An Optimisation Framework for the Strategic Design of Synthetic Natural Gas (BioSNG) Supply Chains

Andrés J. Calderón[a], Paolo Agnolucci[b], Lazaros G. Papageorgiou[a,*]

[a] Department of Chemical Engineering, University College London, London WC1E 7JE, UK

[b] Institute for Sustainable Resources, University College London, London, WC1H 0NN, UK

[*] Corresponding author. E-mail address: l.papageorgiou@ucl.ac.uk (L.G. Papageorgiou).

Abstract

A general optimisation framework based on a spatially-explicit multiperiod mixed integer linear programming (MILP) model is proposed to address the strategic design of BioSNG supply chains. The framework considers procurement of feedstocks, plantation of energy crops, and different modes for transportation of feedstocks and final products. The mathematical framework allows researches and policy makers to investigate scenarios that promote the development of BioSNG supply chains in a regional and/or national context. The capabilities of the proposed model are illustrated through the implementation of a set of case studies based on the UK. The results revealed that domestic resources in the UK can supply up to 21.4% of the total gas demand projected by the UK National Grid in the scenario "Slow progression" for a planning horizon of 20 years. However, despite the considerable potential for production of BioSNG, the role of the government through schemes such as feed-in tariff and Renewable Obligation Certificates (ROCs) is crucial in order to make the development of these resources economically attractive for private sectors.

Keywords

Mixed integer linear programming; BioSNG supply chains; Feed-in tariffs; Renewable obligation certificates; Renewable resources.

1 Introduction

The BP Statistical Review of World Energy estimated that 86.7% of the total primary energy consumption was supplied by fossil fuels in 2013 [1], in which oil and coal are the world's leading fuels with 32.9% and 30.1% of total global consumption, respectively, followed by natural gas accounting for 23.7%. Furthermore, it is expected that the world's primary energy consumption will increase 41% in 2035 compared to 2012, which means an average annual growth rate of 1.5% according to the BP Energy Outlook 2035 [2]. Among non-fossil fuels, consumption of renewable energy sources was estimated to be 2% in 2012 and expected to increase up to 7% in 2035, matching the consumption from hydropower.

An energy supply chain based primarily on fossil fuels could raise concerns regarding energy supply security and energy sustainability. This has led to a worldwide tendency of establishing policies that support the development of renewable energy sources and sustainable technologies as well as facilitate their market penetration. In this context, the European Commission (EC) has devoted big efforts in designing and implementing policies that support the development of alternative energy sources. Based on 1990's levels, the EC has set binding targets to reduce 20% of the greenhouse gas (GHG) emissions by 2020, increase the share of renewable energy up to 20% and increase the energy efficiency to 20% [3]. Additionally, new targets for 2030 are under consultation with the intention of giving continuity and driving progress towards a low-carbon economy [4]. Momentarily, these targets have been set at 30% of reductions in GHG emissions compared to 1990's baseline, 27% share of renewable energy and 25% in energy savings. Furthermore, a target of 80% of reductions of GHG emissions has been proposed by the European Climate Foundation (ECF) [5].

Accordingly, the UK adopted targets regarding reduction of GHG emissions, which resulted in the Fourth Carbon Budget policy included in the Climate Change Act 2008 in which targets for reducing 26% and 80% of GHG emissions (1990's baseline) are proposed for 2020 and 2050, respectively [6]. In terms of energy consumption, it is expected that 15% of the total demand in the UK will be supplied by renewable energy in 2020 [7]. Additionally, a target regarding energy savings was set to 17.9% for 2020 compared to the energy consumption in 2007, and projected to increase to 29.3% by 2030 [8]. As a result, the UK government has implemented mechanisms to promote the development of renewable energy projects. The Feed-in Tariff (FIT) scheme is a government funding program designed to support the development of a range of small-scale renewable and low-carbon electricity generation technologies. Eligible renewable and low-carbon technologies are: Solar Photovoltaic (PV), wind, hydro, anaerobic digestion and micro CHP [9]. The Renewable Obligation Certificates (ROCs) have been designed to support the deployment of large-scale renewable electricity generating stations in the UK. Each supplier in the UK interconnected system must comply with a number of ROCs based on their annual energy generation. The ROCs are allocated to accredited operators for the electricity they generate from renewable sources. The ROCs can be traded among operators in spot markets. The scheme aims to increase the levels of supplied electricity coming from renewable resources. The obligation level is set annually by the UK and devolved governments [10]. Finally, the Renewable Heat Incentive (RHI) is a government financial incentive designed to subsidy technologies for generation of renewable heat in order to reduce GHG emissions. The RHI is fundamental for the UK to meet its renewable energy target of 15% by 2020, as required by the European Union. Among the eligible technologies are: Solid biomass, heat pumps, geothermal, solar, biogas combustion (the biogas must come from anaerobic digestion, gasification or pyrolysis), CHP, and biomethane injection [11].

