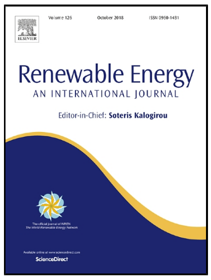

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Incentivising Bioenergy Production: Economic and Environmental Insights from a Regional Optimization Methodology

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Abstract

In conjunction with the European Union (EU) targets, the United Kingdom (UK) Government has introduced a range of mechanisms to foster the development and deployment of low carbon energy technologies and markets. This study focuses on the three main financial incentive schemes to promote renewable energy sector in the UK for electricity, heat and fuel production from renewables, namely feed-in tariff (FiT), Renewable Heat Incentive (RHI) and Renewables Obligation Certificate (RoC), considering the fact that optimal policy design depends on effective analyses of the impacts of incentives on the performance of renewable energy systems. The effects of potential changes in these incentive schemes on the economic and environmental performance of bioenergy sector are investigated using an analytical methodology. The methodology integrates fuzzy decision making and multi objective mathematical modelling in the same framework to capture uncertainties in the system parameters as well as economic and environmental sustainability aspects. Computational experiments are performed on bioenergy production using the entire West Midlands Region in the UK as case study region. The results reveal that the changes in incentive policies have a significant impact on the profitability of the supply chain, whereas environmental performance of the supply chain in terms of total GHG emissions is the least affected performance indicator by the changes in the incentive policies.

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

1. Introduction

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

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

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

The literature has acknowledged that reduction of uncertainties and risks related to economic factors, such as fluctuating market prices, supply and demand, by incentive schemes is central to successful renewable energy implementations (Klessmann et al., 2013). Hence it is important to analyse the effects of different incentive schemes on the performance of renewable energy production systems and supply chains. Researches have contributed to the literature by studying on the role of incentives to promote investments in renewable energy sector in different parts of the world. Among them, Leete et al. (2013) emphasized that deployment of marine renewable energy in the UK is desirable in order to address climate change, meet mandatory EU renewable energy targets and provide significant economic development opportunities. By focussing on investor attitudes and behaviours towards wave and tidal technologies, their research seeks to identify common barriers and incentives to investment through a series of interviews. Elkarmi and Shikhah (2013) studied the effect of introducing financial incentives, such as tax reduction, introduction of a grace period, provision of capital or reduced discount rate, reduced depreciation life of assets, and the usage of accelerated depreciation methods, to promote green electricity generation in Jordan. Mola-Yudego and Pelkonen (2008) analysed the effect of policy incentives in the development of short rotation willow plantations for bioenergy considering 56 municipalities in Sweden, by an aggregate adoption model based on sigmoidal curves. Chinese et al. (2014) introduced a biogas supply chain optimization model to analyse the effects of the previous and current support schemes on the optimal plant size, feedstock mix and profitability. Ibanez-Lopez et al. (2017) used dynamic simulation to assess the overall technical, economic and environmental impact of renewable energy incentives and capacity payment policies. Spain's power industry is simulated to assess the impact of electric power policies. Gürkan and Langestraat (2014) analysed three renewable obligation policies representing UK electricity market with random availabilities and random electricity demand by mathematical modelling. They also provided revenue adequate pricing schemes for the three obligation policies. Connor et al. (2015) discussed the adoption and development of renewable heating policy in the UK focusing on the historical and ongoing policies applied to the support of renewable energy sources of heat in the UK. Devine et al. (2017) presented a simulation-based modelling framework to incorporate consideration of policymaker/consumer risk burden in FiT analyses. They conducted an Irish case study and concluded that commonly employed FiT are only optimal when policymaker risk aversion is extremely low. Ritter and Deckert (2017) presented a wind energy index to assess the wind energy potential of locations in Germany, to compare different turbine types, and to derive the required compensation in terms of locally different FiTs.

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

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

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

The methodology in this study captures uncertainties in the system parameters as well as economic and environmental sustainability aspects by incorporating fuzzy decision making and multi-objective optimization in the same framework. This paper also proposes a modelling approach that covers multiple types of biomass, biomass to energy conversion technologies, biomass pre-processing facilities and bio-products. On that sense, the model is generalizable, the decision makers can utilize our model for different cases with only updating the data set. However, this paper uses the proposed optimization methodology to monitor the impacts of changes in the main incentive schemes, applied in the UK to promote renewable energy investments, on economic and environmental performance of the production chain focusing on three different performance criteria (profitability, investment costs and GHG emissions). However, the proposed methodology, which enhances capital investment and logistics planning decisions for renewable energy systems, can be utilized both to support the development of new investments by identifying the optimal configuration of the supply chain and planning the logistics operations and to monitor the main economic and environmental performance indicators of the existing systems and take the necessary actions for improved performance.

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

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

Renewable energy investments are risky initiatives due to the uncertain nature of many renewable energy sources that causes variability in supply and in market prices. FiT, is introduced as a mechanism to promote investments in energy production using renewable sources by offering long-term contracts, considering the cost of energy generation by renewable sources based production technology, to renewable energy producers. The mechanism aims at promoting greater deployment of renewable technologies and supporting competitiveness with fossil fuel based energy systems by guaranteeing a minimum payment per unit of electricity generated to reduce investors' vulnerability to uncertain market prices and demand. Although it has been asserted that it is theoretically less efficient than quantity-based schemes (Ringel, 2006), FiT has become a preferred policy mechanism which have been adopted and implemented by more than 75 countries, states, and provinces (Eyraud et al., 2011).

