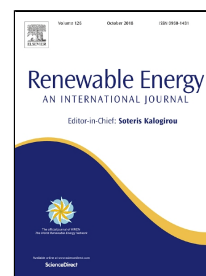


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Incentivising Bioenergy Production: Economic and Environmental Insights from a Regional Optimization Methodology

Şebnem Yılmaz Balaman, James Scott, Aristides Matopoulos, Daniel G. Wright



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29 **Keywords:** Renewable energy; Bioenergy; Financial incentives; Policy making; Optimization;  
30 United Kingdom

## 31 1. Introduction

32 Although bioenergy constitutes an important part of the European Commission's policy  
33 plans for energy such as the Biomass Action Plan (European Commission, 2005) and the  
34 Energy Policy for Europe (European Commission, 2007), there are still some difficulties  
35 hindering the wide spread adoption of these technologies, especially in developed countries,  
36 which include institutional deficiencies, the absence of necessary legal frameworks, economies  
37 of scale, pricing distortions, and limited information on resource base (Elkarmi and Shikhah,  
38 2013). To override such hurdles, government's policy support is highly needed and considered  
39 as the key to moving commercial renewable energy projects development forward. As bio-  
40 based fuel and energy generation is becoming increasingly important, there is a foreseeable  
41 scenario of competition between the emerging renewable energy sector and the traditional  
42 fossil-based energy production throughout the world. In decentralized energy markets, firms  
43 are mainly focused on maximizing their profits while competing with other firms. Investments  
44 in cheap and often polluting technologies tend to serve these goals well. This is in conflict with  
45 the goals set by governments as they aim at reducing pollution and want therefore to create  
46 financial incentives to make investments in cleaner technologies more attractive (Gürkan and  
47 Langestraat, 2014). Financial incentives help in supporting the development of commercial  
48 markets and in reducing the financial life-cycle costs of renewable energy technologies  
49 (Elkarmi and Shikhah, 2013).

50 As such, and as part of the wider EU Climate and Energy package, the UK has agreed a  
51 binding legal commitment to deliver 15% of energy from renewable sources by 2020 (Leete et  
52 al., 2013). In response to international concern surrounding the impacts of climate change, the

53 UK government has committed to ambitious carbon emission reduction targets of 34% by 2020,  
54 and at least 80% by 2050 (HM Government, 2009). To achieve these targets, it is estimated that  
55 30% of UK electricity will need to be generated from renewable sources by 2020 (HM  
56 Government, 2011). In the UK electricity market, since 2002, generators have been obliged to  
57 produce part of their electricity with renewable energy resources in accordance with the  
58 Renewable Obligation Order (Gürkan and Langestraat, 2014).

59 The literature has acknowledged that reduction of uncertainties and risks related to economic  
60 factors, such as fluctuating market prices, supply and demand, by incentive schemes is central  
61 to successful renewable energy implementations (Klessmann et al., 2013). Hence it is important  
62 to analyse the effects of different incentive schemes on the performance of renewable energy  
63 production systems and supply chains. Researches have contributed to the literature by studying  
64 on the role of incentives to promote investments in renewable energy sector in different parts  
65 of the world. Among them, Leete et al. (2013) emphasized that deployment of marine renewable  
66 energy in the UK is desirable in order to address climate change, meet mandatory EU renewable  
67 energy targets and provide significant economic development opportunities. By focussing on  
68 investor attitudes and behaviours towards wave and tidal technologies, their research seeks to  
69 identify common barriers and incentives to investment through a series of interviews. Elkarmi  
70 and Shikhah (2013) studied the effect of introducing financial incentives, such as tax reduction,  
71 introduction of a grace period, provision of capital or reduced discount rate, reduced  
72 depreciation life of assets, and the usage of accelerated depreciation methods, to promote green  
73 electricity generation in Jordan. Mola-Yudego and Pelkonen (2008) analysed the effect of  
74 policy incentives in the development of short rotation willow plantations for bioenergy  
75 considering 56 municipalities in Sweden, by an aggregate adoption model based on sigmoidal  
76 curves. Chinese et al. (2014) introduced a biogas supply chain optimization model to analyse  
77 the effects of the previous and current support schemes on the optimal plant size, feedstock mix

78 and profitability. Ibanez-Lopez et al. (2017) used dynamic simulation to assess the overall  
79 technical, economic and environmental impact of renewable energy incentives and capacity  
80 payment policies. Spain's power industry is simulated to assess the impact of electric power  
81 policies. Gürkan and Langestraat (2014) analysed three renewable obligation policies  
82 representing UK electricity market with random availabilities and random electricity demand  
83 by mathematical modelling. They also provided revenue adequate pricing schemes for the three  
84 obligation policies. Connor et al. (2015) discussed the adoption and development of renewable  
85 heating policy in the UK focusing on the historical and ongoing policies applied to the support  
86 of renewable energy sources of heat in the UK. Devine et al. (2017) presented a simulation-  
87 based modelling framework to incorporate consideration of policymaker/consumer risk burden  
88 in FiT analyses. They conducted an Irish case study and concluded that commonly employed  
89 FiT are only optimal when policymaker risk aversion is extremely low. Ritter and Deckert  
90 (2017) presented a wind energy index to assess the wind energy potential of locations in  
91 Germany, to compare different turbine types, and to derive the required compensation in terms  
92 of locally different FiTs.

93 The review of the literature reveals that there are very few studies that analyse and assess  
94 the impacts of the main incentives on the performance of production systems and supply chains  
95 in bioenergy sector in the UK using an analytical tool. The core driver of this study is to evaluate  
96 the potential effects of the incentive policy changes on bioenergy projects in the UK. To this  
97 aim, a methodology based on fuzzy multi-objective mathematical programming is used to  
98 model the bioenergy supply chain with the purpose of analysing and comparing the impacts of  
99 changes in the main incentive schemes on the economic and environmental performance of  
100 bioenergy generation from multiple types of biomass sources. An analysis on three different  
101 incentive schemes, applied in UK to promote renewable energy investments, is conducted to  
102 investigate which of them have the largest effect on the supply chain performance indicators.

103 This study contributes to the related literature by addressing the three main incentive schemes  
104 that are applied to promote renewable energy in the UK and analysing the effects of these  
105 incentive schemes on the economic and environmental performance of the bioenergy  
106 production chain using a mathematical modelling based analytic methodology, for the first time  
107 in the literature. The computational experiments are performed using the UK region of West  
108 Midland as a case study.

109 Although it is one of the most effective solution approaches to solve multiobjective  
110 optimization problems under an uncertain environment allowing prioritization of different  
111 objectives according to decision makers' preferences, fuzzy multi objective programming is  
112 rarely used in bioenergy supply chain design studies. Integration of fuzzy set theory with multi-  
113 objective linear programming provides further contributions besides reflecting uncertainties in  
114 the model parameters directly into the optimization processes. Firstly, the variation or  
115 vagueness of the decision maker's aspiration level can be incorporated to the model and thus a  
116 more confident solution set can be generated. Also, the solution procedure of fuzzy multi  
117 objective programming is simplified when compared with deterministic multi-objective  
118 programming as the fuzzy multi objective programming does not have to search for the  
119 satisfactory solution in a set of non-inferior solutions by distance based criteria, as required by  
120 the conventional solution procedure of multi-objective programming (Chang & Wang,1997).

121 The methodology in this study captures uncertainties in the system parameters as well as  
122 economic and environmental sustainability aspects by incorporating fuzzy decision making and  
123 multi-objective optimization in the same framework. This paper also proposes a modelling  
124 approach that covers multiple types of biomass, biomass to energy conversion technologies,  
125 biomass pre-processing facilities and bio-products. On that sense, the model is generalizable,  
126 the decision makers can utilize our model for different cases with only updating the data set.  
127 However, this paper uses the proposed optimization methodology to monitor the impacts of

128 changes in the main incentive schemes, applied in the UK to promote renewable energy  
129 investments, on economic and environmental performance of the production chain focusing on  
130 three different performance criteria (profitability, investment costs and GHG emissions).  
131 However, the proposed methodology, which enhances capital investment and logistics planning  
132 decisions for renewable energy systems, can be utilized both to support the development of new  
133 investments by identifying the optimal configuration of the supply chain and planning the  
134 logistics operations and to monitor the main economic and environmental performance  
135 indicators of the existing systems and take the necessary actions for improved performance.

## 136 **2. Main financial incentive schemes to promote renewable energy in the UK**

137 Financial incentive schemes can help in encouraging investments in less developed  
138 technologies as to make them more competitive in the long run. Three incentive schemes for  
139 electricity, heat and fuel production from renewables have been applied to promote renewable  
140 energy sector in the UK, namely Feed-in Tariff (FiT), Renewable Heat Incentive (RHI) and  
141 Renewables Obligation Certificate (RoC) (DECC, 2015).

142 Renewable energy investments are risky initiatives due to the uncertain nature of many  
143 renewable energy sources that causes variability in supply and in market prices. FiT, is  
144 introduced as a mechanism to promote investments in energy production using renewable  
145 sources by offering long-term contracts, considering the cost of energy generation by renewable  
146 sources based production technology, to renewable energy producers. The mechanism aims at  
147 promoting greater deployment of renewable technologies and supporting competitiveness with  
148 fossil fuel based energy systems by guaranteeing a minimum payment per unit of electricity  
149 generated to reduce investors' vulnerability to uncertain market prices and demand. Although  
150 it has been asserted that it is theoretically less efficient than quantity-based schemes (Ringel,  
151 2006), FiT has become a preferred policy mechanism which have been adopted and

152 implemented by more than 75 countries, states, and provinces (Eyraud et al., 2011).