These initiatives are focused on increasing the contribution of alternative energies in the UK energy mix by encouraging private sectors to invest in low-carbon generation technologies. While extensive research has been devoted to developing efficient and scalable low-carbon technologies, their application is rarely regarded as profitable and their use is still limited. Some of the challenges include:

- The implementation of low-carbon conversion technologies requires high capital investments by comparison to conventional technologies [12].
- The production of first-generation biofuels can have negative impacts on agricultural markets given the competition for land and water resources, which can lead to increments in food and biofuels prices [13].
- Second-generation biofuels are an alternative to overcome the competition for land and food [14]. Nonetheless, most of the technologies for second-generation biofuels are still in developing stage. Commercial applications are scarce and their associated costs are estimated to be high in comparison to first-generation conversion technologies.
- Usually, the cultivation of conventional arable crops, such as wheat or corn, is a more profitable activity for farmers and landowners than growing energy crops such as SRC or miscanthus, which risks a continuous supply of feedstock to conversion facilities [15].
- Biomass resources are, in general, highly dispersed in a territory, which results in significant higher costs related to handling machinery, transportation capacity, and skilled labour. Additionally, the energy density of biomass resources is significantly low, e.g. 3.6 kWh/kg for miscanthus bales compared to 12.9 kWh/kg for liquefied petroleum gas (LPG). This is reflected in higher transportation and storage costs due to poor utilisation of the infrastructure capacity [15].

Renewable energy sources and biofuels are expected to become the dominant energy source for power generation and transportation sectors. These sectors have been traditionally driven by fossil fuels, which are regarded as the major contributors of GHG emissions. Nonetheless, the transition from a predominantly fossil-fuel based economy to a more diverse energy mix is challenging. Natural gas, being a cleaner substitute to coal in power generation applications, could play an important role in the transition from fossil to renewable fuels [16]. In the UK, natural gas is a key energy source with a reported share of 33.9% (77.9 billion cubic meters (bcm)) of the total primary energy consumption in 2012 [17]. The UK gas infrastructure is well developed with a marked coverage across the country and capacity for gas imports by pipeline of 99.6 bcm/y and 51.4 bcm/y of LNG in 2010 [18]. Since 2004, when the UK became a net gas importer, the net gas imports by pipeline from Norway and Europe have steadily increased reaching a supply of 45% of the total gas consumption in 2014, putting at risk the energy security of England, Scotland, Wales, and Northern Ireland [19]. This scenario offers an excellent opportunity to investigate alternative processes for the production of natural gas from renewable resources in the UK. Among these, gasification of biomass or waste streams (e.g. wood waste, forestry residues, and residual waste) for the production of synthetic natural gas (BioSNG), which can be delivered using the current gas pipeline network [20], is an important alternative to be considered in order to reach the objectives set by the UK government and contribute to the national energy security.

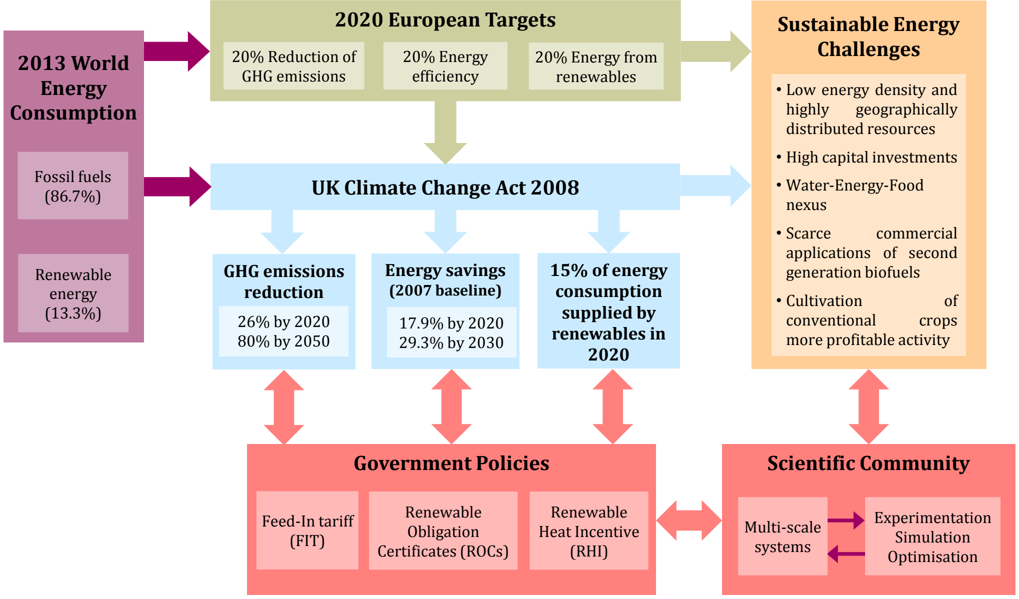


Figure 1. Global context

BioSNG is typically produced via an initial gasification step followed by gas conditioning (tar removals), BioSNG synthesis (methanation) and gas upgrading [21]. Currently, there are initiatives to develop BioSNG plants based on gasification across Europe. Gasification was initially developed for production of gas from coal in 1800's and its applications have been extended to production of methane and liquid fuels from coal [22] and [23]. Coal gasification has been successfully implemented at commercial scales in South Africa, China and United States [24]. However, the application of gasification as a renewable technology is a recent concept still in development stage. Currently, the Energy Research Center of Netherlands (ECN), the Center for Solar Energy and Hydrogen Research

(ZSW) in Germany, and the Paul-Scherrer Institut (PSI) in Switzerland are leading the investigation of gasification for woody biomass [21]. Van Der Meijden et al. [25] and Van Der Drift et al. [26] identified the concept developed by ECN, based on allothermal gasification, as the preferred technology for the production of BioSNG with efficiencies ranging from 67 to 70%. The production cost for a 100 MWth input capacity plant in Netherlands was estimated between 7.8 €/GJ and 8.5 €/GJ in 2004 [27]. The authors also determined that pressurization of the indirect gasifier will further improve the efficiency of the process.