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

Initially, the RHI only covers the non-domestic installation of renewable heat technologies (DECC, 2011). However, the government proposed to include financial payment for the deployment of these technologies for domestic usage (Phase 2 of the RHI) to promote more uptakes in the household sector following a consultation in September 2012 (DECC, 2012b). Similar to the FiT scheme, the RHI will guarantee a fixed payment per kWh of heat generated by a renewable heat technology for a particular contract duration. For the domestic installation, the government proposed a rate of £0.0173 per kWh paid for a contract period of 7 years (DECC, 2012b). The scheme has been commenced in spring 2014. The RHI rate is index-linked and the yearly rate will be determined in proportion to the change in the Retail Price Index (RPI) of the previous year (DECC, 2011), e.g. if the RPI is 3%, the RHI rate per kWh for that year will be increased by 3%.The government projected that by 2020, the domestic sector will contribute approximately 3.3TWh annually with a projected number of installations totalling to roughly 380,000 (DECC, 2012b).

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

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

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

3. Methodology

3.1. Fuzzy Multi Objective Decision Making Procedure

In this section, the fuzzy multi-objective decision making methodology, which is adapted to solve the multi-objective mathematical model, is explained. The solution methodology combines fuzzy set theory and ε-constraint methods, more specifically ε-constraint method is extended by integrating fuzzy logic.

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

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

Step 1. Develop the linear programming model of the problem

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

The first objective function, namely maximization of supply chain profit, comprises revenue and cost elements. Each revenue and cost element is formulated in the following equations. Formulation of the total revenue represents the revenues from product, by-product and energy sales. To determine the revenue from biofuel and bioenergy sales and analyse the impact of changes in different incentive schemes on the economic and environmental performance of the supply chain, the unit sale prices of biofuel and bioenergy are divided into two elements; base prices and the values of incentives based on the type of biofuel/bioenergy sold, type of production technology and type of incentive. The sum of these two elements gives unit sale prices. The formulations contain operational costs (comprising variable and fixed costs), transportation costs, biomass purchasing cost and auxiliary material cost, respectively. Variable operational costs are dependent on the quantity of material to be processed in energy production, pre-processing and CHP plants, whereas fixed operational costs are calculated based on the capacity of energy production, pre-processing and CHP plants. Variable transportation costs are distance dependent, while fixed transportation costs are calculated based on the quantity of material to be transported between locations. The first objective function can be calculated as follows;

$$Max\ Z_1 = \left[Total\ Revenue - \begin{pmatrix} Operational\ Cost + Transportation\ Cost \\ + Biomass\ Purchasing\ Cost + Water\ Cost \end{pmatrix} \right] \tag{1}$$

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

$$Operational\ Cost = \begin{array}{l} \left[\begin{array}{l} \left(\sum_{j=1}^{J} \sum_{e=1}^{E} \sum_{c=1}^{C} VO_{ec} \cdot \left(\sum_{i=1}^{I} \sum_{b=1}^{B} S_{cb}^{ij} \right) \right) + \left(\sum_{k=1}^{K} \sum_{p=1}^{P} \sum_{t=1}^{T} VO_{pt} \cdot \left(\sum_{j=1}^{J} \sum_{b=1}^{B} S_{tb}^{jk} \right) \right) \\ + \left(\sum_{q=1}^{Q} \sum_{t=1}^{T} VOCHP_{q} \cdot \left(\sum_{k=1}^{K} \sum_{n=1}^{N} E_{tn}^{k} \right) \right) \end{array} \right] \\ + \left[\begin{array}{l} \left(\sum_{j=1}^{J} \sum_{e=1}^{E} \sum_{c=1}^{C} FO_{ec} \cdot C2_{ec} \cdot B_{ec}^{j} \right) + \left(\sum_{k=1}^{K} \sum_{p=1}^{P} \sum_{t=1}^{T} FO_{pt} \cdot C1_{pt} \cdot A_{pt}^{k} \right) \\ + \left(\sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{n=1}^{N} FOCHP_{q} \cdot CE_{qn} \cdot CHP_{q}^{k} \right) \end{array} \right] \end{array}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Capacity: Eqs. 6 and 7 limit the amount of biomass transported to the facilities and plants to the maximum capacity of the corresponding capacity levels of plants/facilities. Eq. 8 restricts the amount of energy produced in energy plants to the maximum capacity of the corresponding capacity levels of these plants.

