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Cost and potential of carbon abatement from the UK perennial energy crop market

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Running header

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Abstract

Biomass produced from perennial energy crops is expected to contribute to UK renewable energy targets, reducing the carbon intensity of energy production. The UK government has had incentive policies in place targeting both farmers and power plant investors to develop this market, but growth has been slower than anticipated. Market expansion requires the interaction of farmers growing these crops, with the construction of biomass power plants or other facilities to consume them. This paper uses an agent-based model to investigate behaviour of the UK energy crop market and examines the cost of emission abatement that the market might provide. The model is run for various policy scenarios attempting to answer the following questions: Do existing policies for perennial energy crops provide a cost effective mechanism in stimulating the market to achieve emissions abatement? What are the relative benefits of providing incentives to farmers or energy producers? What are the trade-offs between increased or decreased subsidy levels and the rate and level of market uptake, and hence carbon abatement? The results suggest that maintaining the energy crop scheme, which provides farmers' establishment grants, can increase both the emissions abatement potential and cost effectiveness. A minimum carbon equivalent abatement cost is seen at intermediate subsidy levels for energy generation. This suggests that there is an optimum level that cost effectively stimulates the market to achieve emissions reduction.

Introduction

Biomass could supply 8-11% of the UK's total primary energy demand by 2020 (DfT, DECC, & DEFRA, 2012), and form a significant part of meeting the legally binding target of 15% of its energy consumption from renewable sources (DECC, 2011a). The greatest growth in UK domestic biomass supply is expected to come from agricultural residues and energy crops (DfT, DECC, & DEFRA, 2012). It has been suggested that between 930 and 3630 kha of land in England and Wales could be used for growing dedicated perennial energy crops, Miscanthus and willow or poplar grown as Short rotation coppice (SRC), without impinging on food production (DfT, DECC, & DEFRA, 2012). However, uptake of these crops has been limited; only 11 kha in 2011, with the planting rate dropping to only 0.5 kha yr^{-1} from 2008-11 (DEFRA & Government Statistical Service, 2013), with evidence this is driven by farmers behaviour causing a spatial diffusion process (Alexander *et al.*, 2013). Although there is currently no target for areas of these crops, 350 kha by 2020 was suggested in the Biomass Strategy (DEFRA, 2007), but it is now expected that the actual figure will be much lower (Aylott & McDermott, 2012).

Different policies have been available to support the UK energy crop market. Subsides have been targeted at both the farmers and the energy producers. Farmers in England have had access to grants covering 50% of the establishment costs for planting Miscanthus or SRC (Natural England, 2009). While renewable electricity generators have been able to receive support under the Renewable Obligation (RO) mechanism (Ofgem, 2013). The number of Renewable Obligation Certificates (ROCs) electricity generators receive varies based on the amount renewable electricity generated, and a support band determined by technology and commissioning date. These certificates can then be sold (from 2009 to 2012 prices have ranged been between £37 to 40 ROC^{-1} (Ofgem, 2012)), providing the generator with a premium in addition to the wholesale electricity price. More recently, Renewable Heat Incentives (RHIs) have also been available for the generators of renewable heat. However the existing subsidy arrangements are in flux; the RO scheme ends in 2017, and the energy crops establishment grant closed to new applications at the end of August 2013, although planting of approved areas will continue, potentially until 2015. Electricity Market Reform (EMR) proposals, which are effectively the replacement for RO, have been published (DECC, 2013a). The stated aim of the EMR 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 Contract for Difference (CfD), a carbon price floor, and a capacity market. Under CfD, generators revenues, from electricity and ROCs, is replaced by a single fixed price level known as the ‘strike price’. The draft CfD strike prices are claimed to have been set to be consistent with the ROCs, however dedicated biomass would require combined heat and power (CHP) facilities to receive support (DECC, 2013a). It is unclear whether there will be a replacement for the Energy Crop Scheme, or the timing or the form that any replacement might take, but there are calls for a new scheme (Aylott & McDermott, 2012; Lindegaard, 2013).

Biomass energy is sometimes assumed or stated as having zero net emissions of Carbon dioxide (CO_2) (Al-Mansour & Zuwala, 2010; Bertrand, 2013), or given a zero emissions factor (HM Treasury & HM Revenue & Customs, 2010). However, although the carbon released during the energy production as been captured during the growth of the plant, there are direct and indirect sources of potential emissions. Direct emissions relate to the production, transport, handling and processing lifecycle stages, while indirect emission can occur due to land use change potentially causing soil carbon changes. Several assessments of greenhouse gas (GHG) emissions have been undertaken for energy crop production or related generation technologies (Bullard & Metcalfe, 2001; Bauer, 2008; St. Clair, Hillier, & Smith, 2008; Cherubini & Jungmeier, 2009; Wiltshire & Hughes, 2011; Perilhon *et al.*, 2012). These have typically assumed average values for energy crop yield, transport distance and power plant parameters. In fact these will vary, for example between farms, due to the location of production and consumption, and by the size and type of power plant. Although there is some work including spatially specific crop yields to determine maps of potential emissions (Hillier *et al.*, 2009), no study to date has considered how the behavioural aspects of adoption, such as imitation of behaviour and diffusion of innovation, may impact the resulting emissions, or how this might be impacted by changes in subsidies.

This paper uses an agent-based model to investigate the UK energy crop market and examines the cost of CO_2 equivalent (CO_2e) abatement that the market could provide. An existing GHG balance assessment (St. Clair, Hillier, & Smith, 2008) is used as a framework to assess the emissions. The model is run for various policy scenarios, representing possible subsidy trajectories and divisions of support between farmers and energy producers, attempting to answer the following questions: Do existing policies for perennial energy crops provide a cost effective mechanism in stimulating the market to achieve emissions abatement? What are the relative benefits of providing incentives to farmers or energy producers? What are the trade-offs between increased or decreased subsidy levels and the rate and level of market uptake, and hence carbon abatement? A sensitivity analysis is also conducted to determine the behaviour of the system to a range of parameters, the results of which are used to further understand the policy scenario results. The paper describes the method for calculation of emissions from generating energy crop electricity and emissions avoided from displacement of this electricity from another source. The agent-based model and the scenarios used are then outlined, before the results are then presented and discussed.

Materials and methods

Emissions from energy crop electricity generation

Emissions for each energy crop and associated management were calculated based on initial estimates set out in St. Clair *et al.* (2008), with some modifications. Emissions from the production of the Miscanthus rhizomes, willow cuttings and removal of the crop at the end of its productive life were added. Emissions associated with the production of Miscanthus rhizomes have been estimated as 278.7 kg CO_2e ha^{-1} (Bullard & Metcalfe, 2001). For willow cuttings an estimate of 174.2 kg CO_2e ha^{-1} was used since no specific figure was available and it was assumed emissions proportional to the level of input required to grow the rhizomes and cuttings, as approximated by their respective costs (Turley & Liddle, 2008). Emissions were also added for crop removal; both crops were assumed to require broad-spectrum herbicide and sub-soiling. Fertiliser application practices were assumed to follow the National Non-Food Crops Centre guidelines (NNFCC, 2010a, 2010b). Miscanthus does not require significant fertiliser application as it recycles nutrients into the rhizome. However at establishment it is recommended to apply 85 kg ha^{-1} N and 45 kg ha^{-1} each of P and K (NNFCC, 2010a). An additional 40 kg ha^{-1} N may also be required and these are assumed to be applied after year 5 and 10. For SRC willow, sewage sludge or manure is recommend at establishment and after each harvest. The use of 100 kg ha^{-1} of N from 0.6% N manure at establishment and after each harvest application was assumed (NNFCC, 2010b). The application of fertiliser creates direct emissions from increased production of nitrous oxide (N_2O) due to the higher levels of N, and indirect emissions from volatilisation, leaching and run-off. Emissions are also caused by the fertilisers' production, transport and application. The direct emissions are estimated to be 1% applied (IPCC, 2006), with lower indirect rates through volatilisation, leaching and run-off. However for inorganic fertilisers the production emissions can be significant (Wood & Cowie, 2004). Using a farm carbon calculator (Hillier, 2013) the impact of each of the fertiliser regimes was estimated assuming well drained soil, of medium soil organic carbon (between 1.72% and 5.16% soil organic matter), and medium texture. The emission for Miscanthus was estimated as 915.1 kg CO_2e ha^{-1} at establishment and 518.8 kg CO_2e ha^{-1} in years 5 and 10. For SRC willow, the estimate was 428.9 kg CO_2e ha^{-1} for each manure application (Hillier, 2013). No account was taken of changes in soil organic carbon; the justification and potential consequences of this assumption are explored in the discussion section. Table 1~~Table 1~~ summarises, for each energy crop, the emission parameters associated with crop production.