A gasification-based plant requires high initial investments which can affect negatively its economics. As the gasification step has been identified to have the highest exergy losses in the production of BioSNG [28], energy integration has been suggested in order to improve not only the economic performance but also the process sustainability [29]. Heyne et al. [30] reported global efficiencies between 90% and 96% for a BioSNG production process integrated with an existing biomass CHP steam power cycle. The authors concluded that the production of BioSNG is not affected by the different methods of integration. Likewise, Tremel et al. [31] reported global efficiencies of up to 90% when a fully integrated process is considered. Moreover, optimisation techniques have been implemented in single-site applications to address diverse energy integration strategies for the polygeneration of BioSNG, heat, and power from biomass [32], [33] and [34]. The authors concluded that process integration and energy recovery enables an energetically and economically viable process.

The production of BioSNG can substantially benefit from a well-developed national gas pipeline network, traditionally used for transportation of conventional gas. However, the injection of BioSNG into a conventional gas pipeline network represents a major concern within the research and engineering community. Nonetheless, some authors have reported to be technically feasible to transport BioSNG through the conventional gas pipeline networks [35] and [36]. This has important repercussions on the development of BioSNG in a regional or national context as it facilitates the transportation of BioSNG from processing facilities to final customers and reduces considerably investments in transportation infrastructure. Regarding the development of BioSNG in a regional and/or national context, it has been suggested the installation of 12 BioSNG plants each with input capacity of 1000 MWth to supply 9% of the total primary energy consumption in Netherlands [37]. In the UK, the development of a 50-MWth demonstration facility in Teesside has been proposed in order to investigate technical uncertainties associated with BioSNG production such as injection of BioSNG into the national grid and feedstock procurement schemes, and to encourage investment from private sectors [38]. Furthermore, feedstocks such as stemwood, forestry residues, arboricultural arisings, sawmill coproducts, and clean wood waste were identified as suitable raw materials for BioSNG production in the short-term (before 2020) whereas BioSNG production from straw, miscanthus, and municipal solid waste is considered to be attainable in the long-term (after 2020) [39].

A successful implementation of renewable technologies in a regional and/or national context would require a thorough integration of three main components: feedstock procurement rates, production optimisation, and product transportation. This must be addressed while taking into account regional targets and government policies. Mathematical modelling and optimisation techniques are powerful tools that provide a systematic methodology to tackle these problems [40] and [41]. A substantial amount of research has been dedicated to the development of methodologies for the assessment of supply chain networks for the production of biofuels. Several optimisation frameworks have been developed to address the design and optimisation of ethanol supply chains in which decisions such as feedstock transportation routes, location and installed capacity of processing facilities, technology selection, and ethanol transportation are optimised with respect to an economic objective [42], [43], [44] and [45]. Some optimisation frameworks have been developed based on spatially-explicit formulations to better account for regional discretisation which provides flexibility to design the optimal transportation network for feedstocks and final products across a country [46], [47], [48] and [49]. The effects of economies of scale have been subject of research [50] and [51], as well as coproduction of heat and power by considering energy integration in processing facilities [52] and [53], which can significantly improve the economic performance and environmental benefits of sustainable processes [54]. Other authors have investigated the impact of market conditions and the government role in the development of biofuel supply chains [55] and

[56]. Furthermore, multiobjective optimisation techniques have been implemented for the optimal design and planning of biofuel supply chains while considering not only economic performance but also environmental and social aspects [57], [58], [59], [60], [61] and [62]. Finally, several optimisation frameworks have been proposed to deal with uncertainty in parameters such as feedstocks costs, price of final products, and future demand which can greatly affect the optimal decisions when compared to deterministic models [63], [64] and [65]. Regarding BioSNG supply chains, Steubing et al. [66] proposed a snapshot model for the optimal design of a supply chain for the production of BioSNG, heat and electricity from wood while maximising profit and minimising environmental impact. The authors reported that the environmental impact benefits from installation of plants with capacities ranging between 5 MW and 40 MW, whereas the economic performance increases when plants with capacities between 100 MW and 200 MW are installed.