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

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

$$\sum_{t=1}^{T} E_{tn}^{k} \le \sum_{q=1}^{Q} CHP_{q}^{k} \cdot CE_{qn} \quad \forall k, \forall n \tag{8}$$

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

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

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

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

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

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

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

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

$$\sum_{k=1}^{K}\sum_{t=1}^{T} SBP_{ft}^{kl} \le D_{f}^{l} \quad \forall l, \forall f \tag{15}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} SP_{tu}^{kl} \ge D_{u}^{l} \quad \forall l, \forall u \tag{16}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} SE_{n}^{kl} \ge D_{n}^{l} \quad \forall l, \forall n \tag{17}$$

Step 2. Convert problem P into problem P_0

The linear programming problem developed in Step 1 is transformed into problem represented by below formulations according to the basic principles of the ε-constraint method. In P_0, the objective function is corresponding to Z_1 of P, and Z_2 and Z_3 of P is dealt with as a constraint of P_0. Problem P_0 can be represented as follows:

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

Step 3. Construct the payoff table and determine ε_2 and ε_3

To solve problem P_0, we need to determine ε_2 and ε_3 (upper bound for the second and third objective functions) that is limited by the range of objective functions f_2 and f_3. To obtain the appropriate ranges of f_2 and f_3, developed multi objective model is solved as a single objective problem using each time only one objective and ignore the others to specify the efficient solutions (i.e. upper bound, expected value and lower bound) for f_2 and f_3. For this purpose, a fuzzy logic based procedure is utilized and the problem is divided into sub problems. Each time, one of the upper, lower and expected values of the fuzzy parameters are taken into consideration and sub problems are solved according to one of the objective functions. For this purpose, a scenario based approach developed by Yılmaz Balaman (2016) is utilized in this study. The problem is divided into nine sub problems (SP) based on a scenario approach. Scenarios represent the best, expected and worst situations for three objective functions, which are constructed by taking into consideration the upper, lower and expected values of the fuzzy parameters. After constructing the scenarios, the model is solved according to one of the profit maximization, investment cost minimization or GHG emissions minimization objectives under three scenarios and the corresponding value for each objective function at each solution is determined. Based on the findings, the payoff table, which is an asymmetric matrix where the matrix elements represent the optimum values of the corresponding objective function, is constructed. The lower, upper and expected values of each objective function are determined based on the payoff table.

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

Solve the problem P_0 with different values of ε_2 and ε_3 (i.e. upper, expected and lower values from the payoff table), and finally, obtain a set of pareto optimal solutions. After a set of pareto optimal solutions are obtained, a decision maker may wish to select a preferred one from them and may also want to know its degree of optimality. The fuzzy logic based approach (Esmaili et al., 2011) can both provide a most preferred solution and also indicate its degree of optimality. This approach utilizes membership functions which are used to formulate fuzzy numbers depending on the problem specific characteristics. Lai & Hwang (1994) stated that, the grade of a membership function indicates a subjective degree of satisfaction within given tolerances. A membership function, usually denoted by "μ", associates each point in a fuzzy set F with a real number in the closed interval [0, 1]. It indicates the grade of membership of an element in a fuzzy set F. Thus, the nearer the value of membership function to unity, the higher the grade of membership of an element in a fuzzy set F. A membership function can be viewed as an quantification of the ambiguity of set F.

In this paper, the fuzzy logic based approach (Esmaili et al., 2011) is applied to assist in choosing a preferred solution. In the m-objective optimization problem with k pareto optimal solutions, the membership function μ_i^k indicates the degree of optimality for the *ith* objective function in the *kth* solution. It is defined as follows;

1. In the case of objective functions being minimized;

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

2. In the case of objective functions being maximized;

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

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

Step 5. Find the most preferred solution

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

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

The solution with the maximum value of μ_i^k is selected as the most preferred solution.

3.2. Case Study

To explore the impacts of the main incentive schemes on the economic and environmental performance of bioenergy supply chains, computational experiments are performed for the WM region in the UK using the proposed optimization methodology. To this aim, seven regions in the WM, namely Birmingham, Coventry, Solihull, Sandwell, Walsall, Wolverhampton and Dudley, are considered to design a comprehensive supply chain. Four types of biowaste (cattle manure, laying chicken manure, broiler chicken manure, waste wood) and one energy crop (maize) are assumed to be the potential biomass inputs. The existing yields and geographic distribution data on biowaste from husbandry are adopted from UK Department for Environment, Food & Rural Affairs (DEFRA) - farming statistics (DEFRA, 2015). Data on maize yields and geographical distribution of the maize fields are gathered from DEFRA - annual statistics on the structure of the agricultural industry (2015).

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

Figure 1. Case study region map.

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

The electrical and thermal efficiency of the cogeneration units are taken as 33% and 43% (DECC, 2008). The conversion rate of wood to wood pellet is taken as 0.84 (Uslu et al.,2008). The generated electrical energy, thermal energy and biomethane are assumed to be fed into the national electricity distribution network, on-site heating system and natural gas pipeline network. Three capacity levels are considered for the pre-processing facilities, biomass to biofuel conversion plants and CHP units. These capacity levels reported in Table 2.

Table 2. Capacity levels of the plants.

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

Table 3. Energy prices in the UK.

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

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

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

Environmental parameters: Data on GHG emissions associated with wood pellet production in pretreatment facilities and bioenergy production in plants are depicted in Table 5. GHG emissions from truck transportation is obtained as 0.692514 kg CO_2-eq / km from DEFRA Carbon Conversion Factors Dataset (2015d). Data on the GHG emissions associated with transportation are derived from the literature. Table 6 lists the GHG emissions for transporting cattle manure, poultry manure, wood pellet, maize and biofertilizer by road transport.

Table 5. Data on GHG emissions associated with production.