Handling for on-farm storage and handling for transport loading and unloading where both estimated as 3.29 kg CO_2e t^{-1} (Elsayed, Matthews, & Mortimer, 2003). Haulage emissions where taken as 0.17574 kg CO_2e t^{-1} km^{-1}, assuming a return trip with an average load returning empty for an articulated carrier >33t (DECC, 2013b). Biomass Ash disposal was included in the transport cost assuming 60 kg t^{-1} of fuel is used (Elsayed, Matthews, & Mortimer, 2003). As these figures are for mass of material handled and crop yield are in oven dried ~~tons~~ tonnes (odt), these figures were adjusted to account for moisture contents of 15% for Miscanthus and 30% for SRC willow (Hillier *et al.*, 2009). Storage is calculated using ~~tons~~ tonnes of fuel produced (t_p), while transportation is calculated using ~~tons~~ tonnes of fuel supplied (t_s). Where crops are unsold, these figures will differ in a given period.

The CO_2 produced by the combustion in the electricity generation process is not included, as unlike other fuels, it does not increase atmospheric CO_2 since an equivalent amount is captured during crop growth. However methane (CH_4) and N_2O, gases with higher global warming potentials (Forester *et al.*, 2007), are both emitted and need to be included in these calculations. The rate of emission per MWh of feed fuel (MWh_f) were taken as 0.0072 kg CH_4 MWh_f^{-1} and 0.018 kg N_2O MWh_f^{-1} (Elsayed, Matthews, & Mortimer, 2003). The construction of a biomass power plant involves significant GHG emissions associated with the production of steel and concrete (Jungmeier, Resch, & Spitzer, 1998). Emissions per MWh of installed plant capacity (MWh_i), was taken as 38.5 kg CO_2 MWh_i (Georgakellos, 2012). These construction emissions are fixed, and once the plant is built will occur whether the plant operates at full capacity or not. Table 2~~Table 2~~ gives a summary of these figures.

To demonstrate how these figures are used to calculate emissions, we use an exemplar of the emissions to produce 1 MWh of electricity (MWh_e). Taking a 12 odt ha^{-1} yield on both crops and a transport distance of 50km, with the same 1.6 tortuosity factor, and a biomass electricity plant with 30% efficiency, gives a total equivalent emissions of 91 kg CO_2e MWh_e^{-1} for Miscanthus and 102 kg CO_2e MWh_e^{-1} for SRC (Figure 1~~Figure 1~~). These figures are in-line with previously published figures. Evans *et al.*(2010) reviewed previous assessments of CO_2 equivalent emissions from biomass generation, finding a mean of 62.5 kg CO_2 MWh_e^{-1}, with the highest being 132 kg CO_2 MWh_e^{-1}. The highest figure was for SRC willow power production (Styles & Jones, 2007). These values also lie within the range published in the UK Biomass strategy for SRC chips (DfT, DECC, & DEFRA, 2012).

Abated emissions

Electricity generated from perennial energy crops displaces generation from other sources. In 2010, the UK grid emissions were 522 kg CO_2e MWh_e^{-1}, with 457 kg CO_2e MWh_e^{-1} from direct sources and 65 kg CO_2e MWh_e^{-1} from indirect sources, i.e. production and distribution of fuel (AEA, 2012). Using the same indirect emissions, the figures for coal and gas were 951 kg CO_2e MWh_e^{-1} and 400 kg CO_2e MWh_e^{-1}, respectively (DECC, 2013b). Figure 2~~Figure 2~~ compares coal, grid and gas CO_2e emissions to the example cases for Miscanthus and SRC willow. Although the displaced source could be considered to change over time and the grid average figure is expected to reduce (DfT, DECC, & DEFRA, 2012), the use of coal has recently increased, now accounting for 39% of the UK's electricity generation in 2012 (DECC, 2013c). Accordingly the analysis was undertaken with both the coal and grid average emission factors.

Agent-based model

An agent-based model (ABM) of the perennial energy crop market (Alexander *et al.*, 2013) was used to simulate the market development under various scenarios. ABM allows the dynamic representation of decision makers and their interactions, with the system behaviour emerging through agent interactions with one another and their environment (Rounsevell, Robinson, & Murray-Rust, 2012). The approach was selected as an ABM allows the spatial and dynamic behaviour of complex systems to be investigated (Zimmermann, Heckelei, & Domínguez, 2009), and supports the two-way interaction between micro and macro scales (Happe, 2004), features which many other approaches find intractable.

A summary of the construction and workings of the model used are described here, full description is available in Alexander *et al.* (2013). The model has a set of farmer agents and a set of power plant investor agents (see Figure 3~~Figure 3~~). Farmers each manage a 1km^2 (100 ha) parcel of agricultural land, making crop selection decisions based on their resources (including spatially specific crop yields (Tallis *et al.*, 2012; Hastings *et al.*, 2014)), individual preferences and market conditions. Each farmers first applies a behavioural test to determine whether they are willing to consider adoption, before applying a farm scale economic model with risk aversion, to determine an optimum crop selection given their spatial resources and initially randomly allocated preferences (Alexander & Moran, 2013). Farmers' willingness to consider adoption is determined by drawing on their own previous experience, or where there have none, by looking at the local level of adoption in their neighbour farms. Farmers are taken as willing to consider energy crops if the proportion of successful local adoption is greater than their threshold value, which is randomly assigned from a normal distribution. The initial rate of adoption, or proportion of innovators (Rogers, 1995), is the fraction of farmers willing to consider adoption without any previous local adoptions, the baseline value is 2.5%.

Areas unsuitable for energy crops for social or environmental reasons were constrained for selection (Lovett, Sünnenberg, & Dockerty, 2014). Power plant investor agents make decisions to invest in the construction and operation of power plants, that consume the energy crops, based on the expectation of the project achieving an internal rate of return, on their investment, greater than their hurdle rate (Oxera Consulting, 2011). A single delivered market price exists, which was adjusted exponentially at each year based on the level of market disequilibrium, i.e. if there is excess demand the price is increased, while if there is excess supply it is reduced. All monetary values were calculated in 2010 terms.

The model runs with a time-step of one year, starting in 2010 and continuing until 2050. A detailed description of the market emerges as the model runs proceed, including farm crop selected at a 1km^2 resolution and knowledge of the sites, sizes and technologies of the electricity power plants. This allows specific calculations of the emissions for each lifecycle stage, as the location of supply (including crop spatially specific yields), demand, and with known transport distances. Specifically, the model output helps to determine 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 subsides provided to support market development. The total CO2e emissions abated and the total cost of subsidy were determined across the 40-year time period, allowing an average implied cost of carbon abatement to be calculated.

The model has stochastic elements, and therefore requires multiple runs to explore the distribution of output[1]. For each scenario a set of 20 runs were executed and the results of this set analysed. There are computational constraints to doing increasing numbers of runs, the results presented represents 1.93 million (SPECfp) hours of CPU time on the Edinburgh Compute and Data Facility (Richards & Baker, 2008). The behaviour was determined for a range of subsidy policy scenarios, and other scenarios, chosen as part of a sensitivity analysis, detailed below.