In the light of the previous survey, available literature addressing the optimal development of nationwide supply chains for the production of BioSNG from biomass and/or waste streams is scarce. The purpose of this work is to present a systematic methodology based on a mathematical framework that contributes to the knowledge of the design and optimisation of BioSNG supply chains in a regional and nationwide context. Moreover, available studies in the UK address the economic feasibility only for single-site BioSNG projects. However, as the support of the UK government and private sectors for developing this technology increases, an integrated framework is needed in order to evaluate the potential of BioSNG as an alternative energy source in the UK and its role in meeting national targets. This paper aims to fill in that gap by providing a comprehensive decision-making support tool for the evaluation of a future BioSNG supply chain development based on domestic renewable resources and waste streams in the UK. In order to address the problem, a spatially-explicit multiperiod mixed integer linear programming (MILP) model is proposed for the strategic design and economic optimisation of a second generation nationwide BioSNG supply chain. The optimisation framework considers co-production of heat & power, location and selection of optimum capacities for processing facilities, economies of scale, different types of feedstocks as well as their geographic distribution, land utilisation and optimal cultivation rates for new specialised energy crops, and design of the transportation network from feedstocks suppliers to processing facilities and final products to demand centres. In addition, government incentives for production and injection of BioSNG into the national grid (Feed-in tariffs) and for generation of renewable energy (ROCs) are considered.

The remaining of the paper is organised as follows: in section 2 we present the problem statement along with a simplified superstructure showing the main components of a BioSNG supply chain. In section 3 we present a detailed discussion of the corresponding mathematical formulation which includes economic objective function, production and demand constraints, and cost-related constraints. Next, a case study based on the UK, discussed in section 4, is implemented to demonstrate the capabilities of the proposed framework. The optimisation results are discussed in section 5. Finally, the contributions and future extensions of this work are discussed in section 6.

2 Problem statement

The development of a supply chain for the production of BioSNG involves several strategic, logistic and operational decisions, including feedstock utilisation rate, cultivation rate of new energy crops, feedstock transportation modes, location and capacity for processing facilities, and production rates of final products. A generic BioSNG supply chain is presented in Figure 2.

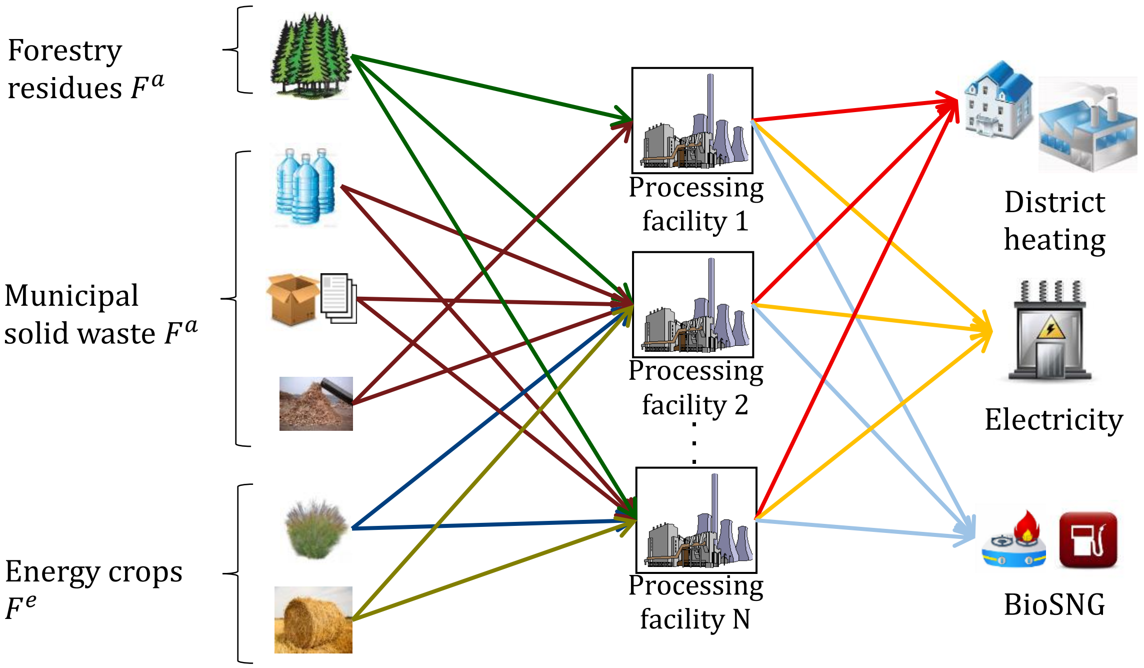


Figure 2. Generic BioSNG supply chain

The BioSNG supply chain considers a set of feedstocks suitable for BioSNG production $(f \in F)$ which are divided into a set of on-site available feedstocks $(f \in F^a)$, such as forestry residues, straw, and residual waste, and a set of new potential feedstocks $(f \in F^e)$ that require initial investments before they can be used in BioSNG production, such as miscanthus. The availability of these resources distributed along a set of regions $(g \in G)$ is considered to be given. These regions also serve as potential locations for installation of new processing facilities $(k \in K)$ where raw feedstock is converted into final products $(p \in P)$, i.e., BioSNG, heat and/or power. In order to include economies of scale, the relationship between plant capacities and capital expenditures is discretised in linear segments $(s \in S)$ by implementing a piecewise linearisation approach. Different transportation modes $(l \in L)$ are available for raw feedstocks and BioSNG. The available transportation modes for feedstocks or final products between regions are defined by the set $\eta_{igg'l}$ where $(i \in I)$ contains all the resources, i.e., feedstocks and final products, considered in the BioSNG supply chain. Biomass and residual waste can be transported either by truck or railroad. BioSNG can be transported as compressed natural gas by trailer from the processing plants to the gas network. It is worth to mention that power and heat have their own transmission systems whose incorporation in the mathematical formulation would require additional complex technical and operational considerations [67], [68], [69] and [70] .Therefore, for the sake of simplicity, these systems are not considered in the present formulation; instead, it is assumed that they are sold locally. In general, the BioSNG Supply Chain design problem can be defined as follows:

Given the input data:

- Geographical distribution of demand centres
- Gas, power and heat demand over the entire planning horizon
- Feedstock types and their geographical availability
- Geographical distribution of land availability for new crops
- Feedstock production costs

- Capital and operating costs for transportation modes
- Transport logistics (modes, capacities, distances, availability)
- Technical (yields) and economic (capital and operating costs) parameters as a function of feedstock types and production technology
- Gas, power and heat market prices
- Government incentives (Feed-in tariff and ROCs)

The key variables to be optimised over the planning horizon are:

- Feedstock procurement rate for each feedstock type
- BioSNG production rates
- Technology selection, locations and scales of BioSNG production facilities
- Biomass cultivation sites
- Flows of each feedstock type and BioSNG between regions
- Modes of transport of delivery for biomass and biofuel

The BioSNG supply chain is formulated as a spatially-explicit multiperiod and single objective MILP model. The goal is the maximisation of Net Present Value (NPV) subject to logistical, operational and economic constraints.

3 Mathematical formulation

In this section, we present a deterministic optimisation model for the strategic design and planning of BioSNG supply chains. The proposed model is defined by material balances, production and demand constraints, logistic constraints and economic constraints. The features of the model are discussed in detail in the following sections.

3.1 Objective function

The objective function of the model is the maximisation of the net present value, NPV, subject to operational and logistic constraints. The net present value is expressed as the cash flow, CF_t, minus the capital expenditures, $CAPEX_t$, as shown in Equation (1). The parameters $DfCF_t$ and $DfCA_t$ are the corresponding discount factors.

$$max \quad NPV = \sum_{t} (DfCF_t * CF_t - DfCA_t * CAPEX_t) \tag{1}$$

3.1.1 Capital investments

Capital expenditures, $CAPEX_t$, are calculated as the summation of the investment in integrated facilities, $CAPEX\_IN_t$, investment in infrastructure for BioSNG transportation, $CAPEX\_TR_t$, and investment in new energy crops for BioSNG production, $CAPEX\_EC_t$, as shown in Equation (2).

$$CAPEX_t = CAPEX\_IN_t + CAPEX\_TR_t + \ CAPEX\_EC_t \quad \forall\, t \tag{2}$$

3.1.2 Cash flow and depreciation

Cash flow is defined as the profit before taxes, $PROFIT_t$, plus depreciation of assets, $DEP_{t't}$, minus taxes, TAX_t, as presented in Equation (3).

$$CF_t = PROFIT_t + \sum_{t'} DEP_{t't} - TAX_t \quad \forall\, t \tag{3}$$

The linear method is used to calculate the depreciation, $DEP_{tt'}$ as a function of capital expenditures using a given depreciation rate, $DepF_{tt'}$ as expressed in Equation (4). $DEP_{tt'}$ represents the depreciation during period t' for investments made in a previous period t:

$$DEP_{tt'} = DepF_{tt'}(CAPEX\_IN_t + CAPEX\_TR_t) \quad \forall\, t, t' \tag{4}$$

Where $CAPEX\_IN_t$ and $CAPEX\_TR_t$ correspond to capital expenditures for integrated facilities and new infrastructure for BioSNG transportation, respectively. Investment costs related to energy crops (pre-planting and establishment costs), $CAPEX\_EC_t$, are considered non-depreciable.

3.1.3 Income

The income for each period, $INCOME_t$, is calculated based on the total production, P_{pgt}, where $(p \in P)$ corresponds to final products, i.e., BioSNG, heat, and, power. Similarly, set $(g \in G)$ relates to regions considered in the BioSNG supply chain. Additionally, final products prices, $Price_{pt}$, and possible government incentives, Inc_{pt}, are included as described in Equation (5):

$$INCOME_t = \sum_{pg} \left(Price_{pt} + Inc_{pt}\right) * P_{pgt} \quad \forall\, t \tag{5}$$

3.1.4 Profit and taxes

The net profit associated with the BioSNG supply chain operation is calculated as the income, $INCOME_t$, minus operating expenditures, $OPEX_t$, and minus depreciation, as defined in Equation (6).

$$PROFIT_t = INCOME_t - OPEX_t - \sum_{t'} DEP_{t't} \quad \forall\, t \tag{6}$$

In this formulation we consider that taxes apply only when profit is positive, taxes are set to zero otherwise. The taxation charge is estimated based on a tax rate, Tr, and profit. These conditions are modelled by Equations (7) and (8). In case of a different tax system for a particular case study, Equations (7) and (8) should be modified accordingly.