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

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

3.3. Results and Discussion

This section presents and analyses the results of our computational experiments focusing on the effects of the main incentive schemes on the performance of the regional supply chain designed by the optimization model. As stated previously, this paper utilizes the proposed optimization methodology to analyze the impacts of changes in three main incentive schemes, applied in the UK to promote renewable energy investments, on economic and environmental performance of the production chain. Hence the details about the modelling choices related to the configuration of the regional supply chain and logistics planning decisions made by the optimization methodology are not given in this paper since it is not the main focus of this paper. However, they can be provided upon special request.

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

Table 7. Results of the incentive analysis.

Effects of incentive schemes on the profitability

Figure 2 a, b, and c illustrates the impact of the incentive schemes on the profitability of the supply chain. The results reveal that, the profitability of the supply chain is mostly affected by the change of RoC, which is followed by FiT, when the optimistic cases (10% increase in incentives) are considered. The increase of RoC and FiT values by 10% cause a rise in monthly profit by 17% and 15%, respectively, whereas the increase of RHI by 10% makes the least change on the profit increasing it by 10%. However, for pessimistic cases the impact pattern is different from the optimistic cases. In this case, the monthly profit is mostly affected by the change of RHI, and secondly RoC. The reductions in RHI and RoC values by 10% decrease the monthly profit by 13.5% and 10%, respectively. The decrease of FiT by 10% makes the least change on the profit reducing it by 7%. It can also be concluded that, improvements in the RoC scheme which lead increases in the RoC incentive values, will be for the benefit of investors whose major consideration is the profitability of the biomass based energy systems and supply chains. On the other hand, in the case of a cut down on the incentives, e.g. in economic downturns, financial bottlenecks or economic crisis, the profitability of the biomass based energy supply chains will be mostly impacted by the reductions in RHI.

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.

Effects of incentive schemes on total investment cost

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

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.

Effects of incentive schemes on the level of GHG emissions

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

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.

4. Conclusions and Policy Implications

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

It can be concluded that among three performance indicators (two economic and one environmental), profitability of the supply chain is the one that is mostly affected by the changes in the incentive policies. However, the incentive schemes that have the biggest effect on the profitability changes according to the upward and downward trends in the economic policies which create optimistic and pessimistic cases in our analyses. The change in the RoC incentive value has the biggest effect on the total profit obtained from the supply chain if there is an upward trend in the economic policies on renewable energy systems. It should be concluded that, if profitability of the bioenergy systems is desired to be increased to encourage new investments in renewable energy sector, RoC incentives should be the first to be increased among these three schemes. For the cases of downward trend in economic policies (pessimistic case, i.e. reductions in incentives) in renewable energy, RHI is the scheme that has the biggest effect on the profitability of the chain. Hence, RHI values should be the last to be reduced in downward economic conjuncture (i.e. economic downturns, financial bottlenecks or economic crisis) to prevent losses in profitability of the existing investments.

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

The results reveal that, environmental performance of the supply chain in terms of total GHG emissions is the least affected performance indicator by the changes in the incentive policies. If environmental performance of renewable energy systems is the most important consideration in policy making, incentive values in the scope of RoC scheme, should not be reduced significantly in cases of a downward trend in economic policies. According to the results, configuration of the supply chain optimized by the developed methodology results in higher GHG emissions in case of lower RoC and FiT values in downwards economic conjuncture. However, the decrease in RHI value has an insignificant effect on the GHG emissions. In the case of an upward trend in economic policies, increases in all three incentive schemes have an insignificant impact on the level of GHG emissions.

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

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

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Appendix. Notations used in the model

Indices	
i	*Biomass source sites*
j	*Candidate locations for facilities*
k	*Candidate locations for energy plants*

l	*Demand nodes*
b	*Biomass types*
u	*Product types*
f	*Byproduct types*
n	*Energy type*
v	*Incentive type*
p	*Biomass capacity levels for energy plants*
e	*Biomass capacity levels for facilities*
q	*Electrical energy production capacity levels of CHP units*
t	*Energy conversion technology*
c	*Facility type*
Decision Variables	
1. Binary variables	
A_{pt}^{k}	*1 if an energy plant of capacity p and technology t is located at k, 0 otherwise*
B_{ec}^{j}	*1 if a facility of capacity e and type c is located at j, 0 otherwise*
CHP_{q}^{k}	*1 if a CHP of capacity q is located in an energy plant at k, 0 otherwise*
2. Positive variables	
S_{cb}^{ij}, S_{tb}^{jk}	*Amount of biomass b shipped from; biomass source site i to facility j with type c, facility j to energy plant k with technology t (ton)*
SP_{tu}^{kl}	*Amount of product u produced in energy plant k with technology t to meet demand of node l (m³)*
SBP_{tf}^{kl}	*Amount of byproduct f distributed from energy plant k with technology t to demand node l (ton)*
SE_{tn}^{kl}	*Amount of energy n produced in plant k with technology t to meet demand of node l (kWh)*
PR_{tu}^{k}	*Amount of product u produced at energy plant k with technology t (m³)*
BP_{tf}^{k}	*Amount of byproduct f produced at energy plant k with technology t (ton)*
E_{tn}^{k}	*Amount of energy n produced at plant k (kWh)*
W^{k}	*Amount of auxiliary material consumed at energy plant k (ton)*
Parameters	
1.Biomass supply and product demand	
$D_{u}^{l}, D_{f}^{l}, D_{n}^{l}$	*Amount of demand; of product u, byproduct f and energy n at demand node l (m³)*
BS_{b}^{i}	*Amount of available biomass b at biomass source site i (ton)*
2. Capacities	
C_{pt}, C_{ec}	*Biomass capacity of; energy plant of capacity level p with technology t, facility of capacity level e with type c*
CE_{qn}	*Installed capacity of CHP of capacity level q for energy n (kWe/ kWth)*
3. Costs and prices	
$I_{pt}, I_{ec}, ICHP_{q}$	*Unit investment cost of; energy plant of capacity level p with technology t, facility of capacity level e with type c (€/ton), CHP of capacity level q (€/kWh)*
$VO_{pt}, VO_{ec}, VOCHP_{q}$	*Unit variable operational cost of; energy plant of capacity level p with technology t, facility of capacity level e with type c (€/ton), CHP of capacity level q (€/kWh)*
$FO_{pt}, FO_{ec}, FOCHP_{q}$	*Unit fixed operational cost of; energy plant of capacity level p with technology t, facility of capacity level e with type c (€/ton-month), CHP of capacity level q (€/kW-month)*
P_{b}, PW	*Unit cost of biomass b, auxiliary material (€/ton)*
P_{ft}	*Unit price of product u (€/m³) and byproduct f (€/ton),*

