higher  
273 emission abatement scenarios, which have higher subsidies, but an equal carbon  
274 price.

275 The subsidy levels that produce iso-carbon emission abatement were determined in  
276 the same manner as for the iso-carbon price. These points were determined for  
277 emissions abatement from 0.5 Mt CO<sub>2</sub>e to 16 CO<sub>2</sub>e, doubling the abatement between  
278 each value; the figures are plotted in Figure 4. Similar to the iso-carbon price lines,  
279 some points of the highest and lowest abatements fall outside of the scenarios tested,  
280 and are therefore omitted. Figure 4 shows that a repeated doubling of emissions  
281 abatement can be achieved by an approximately constant increase in total subsidy  
282 provided, as the lines plotted are broadly parallel and at a constant spacing. This

283 suggests a relatively constant relationship between changes in the subsidy levels and  
284 an exponential change in emissions abatement.

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

## 290 **4 Discussion**

291 To stimulate electricity generation or carbon abatement, the most cost-effective  
292 policy scenario tested was with no farmer support and a subsidised biomass  
293 electricity minimum price of £94 MWh<sup>-1</sup>. The results suggest this would achieve an  
294 average subsidy cost of £50 MWh<sup>-1</sup>, although only a small market would be created  
295 generating 0.3 TWh year<sup>-1</sup>, and abating 0.3 MtCO<sub>2</sub>e year<sup>-1</sup>. However, if the aim is  
296 for more substantial electricity generation or carbon abatement, then providing direct  
297 farmer support was found to provide the most cost-effective mix of policy measures.  
298 The potential for electricity generation and carbon abatement of around 90 times  
299 greater than this case, was seen within the policy scenarios tested.

300 For each level of farmer support, the minimum carbon equivalent abatement and  
301 biomass electricity costs are obtained in scenarios with an intermediate subsidy level  
302 for electricity generators. That is, the lowest implied carbon prices or biomass  
303 support costs are not seen in either the lowest or highest renewable energy subsidy  
304 scenarios. For example, with a 50% establishment grant the lowest average carbon  
305 price of £57 t CO<sub>2</sub>e<sup>-1</sup> and lowest support of £50 MWh<sup>-1</sup> were obtained with a

306 minimum subsidised biomass electricity price of £87 MWh<sup>-1</sup>. This behaviour arises,  
307 as there is an interaction between economies of scale, primarily from the electricity  
308 generators, and the increasing subsidy costs. Economies of scale occur as larger  
309 plants are more efficient and the more developed markets are associated with lower  
310 failure rates. The additional costs are initially more than offset by efficiency gains;  
311 as the support level raises from the lowest subsidy scenarios, so the carbon price and  
312 falls. However, eventually with further increases in the support level, the gains are  
313 unable to overcome the escalating cost of the policy measures, and the subsidy costs  
314 in terms of electricity generated and carbon abatement rises. This suggests that an  
315 intermediate level of support for biomass electricity may be most cost effective at  
316 stimulating emission reductions and the generation of biomass electricity from the  
317 energy crop market. Nonetheless, the total carbon abatement, electricity generated  
318 and subsidy costs all rise with an increases in the rate of subsidy renewable energy  
319 subsidy (Figure 1,A).

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



330 [18,70]. There is an expectation that this will cause the, albeit limited, current  
331 market momentum to be lost [70], as occurred during the previous gap in funding in  
332 2006 [18]. There may be alternative mechanisms to support farmers to grow these  
333 crops, perhaps through the Common Agricultural Policy, which merits further  
334 investigation [70].

#### 335 **4.1 Adoption time lags and path dependence**

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

349 The energy crop market displays path dependence, arising from the reinforcement of  
350 the location of plant construction and energy crop selection, based on the locations of  
351 the previous plants and energy crops. Once a plant has been built at a location, and a  
352 number of farmers have adopted to produce supply for that plant, that area is more

353 likely to be selected for further plant development, and associated energy crop  
354 growth. The existence of farmers already growing energy crops increases the  
355 number of farmers who are willing to consider growing them. The increased pool of  
356 farmers potentially increases the availability of supply, which in turn increases the  
357 likelihood, and the potential size, of further plants in that proximity. The spatial  
358 reinforcement, or agglomeration, means that initial plant locations can create a  
359 significant influence on the overall outcome. The significance of this effect is  
360 supported by the adoption patterns and locations observed in Swedish SRC market  
361 [37] and is also a part of a proposed conceptual framework for the introduction of  
362 energy crops [71].