$$TAX_t \geq Tr * PROFIT_t \quad \forall\, t \tag{7}$$

$$TAX_t \geq 0 \quad \forall\, t \tag{8}$$

3.1.5 Operating expenditures

Operating expenditures are estimated as the sum of feedstock costs, FC_t, production costs, PC_t, and transportation costs, TC_t, as shown in Equation (9).

$$OPEX_t = FC_t + PC_t + TC_t \quad \forall\, t \tag{9}$$

The feedstock costs include payments for acquisition of available feedstocks and operation of new cultivated areas for production of energy crops. Productions costs refer to expenses incurred for operating processing facilities. Finally, transportation costs take into account expenses related to biomass, residual waste, and BioSNG transportation.

3.2 Production constraints

Initially, a global balance is included to account for the production, demand, and transfers of resources i, i.e., feedstocks and final products, between regions g and g' in time period t, as depicted in Equation (10):

$$P_{igt} + \sum_{l} \sum_{g' \in \eta_{ig'gl}} Q_{ig'glt} = D_{igt} + \sum_{l} \sum_{g' \in \eta_{igg'l}} Q_{igg'lt} \quad \forall\, i, g, t \tag{10}$$

P_{igt} and D_{igt} correspond to the production and demand of resources i in region g and in time period t, respectively. Variable $Q_{ig'glt}$ represents transfers of resources i between regions g and g' via transport mode l during time period t. The feasible connections between resources, regions, and available transportation modes are predefined by the set $\eta_{igg'l}$. The production P_{igt} encompasses production of new energy crops, procurement of available feedstocks, and final products. Moreover, D_{igt} comprises demand of both new and available feedstocks required by potential processing facilities, and demand of final products, which is subsequently related to specific demand data according to the case study.

3.2.1 Available feedstocks

The procurement rate P_{fgt} of feedstock available onsite ($f \in F^a$) is modelled through Equation (11). In this case, feedstocks are assumed to be readily available onsite, therefore, new areas for cultivation are not required.

$$\gamma * LHV_f * Fmin_{fgt} \leq P_{fgt} \leq \gamma * LHV_f * Fmax_{fgt} \quad \forall\, f \in F^a, g, t \tag{11}$$

The procurement rate is limited by parameters $Fmax_{fgt}$ and $Fmin_{fgt}$ which refer to the maximum local availability and minimum flow rates. Parameter LHV_f corresponds to the low heating value of the feedstocks. Scalar γ is a conversion factor introduced for consistency of units.

3.2.2 Energy crops

In addition to currently available feedstocks, cultivation of new energy crops, e.g. Miscanthus, short-rotation coppice, switchgrass, for the production of BioSNG is considered. The cultivation rate of new feedstocks is estimated based on the feedstock productivity, $Yield_{fgt}$, which varies according to land quality and type of feedstock, and the total cultivation area, $TArea_{fgt}$, required for feedstocks ($f \in F^e$) in region g and time period t. The corresponding formulation is presented in Equation (12).

$$P_{fgt} = \gamma * LHV_f * Yield_{fgt} * TArea_{fgt} \quad \forall f \in F^e, g, t \tag{12}$$

The total cultivation area $TArea_{fgt}$ required for new plantations along the planning horizon is expressed by Equation (13):

$$TArea_{fgt} = TArea_{fg,t-1} + A_{fgt} \quad \forall f \in F^e, g, t \tag{13}$$

Where A_{fgt} is the new added area for cultivations of feedstocks ($f \in F^e$) in region g during time period t. The cultivation of energy crops in new areas can take several years before harvesting, e.g., ~3 years for Miscanthus [71], which makes the role of the government crucial to encourage their cultivation, possibly, through long-term agreements with farmers. Accordingly, Equation (13) ensures that an area that has been chosen for energy crops cultivation will not be reduced or completely abolished in the next period which could be negative for the economy of farmers. The total cultivation area is limited by the local available land which is estimated as the total area of a region g, represented by parameter $Land_{gt}$, multiplied by a factor of land usage δ_{gt} which represents the fraction of suitable land that can be used in region g and time period t for growing energy crops, as shown in Equation (14).

$$\sum_{f \in F^e} TArea_{fgt} \leq \delta_{gt} Land_{gt} \quad \forall g, t \tag{14}$$

Finally, the suitable land for new plantations cannot be used entirely for energy crops due to sustainability issues and risks associated with land competition [72], thus, Equation (15) is introduced to constraint the maximum total area that can be used for new energy crops, represented by parameter $MaxLand_t$.

$$\sum_{f \in F^e, g} TArea_{fgt} \leq MaxLand_t \quad \forall t \tag{15}$$

3.2.3 Final products

In this framework, integrated plants will be considered as potential facilities for the production of BioSNG and coproducts, e.g. heat and power, from raw feedstocks. In this case, the feedstocks are pre-processed and converted into final products in the same facilities. The production from integrated plants can be related to the regional production by means of Equation (16).