PB_{ut}	*Unit base price of product u produced by technology t (€/m³)*
PI_{vut}	*Value of incentive type v for product u produced by technology t (€/m³)*
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)*
4. Distances	
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)*
5. Conversion rates	
r_{but}, r_{bft}	*Conversion rate of biomass b; to product u by plant technology t (m³/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/m³)*
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 (%)*
6. Carbon Emissions	
g_t	*GHG emissions associated with energy production by plant with technology t (*kg CO_2 eq/kWh*)*
g_c	*GHG emissions associated with treatment by facility with technology c (*kg CO_2 eq/ton*)*
$gt_{b/f}$	*GHG emissions associated with biomass b, byproduct f transportation (*kg CO_2 eq/ ton-km*)*
g	*GHG emissions associated with transportation mode (*kg CO_2 eq/ km*)*
7. Other parameters	
DF	*Discounting factor*
CT	*Capacity of transportation vehicle (ton)*

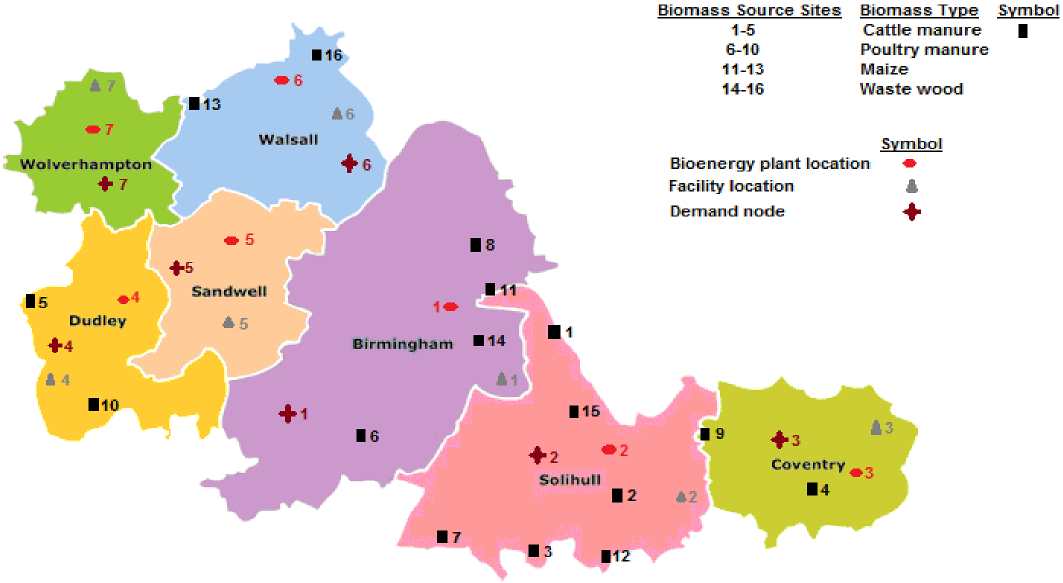

Figure 1. Case study region map

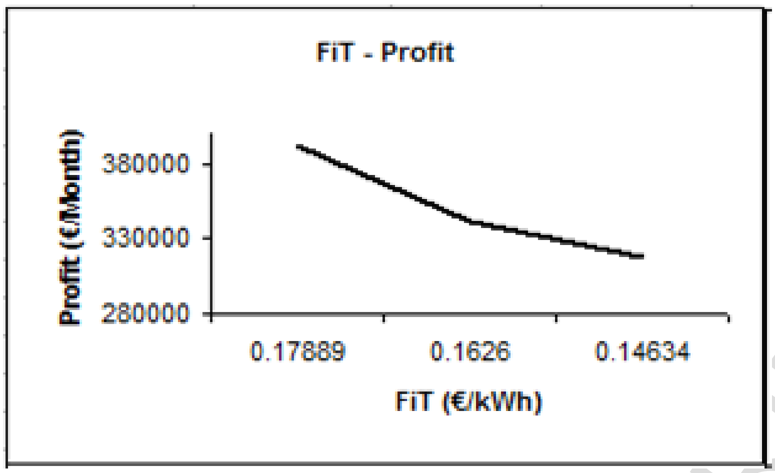

Figure 2(a). The impact of the FiT on the profitability of the supply chain

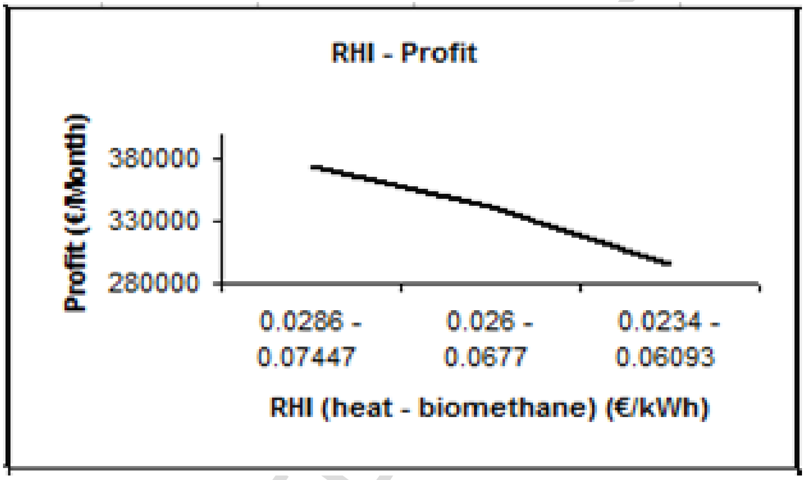

Figure 2(b). The impact of the RHI on the profitability of the supply chain

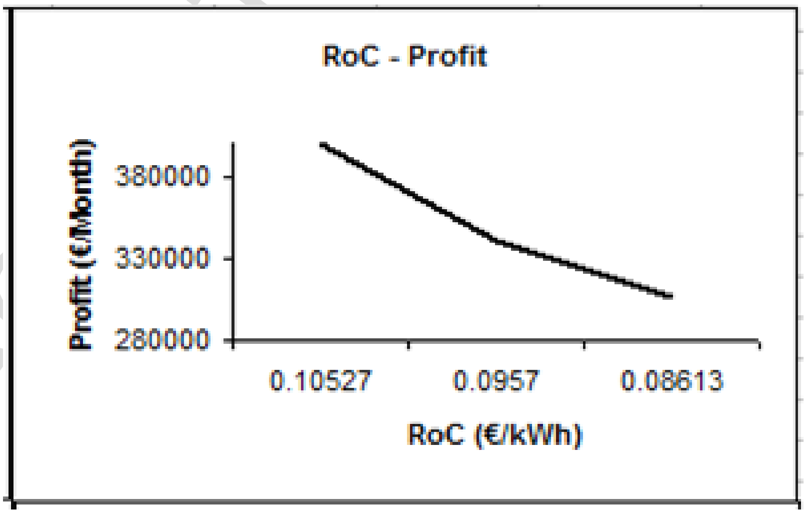

Figure 2(c). The impact of the RoC on the profitability of the supply chain

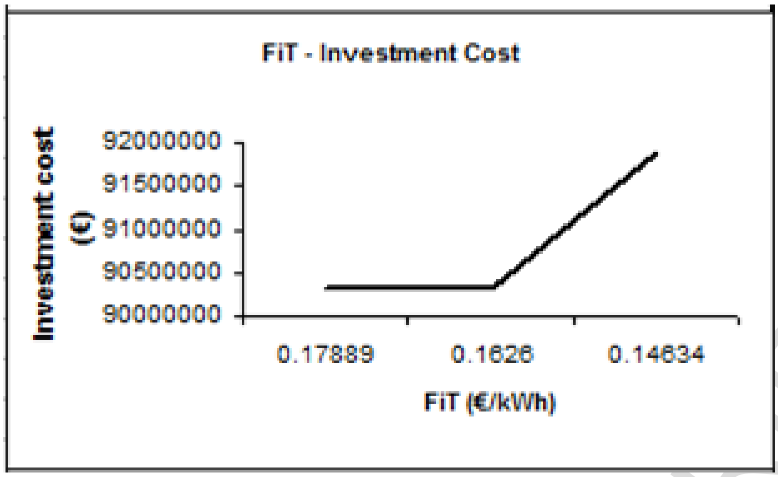

Figure 3(a). The impact of the FiT on the total investment cost of the supply chain

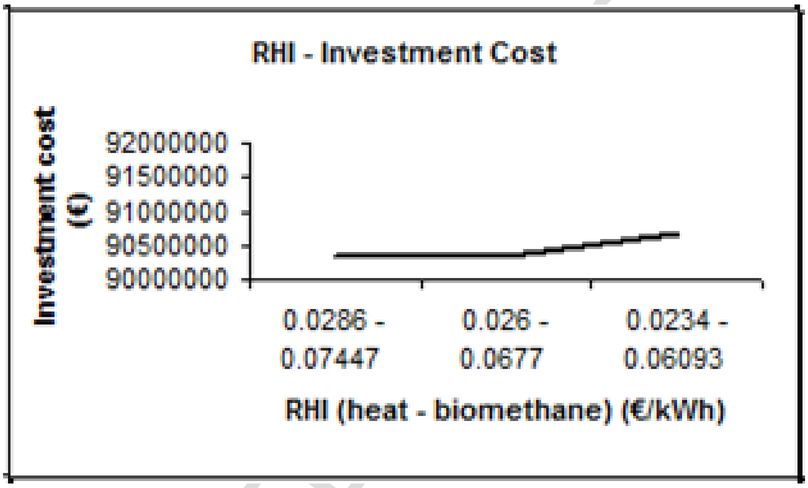

Figure 3(b). The impact of the RHI on the total investment cost of the supply chain