153 The main sources of renewable heat generation in the UK in 2010 were direct biomass  
154 combustion (nearly 90% of the total renewable heat generated in the UK), active solar thermal  
155 systems (8%), and heat pumps (2%) (DECC, 2014). In April 2014 the UK's Department of  
156 Energy and Climate Change (DECC) launched the domestic RHI (DECC, 2014), with the claim  
157 that it is "the world's first long-term financial support programme for renewable heat, offering  
158 home-owners payments to offset the cost of installing low carbon systems" (Snape et al., 2015).  
159 The RHI tariffs are "set to compensate householders for the additional costs of installing  
160 renewable heat technologies compared to conventional heating technologies" (DECC, 2013b).  
161 The renewable heat incentive (RHI) is a financial incentive that aims at encouraging uptake of  
162 renewable heat technologies in the UK (Energy Saving Trust, 2012b). The UK government  
163 projected that the RHI will contribute to ensure that 12% of the heating will come from  
164 renewable sources by 2020 (DECC, 2011). This scheme covers a number of heat technologies  
165 namely biomass boiler, heatpump, solar thermal system and biomethane and biogas combustion  
166 (DECC, 2011).

167 Initially, the RHI only covers the non-domestic installation of renewable heat technologies  
168 (DECC, 2011). However, the government proposed to include financial payment for the  
169 deployment of these technologies for domestic usage (Phase 2 of the RHI) to promote more  
170 uptakes in the household sector following a consultation in September 2012 (DECC, 2012b).  
171 Similar to the FiT scheme, the RHI will guarantee a fixed payment per kWh of heat generated  
172 by a renewable heat technology for a particular contract duration. For the domestic installation,  
173 the government proposed a rate of £0.0173 per kWh paid for a contract period of 7 years  
174 (DECC, 2012b). The scheme has been commenced in spring 2014. The RHI rate is index-linked  
175 and the yearly rate will be determined in proportion to the change in the Retail Price Index  
176 (RPI) of the previous year (DECC, 2011), e.g. if the RPI is 3%, the RHI rate per kWh for that



177 year will be increased by 3%.The government projected that by 2020, the domestic sector will  
178 contribute approximately 3.3TWh annually with a projected number of installations totalling to  
179 roughly 380,000 (DECC, 2012b).

180 One way of creating incentives is by means of a renewable energy obligation. This is a  
181 target on the proportion of electricity that should come from renewable resources and is  
182 imposed on one group of operators in the market. In several US states and in European countries  
183 like Belgium, Poland, Romania, Sweden, Italy, and UK, a renewable obligation is in effect  
184 (Allan et al., 2011). The Renewables Obligation (RO) is the UK's central mechanism for the  
185 financial support of renewable electricity sources. It does not provide direct support for RES-  
186 H but since it does support electrical production from biomass, Combined Heat and Power  
187 (CHP) systems are effectively subsidised, potentially accelerating deployment. Changes to the  
188 RO mean that biomass-fired CHP receives higher subsidies than systems without CHP for their  
189 electrical generation (Ofgem, 2013). Clearly, the application of this form of support for  
190 electrical generation using biomass also drives competition for biomass resource. The RO will  
191 be phased out over the period 2014-2017 in favour of Contracts for Difference, a mechanism  
192 aiming to operate with similarities to a FiT (DECC, 2011).

193 Table 1 provides summarized information on these schemes. For more detailed information  
194 on current values of incentives according to different renewable energy technologies, the  
195 references given in Table 1 can be utilized.

196 **Table 1. Renewable energy support and incentive schemes in UK (Ang et al., 2016).**

197

### 198 **3. Methodology**

#### 199 **3.1. Fuzzy Multi Objective Decision Making Procedure**

200 In this section, the fuzzy multi-objective decision making methodology, which is adapted to  
201 solve the multi-objective mathematical model, is explained. The solution methodology

202 combines fuzzy set theory and  $\varepsilon$ -constraint methods, more specifically  $\varepsilon$ -constraint method is  
203 extended by integrating fuzzy logic.

204  $\varepsilon$ -constraint method is one of the most widely used and well-organized techniques to handle  
205 the multi-objective structure of complex problems (Haimes et al.,1971). The method is aimed  
206 to minimize only one objective function (commonly, it may be the most preferred or primary  
207 one) and to limit the others by some allowable values  $\varepsilon_i, i \in \{1, \dots, m\}$ , and in this way,  
208 transforming the multi-objective optimization problem into a single-objective problem. For  
209 more detailed information on the  $\varepsilon$ -constraint method Mavrotas (2009) can be referred.

210 In this paper a modified version of the  $\varepsilon$ -constraint method (Yılmaz Balaman, 2016) is used  
211 to address uncertainty in the system parameters and different sustainability aspects in the same  
212 framework by combining the method with fuzzy set theory. The modified  $\varepsilon$ -constraint method  
213 for the proposed problem is described as the following steps.

#### 214 ***Step 1. Develop the linear programming model of the problem***

215 In this step, the mathematical formulation of the optimization model is proposed. The notations  
216 of the mathematical formulations are presented in Appendix A. A multi-objective model is  
217 proposed to reflect the multidimensional nature of the renewable energy supply chain  
218 optimization problem under concern. The model includes three objectives representing the  
219 economic and environmental performance of the supply chain. The formulation regarding to  
220 these objectives are presented in the following.

221 The first objective function, namely maximization of supply chain profit, comprises revenue  
222 and cost elements. Each revenue and cost element is formulated in the following equations.  
223 Formulation of the total revenue represents the revenues from product, by-product and energy  
224 sales. To determine the revenue from biofuel and bioenergy sales and analyse the impact of

225 changes in different incentive schemes on the economic and environmental performance of the  
 226 supply chain, the unit sale prices of biofuel and bioenergy are divided into two elements; base  
 227 prices and the values of incentives based on the type of biofuel/bioenergy sold, type of  
 228 production technology and type of incentive. The sum of these two elements gives unit sale  
 229 prices. The formulations contain operational costs (comprising variable and fixed costs),  
 230 transportation costs, biomass purchasing cost and auxiliary material cost, respectively. Variable  
 231 operational costs are dependent on the quantity of material to be processed in energy  
 232 production, pre-processing and CHP plants, whereas fixed operational costs are calculated  
 233 based on the capacity of energy production, pre-processing and CHP plants. Variable  
 234 transportation costs are distance dependent, while fixed transportation costs are calculated  
 235 based on the quantity of material to be transported between locations. The first objective  
 236 function can be calculated as follows;

$$\text{Max } Z_1 = \left[ \text{Total Revenue} - \left( \begin{array}{l} \text{Operational Cost} + \text{Transportation Cost} \\ + \text{Biomass Purchasing Cost} + \text{Water Cost} \end{array} \right) \right] \quad (1)$$

$$\text{Total Revenue} = \left[ \left( \sum_{k=1}^K \sum_{l=1}^L \sum_{t=1}^T \sum_{u=1}^U SP_{tu}^{kl} \cdot \left( PB_{ut} + \sum_{v=1}^V PI_{vut} \right) \right) + \left( \sum_{k=1}^K \sum_{l=1}^L \sum_{t=1}^T \sum_{f=1}^F SBP_{tf}^{kl} \cdot P_{ft} \right) + \right. \\ \left. \left( \sum_{k=1}^K \sum_{l=1}^L \sum_{n=1}^N \sum_{t=1}^T SE_{tn}^{kl} \cdot \left( PB_{nt} + \sum_{v=1}^V PI_{vnt} \right) \right) \right]$$

$$\text{Operational Cost} = \left[ \left( \sum_{j=1}^J \sum_{e=1}^E \sum_{c=1}^C VO_{ec} \cdot \left( \sum_{i=1}^I \sum_{b=1}^B S_{cb}^{ij} \right) \right) + \left( \sum_{k=1}^K \sum_{p=1}^P \sum_{t=1}^T VO_{pt} \cdot \left( \sum_{j=1}^J \sum_{b=1}^B S_{tb}^{jk} \right) \right) \right] \\ + \left( \sum_{q=1}^Q \sum_{t=1}^T VO_{CHP_q} \cdot \left( \sum_{k=1}^K \sum_{n=1}^N E_{tn}^k \right) \right)$$

$$+ \left( \sum_{j=1}^J \sum_{e=1}^E \sum_{c=1}^C FO_{ec} \cdot C2_{ec} \cdot B_{ec}^j \right) + \left( \sum_{k=1}^K \sum_{p=1}^P \sum_{t=1}^T FO_{pt} \cdot C1_{pt} \cdot A_{pt}^k \right) \\ + \left( \sum_{k=1}^K \sum_{q=1}^Q \sum_{n=1}^N FO_{CHP_q} \cdot CE_{qn} \cdot CHP_q^k \right)$$

$$\begin{aligned}
\text{Transportation Cost} = & \left[ \sum_{b=1}^B TV_b \cdot \left( \sum_{i=1}^I \sum_{j=1}^J d^{ij} \cdot \left( \sum_{c=1}^C S_{cb}^{ij} \right) \right) \right. \\
& \left. + \sum_{b=1}^B TV_b \cdot \left( \sum_{j=1}^J \sum_{k=1}^K d^{jk} \cdot \left( \sum_{t=1}^T S_{tb}^{jk} \right) \right) + \sum_{f=1}^F TV_f \cdot \left( \sum_{k=1}^K \sum_{l=1}^L d^{kl} \cdot \left( \sum_{t=1}^T SBP_{f}^{kl} \right) \right) \right] \\
& + \left[ \sum_{b=1}^B TF_b \cdot \left( \sum_{i=1}^I \sum_{j=1}^J \sum_{c=1}^C S_{cb}^{ij} \right) + \sum_{b=1}^B TF_b \cdot \left( \sum_{j=1}^J \sum_{k=1}^K \sum_{t=1}^T S_{tb}^{jk} \right) \right] \\
& + \left[ \sum_{f=1}^F TF_f \cdot \left( \sum_{k=1}^K \sum_{l=1}^L \sum_{t=1}^T SBP_{f}^{kl} \right) \right]
\end{aligned}$$

$$\text{Biomass Purchasing Cost} = \left[ \sum_{i=1}^I \sum_{j=1}^J \sum_{c=1}^C \sum_{b=1}^B P_b \cdot S_{cb}^{ij} \right]$$

$$\text{Auxiliary Material Cost} = \left( \sum_{k=1}^K W^k \cdot PW \right)$$

237 Eq. 2 shows the second objective function, namely minimization of total capital investment  
238 cost. Total capital investment cost is the sum of investment cost of biomass pre-processing  
239 facilities, investment cost of bioenergy plants and investment cost of CHP units, which are  
240 respectively shown in brackets.