Scenario and sensitivity definitions

Subsidies are available for the producers of electricity, through renewable obligation certificates (ROCs). The rate of future allocation over time is not known, so alternative scenarios were examined. It was assumed that the current rate of 2.0 ROC $\mathrm{MWh_e}^{-1}$ would continue until 2014 and then decrease, as per the Renewables Obligation Banding Review 2013-17, to reflect the expectation of lower costs (DECC, 2011b). It was also assumed that decreases would occur over 10 years and then reach a constant level. This lower level was varied from 0.0 to 2.0 ROC $\mathrm{MWh_e}^{-1}$, see Figure 4~~Figure 4~~. Total revenue from sales of electricity and ROCs are shown on the secondary y-axis. The scenario with a minimum of 1.0 ROC $\mathrm{MWh_e}^{-1}$ is taken as the baseline scenario, which brings it more into line with the default ROC band (Ofgem, 2013). The ROC rate is determined using the plant construction date, and held constant for the lifetime of that

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[1] The model can be configured with a random number seed. If the same seed is used, the pseudo-random events follow the same sequence and repeatable results are obtained. The results presented have an automatically generated and different seed for each run.

plant; i.e. it assumes grandfathering rights of ROC payments as per the Department of Energy and Climate Change proposals (DECC, 2011b). In addition, farmers can currently receive grants for perennial energy crops; the current rate is 50% of establishment costs (Natural England, 2009), and this is taken as the baseline scenario. The model behaviour was determined for each of the ROC rate scenarios with establishment grant rates of 0%, 50% and 100%.

The parameters used for the sensitivity analysis are shown in Table 3~~Table 3~~. Climate scenarios are taken from the UKCP09 climate data, with the category specifying the climate forcing emission scenarios (Murphy *et al.*, 2009), and were used to estimate energy crop and conventional crop yields (Alexander *et al.*, 2014).

Results

Policy scenario results

As the model proceeds from 2010 to 2050 the crop selection and power plant locations vary, causing changes in the level and cost of emissions abatement. In general, as the market expands over time, the annual abatement start from a low level and increases, while the cost of carbon starts high and gradually decreases. Figure 5~~Figure 5~~ shows the output from a sample run from the 1.0 ROC MWh_e^{-1} minimum ROC rate scenario, assuming that coal generation is displaced.

These values were annualised over the modelled period of 2010-50, for each run, and plotted as a carbon price against an annualised CO_2e reduction. The results using an establishment grant of 50% and minimum ROC rates of 0.6-1.4 ROC MWh_e^{-1} are shown in Figure 6~~Figure 6~~. The variability in results, within a scenario, as shown on this scatter plot, is caused by the model's stochasticity. In the 1.0 ROC MWh_e^{-1} scenario, three distinct clusters can be observed. First, a high carbon price (~£82 t CO_2e^{-1}) and low emissions reduction potential (~0.1 Mt CO_2e), second a more moderate carbon price (~£60 t CO_2e^{-1}) and somewhat higher emissions reduction (~0.5 Mt CO_2e), and finally a similar carbon price (~£60 t CO_2e^{-1}), but greater emissions reduction (~2 Mt CO_2e). Within each cluster of results a consistent geographic pattern is observed. Figure 7~~Figure 7~~, points A, B and C show examples of the 2040 distribution of power plants and farmers' energy crop selection from each cluster, with the corresponding case marked in Figure 6~~Figure 6~~. The frequency of runs where a significant market is not established, Figure 6~~Figure 6~~, point A, increases as the minimum ROC rate is reduced. At a minimum ROC rate of zero, all runs exhibit this behaviour. In scenarios with a minimum ROC rates above 1.0 ROC MWh_e^{-1}, cases occur where a more widespread market develops (Figure 7~~Figure 7~~, point D). The prevalence of runs showing such widespread patterns increases as the subsidy rate increases. The geographic spread also increases at higher subsidy levels (Figure 7~~Figure 7~~ point E).

The carbon prices were plotted against the mean annual emission reduction between 2010 and 2050, assuming displacement of coal, for each establishment grant rate (Figure 8~~Figure 8~~). The resulting curves display how the level of support available to electricity generators, via ROCs, affects both the level of uptake (and hence emissions reduction), and the cost-effectiveness of the subsidy regime. As demonstrated in Figure 6~~Figure 6~~, there is variation between each run for any set of parameters. Figure 9~~Figure 9~~ shows the 50% establishment grant curve with error bars for the standard deviation of both emission reductions and the carbon price, using grid average electricity generation displacement. The variation in the potential behaviours (Figure 6~~Figure 6~~ and Figure 7~~Figure 7~~) leads to relatively a high standard deviations, particularly at lower subsidy levels.

Varying the electricity generator subsidy scenario, for a fixed establishment grant rate, produces a u-shaped curve of carbon price against emissions reduction, as shown in Figure 8~~Figure 8~~. This indicates that there is a subsidy level that offers a maximum cost-efficiency of carbon equivalent abatement. At lower subsidy levels lower market uptake occurs, leading to lower abatement, but at a higher total subsidy cost per unit of CO_2e abated. At subsidy levels above the minimum carbon price level, a greater market adoption and so greater carbon abatement emerges, but the increased rate of subsidy also leads to progressively higher costs of carbon. Table 4~~Table 4~~ shows the points for each establishment grant scenario with the lowest carbon price, showing the emissions reduction and carbon price assuming both coal and grid average generation displacement. Comparing the three abatement curves in Figure 8~~Figure 8~~ shows the 50% establishment grant scenario is always at or above the no establishment grant scenario. Therefore a subsidy level with a 50% establishment grant is always at least as cost-effective at producing any level of abatement as an alternative with no establishment grant. Between the 50% and 100% establishment grant scenarios the situation is more complex. The 100% scenario has higher abatement, often at relatively small extra cost of carbon, however the lowest cost is on the 50% establishment grant curve.

The abatement curve for 50% establishment grant rate is shown in Figure 8~~Figure 8~~ and Figure 9~~Figure 9~~ respectively, calculated assuming coal and grid average displacement. Similarly, Table 4~~Table 4~~ shows both figures for the most cost-effective points for each establishment grant scenario. These show that the coal assumption has a close to doubling of the abatement potential and consequently a halving of the cost of abatement, in comparison to the grid average. The electricity generation that could be considered to be ‘displaced’ may change over time and the grid average figure is expected to reduce over time (DfT, DECC, & DEFRA, 2012). Therefore it could be argued that using current coal displacement overstates the emissions abatement. However, the rise, from 29% to 39% in 2012, of coal usage to generate the UK’s electricity provides some justification for considering both options (DECC, 2013c). Also biomass electricity is dispatchable and non-intermittent, like coal, which is likely to be increasingly important within a generation mix with growing amounts of intermittent and non-dispatchable renewables, such as wind and solar.

Sensitivity analysis results

The sensitivity analysis for the model runs using the parameter adjustments (in Table 3~~Table 3~~) is shown in Figure 10~~Figure 10~~. Results are categorised into scenarios that reduce emissions abatement, have no significant effect, or increase abatement, see Table 5~~Table 5~~.

Discussion

The model scenarios provide a range of policy-relevant insights that are discussed further here. The reasons for the model behaviour, limitations of the approach, and opportunities for further research are also considered.

The current Energy Crop Scheme, providing farmers with 50% establishment grants, appears to fulfil an important role in stimulating market development and increasing the cost-effectiveness of carbon abatement (Figure 8~~Figure 8~~ & Table 4~~Table 4~~). The current scheme closed to new applications in at the end of August 2013, and it is not clear what, if anything, will replace it. There is some expectation that this will cause the currently, albeit limited, market momentum to be lost (Lindegaard, 2013), as occurred during the previous gap in funding in 2006 (Aylott & McDermott, 2012). The results here also suggest there could be implications for the size and efficiency of the energy crop market;

i.e. lower uptake, emissions abatement, and cost effectiveness, if no replacement is put in place. Even if higher subsidy levels were available to the power generators, the overall system would achieve less adoption and more costly emissions reductions without direct farmer support. The results also suggest that increasing the farmer support for energy crops, above 50% of establishment cost, increases total abatement from the market, at a relatively small increase in the carbon price (a 100% establishment grant supports a six-fold increase in abatement to 6.7 Mt CO_2e for a £1 t CO_2e^{-1} increase in carbon price, compared to the 50% establishment grant). However there are many other polices, e.g. changes to single farm payments, that could be constructed that would provide alternative mechanisms to stimulate farmers to adopt energy crops, with only the existing Energy Crop Scheme having been modelled and investigated. Therefore further investigations are merited. Proposals have been made by others, to providing farmers with interim, flat-rate payments per hectare over the first 5-6 years (Lindegaard, 2013), the impact of which are worth exploring.