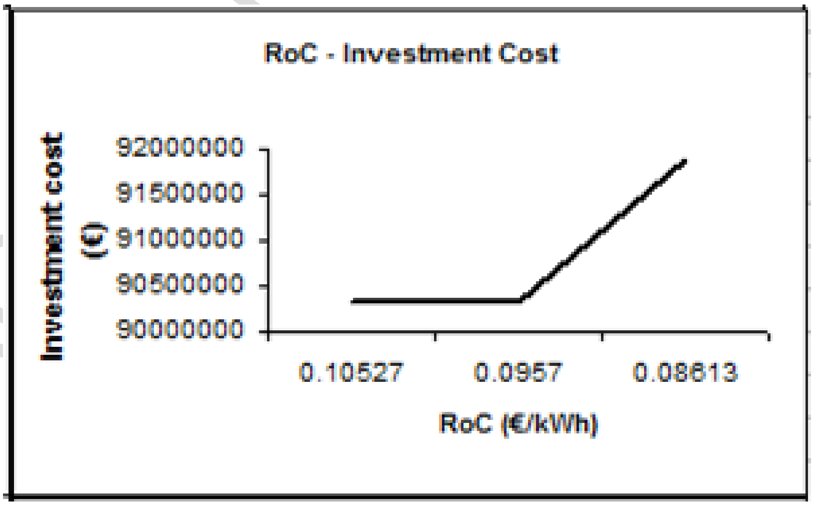

Figure 3(c). The impact of the RoC on the total investment cost of the supply chain

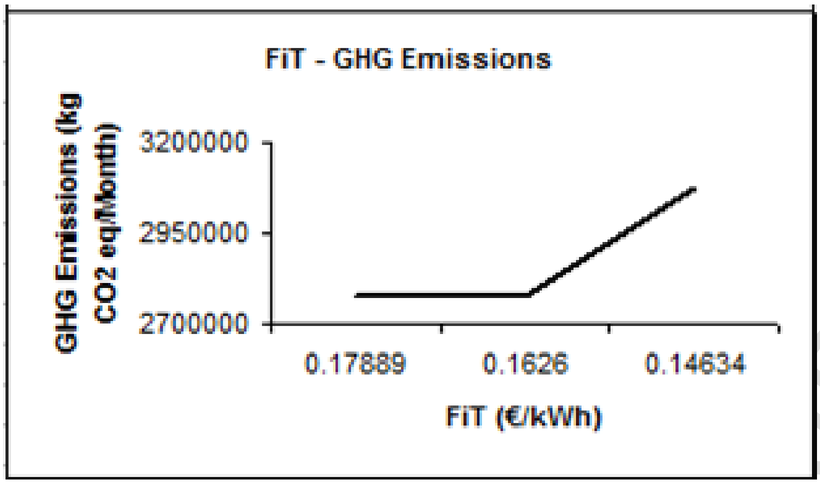

Figure 4(a). The impact of the FiT on the total investment cost of the supply chain

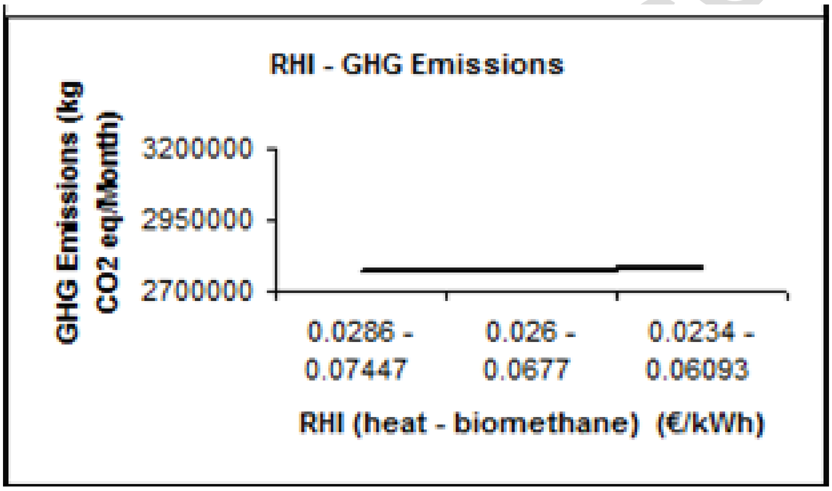

Figure 4(b). The impact of the RHI on the total investment cost of the supply chain