$$\text{Min } Z_2 = \left( \sum_{j=1}^J \sum_{e=1}^E \sum_{c=1}^C I_{ec} \cdot C_{ec} \cdot B_{ec}^j \right) + \left( \sum_{k=1}^K \sum_{p=1}^P \sum_{t=1}^T I_{pt} \cdot C_{pt} \cdot A_{pt}^k \right) + \left( \sum_{k=1}^K \sum_{q=1}^Q I_{CHP_q} \cdot CE_{qn} \cdot CHP_q^k \right) \quad (2)$$

241 Eq. 3 shows the third objective function, namely minimization of GHG emissions associated  
242 with energy production, pre-processing and transportation activities. Transportation related  
243 GHG emissions comprise two components; (1) emissions caused by transportation vehicle  
244 which depends on the type and capacity of vehicle and transportation distance, (2) emissions  
245 related to the material to be transported which is related to the distance between locations and  
246 the quantity and type of material to be transported between locations.

$$\text{Min } Z_3 = GHG_{\text{Energy Production}} + GHG_{\text{Pre-Processing}} + GHG_{\text{Transportation}} \quad (3)$$

$$GHG_{\text{Energy Production}} = \left( \sum_{k=1}^K \sum_{t=1}^T \left( \sum_{n=1}^N g_t \cdot E_{tn}^k \right) \right)$$

$$GHG_{\text{Energy Production}} = \left( \sum_{i=1}^I \sum_{j=1}^J \left( \sum_{c=1}^C \sum_{b=1}^B g_c \cdot S_{cb}^{ij} \cdot d_{bc} \right) \right)$$

$$GHG_{\text{Transportation}} =$$

$$\left( g \cdot 2 \cdot d^{ij} \cdot \left( \sum_{c=1}^C \sum_{b=1}^B S_{cb}^{ij} / CT \right) \right) + \left( \sum_{b=1}^B g t_b \cdot \left( \left( \sum_{i=1}^I \sum_{j=1}^J d^{ij} \cdot \sum_{c=1}^C S_{cb}^{ij} \right) + \left( \sum_{j=1}^J \sum_{k=1}^K d^{jk} \cdot \sum_{t=1}^T S_{tb}^{jk} \right) \right) \right) \\ + \left( g \cdot 2 \cdot d^{kl} \cdot \left( \sum_{t=1}^T \sum_{f=1}^F SBP_{tf}^{kl} / CT \right) \right) + \left( \sum_{f=1}^F g t_f \cdot \left( \sum_{k=1}^K \sum_{l=1}^L d^{kl} \cdot \sum_{t=1}^T SBP_{tf}^{kl} \right) \right)$$

247

248 Eqs. 4-20 represent the constraints of the model.

249 *Supply*: Eq. 4 restricts the biomass procurement amount from a supply region by the total  
250 available biomass in that region.

$$\sum_{c=1}^C \sum_{j=1}^J S_{cb}^{ij} \leq BS_b^i \quad \forall i, \forall b \quad (4)$$

251 *Material Flow*: Eq. 5 ensures the flow balance of the biomass supplied from biomass source  
252 site to pre-treatment/storage facility and from facility to biomass to biofuel conversion plant  
253 considering the conversion rate of biomass in the pre-treatment process.

$$\sum_{i=1}^I \sum_{c=1}^C S_{cb}^{ij} \cdot d_{bc} = \sum_{k=1}^K \sum_{t=1}^T S_{tb}^{jk} \quad \forall j, \forall b \quad (5)$$

254 *Capacity*: Eqs. 6 and 7 limit the amount of biomass transported to the facilities and plants to  
255 the maximum capacity of the corresponding capacity levels of plants/facilities. Eq. 8 restricts

256 the amount of energy produced in energy plants to the maximum capacity of the corresponding  
 257 capacity levels of these plants.

258

$$\sum_{j=1}^J \sum_{b=1}^B S_{tb}^{jk} \leq \sum_{p=1}^P A_{pt}^k \cdot C_{pt} \quad \forall k, \forall t \quad (6)$$

$$\sum_{i=1}^I \sum_{b=1}^B S_{cb}^{ij} \leq \sum_{e=1}^E B_{ec}^j \cdot C_{ec} \quad \forall j, \forall c \quad (7)$$

$$\sum_{t=1}^T E_{tn}^k \leq \sum_{q=1}^Q CHP_q^k \cdot CE_{qn} \quad \forall k, \forall n \quad (8)$$

259 *Production and Distribution:* Eqs. 9 and 10 calculate the amount of biofuel produced in and  
 260 distributed from the biomass conversion plants. In Eq. 9, the biofuel production amount is  
 261 determined based on biomass to biofuel conversion rate for each type of biomass resource. In  
 262 Eq. 10 the amount of product to be distributed without converting to energy is determined based  
 263 on the percentage of product to be converted to energy (%). Eqs. 11 and 12 calculate the amount  
 264 of digestate produced in and distributed from the biomass conversion plants. In Eq. 11, the by-  
 265 product production amount is determined based on biomass to by-product conversion rate for  
 266 each type of biomass resource. Eq. 13 calculates the amount of energy produced in energy  
 267 plants considering the percentage of product to be converted to energy, biofuel to energy  
 268 conversion rate for each type of biofuel and Conversion efficiency of cogeneration unit. Eq. 14  
 269 ensures that all produced energy is distributed.

$$\sum_{j=1}^J \sum_{b=1}^B S_{tb}^{jk} \cdot r_{but} = PR_{ut}^k \quad \forall k, \forall u, \forall t \quad (9)$$

$$PR_{ut}^k \cdot \left( 1 - \sum_{n=1}^N y_{tun}^k \right) = \sum_{l=1}^L SP_{tu}^{kl} \quad \forall k, \forall u, \forall t \quad (10)$$

$$\sum_{j=1}^J \sum_{b=1}^B S_{tb}^{jk} \cdot r_{bft} = BP_{kft} \quad \forall k, \forall f, \forall t \quad (11)$$

$$BP_{kft} = \sum_{l=1}^L SBP_{ft}^{kl} \quad \forall k, \forall f, \forall t \quad (12)$$

$$\sum_{t=1}^T \sum_{u=1}^U PR_{ut}^k \cdot y_{tun}^k \cdot e_{un} \cdot cv_n = E_{tn}^k \quad \forall k, \forall n \quad (13)$$

$$E_{tn}^k = \sum_{l=1}^L SE_{tn}^{kl} \quad \forall k, \forall t, \forall n \quad (14)$$

270 *Demand:* Eq. 15 limits the digestate distribution amount by the corresponding demand in the  
 271 demand nodes (to prevent the disposal of the excess digestate). Eq. 16 ensures that all the  
 272 biofuel demand of the demand nodes is fulfilled. Eq. 17 ensures that energy demands of all  
 273 demand nodes are fulfilled.

$$\sum_{k=1}^K \sum_{t=1}^T SBP_{ft}^{kl} \leq D_f^l \quad \forall l, \forall f \quad (15)$$

$$\sum_{k=1}^K \sum_{t=1}^T SP_{tu}^{kl} \geq D_u^l \quad \forall l, \forall u \quad (16)$$

$$\sum_{k=1}^K \sum_{t=1}^T SE_n^{kl} \geq D_n^l \quad \forall l, \forall n \quad (17)$$

274

## 275 **Step 2. Convert problem P into problem P<sub>0</sub>**

276 The linear programming problem developed in Step 1 is transformed into problem represented  
 277 by below formulations according to the basic principles of the  $\epsilon$ -constraint method. In P<sub>0</sub>, the  
 278 objective function is corresponding to Z<sub>1</sub> of P, and Z<sub>2</sub> and Z<sub>3</sub> of P is dealt with as a constraint  
 279 of P<sub>0</sub>. Problem P<sub>0</sub> can be represented as follows:

$$\begin{aligned}
& \text{Max } Z_1(x) \\
& \text{st } Z_2(x) \leq \varepsilon_2, \\
& \quad Z_3(x) \leq \varepsilon_3, \\
& \text{and other constraints}
\end{aligned} \tag{18}$$

280 **Step 3. Construct the payoff table and determine  $\varepsilon_2$  and  $\varepsilon_3$**

281 To solve problem  $P_0$ , we need to determine  $\varepsilon_2$  and  $\varepsilon_3$  (upper bound for the second and third  
282 objective functions) that is limited by the range of objective functions  $f_2$  and  $f_3$ . To obtain the  
283 appropriate ranges of  $f_2$  and  $f_3$ , developed multi objective model is solved as a single objective  
284 problem using each time only one objective and ignore the others to specify the efficient  
285 solutions (i.e. upper bound, expected value and lower bound) for  $f_2$  and  $f_3$ . For this purpose, a  
286 fuzzy logic based procedure is utilized and the problem is divided into sub problems. Each time,  
287 one of the upper, lower and expected values of the fuzzy parameters are taken into consideration  
288 and sub problems are solved according to one of the objective functions. For this purpose, a  
289 scenario based approach developed by Yılmaz Balaman (2016) is utilized in this study. The  
290 problem is divided into nine sub problems (SP) based on a scenario approach. Scenarios  
291 represent the best, expected and worst situations for three objective functions, which are  
292 constructed by taking into consideration the upper, lower and expected values of the fuzzy  
293 parameters. After constructing the scenarios, the model is solved according to one of the profit  
294 maximization, investment cost minimization or GHG emissions minimization objectives under  
295 three scenarios and the corresponding value for each objective function at each solution is  
296 determined. Based on the findings, the payoff table, which is an asymmetric matrix where the  
297 matrix elements represent the optimum values of the corresponding objective function, is  
298 constructed. The lower, upper and expected values of each objective function are determined  
299 based on the payoff table.