$$P_{pgt} = \sum_{k} \sum_{f \in F_k} PIN_{fkpgt} \quad \forall\, p, g, t \tag{16}$$

P_{pgt} refers to the production of p in region g and time period t. PIN_{fkpgt} indicates the production of a potential integrated plant processing feedstock f with technology k to produce p in region g during time period t. Set F_k contains connections between feedstocks f that can be processed with technologies k. A global balance for integrated plants relating their production of BioSNG, $PIN_{fk,biosng,gt}$, with the corresponding demand of feedstocks, DIN_{fkgt}, can be expressed as shown in Equation (17).

$$PIN_{fk,biosng,gt} = \beta IN_{fk,biosng} * DIN_{fkgt} \quad \forall\, k, f \in F_k, g, t \tag{17}$$

Parameter $\beta IN_{fk,biosng}$ accounts for the efficiency of an integrated plant using feedstock f to produce BioSNG via technology k. Equation (17) is valid only for all the feasible connections predefined in set F_k. Besides BioSNG, heat & power are important coproducts derived from energy integration which increases the global efficiency of the BioSNG production and therefore would benefit the economic performance [31]. A general scheme showing energy integration in BioSNG facilities is depicted in Figure 3.

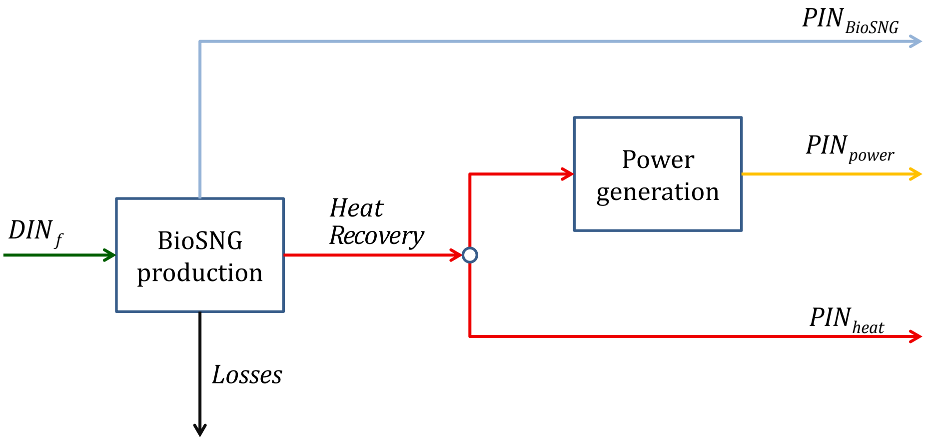


Figure 3. Optional energy integration for BioSNG production

As the production of BioSNG is the main objective, we consider that the efficiency from feedstocks to BioSNG is known and will not be affected by the co-generation of heat and/or power. That is, the production of syngas will be used exclusively for BioSNG production and will not be diverted for cogeneration of heat & power. On the other hand, the production of power will be affected by the production of heat and vice versa. In addition, the generation of power from heat is subject to an efficiency denoted by μ. This is taken into account in the mathematical formulation by including a global balance across integrated facilities as depicted in Equation (18).

$$\frac{PIN_{fk,power,gt}}{\mu} + PIN_{fk,heat,gt} \leq \beta IN_{fk,heat} * DIN_{fkgt} \quad \forall\, k, f \in F_k, g, t \tag{18}$$

This equation relates the demand of an integrated plant, DIN_{fkgt}, with the production of heat, $PIN_{fk,heat,gt}$, and power, $PIN_{fk,power,gt}$, by introducing the efficiency of heat recovery, $\beta IN_{fk,heat}$, and the efficiency of power generation, μ. This formulation determines the optimal proportion of heat and power generated in a certain processing plant.

3.3 Demand constraints

The demand D_{igt} (see Equation (10)) refers not only to the demand of final products, i.e. BioSNG, heat, and power, but also to the demand of feedstocks in integrated plants in a certain region as described in section 3.2. The corresponding equations relating these variables are presented next.

3.3.1 Feedstocks demand

Demand of feedstocks in each potential new facility must be related to the regional demand of such feedstocks. In this case, it is not necessary to include different demand constraints for available and new feedstocks, unlike the production constraints (see sections 3.2.1 and 3.2.2). Therefore, the demand for both types of feedstocks can be expressed in just one constraint as shown in Equation (19).

$$D_{fgt} = \sum_{k: f \in F_k} DIN_{fkgt} \quad \forall\, f, g, t \tag{19}$$

Variable D_{fgt} refers to the total regional demand of feedstocks ($f \in F$) during time period t.