High sensitivity is seen to the establishment grant rates. It was the only subsidy adjustment examined that encourages greater uptake and emissions abatement, while not significantly increasing the carbon price (Figure 10~~Figure 10~~). Moving from the baseline 50% rate to 100% shows an increase of abatement from 1.1 to 6.7 Mt CO_2e yr^{-1}, (with coal generation displacement), with only a marginal implied carbon price increase from £63 t CO_2e^{-1} to £64 t CO_2e^{-1}. The high sensitivity to the rate of this subsidy is a consequence of it providing support across all time periods. Similarly, Figure 8~~Figure 8~~

shows that, at higher levels of abatement, the 100% establishment grant is more cost-effective.

Subsidising farmers directly, rather than via the biomass plants therefore appears to have potential benefits. This may be due to the distribution of margins between farmers and power plant operators; for example, in the baseline scenario, 86% of gross margin went to farmers. The adoption of energy crops by farmers requires them to overcome opportunity costs, and to make a return on the establishment investment. Since there are obvious (land) barriers to entering the supply of biomass, farmers could also be viewed as oligopolists. Supply prices, therefore, have a tendency to increase to the level where power plants are only marginally profitable. The main assumption that drives this behaviour would appear to be a single delivered market price for all market participants. Perhaps in reality, due to transactions costs, farmers might get a poorer deal. Opportunity for further work exists in investigating how transactions costs and market power alter the behaviours and efficiency of the market overall.

Intermediate subsidy levels have been shown to produce maximum cost effectiveness (Figure 8~~Figure 8~~ & Table 4~~Table 4~~), as the subsidy level increases the reduced failure rate and increased plant sizes allow for a more efficient system to emerge. Initially, the efficiency gains are sufficient to offset the increasing subsidy cost, leading to falls in the carbon price. Eventually, the costliness of the measure overcomes any efficiency gains, creating a rising carbon price, perhaps due to reduced scope for further efficiency gains once the market is already well established. The crossover produces the minimum carbon price observed. Where a market fails to establish, there are inefficiencies as some farmers may have planted crops and power stations have been built that may not be economic. The results show higher rates of farmers switching away from established energy crops at lower support levels. The level of negative experience of energy crops varies from 92% at 0 ROC MWh_e^{-1} to 3% at 2.0 ROC MWh_e^{-1}, due to higher prices and less susceptibility to having crops that cannot be sold or that need to be transported large distances. Benefits from economies of scale arise as larger markets are able to support larger power plants, which have lower per MW construction costs and higher power efficiencies (Mott MacDonald, 2011). Model runs start by initially selecting 1MW grate plants, before potentially moving through 10MW grate plants, to then be dominated by 30MW circulating fluidised bed (CFB) plants, with some 300MW CFB plants selected in the highest adoption scenarios. Although not represented in the model, the availability of machinery for planting and harvesting these crops would act to increase these economies of scale (Aylott & McDermott, 2012). If all the areas suitable for energy crops were to be selected, any increases in subsidy would not create additional uptake, and would only result in higher subsidy costs without additional abatement. However, even in the highest support scenario, with 100% establishment grant and 2.0 ROC MWh_e^{-1}, the average maximum energy crop area obtained 2.9 Mha, which is less than the published upper estimate of 3.63 Mha that could be grown without impinging on food production (DfT, DECC, & DEFRA, 2012). At these levels, higher support still encourages greater uptake and produces further emissions abatement.

Examining the behaviour of other parameters, a high sensitivity was observed in the behavioural aspects of farmers' adoptions, through the initial rate of farmers willing to consider adoption (Figure 10~~Figure 10~~). If adoption rates were to be increased, perhaps through awareness or otherwise reducing farmers' perceived barriers, this would be expected to have a substantial effect on the rate and level of uptake. There is evidence, from both empirical and modelled results, that a spatial diffusion process of adoption is created by farmers' behaviours, leading to long time lags, of at least 20 years, before full adoption is approached (Alexander *et al.*, 2013). Although some studies on the topic have been conducted (Sherrington, Bartley, & Moran, 2008; Convery *et al.*, 2012), there is still considerable uncertainty in this area and scope for more work to investigate psychological barriers to adoption of novel crops, and methods to enhance awareness or increase knowledge exchange through farmer social networks, in an attempt to stimulate uptake.

Electricity prices showed the largest sensitivity of the parameters tested, with a change in electricity price of £10 MWh_e^{-1} either side of £50 MWh_e^{-1} having a dramatic impact. The sensitivity to electricity prices is greater than that to the minimum ROC rates. This is because revenue changes occur immediately and over the entire period, whereas changing the ROC rate takes effect gradually, and only reduces revenue for plants built after 2015. The reduction in the carbon price with increased electricity prices is due to this additional plant revenue not being accounted for as a subsidy.

The impact on soil organic carbon (SOC) is not included in this analysis. There are potential changes in SOC due to direct land use change (dLUC), when a previous land use is displaced by growing energy crops, and indirect land use change (iLUC), where the displaced previous land use potentially shifts to an alternative area, possibly in another part of the world (Gawel & Ludwig, 2011). SOC changes from energy crop dLUC can be estimated from soil type and former land use (Hillier *et al.*, 2009). If iLUC occurs, the resulting SOC changes are uncertain, but potentially large relative to the carbon impacts of growing and using bioenergy crops (DfT, DECC, & DEFRA, 2012). The UK biomass strategy suggests the theoretical maximum available land, in England and Wales, for SRC and Miscanthus, that does not impinge on food production, to be between 0.93 and 3.63 Mha (DfT, DECC, & DEFRA, 2012). Other land use studies suggest that large areas of land could be available, based on assumptions regarding the rate of technology development and the effect on production levels (Rounsevell *et al.*, 2006), implying that even the high adoption scenarios might be feasible in terms of land availability. All model runs fall within the upper range, and only the runs towards the highest support levels (100% establishment grant and minimum ROC rate > 1.6 ROC MWh_e^{-1}) have an average area of energy crops above the lower estimate, implying the iLUC impact may be small. Due to the nature of the model, crop selection varies over time, and therefore areas selected for energy crops may only produce for a short time period. Such reversibility makes accounting for dLUC more problematic, in part contributing to its exclusion from the analysis. Where iLUC does occur, the exclusion of both land use changes should act to offset one another.

The model represents the UK energy crop market with dedicated biomass power plants, without including other sources of demand or supply of biomass. Other sources of demand exist for biomass, e.g. existing coal fired power stations, either through co-firing or complete biomass conversion, and also other types of biomass facilities, such as dedicated biomass plants with CHP. Similarly, there is supply from imports, crop residues, wastes and forestry. The modelling simplification can be partially justified because of the current RO payment rates. There is a 0.5 ROC $MWh_e{}^{-1}$ premium for dedicated biomass plant using energy crops, at current levels this equates to £18.50 $MWh_e{}^{-1}$, providing a significant incentive to solely use these crops. The current RO rates do not have a premium for energy crops usage in co-firing, providing from only 0.5 ROC $MWh_e{}^{-1}$, compared to 2.0 ROC $MWh_e{}^{-1}$ for new dedicated biomass plants (Ofgem, 2013). It is believed that at these rates, it is not economic to use energy crops for co-firing (DECC, 2012). However EMR proposes to remove the energy crop premium and stop funding dedicated biomass power plants in favour of CHP (Aylott & McDermott, 2012), impacting on how the market may develop (Chazan, 2013). Although there may be problems finding suitable sinks for heat, particularly with the larger plants (Chazan, 2013). This potential policy change means that further work to include CHP, is required, and ideally should also include other sources of biomass. Although it is difficult to quantify the impact of including these aspects on system behaviour the increase in market efficiency with higher subsidy levels appears robust and would be expected to be maintained. Adding alternative uses would reduce the overall cost of carbon if perverse incentives were avoided in the policies implemented, i.e. the economic and emissions scenarios are aligned.