300



301 **Step 4. Obtain a set of pareto optimal solutions and calculate the membership function values**

302 Solve the problem  $P_0$  with different values of  $\varepsilon_2$  and  $\varepsilon_3$  (i.e. upper, expected and lower values  
 303 from the payoff table), and finally, obtain a set of pareto optimal solutions. After a set of pareto  
 304 optimal solutions are obtained, a decision maker may wish to select a preferred one from them  
 305 and may also want to know its degree of optimality. The fuzzy logic based approach (Esmaili  
 306 et al., 2011) can both provide a most preferred solution and also indicate its degree of  
 307 optimality. This approach utilizes membership functions which are used to formulate fuzzy  
 308 numbers depending on the problem specific characteristics. Lai & Hwang (1994) stated that,  
 309 the grade of a membership function indicates a subjective degree of satisfaction within given  
 310 tolerances. A membership function, usually denoted by “ $\mu$ ”, associates each point in a fuzzy set  
 311  $F$  with a real number in the closed interval  $[0, 1]$ . It indicates the grade of membership of an  
 312 element in a fuzzy set  $F$ . Thus, the nearer the value of membership function to unity, the higher  
 313 the grade of membership of an element in a fuzzy set  $F$ . A membership function can be viewed  
 314 as an quantification of the ambiguity of set  $F$ .

315 In this paper, the fuzzy logic based approach (Esmaili et al., 2011) is applied to assist in  
 316 choosing a preferred solution. In the m-objective optimization problem with  $k$  pareto optimal  
 317 solutions, the membership function  $\mu_i^k$  indicates the degree of optimality for the  $i$ th objective  
 318 function in the  $k$ th solution. It is defined as follows;

319 **1. In the case of objective functions being minimized;**

$$\mu_i^k = \begin{cases} 1 & ; f_i^k(x) \leq l_i \\ \frac{u_i - f_i^k(x)}{u_i - l_i} & ; l_i < f_i^k(x) \leq u_i \\ 0 & ; f_i^k(x) > u_i \end{cases} \quad (19)$$

320 **2. In the case of objective functions being maximized;**

$$\mu_i^k = \begin{cases} 1 & ; f_i^k(x) > u_i \\ \frac{f_i^k(x) - l_i}{u_i - l_i} & ; l_i < f_i^k(x) \leq u_i \\ 0 & ; f_i^k(x) < l_i \end{cases} \quad (20)$$

321 where  $l_i$  and  $u_i$  denote the lower and upper limits of objective function  $f_i$  of  $P$ , respectively, and  
 322  $f_i^k(x)$  represents the value of the  $i$ th objective function in the  $k$ th pareto optimal solution, such  
 323 that  $f_i^k(x) \in [l_i, u_i]$ .

### 324 **Step 5. Find the most preferred solution**

325 If a decision maker offers a preferred weight vector, which represents the relative importance  
 326 of each objective according to the decision maker's preferences, for the cost minimization and  
 327 emission minimization objectives, for each solution  $k$ , the membership degree  $\mu^k$  is calculated  
 328 based on its individual membership functions by adding weight factors as follows:

$$\mu^k = \frac{\sum_{i=1}^m w_i \cdot \mu_i^k}{\sum_{i=1}^m w_i} \quad (21)$$

329 The solution with the maximum value of  $\mu_i^k$  is selected as the most preferred solution.

### 330 **3.2. Case Study**

331 To explore the impacts of the main incentive schemes on the economic and environmental  
 332 performance of bioenergy supply chains, computational experiments are performed for the WM  
 333 region in the UK using the proposed optimization methodology. To this aim, seven regions in  
 334 the WM, namely Birmingham, Coventry, Solihull, Sandwell, Walsall, Wolverhampton and  
 335 Dudley, are considered to design a comprehensive supply chain. Four types of biowaste (cattle  
 336 manure, laying chicken manure, broiler chicken manure, waste wood) and one energy crop

337 (maize) are assumed to be the potential biomass inputs. The existing yields and geographic  
338 distribution data on biowaste from husbandry are adopted from UK Department for  
339 Environment, Food & Rural Affairs (DEFRA) - farming statistics (DEFRA, 2015). Data on  
340 maize yields and geographical distribution of the maize fields are gathered from DEFRA -  
341 annual statistics on the structure of the agricultural industry (2015).

342 We consider meeting the corresponding biomethane, electricity and heat demands in a  
343 particular area in each of the considered regions. The numbers of addresses in the area  
344 considered in each region are given in Table 2. Data on the demands came from DECC (2013)  
345 and DECC National Heat Map (2012). The map of the case study region is depicted in Figure  
346 1 with biomass source sites, demand nodes, and candidate locations for energy plants and  
347 facilities considered in this study.

348 **Figure 1. Case study region map.**

349  
350 Anaerobic digestion (AD) and gasification (G) technologies are considered to convert biomass  
351 into biofuel. AD is utilized to produce biofuel (biomethane) from organic wastes and maize, a  
352 proportion of which is converted into electrical and thermal energy in CHP engines. Biofuel  
353 (syngas) produced from waste wood by G is assumed to be transformed into electrical and  
354 thermal energy entirely by CHP engines. Collection and pre-treatment facilities to store, treat  
355 and distribute biomass are considered as pre-processing facilities. The potential locations for  
356 energy plants and facilities are chosen based on UK renewable energy planning database.

357 The electrical and thermal efficiency of the cogeneration units are taken as 33% and 43%  
358 (DECC, 2008). The conversion rate of wood to wood pellet is taken as 0.84 (Uslu et al.,2008).  
359 The generated electrical energy, thermal energy and biomethane are assumed to be fed into the  
360 national electricity distribution network, on-site heating system and natural gas pipeline

361 network. Three capacity levels are considered for the pre-processing facilities, biomass to  
362 biofuel conversion plants and CHP units. These capacity levels reported in Table 2.

363 **Table 2. Capacity levels of the plants.**

364

365 *Economic parameters:* Considering the incentives and the base prices, the ultimate prices for  
366 electricity, heat and biomethane are calculated for both AD and G. The data related to incentives  
367 are gathered from the sources depicted in Table 1 and the base prices are derived from Digest  
368 of UK Energy Statistics. Table 3 depicts the electricity, heat and biomethane prices calculated  
369 based on base prices and incentives.

370 **Table 3. Energy prices in the UK.**

371

372 DECC (2012) is utilized to obtain the data on plant investment and operational costs. The  
373 operational costs consist of fixed and variable costs, which are calculated based on the installed  
374 capacity and the amount biomass processed in the plants and facilities, respectively. The unit  
375 investment and operational costs according to capacity levels are reported in Table 4. Unit costs  
376 are computed considering monthly biomass capacity of the facilities and plants, and installed  
377 power of the CHP.

378 **Table 4. Unit investment costs per installed capacity depending on capacity levels.**

379

380 We consider that biomass feedstock is transported from source sites to facilities and from  
381 facilities to plants, and that biofertilizer is transported between plants and energy crop fields.  
382 Data on unit costs of transporting biomass and biofertilizer are derived from the literature and  
383 updated for the local conditions regarding the data gathered from local logistics firms.

384 *Environmental parameters:* Data on GHG emissions associated with wood pellet production in  
385 pretreatment facilities and bioenergy production in plants are depicted in Table 5. GHG

386 emissions from truck transportation is obtained as 0.692514 kg CO<sub>2</sub>-eq / km from DEFRA  
387 Carbon Conversion Factors Dataset (2015d). Data on the GHG emissions associated with  
388 transportation are derived from the literature. Table 6 lists the GHG emissions for transporting  
389 cattle manure, poultry manure, wood pellet, maize and biofertilizer by road transport.

390 **Table 5. Data on GHG emissions associated with production.**

391 **Table 6. Data on the GHG emissions associated with transportation.**

392

393 *Fuzzy parameters:* The following parameters, which may fluctuate due to changing conditions  
394 about governmental policies, competition between firms, biomass based production techniques  
395 and technologies as well as environmental conditions about weather, soil ...etc., are captured  
396 as fuzzy parameters in this study; (1) Energy prices, (2) Biomass yields, (3) Investment and  
397 operational costs, (4) Transportation costs, (5) Cost of biomass and auxiliary material, (6) Level  
398 of GHG emissions. To fuzzify these parameters, the coefficients corresponding to each of the  
399 above mentioned parameters are defined within a range in the model. To this aim, the lower  
400 and upper bounds for these coefficients are assumed to be 90% and 110% of their expected  
401 values. Expected values are the current values of parameters in the application time (given in  
402 the tables in Case Study section). These coefficients are utilized in the scenario based approach  
403 in the third step of the solution methodology to establish nine sub problems each represent the  
404 best, expected and worst situations for three objective functions, which are constructed by  
405 taking into consideration the upper, lower and expected values of the fuzzy parameters.

406

### 407 **3.3. Results and Discussion**

408 This section presents and analyses the results of our computational experiments focusing on  
409 the effects of the main incentive schemes on the performance of the regional supply chain  
410 designed by the optimization model. As stated previously, this paper utilizes the proposed  
411 optimization methodology to analyze the impacts of changes in three main incentive schemes,  
412 applied in the UK to promote renewable energy investments, on economic and environmental  
413 performance of the production chain. Hence the details about the modelling choices related to

414 the configuration of the regional supply chain and logistics planning decisions made by the  
415 optimization methodology are not given in this paper since it is not the main focus of this paper.  
416 However, they can be provided upon special request.