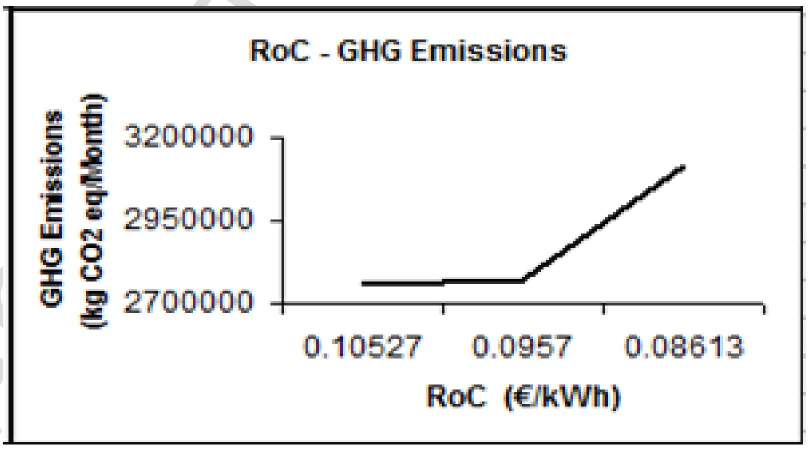

Figure 4(c). The impact of the RoC on the total investment cost of the supply chain

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)	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) Reference for incentive values: http://www.epowerauctions.co.uk/erocrecord.htm
2010	Feed-in Tariffs (FITs)	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). Reference for incentive values: https://www.ofgem.gov.uk/system/files/docs/2016/04/01_april_2016_tariff_table.pdf
2011	Renewable Heat Incentive (RHI)	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). Reference for incentive values: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-renewable-heat-incentive-rhi/tariffs-apply-non-domestic-rhi-great-britain

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

Capacity Level	**Unit investment cost of G plants (€/ton)** ***(DECC, 2012)***	**Unit investment cost of AD plants (€/ton)** ***(DECC, 2012)***	**Unit investment cost of CHP (€/kWe)** ***(DECC, 2012)***	**Unit investment cost of PT facilities(€/ton) (Rentizelas et al., 2014)**
1	9417	1652	487	842
2	8239	1446	419	739
3	7847	1377	352	709
Capacity Level	**Unit fixed and variable operational costs of G plants (€/ton) (DECC, 2012)**	**Unit fixed and variable operational costs of AD plants (€/ton) (DECC, 2012)**	**Unit fixed (€/kWe) and variable (€/kWh) operational costs of CHP (DECC, 2012)**	
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_2 Eq/ kWh)**	**Reference**
<u>Conversion</u>		
Biogas to energy	$3.67\text{x}10^{-4}$ (kg CO_2 Eq/ kWh)	DEFRA Carbon Conversion Factors Dataset (2015)
Syngas to energy	0.18445 (kg CO_2 Eq/ kWh)	DEFRA Carbon Conversion Factors Dataset (2015)
<u>Pretreatment</u>		
Pelletizing	$1.47\text{x}10^{-4}$ (kg CO_2 Eq/ ton)	Cucek et al. (2010)

Table 6. Data on the GHG emissions associated with transportation

	Cattle Manure (liquid)	**Broiler Hen Manure (Solid)**	**Layer Hen Manure (Liquid)**	**Waste Wood (Logging residues)**	**Wood pellet**	**Maize (Loose)**	**Fertilizer (liquid)**
GHG emissions (kg CO_2 eq/ ton-km)	$5.3x10^{-8}$ Cucek et al. (2010)	$5.3x10^{-8}$ Cucek et al. (2010)	$5.3x10^{-8}$ Cucek et al. (2010)	$5.3x10^{-8}$ Cucek et al. (2010)	$2.4x10^{-7}$ Cucek et al. (2010)	$1.1x10^{-6}$ Cucek et al. (2010)	$5.3x10^{-8}$ 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_2 eq/Month)
Optimistic case **Generation -** 0.10978 **Export -** 0.06908 **Total** – 0.17889	0.026 (heat) 0.0677 (biomethane)	0.0957	392,208	90,331,000	2,773,979
Base case **Generation -** 0.0998 **Export -** 0.0628 **Total** – 0.1626	0.026 (heat) 0.0677 (biomethane)	0.0957	341,197	90,331,000	2,773,974
Pessimistic case **Generation -** 0.08982 **Export -** 0.05652 **Total** – 0.14634	0.026 (heat) 0.0677 (biomethane)	0.0957	317,301	91,888,550	3,075,879
Generation - 0.0998 Export - 0.0628	**Optimistic case** 0.0286 (heat) 0.07447 (biomethane)	0.0957	375,452	90,331,000	2,773,979
Generation - 0.0998 Export - 0.0628	**Base case** 0.026 (heat) 0.0677 (biomethane)	0.0957	341,197	90,331,000	2,773,974
Generation - 0.0998 Export - 0.0628	**Pessimistic case** 0.0234 (heat) 0.06093 (biomethane)	0.0957	294,943	90,684,500	2,785,656
Generation - 0.0998 Export - 0.0628	0.026 (heat) 0.0677 (biomethane)	**Optimistic case** 0.10527	399,221	90,331,000	2,756,173
Generation - 0.0998 Export - 0.0628	0.026 (heat) 0.0677 (biomethane)	**Base case** 0.0957	341,197	90,331,000	2,773,974
Generation - 0.0998 Export - 0.0628	0.026 (heat) 0.0677 (biomethane)	**Pessimistic case** 0.08613	307,083	91,888,550	3,115,758