Results suggest that directly supporting farmers, via an establishment grant, improves cost effectiveness of subsides in reducing GHG emissions, and increases the abatement potential. A subsidy level with a 50% establishment grant is always at least as cost-effective at producing any level of abatement as an alternative with no establishment grant. Further increasing farmer support, to 100% of the establishment costs, is suggested to provide a substantial increase (six-fold) abatement potential, at a relatively low increase in carbon price (£1 t CO_2e^{-1}). The dedicated energy crop market may be able to achieve a cost of carbon, assuming coal generation displacement, of around £60-70 t CO_2e^{-1}, which is in line with a carbon price floor at 2030 (HM Treasury & HM Revenue & Customs, 2011). Abatement potentials are sensitive to subsidy levels, with between 2 and 10 Mt CO_2e at these carbon prices, rising up to 25 Mt CO_2e, at higher carbon prices. Using grid average emissions in place of coal as the displaced fuel approximately halves the net emissions reductions.

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Tables

Table 1. Perennial energy crop production emission parameters (Sources: St. Clair et al. *2008, Bullard & Metcalfe 2001).*

Operation	**Occurrence**	**Miscanthus (kg CO_2e ha^{-1})**	**SRC willow (kg CO_2e ha^{-1})**
Site preparation	At establishment	119.2	70.8
Rhizomes / cuttings	At establishment	278.7	174.2
Planting	At establishment	278.3	251.5
Herbicide / Pesticide	At establishment	35.6	26.8
Fertiliser	See table notes	915.1[a] / 518.8[b]	428.9[c]
Harvesting	At harvest[d]	48.8	57.9
Removal	At end of productive life[e]	63.4	63.4

Notes:

a) Fertiliser applied at Miscanthus establishment.

b) Fertiliser applied at years 5 and 10 for Miscanthus.

c) Fertiliser applied at SRC establishment and after every harvest.

d) Miscanthus harvested annually, and SRC willow harvested every 3 years.

e) 16 and 21 year productive life for Miscanthus and SRC willow respectively.

Table 2. Emission parameters by lifecycle stage.

Source	**Units**	**Value**
Miscanthus production	kg CO_2e ha^{-1}	219.3[a]
SRC willow production	kg CO_2e ha^{-1}	210.6[a]
Storage	kg CO_2e t_p^{-1}	3.29
Loading / unloading	kg CO_2e t_s^{-1}	3.29
Transport	kg CO_2e km^{-1} t_s^{-1}	0.1863[b]
Power plant construction	kg CO_2e MWh_i^{-1}	38.5
Power plant operation	kg CO_2e MWh_f^{-1}	5.54

Notes:

a) Annualised over crop productive life

b) Including ash return transport

Table 3. Parameters used for the sensitivity analysis scenarios.

Parameter	**Low**	**Baseline**	**High**
Initial farmer adoption rate (%)	1.25	2.5	5
Climate emissions scenario	Low[a]	Medium[a]	High[a]
Transport costs: Miscanthus/SRC willow (2010 £ odt^{-1} km^{-1})	0.135/0.085	0.27/0.17	0.54/0.34
Maximum transport distance (km)	40	80	120
Establishment grant rate (%)	0	50	100
Minimum ROC rate (ROC MWh_e^{-1})	0.6	1.0	1.6
Electricity Price (2010 £ MWh_e^{-1})	40	50	60
ROC adjustment rate: period (years)	Fast: 5	10	Slow: 20

Note:

a) Low, Medium and High climate emissions denote the climate forcing in the UKCP09 climate scenarios (Murphy *et al.*, 2009).

Table 4. Scenario with minimum cost of CO_2e abatement for each establishment grant rate.

	Minimum ROC rate ROC MWh^{-1}	**Electricity generated GWh yr^{-1}**	**Biomas emissions Mt CO_2e yr^{-1}**	**Emission reduction: grid Mt CO_2e yr^{-1}**	**Carbon price: grid 2010 £ t CO_2e^{-1}**	**Emission reduction: coal Mt CO_2e yr^{-1}**	**Carbon price: coal 2010 £ t CO_2e^{-1}**
No establishment grant	1.4	26	0.1	0.5	130	0.9	66
50% establishment grant	1.2	73	0.2	1.3	120	2.6	61
100% establishment grant	1.0	187	0.6	3.4	126	6.7	64

Table 5. Sensitivity analysis results classified into parameters that reduce abatement, have no significant impact, or increase abatement.

Parameter	**Reduces abatement**	**No significant change**	**Increases abatement**
Initial farmer adoption rate	Low		High
Climate emissions scenario		Low & High[a]	
Transport costs		Low & High	
Maximum transport distance	Low	High	
Establishment grant rate	Low		High
Minimum ROC rate	Low		High
Electricity Price	Low		High
ROC adjustment rate	Fast		Slow

Note:

a) Low, Medium and High climate emissions denote the climate forcing in the UKCP09 climate scenarios (Murphy *et al.*, 2009).

Figure legends

Figure 1. CO_2 equivalent emissions for 1MWh of electricity generated from Miscanthus and SRC willow, assuming a yield of 12 odt ha^{-1} and a 50 km transportation distance, area proportional to emissions.

Figure 2. Total (direct and indirect) emissions, as CO_2 equivalent, to generate 1MWh of electricity in the UK from various fuels (AEA, 2012; DECC, 2013b). Areas are proportional to emissions and sources overlaid, with the lower emissions fuels towards the top.

Figure 3. Schematic representation of the main agent processes and interactions within the perennial energy crop market model (Alexander et al., 2013).

Figure 4. ROC rates scenarios by year of plant construction.

Figure 5. Carbon price and emissions reduction for each year from a sample run (Figure 6, point C) of 1.0 ROC MWh_e^{-1} minimum ROC rate scenario.

Figure 6. Scatter plot of individual runs with various ROC rates and 50% establishment grant showing cost of carbon abatement against emission reduction, with coal generation displaced.

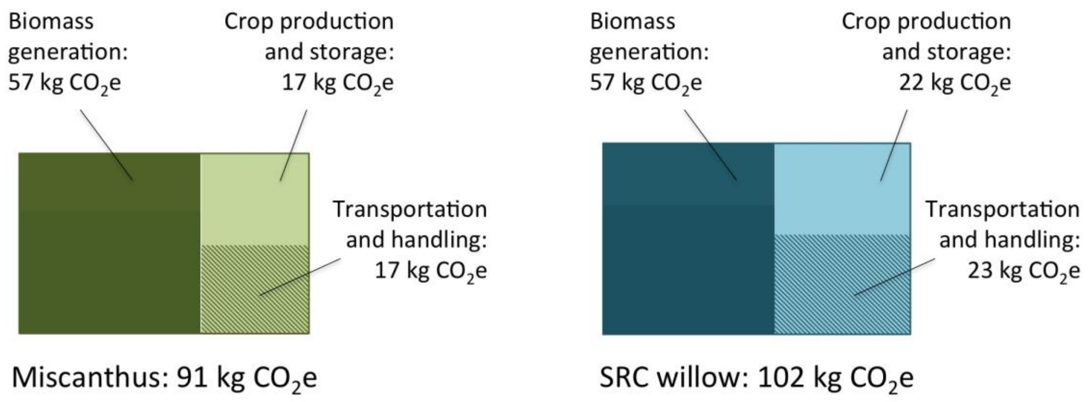
Figure 7. Example distributions of energy crop selection and power plant locations at 2040, A,B & C from examples 1.0 ROC MWh_e^{-1} minimum ROC rate scenario, D & E showing highest CO_2 equivalent abatement from 1.2 & 1.4 ROC MWh_e^{-1} minimum ROC rates runs.