417 Further analyses are performed on three incentive schemes to reveal the impacts of their  
418 changes on profitability of the supply chain, total investment cost and GHG emissions obtained  
419 by configuring the supply chain designed and optimized by the developed model. To this aim,  
420 a sensitivity analysis is performed by considering a  $\pm 10\%$  change in the incentive values under  
421 three cases; optimistic, base and pessimistic case. In optimistic and pessimistic cases, the effects  
422 of 10% rise and 10% decrease in incentives on three performance measures are analyzed,  
423 respectively. As for the base case, the current values of the incentives are considered. Results  
424 of the analyses are presented in Table 7.

425 **Table 7. Results of the incentive analysis.**

426 *Effects of incentive schemes on the profitability*

427 Figure 2 a, b, and c illustrates the impact of the incentive schemes on the profitability of the  
428 supply chain. The results reveal that, the profitability of the supply chain is mostly affected by  
429 the change of RoC, which is followed by FiT, when the optimistic cases (10% increase in  
430 incentives) are considered. The increase of RoC and FiT values by 10% cause a rise in monthly  
431 profit by 17% and 15%, respectively, whereas the increase of RHI by 10% makes the least  
432 change on the profit increasing it by 10%. However, for pessimistic cases the impact pattern is  
433 different from the optimistic cases. In this case, the monthly profit is mostly affected by the  
434 change of RHI, and secondly RoC. The reductions in RHI and RoC values by 10% decrease the  
435 monthly profit by 13.5% and 10%, respectively. The decrease of FiT by 10% makes the least  
436 change on the profit reducing it by 7%. It can also be concluded that, improvements in the RoC  
437 scheme which lead increases in the RoC incentive values, will be for the benefit of investors

438 whose major consideration is the profitability of the biomass based energy systems and supply  
439 chains. On the other hand, in the case of a cut down on the incentives, e.g. in economic  
440 downturns, financial bottlenecks or economic crisis, the profitability of the biomass based  
441 energy supply chains will be mostly impacted by the reductions in RHI.

442 **Figure 2(a). The impact of the FiT on the profitability of the supply chain.**

443 **Figure 2(b). The impact of the RHI on the profitability of the supply chain.**

444 **Figure 2(c). The impact of the RoC on the profitability of the supply chain.**

445

446 *Effects of incentive schemes on total investment cost*

447 Figure 3 a, b, and c illustrates the impact of the incentive schemes on the total investment  
448 cost of the supply chain. The changes in the incentive schemes have a relatively smaller impact  
449 on the total investment cost of the supply chain in comparison with their impact on the profit.  
450 The total investment cost of the supply chain is not impacted by the increase in the incentive  
451 values, which means that the configuration of the supply chain optimized by our model does  
452 not change in case of an upward trend in the incentives. However, the investment cost is affected  
453 by the downward changes in the incentive schemes. RoC and FiT have the greatest effect on  
454 the investment cost, in which a decrease by 10% increases the investment cost by 1.7%.  
455 Whereas, the decrease in the RHI value by 10% increases the cost slightly, by 0.39%. It should  
456 be noted that, although these impact rates seem insignificant, they can create significant changes  
457 in the total investment cost of regional or multi-regional cases, in which the decision makers  
458 face with relatively large scale investment decision making problems. On the other hand, in  
459 local level design cases, e.g. designing a local supply chain for a single company for its own  
460 energy/biofuel production activities, the above mentioned impacts may not change the  
461 configuration decision.

462 **Figure 3(a). The impact of the FiT on the total investment cost of the supply chain.**

463 **Figure 3(b). The impact of the RHI on the total investment cost of the supply chain.**

464 **Figure 3(c). The impact of the RoC on the total investment cost of the supply chain.**

465

466 Effects of incentive schemes on the level of GHG emissions

467 Figure 4 a, b and c illustrates the impacts of the incentive schemes on the total GHG  
468 emissions of the supply chain. The level of GHG emissions by the transportation, energy  
469 production and biomass preprocessing activities in the supply chain designed by the developed  
470 model mostly impacted by the changes in the RoC scheme. A decrease in the RoC incentive by  
471 10% makes the amount of GHG emissions increase by 12.3%. However its increase by the same  
472 percentage does not affect the level of emissions as much as the case of decrease, the increase  
473 in RoC value by 10% decreases GHG emissions by 0.64%. The increases in FiT and RHI values  
474 has a negligible effect on the GHG emissions, their increase by 10% negligibly affects the  
475 amount of environmental emissions. The decrease in RHI value has an insignificant effect on  
476 the GHG emissions as well, it increases the emissions by 0.42%, whereas the decrease in FiT  
477 has a remarkable effect in comparison with that of RHI, 10% increase in FiT causes an increase  
478 with 11% in GHG emissions level. The results suggest that if the minimization of GHG  
479 emissions is a major consideration in the design phase, the incentive values do not have a critical  
480 importance for the decision maker. However, the lower incentive values cause a slight increase  
481 of GHG emissions associated with transportation, energy production and biomass treatment  
482 activities in the supply chain configured by the developed model. As it can be observed from  
483 the results, the model estimates that increases in the values of RoC and FiT incentives have  
484 negligible effect on the GHG emissions, whereas decreases in these incentives result in  
485 significant increase in GHG emissions. The main reason of this may be the model has a  
486 tendency to construct less energy plants and storage/pre-treatment facilities when the incentives



487 are low, which results in reduced production and transportation activities and hence less GHG  
488 emissions related with these activities. The decrease rate of the number of energy plants and  
489 storage/pre-treatment facilities that is determined by the model is higher when the incentives  
490 are low, in comparison with the increase rate of the number of energy plants and storage/pre-  
491 treatment facilities when the incentives are high.

492 **Figure 4(a). The impact of the FiT on the total investment cost of the supply chain.**

493 **Figure 4(b). The impact of the RHI on the total investment cost of the supply chain.**

494 **Figure 4(c). The impact of the RoC on the total investment cost of the supply chain.**

495

#### 496 **4. Conclusions and Policy Implications**

497 This study aims at analysing and evaluating the potential effects of the incentive policy changes  
498 on bioenergy projects in the UK. To this aim, a methodology based on fuzzy multi-objective  
499 mathematical programming is used to compare the main incentive schemes and to highlight the  
500 impacts of changes in these incentives on the economic and environmental performance of  
501 bioenergy production from multiple types of biomass sources. The methodology incorporates  
502 fuzzy decision making and multi-objective optimization, and captures uncertainties in the  
503 systems parameters as well as economic and environmental sustainability aspects. Three  
504 different incentive schemes (FiT, RHI and RoC), which are applied in the UK to promote  
505 renewable energy investments, are focused on to investigate which of them have the largest  
506 effect on the supply chain performance indicators.

507 It can be concluded that among three performance indicators (two economic and one  
508 environmental), profitability of the supply chain is the one that is mostly affected by the changes  
509 in the incentive policies. However, the incentive schemes that have the biggest effect on the  
510 profitability changes according to the upward and downward trends in the economic policies

511 which create optimistic and pessimistic cases in our analyses. The change in the RoC incentive  
512 value has the biggest effect on the total profit obtained from the supply chain if there is an  
513 upward trend in the economic policies on renewable energy systems. It should be concluded  
514 that, if profitability of the bioenergy systems is desired to be increased to encourage new  
515 investments in renewable energy sector, RoC incentives should be the first to be increased  
516 among these three schemes. For the cases of downward trend in economic policies (pessimistic  
517 case, i.e. reductions in incentives) in renewable energy, RHI is the scheme that has the biggest  
518 effect on the profitability of the chain. Hence, RHI values should be the last to be reduced in  
519 downward economic conjuncture (i.e. economic downturns, financial bottlenecks or economic  
520 crisis) to prevent losses in profitability of the existing investments.

521 In the case of an upward trend in economic policies that stimulate increase in incentive  
522 values, investment cost is the least impacted factor among three supply chain performance  
523 indicators. In this case, any increase in incentive values does not impact configuration of the  
524 supply chain (locations, numbers and capacities of bioenergy plants and pre-processing  
525 facilities), and hence investment costs. However, in downward economic conjuncture which  
526 may cause reductions in incentive values, the investment costs are mostly affected by the  
527 reductions RoC and FiT values. It should be concluded that, in this case RoC and FiT values  
528 should not be reduced significantly to not discourage new investments in renewable energy  
529 systems because of possible rises in the investment costs.

530 The results reveal that, environmental performance of the supply chain in terms of total  
531 GHG emissions is the least affected performance indicator by the changes in the incentive  
532 policies. If environmental performance of renewable energy systems is the most important  
533 consideration in policy making, incentive values in the scope of RoC scheme, should not be  
534 reduced significantly in cases of a downward trend in economic policies. According to the  
535 results, configuration of the supply chain optimized by the developed methodology results in

536 higher GHG emissions in case of lower RoC and FiT values in downwards economic  
537 conjuncture. However, the decrease in RHI value has an insignificant effect on the GHG  
538 emissions. In the case of an upward trend in economic policies, increases in all three incentive  
539 schemes have an insignificant impact on the level of GHG emissions.

540 By providing an understanding on the impacts of different incentive schemes on the  
541 performance criteria, this paper helps policy makers in determining which incentive schemes  
542 should be focused on (i.e. reduced, increased or remained constant) in downward and upward  
543 trends in economic policies that stimulate rises and decreases in incentive values, to support  
544 different economic and environmental supply chain performance criteria. The paper also  
545 supports decision makers in renewable energy investments on deciding how the performance  
546 of the system will be affected by the changes in different incentive schemes under different  
547 conditions in economic environment.

548 Although our case study handles a regional case in the UK to guide overall targets on  
549 incentive schemes related to bioenergy production, it is also possible to apply the same  
550 methodology for other cases in different countries to analyse the impacts of changes in incentive  
551 schemes on the supply chain performance criteria. Also, exchange rate assumptions would  
552 clearly affect the results. Future research may apply the proposed methodology to different  
553 cases with additional, case-specific constraints and parameters. The methodology can be easily  
554 adapted to other cases and scenarios to observe the impacts of incentive schemes applied in  
555 different countries on the performance of the supply chain using the same general framework.