#### 363 **4.2 Implication for biofuels**

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

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

### 391 **4.3 Policy developments**

392 The existing subsidy arrangements influencing the energy crop market in the UK are  
393 currently in flux. The RO scheme, supporting renewable electricity generators, ends  
394 in 2017, and the energy crops establishment grant, supporting farmers, closed for  
395 applications in August 2013. The Electricity Market Reform proposals [7], which  
396 are effectively the replacement for the previous Renewable Obligation scheme,  
397 received Royal Assent in December 2013 [74]. The stated aim of the Electricity  
398 Market Reform proposals is to decarbonise energy generation in a cost-effective

399 manner, while maintaining security of supply. It contains three main elements; a  
400 feed-in tariff using the Contract for Difference mechanism, a carbon price floor, and  
401 a capacity market. Under Contract for Difference contracts, a single fixed price level  
402 known as the 'strike price' replaces generators revenues, from electricity and  
403 Renewable Obligations. The draft Contract for Difference strike prices are claimed  
404 to have been set to be consistent with the total revenue under this previous scheme  
405 [7]. The initial strike price is £125 MWh<sup>-1</sup> [64], inline with the policy scenarios  
406 tested.

407 There are several specific elements of the proposed policy changes that have the  
408 potential to radically alter the development of the UK energy crop market. Firstly,  
409 the technologies that are eligible for support are proposed to change. New build  
410 electricity only plants would not receive support; new plants would be required to be  
411 combined heat and power (CHP) facilities to be eligible. Also, co-firing, using a  
412 proportion of biomass in existing coal fired power station, would no longer be  
413 supported, and only complete conversion to biomass from these facilities would be  
414 accepted. Secondly, the energy crop premium would be removed, this currently pays  
415 an additional 0.5 ROC MWh<sup>-1</sup> (or around £18-20 MWh<sup>-1</sup>) for producing electricity  
416 from energy crops, in comparison to other sources of biomass. Thirdly the terms of  
417 the support contracts are being changed. Perhaps most importantly, the contract  
418 length with RO was 20 years, but with the Contract for Difference scheme it would  
419 be reduced to 15 years in general, but with a cap, specifically for biomass contacts, to  
420 cease paying in 2027. After these contracts end, the support for renewable projects  
421 will be indirectly through the climate change levy. The climate change levy is a tax  
422 applied to the fossil fuels used to generate electricity, with a minimum level via the

423 carbon price floor. The carbon price floor is due to be £70 Mt CO<sub>2</sub>e<sup>-1</sup> in 2030, which  
424 is expected to increase the wholesale electricity price from £50 MWh<sup>-1</sup> to £70 MWh<sup>-1</sup>  
425 by 2030 [75], in 2012 terms. However, the 2014 budget saw the planned increases  
426 in the carbon price floor being stopped in 2016, by the imposition of a £18 t CO<sub>2</sub>e<sup>-1</sup>  
427 cap [76]. Fourthly, and finally, as already mentioned the Energy Crop Scheme,  
428 supporting farmers with establishment grants, closed to applications in August 2013.

429 Most of these policy developments can be seen as negative for the potential for the  
430 energy crop market. Consequentially, in the short term the market expansion may be  
431 restricted. Evidence of this can be seen from the pulling out of some large biomass  
432 projects, for example a proposed 300 MW plant at Blyth, and a further three 120  
433 MW plants in Scotland [77,78]. The results also support this view, suggesting the  
434 market would generate 1 TWh year<sup>-1</sup> of electricity (0.3% of UK electricity and 0.1%  
435 of primary energy demand) and abate 1 Mt CO<sub>2</sub>e year<sup>-1</sup>, assuming the current lack of  
436 farmer subsidy and subsidised renewable electricity revenue reducing to £100 MWh<sup>-1</sup>  
437 by 2024. Despite this outlook, longer-term the need for a source of feedstock for  
438 second-generation biofuels may increase the significance of the energy crop market.

## 439 **5 Conclusions**

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

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

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

464

## 465 **6 Acknowledgements**

466 The research was supported by the UKERC project: "Spatial analysis and mapping  
467 of energy crops in GB to 2050", and the TSB/NERC project: "Using environmental  
468 data to help industry invest in the UK biomass market". The research made use of

469 resources provided by the Edinburgh Compute and Data Facility  
470 (<http://www.ecdf.ed.ac.uk/>). We also acknowledge our financial supporters: the  
471 Scottish Government Rural and Environmental Science and Analytical Services  
472 division through ClimatexChange (<http://www.climatexchange.org.uk/>). The authors  
473 would like to thank Pete Smith, Jonathan Hillier and Astley Hastings (University of  
474 Aberdeen), Gilla Sunnenberg and Andrew A Lovett (University of East Anglia),  
475 Matthew J Tallis (University of Portsmouth), Eric Casella (Forest Research) and Gail  
476 Taylor (University of Southampton) for providing the datasets used.

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676

677 **Figure captions**

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

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

684 Figure 3: Iso-carbon price curves for carbon prices in the range £65-90 tCO<sub>2</sub>e<sup>-1</sup>,  
685 assuming displacement of coal generation.

686 Figure 4: Iso-carbon emission abatement curves for carbon abatement in the range  
687 0.5-16 Mt CO<sub>2</sub>e<sup>-1</sup>, assuming displacement of coal generation.