Figure 8. Cost of carbon abatement against annual emission reduction for various subsidy policies, assuming displacement of coal generation. The values below each point show the minimum ROC rates (ROC MWh_e^{-1}) used in that scenario.

Figure 9. Carbon price against emission reduction, using gird average generation displacement, as minimum ROC rate is varied and 50% establishment grant, error bars showing standard deviations from a set of 20 runs for the same set of parameters.

Figure 10. Sensitivity of carbon price and emissions reduction to a range of parameter adjustments assuming displacement of coal generation. Note: Low and High climate emissions denote the climate forcing in the UKCP09 climate scenarios (Murphy et al., 2009).

Figures



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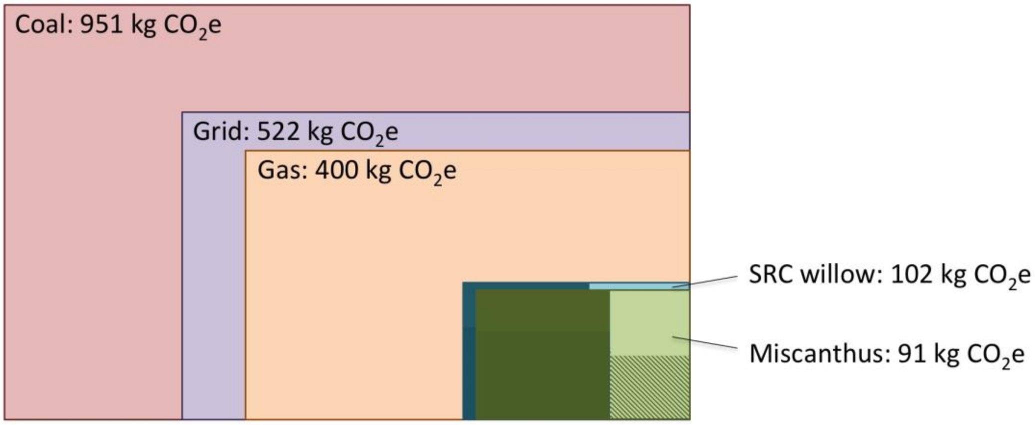

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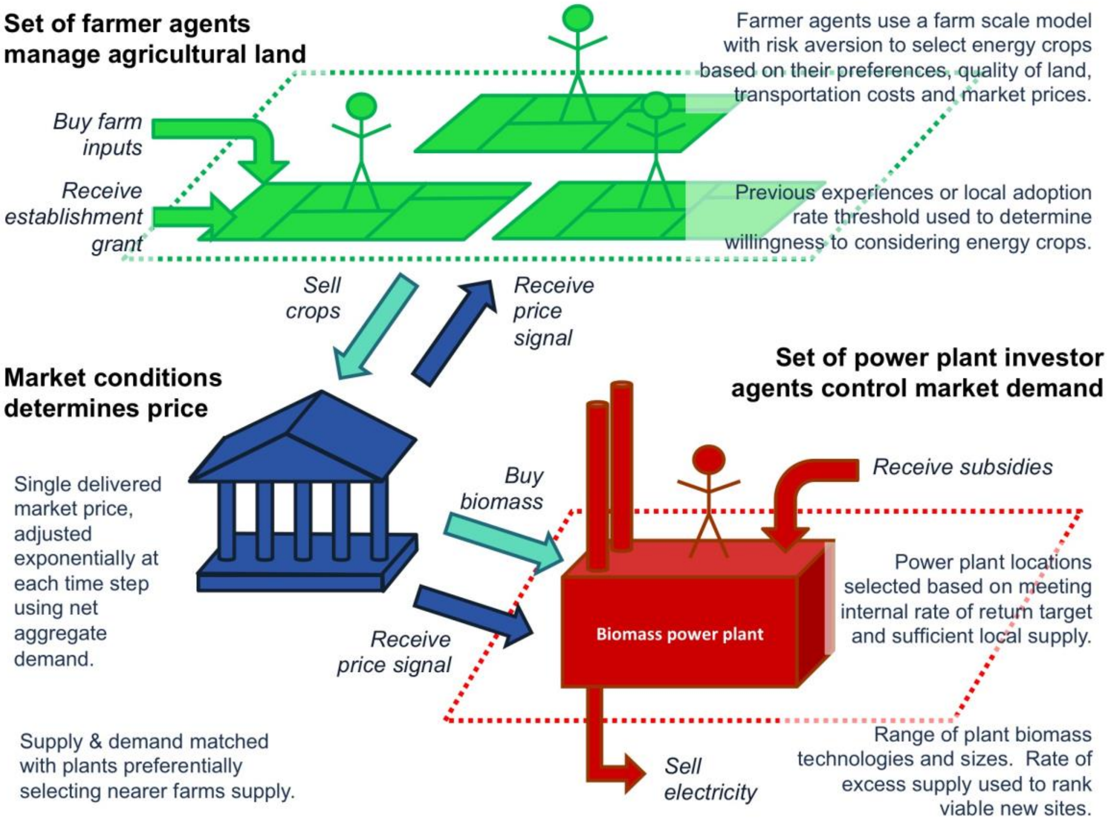

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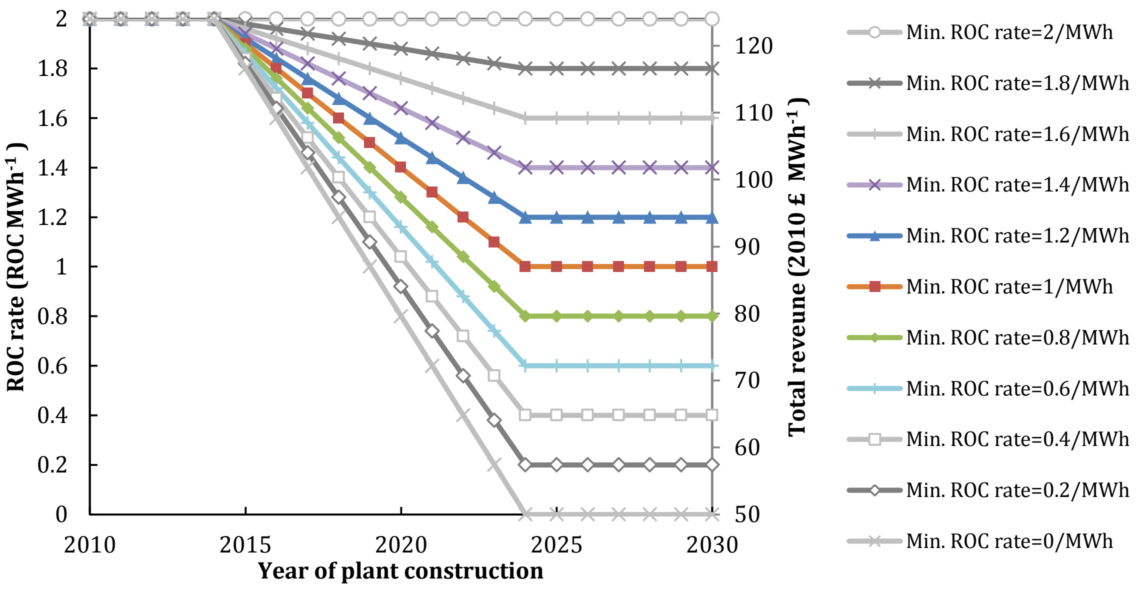