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## 655 **Appendix. Notations used in the model**

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### *Indices*

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<i>i</i>	<i>Biomass source sites</i>
<i>j</i>	<i>Candidate locations for facilities</i>
<i>k</i>	<i>Candidate locations for energy plants</i>

$l$	<i>Demand nodes</i>
$b$	<i>Biomass types</i>
$u$	<i>Product types</i>
$f$	<i>Byproduct types</i>
$n$	<i>Energy type</i>
$v$	<i>Incentive type</i>
$p$	<i>Biomass capacity levels for energy plants</i>
$e$	<i>Biomass capacity levels for facilities</i>
$q$	<i>Electrical energy production capacity levels of CHP units</i>
$t$	<i>Energy conversion technology</i>
$c$	<i>Facility type</i>

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**Decision Variables**


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**1. Binary variables**


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$A_{pt}^k$	<i>1 if an energy plant of capacity <math>p</math> and technology <math>t</math> is located at <math>k</math>, 0 otherwise</i>
$B_{ec}^j$	<i>1 if a facility of capacity <math>e</math> and type <math>c</math> is located at <math>j</math>, 0 otherwise</i>
$CHP_q^k$	<i>1 if a CHP of capacity <math>q</math> is located in an energy plant at <math>k</math>, 0 otherwise</i>

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**2. Positive variables**


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$S_{cb}^{ij}, S_{tb}^{jk}$	<i>Amount of biomass <math>b</math> shipped from; biomass source site <math>i</math> to facility <math>j</math> with type <math>c</math>, facility <math>j</math> to energy plant <math>k</math> with technology <math>t</math> (ton)</i>
$SP_{tu}^{kl}$	<i>Amount of product <math>u</math> produced in energy plant <math>k</math> with technology <math>t</math> to meet demand of node <math>l</math> (<math>m^3</math>)</i>
$SBP_{tf}^{kl}$	<i>Amount of byproduct <math>f</math> distributed from energy plant <math>k</math> with technology <math>t</math> to demand node <math>l</math> (ton)</i>
$SE_{in}^{kl}$	<i>Amount of energy <math>n</math> produced in plant <math>k</math> with technology <math>t</math> to meet demand of node <math>l</math> (kWh)</i>
$PR_{tu}^k$	<i>Amount of product <math>u</math> produced at energy plant <math>k</math> with technology <math>t</math> (<math>m^3</math>)</i>
$BP_{tf}^k$	<i>Amount of byproduct <math>f</math> produced at energy plant <math>k</math> with technology <math>t</math> (ton)</i>
$E_{in}^k$	<i>Amount of energy <math>n</math> produced at plant <math>k</math> (kWh)</i>
$W^k$	<i>Amount of auxiliary material consumed at energy plant <math>k</math> (ton)</i>

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**Parameters**


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**1. Biomass supply and product demand**


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$D_u^l, D_f^l, D_n^l$	<i>Amount of demand; of product <math>u</math>, byproduct <math>f</math> and energy <math>n</math> at demand node <math>l</math> (<math>m^3</math>)</i>
$BS_b^i$	<i>Amount of available biomass <math>b</math> at biomass source site <math>i</math> (ton)</i>

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**2. Capacities**


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$C_{pt}, C_{ec}$	<i>Biomass capacity of; energy plant of capacity level <math>p</math> with technology <math>t</math>, facility of capacity level <math>e</math> with type <math>c</math></i>
$CE_{qn}$	<i>Installed capacity of CHP of capacity level <math>q</math> for energy <math>n</math> (kWe/ kWth)</i>

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**3. Costs and prices**


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$I_{pt}, I_{ec}, ICHP_q$	<i>Unit investment cost of; energy plant of capacity level <math>p</math> with technology <math>t</math>, facility of capacity level <math>e</math> with type <math>c</math> (€/ton), CHP of capacity level <math>q</math> (€/kWh)</i>
$VO_{pt}, VO_{ec}, VOCHP_q$	<i>Unit variable operational cost of; energy plant of capacity level <math>p</math> with technology <math>t</math>, facility of capacity level <math>e</math> with type <math>c</math> (€/ton), CHP of capacity level <math>q</math> (€/kWh)</i>
$FO_{pt}, FO_{ec}, FOCHP_q$	<i>Unit fixed operational cost of; energy plant of capacity level <math>p</math> with technology <math>t</math>, facility of capacity level <math>e</math> with type <math>c</math> (€/ton-month), CHP of capacity level <math>q</math> (€/kW-month)</i>
$P_b, PW$	<i>Unit cost of biomass <math>b</math>, auxiliary material (€/ton)</i>
$P_{ft}$	<i>Unit price of product <math>u</math> (€/m<sup>3</sup>) and byproduct <math>f</math> (€/ton),</i>

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$PB_{ut}$	Unit base price of product $u$ produced by technology $t$ (€/m <sup>3</sup> )
$PI_{vut}$	Value of incentive type $v$ for product $u$ produced by technology $t$ (€/m <sup>3</sup> )
$PB_{nt}$	Unit base price of energy $n$ produced by technology $t$ (€/kWh)
$PI_{vnt}$	Value of incentive type $v$ for energy $n$ produced by technology $t$ (€/kWh)
$TV_{b/f}$	Unit fixed transportation cost of shipping biomass $b$ , byproduct $f$ (€/ton)
$TF_{b/f}$	Unit variable transportation cost of shipping biomass $b$ , byproduct $f$ (€/ton-km)

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#### 4. Distances

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$d^{ij}, d^{jk}, d^{kl}$	Distances from; biomass source site $i$ to facility $j$ , facility $j$ to plant $k$ , plant $k$ to demand node $l$ (km)
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#### 5. Conversion rates

$r_{but}, r_{bft}$	Conversion rate of biomass $b$ ; to product $u$ by plant technology $t$ (m <sup>3</sup> /ton), to byproduct $f$ by plant technology $t$ (%)
$d_{bc}$	Conversion rate of raw biomass $b$ into treated biomass in facility with type $c$ (%)
$e_{un}$	Conversion rate of product $u$ to energy $n$ (kWh/m <sup>3</sup> )
$cv_n$	Conversion efficiency of cogeneration unit for energy $n$ (%)
$y_{tun}^k$	Percentage of product $u$ to be converted to energy $n$ in plant $k$ with technology $t$ (%)

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#### 6. Carbon Emissions

$g_t$	GHG emissions associated with energy production by plant with technology $t$ (kg CO <sub>2</sub> eq/kWh)
$g_c$	GHG emissions associated with treatment by facility with technology $c$ (kg CO <sub>2</sub> eq/ton)
$gt_{b/f}$	GHG emissions associated with biomass $b$ , byproduct $f$ transportation (kg CO <sub>2</sub> eq/ ton-km)
$g$	GHG emissions associated with transportation mode (kg CO <sub>2</sub> eq/ km)

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#### 7. Other parameters

$DF$	Discounting factor
$CT$	Capacity of transportation vehicle (ton)

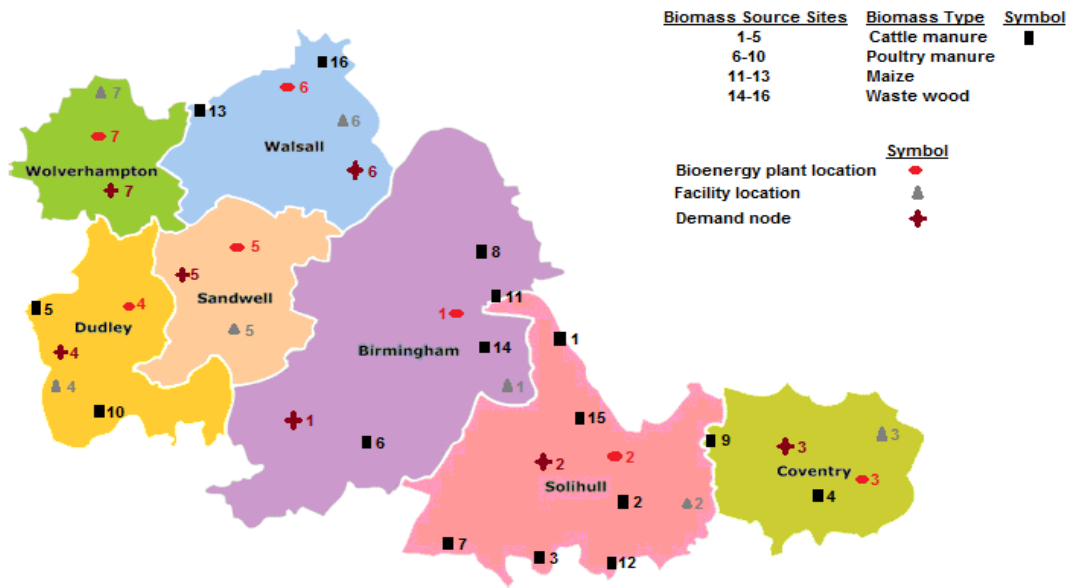


Figure 1. Case study region map

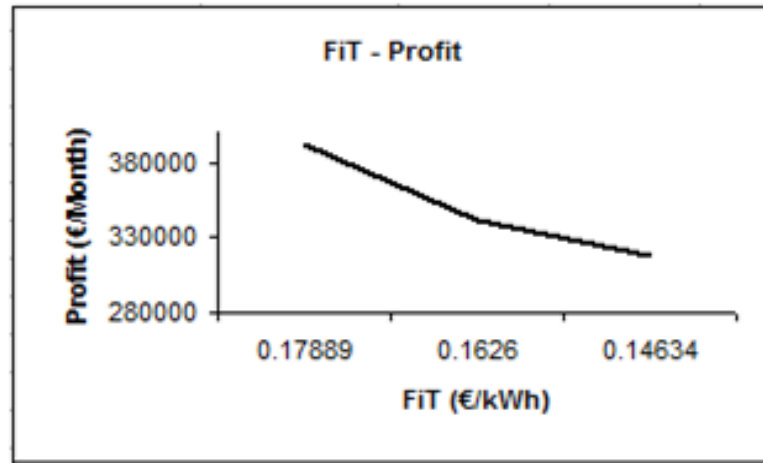


Figure 2(a). The impact of the FiT on the profitability of the supply chain

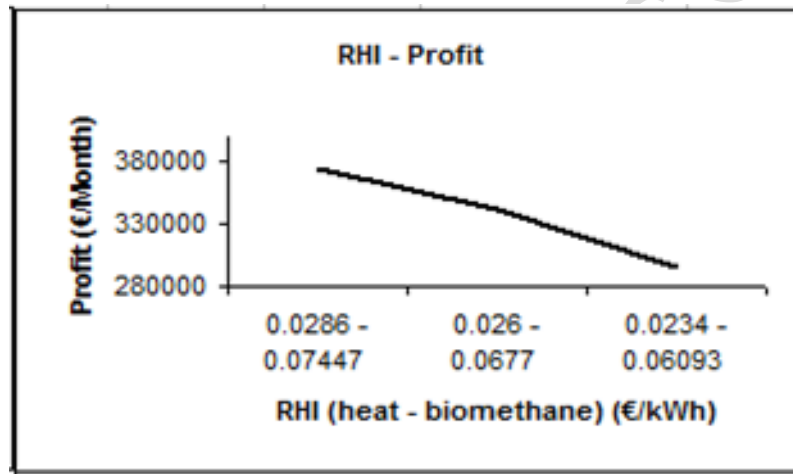


Figure 2(b). The impact of the RHI on the profitability of the supply chain

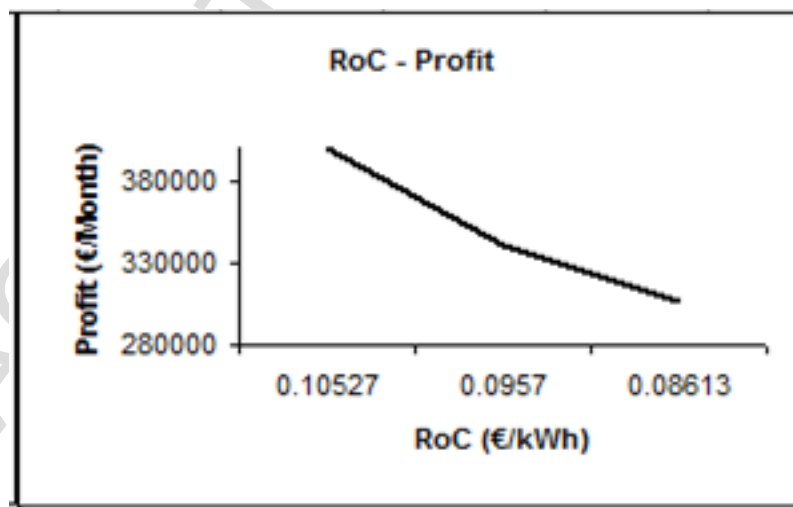
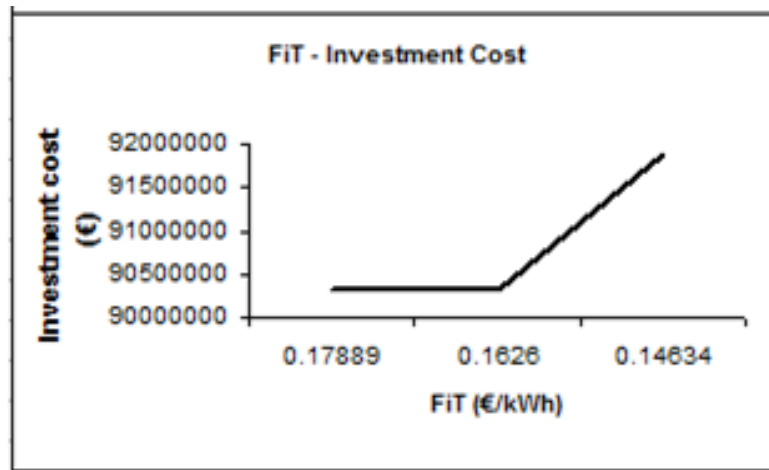
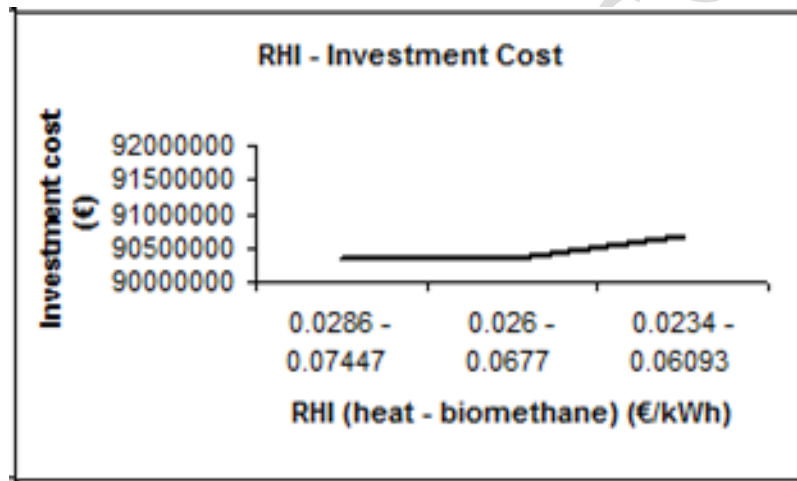


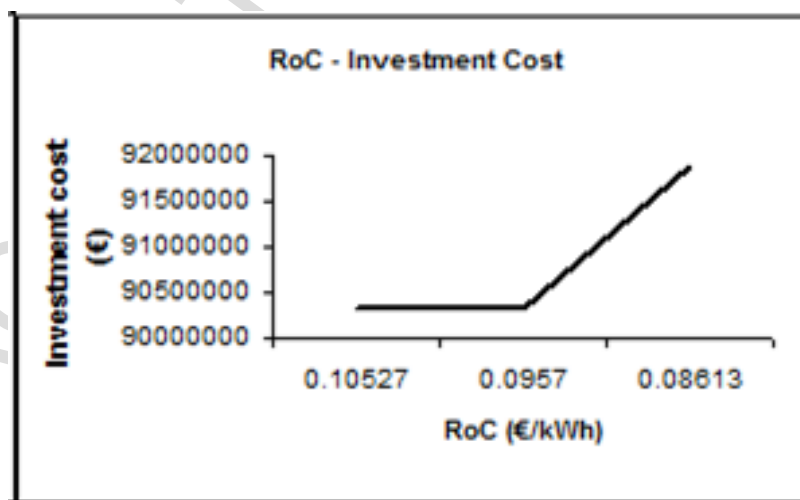
Figure 2(c). The impact of the RoC on the profitability of the supply chain



**Figure 3(a).** The impact of the FiT on the total investment cost of the supply chain



**Figure 3(b).** The impact of the RHI on the total investment cost of the supply chain



**Figure 3(c).** The impact of the RoC on the total investment cost of the supply chain

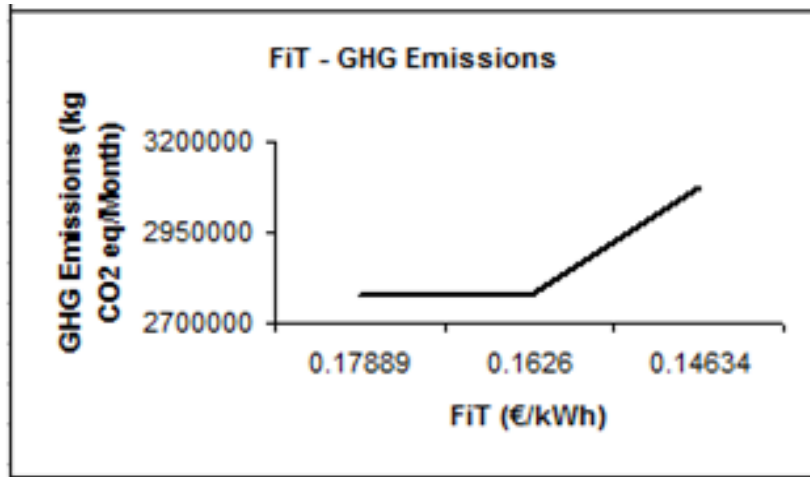


Figure 4(a). The impact of the FiT on the total investment cost of the supply chain

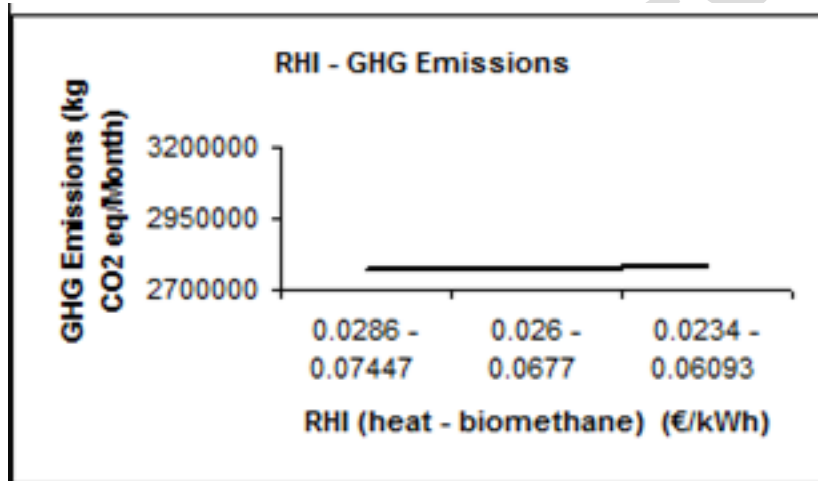


Figure 4(b). The impact of the RHI on the total investment cost of the supply chain