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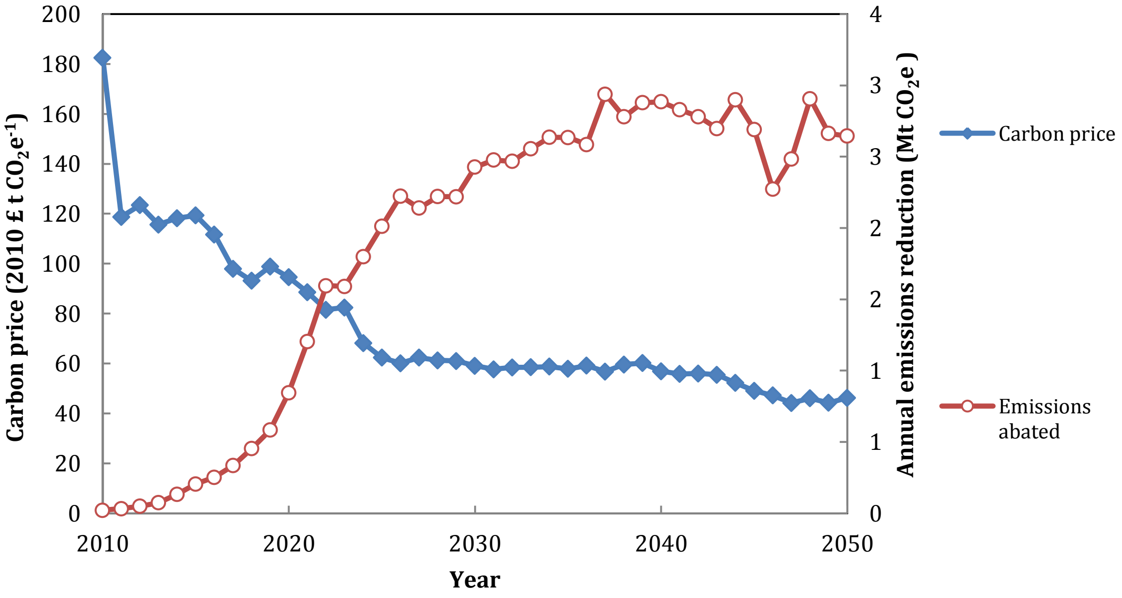

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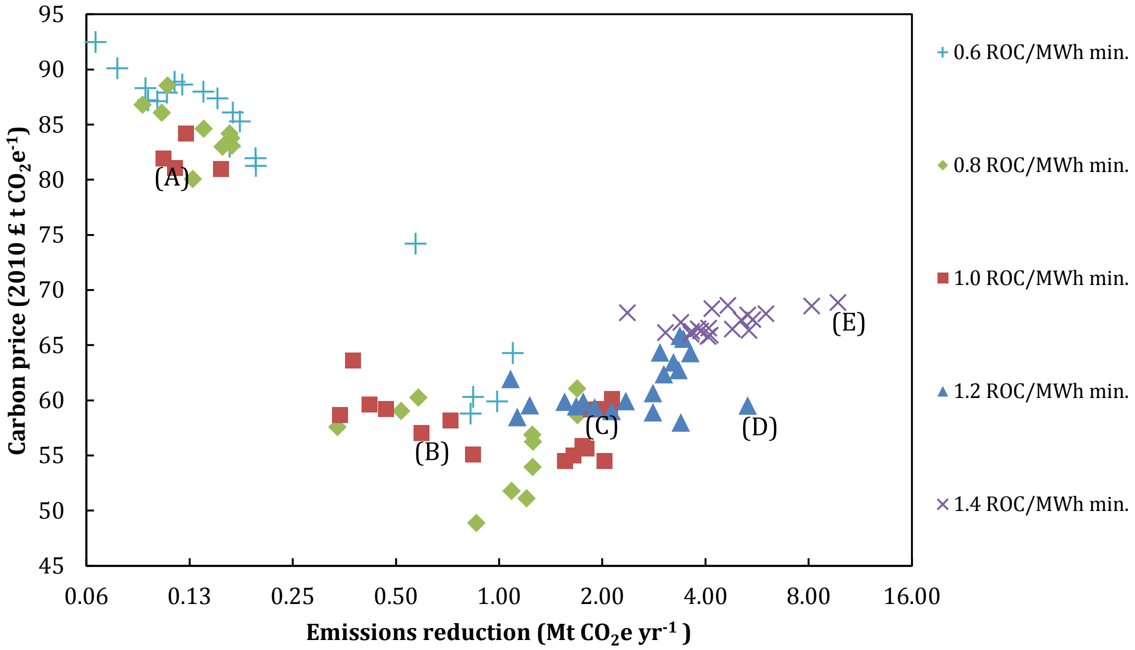

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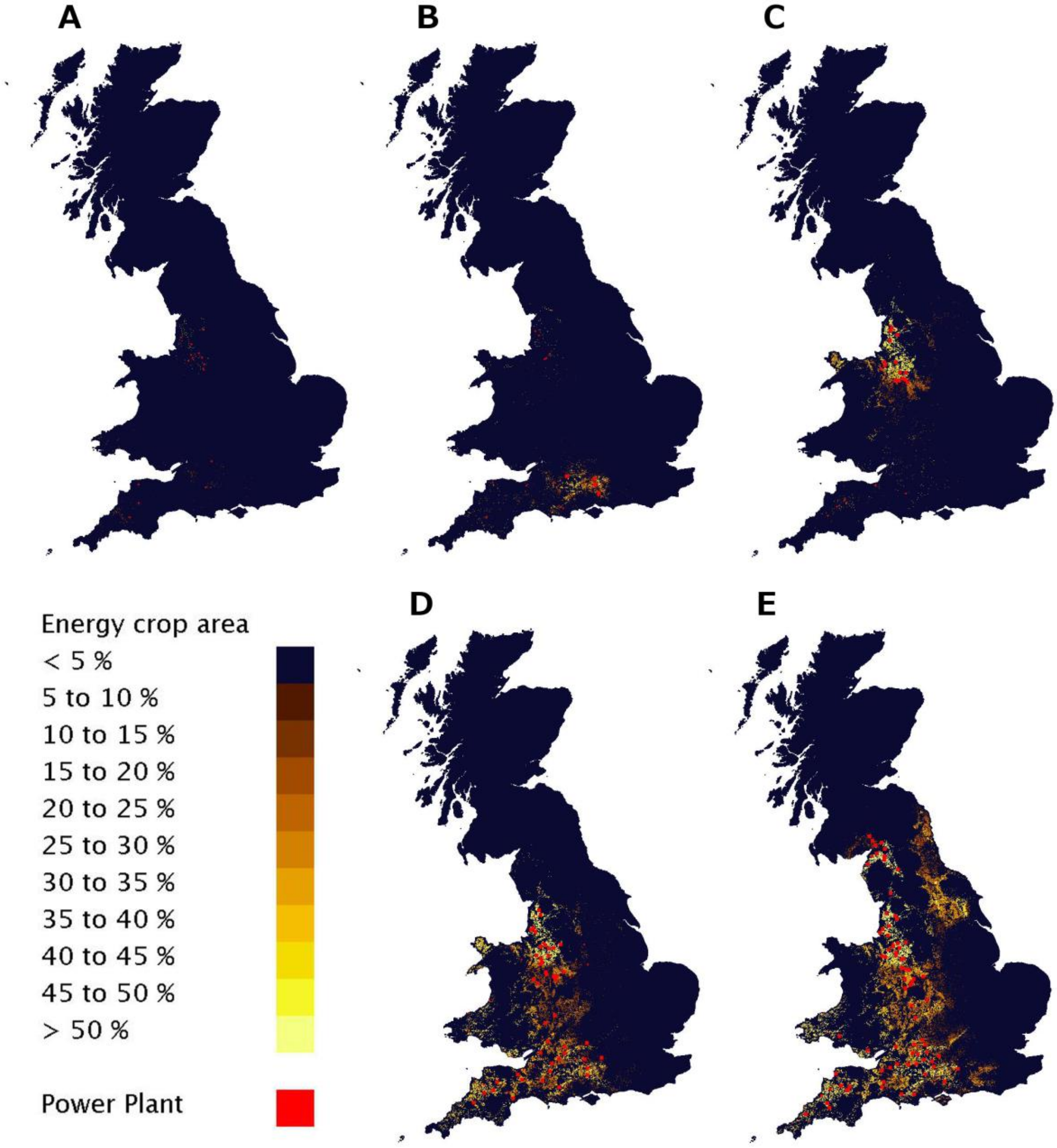