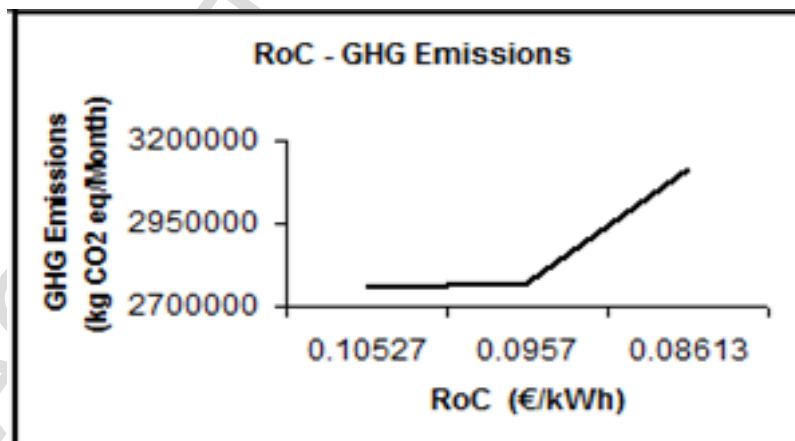


Figure 4(c). The impact of the RoC on the total investment cost of the supply chain

**Highlights:**

1. The study focuses on the main incentive schemes to promote renewable energy in the UK.
2. Feed-in tariff, Renewable Heat Incentive and Renewables Obligation Certificate schemes are focused on.
3. The effects of changes in renewable energy incentives on bioenergy sector are analyzed and discussed.
4. A methodology based on fuzzy multi objective mathematical modelling is used.
5. Computational experiments are performed using the entire West Midlands Region in the UK as case study region.

**Table 1.** Renewable energy support and incentive schemes in UK (Ang et al., 2016)

Year started	Name of policy	Brief description
2002	Renewables Obligation (RO)	<p>The RO incentivises large-scale renewable electricity generation by requiring electricity suppliers to source a specified proportion of the electricity they provide from renewable sources. In exchange for purchasing renewable electricity, suppliers receive Renewables Obligation Certificates (RoCs). Suppliers who do not purchase enough RoCs to meet their obligation must pay a ‘buy-out price’ set by the government. The RO will close to new generators in 2017. Electricity generation accredited under the RO will continue to receive its full lifetime of support of 20 years until the programme closes in 2037. (DECC, 2015a)</p> <p>Reference for incentive values:  <a href="http://www.epowerauctions.co.uk/erocrecord.htm">http://www.epowerauctions.co.uk/erocrecord.htm</a></p>
2010	Feed-in Tariffs (FITs)	<p>FITs incentivises small-scale low carbon electricity generation by requiring energy suppliers to make payments to households and businesses with certified installations. Payments include a generation tariff for each unit of electricity generated and an export tariff for each unit of electricity exported to the grid. Eligible installations include technologies that generate up to 5 MW of electricity using solar photovoltaic, wind or water turbines, anaerobic digestion or micro-combined heat and power (DECC, 2015b).</p> <p>Reference for incentive values:  <a href="https://www.ofgem.gov.uk/system/files/docs/2016/04/01_april_2016_tariff_table.pdf">https://www.ofgem.gov.uk/system/files/docs/2016/04/01_april_2016_tariff_table.pdf</a></p>
2011	Renewable Heat Incentive (RHI)	<p>The RHI provides a tariff to businesses, the public sector and non-profit organisations for the installation of renewable heat technologies. Eligible technologies include solid biomass, ground-source or water-source heat pumps, deep geothermal, solar thermal collectors, biomethane injection and biogas combustion (DECC, 2015c).</p> <p>Reference for incentive values:  <a href="https://www.ofgem.gov.uk/environmental-programmes/non-domestic-renewable-heat-incentive-rhi/tariffs-apply-non-domestic-rhi-great-britain">https://www.ofgem.gov.uk/environmental-programmes/non-domestic-renewable-heat-incentive-rhi/tariffs-apply-non-domestic-rhi-great-britain</a></p>

**Table 2.** Capacity levels of the plants

Capacity Level	Total biomass capacity of G plants (t/month) (ukwin.org.uk)	Total biomass capacity of AD plants (t/month) (wrap.org.uk)	Installed capacity of cogeneration unit (kWe) (DECC, 2008)	Total biomass capacity of PT facilities (t/month) (ukwin.org.uk)	Total biomass capacity of CO facilities (t/month)
1 (Minimum Capacity)	1500	6000	2000	1500	6000
2 (Medium Capacity)	3000	12,000	3500	3000	12,000
3 (Maximum Capacity)	4500	18,000	5000	4500	18,000



**Table 3.** Energy prices in the UK

	Anaerobic Digestion			Gasification		
	Electricity	Heat	Biomethane	Electricity	Heat	Biomethane
Base Price (€/kWh)	0.057	0.04	0.0316	0.057	0.04	No production
FiT (€/kWh)						
Generation	0.0998	-	-	-	-	
Export	0.0628	-	-	-	-	
RHI (€/kWh)	-	0.026	0.0677	-	0.026	
RoC (€/kWh)	-	-	-	0.0957	-	
Total (€/kWh)	0.2196	0.066	0.0993	0.1527	0.066	

**Table 4.** Unit investment costs per installed capacity depending on capacity levels

<b>Capacity Level</b>	<b>Unit investment cost of G plants (€/ton) (DECC, 2012)</b>	<b>Unit investment cost of AD plants (€/ton) (DECC, 2012)</b>	<b>Unit investment cost of CHP (€/kWe) (DECC, 2012)</b>	<b>Unit investment cost of PT facilities(€/ton) (Rentizelas et al., 2014)</b>
1	9417	1652	487	842
2	8239	1446	419	739
3	7847	1377	352	709
<b>Capacity Level</b>	<b>Unit fixed and variable operational costs of G plants (€/ton) (DECC, 2012)</b>	<b>Unit fixed and variable operational costs of AD plants (€/ton) (DECC, 2012)</b>	<b>Unit fixed (€/kWe) and variable (€/kWh) operational costs of CHP (DECC, 2012)</b>	
1	55.33 -17.65	10.36 - 6.04	7 - 0.0072	
2	48.4 - 15.5	9.067 - 5.29	6.54 - 0.0064	
3	46.1 - 14.73	8.635 - 5.03	6 - 0.006	

**Table 5.** Data on GHG emissions associated with production

Source of GHG emissions	GHG emissions (kg CO <sub>2</sub> Eq/ kWh)	Reference
<b><u>Conversion</u></b>		
Biogas to energy	3.67x10 <sup>-4</sup> (kg CO <sub>2</sub> Eq/ kWh)	DEFRA Carbon Conversion Factors Dataset (2015)
Syngas to energy	0.18445 (kg CO <sub>2</sub> Eq/ kWh)	DEFRA Carbon Conversion Factors Dataset (2015)
<b><u>Pretreatment</u></b>		
Pelletizing	1.47x10 <sup>-4</sup> (kg CO <sub>2</sub> Eq/ ton)	Cucek et al. (2010)

**Table 6.** Data on the GHG emissions associated with transportation

	<b>Cattle Manure (liquid)</b>	<b>Broiler Hen Manure (Solid)</b>	<b>Layer Hen Manure (Liquid)</b>	<b>Waste Wood (Logging residues)</b>	<b>Wood pellet</b>	<b>Maize (Loose)</b>	<b>Fertilizer (liquid)</b>
<b>GHG emissions (kg CO<sub>2</sub> eq/ ton- km)</b>	5.3x10 <sup>-8</sup> Cucek et al. (2010)	5.3x10 <sup>-8</sup> Cucek et al. (2010)	5.3x10 <sup>-8</sup> Cucek et al. (2010)	5.3x10 <sup>-8</sup> Cucek et al. (2010)	2.4x10 <sup>-7</sup> Cucek et al. (2010)	1.1x10 <sup>-6</sup> Cucek et al. (2010)	5.3x10 <sup>-8</sup> Cucek et al. (2010)

**Table 7.** Results of the incentive analysis

FiT (€/kWh)	RHI (€/kWh)	RoC (€/kWh)	Profit (€/Month)	Investment Cost (€)	GHG Emissions (kg CO <sub>2</sub> eq/Month)
<b>Optimistic case</b>					
Generation - 0.10978	0.026 (heat)	0.0957	392,208	90,331,000	2,773,979
Export - 0.06908	0.0677 (biomethane)				
<b>Total - 0.17889</b>					
<b>Base case</b>					
Generation - 0.0998	0.026 (heat)	0.0957	341,197	90,331,000	2,773,974
Export - 0.0628	0.0677 (biomethane)				
<b>Total - 0.1626</b>					
<b>Pessimistic case</b>					
Generation - 0.08982	0.026 (heat)	0.0957	317,301	91,888,550	3,075,879
Export - 0.05652	0.0677 (biomethane)				
<b>Total - 0.14634</b>					
Generation - 0.0998	<b>Optimistic case</b>	0.0957	375,452	90,331,000	2,773,979
Export - 0.0628	0.0286 (heat)				
	0.07447 (biomethane)				
Generation - 0.0998	<b>Base case</b>	0.0957	341,197	90,331,000	2,773,974
Export - 0.0628	0.026 (heat)				
	0.0677 (biomethane)				
Generation - 0.0998	<b>Pessimistic case</b>	0.0957	294,943	90,684,500	2,785,656
Export - 0.0628	0.0234 (heat)				
	0.06093 (biomethane)				
Generation - 0.0998	0.026 (heat)	<b>Optimistic case</b>	399,221	90,331,000	2,756,173
Export - 0.0628	0.0677 (biomethane)	0.10527			
Generation - 0.0998	0.026 (heat)	<b>Base case</b>	341,197	90,331,000	2,773,974
Export - 0.0628	0.0677 (biomethane)	0.0957			
Generation - 0.0998	0.026 (heat)	<b>Pessimistic case</b>	307,083	91,888,550	3,115,758
Export - 0.0628	0.0677 (biomethane)	0.08613			