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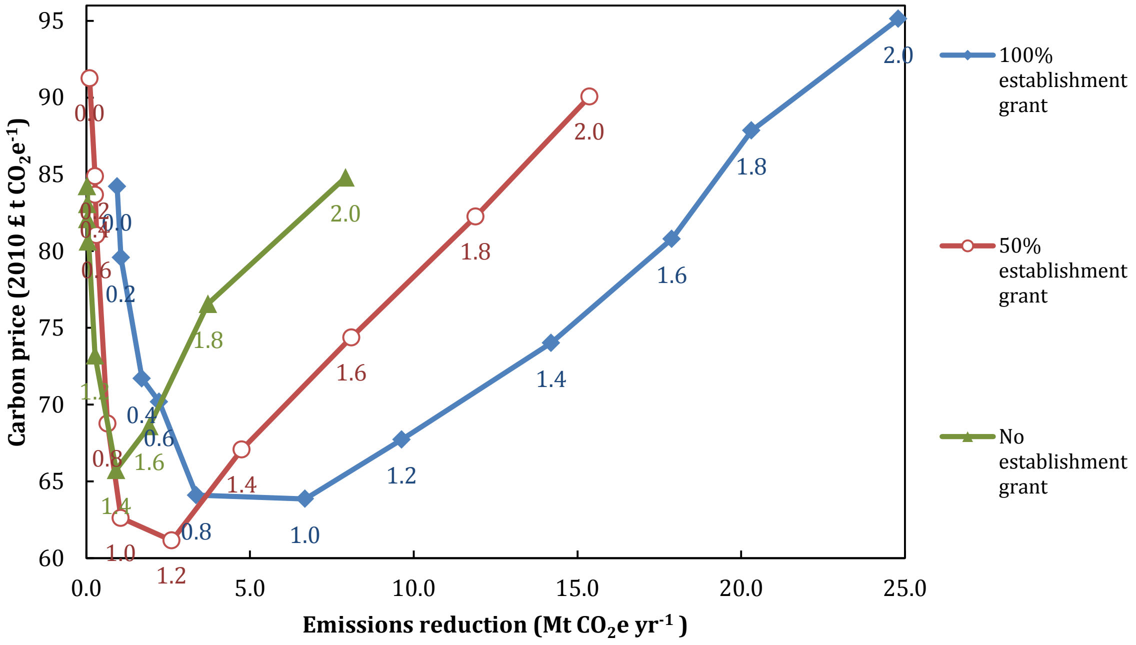

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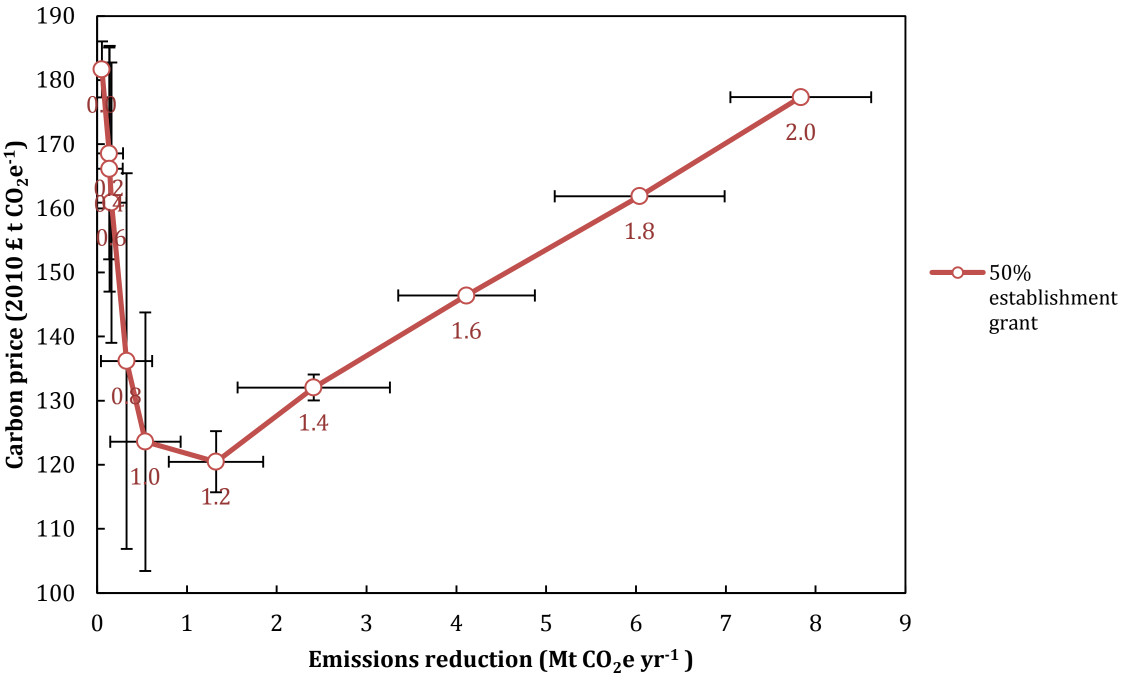

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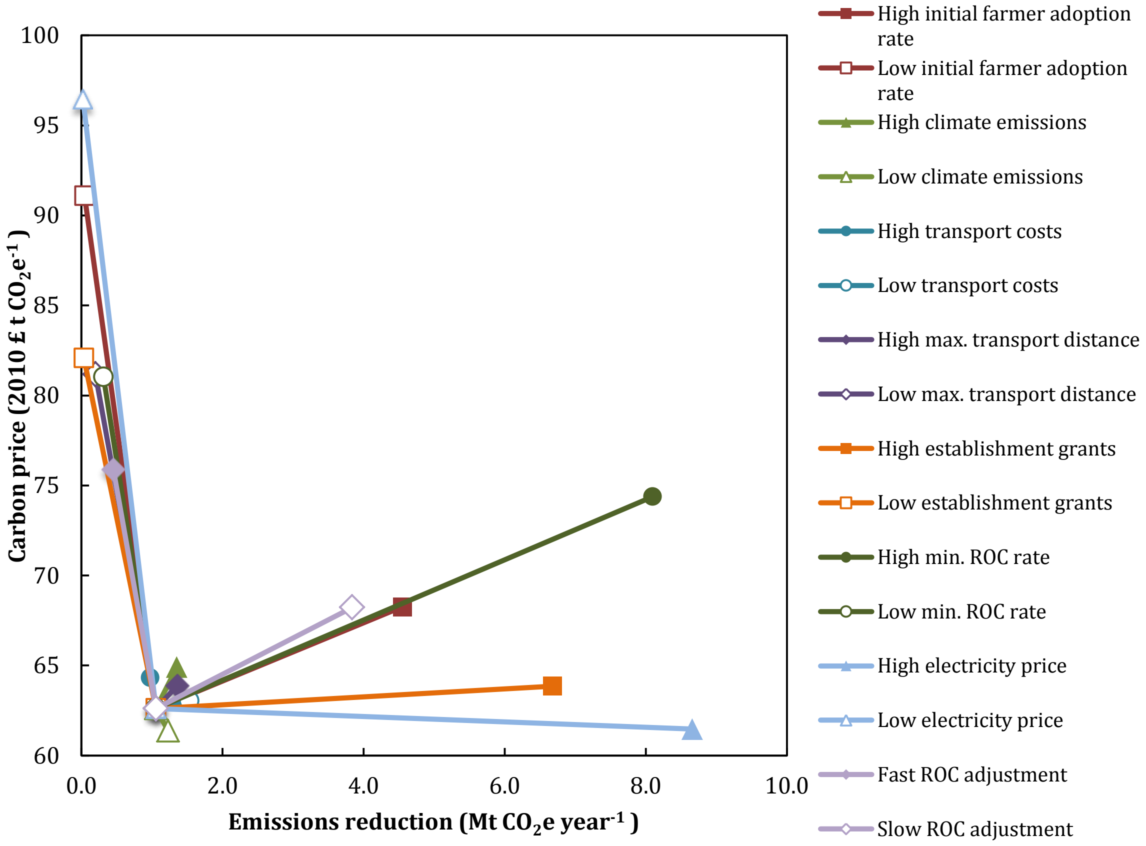

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