3.3.2 Final products demand

One of the major advantages of BioSNG is its compatibility with conventional natural gas which makes possible the transportation of BioSNG through conventional gas pipeline transportation networks. Accordingly, in this model it is assumed that the BioSNG will be injected into the existing National Grid Transmission System, specifically in points that are connected to the Gas Distribution Network (GDN). In the UK, the GDN is divided into Local Distribution Zones (LDZs) which are in charge of transporting natural gas from the injection points to final customers. In this work, it is considered that the BioSNG is used to supply customers that require medium to low gas pressure supply. Therefore, the demand will be set based on the LDZs. In order to maintain a general mathematical framework, it is assumed that the geographical distribution of the LDZs do not match the distribution of regions g. This is taken into account by including Equations (20) and (21):

$$D_{pgt} = \sum_{z:g \in G_z} DGZ_{pgzt} \quad \forall\, p, g, t \tag{20}$$

$$\sum_{g \in G_z} DGZ_{pgzt} \leq Dem_{pzt} \quad \forall\, p, z, t \tag{21}$$

The previous equations allow to link the demand of products p in regions g, represented by variable D_{pgt}, with the demand of products p in LDZ regions z, represented by parameter Dem_{pzt}. The set G_z contains the regions g that have at least one injection point belonging to a Local Distribution Zone z. As the final goal is maximisation of net present value, the demand constraint is written as an upper bound. In case of power and heat cogeneration, it is assumed that they are sold locally and therefore no transportation cost is incurred.

3.4 Capital investments

The estimation of capital investments depend on three components: (1) investments in new processing facilities, (2) investment in new infrastructure for BioSNG transportation from processing facilities to injection points, and (3) investments associated with cultivation of new energy crops. The corresponding mathematical formulation is presented as follows.

3.4.1 Processing facilities

As the capacity of a plant increases, the investment costs per unit of installed capacity are reduced. This is known as economies of scale and follows a non-linear curve pattern that resembles a power curve. The effect of economies of scale is taken into account in the mathematical formulation, however, in order to keep the model linear. The capital investment costs for integrated plants are linearised by implementing a piecewise linear approximation approach. The concave curve is split up into several linear segments s as depicted in Equation (22).

$$CMin_{ks} * \delta IN_{fkgts} \leq CAPIN_{fkgts} \leq CMax_{ks} * \delta IN_{fkgts} \quad \forall\, k, f \in F_k, g, t, s \tag{22}$$

The variable $CAPIN_{fkgts}$ refers to new installed capacity of integrated plants in region g and time period t. Parameters $CMin_{ks}$ and $CMax_{ks}$ limit the minimum and maximum capacity that can be installed for an integrated plant with technology k if segment s is chosen. δIN_{fkgts} is a binary variable taking the value of 1 if an integrated plant is installed for processing feedstock f with technology k in region g and time t with a capacity limited by the segment s; otherwise is 0. Only one segment can be activated, and only one integrated plant for each type of feedstock is allowed to be installed in region g. These conditions are modelled through Equations (23) and (24), respectively.

$$\sum_{s} \delta IN_{fkgts} \leq 1 \quad \forall\, k, f \in F_k, g, t \tag{23}$$

$$\sum_{s} \sum_{k: f \in F_k} \delta IN_{fkgts} \leq 1 \quad \forall\, f, g, t \tag{24}$$

Equation (25) accounts for the total installed capacity of an integrated plant processing feedstock f with technology k in region g during time t.

$$ToCAPIN_{fkgt} = ToCAPIN_{fkg,t-1} + \sum_{s} CAPIN_{fkgts} \quad \forall\, k, f \in F_k, g, t \tag{25}$$

The maximum amount of feedstock f that can be processed in an integrated plant, DIN_{fkgt}, is limited by its total installed capacity, $ToCAPIN_{fkgt}$, the capacity factor Cf, and the availability factor Avf. The capacity factor refers to the ratio between the actual production in a certain period and the nameplate capacity of the plant. The availability factor is the fraction of time that a plant can operate before maintenance is required. In general, these values correspond to the fraction of the capacity that can actually be used as described in Equation (26).

$$DIN_{fkgt} \leq Cf * Avf * \alpha * ToCAPIN_{fkgt} \quad \forall\, k, f \in F_k, g, t \tag{26}$$

Scalar α corresponds to the number of hours in a year. Finally, the total investment cost, $CAPEX\_IN_t$, is calculated by means of Equation (27):

$$CAPEX\_IN_t = \sum_{kgs} \sum_{f \in F_k} \left(bIN_{fks} * \delta IN_{fkgts} + aIN_{fks} * CAPIN_{fkgts} \right) \quad \forall\, t \tag{27}$$

Where aIN_{fks} and bIN_{fks} are parameters that represent variable and fixed investment costs. This information results from the linearisation of the corresponding investment cost curve.

3.4.2 BioSNG transportation infrastructure

It is assumed that new facilities are required for BioSNG transportation. In this case, only Compressed Natural Gas (CNG) for BioSNG transportation is included. A modified mathematical formulation from previous works [73,74] is incorporated to account for investments in new facilities for BioSNG transportation as shown in Equation (28):

$$\begin{aligned} CAPEX\_TR_t = & \sum_{(gg'l) \mid \in \eta_{biosng,gg'l}} \frac{\psi * TMC_l * Q_{igg'lt}}{TMA_l^{Reg} * TCap_l * LHV_i} \left(\frac{2 * AD_{gg'l}}{SP_l} + LUT_l \right) \\ & + \sum_{(gl) \mid l = \{trailer\}} \frac{\psi * TMC_l * LocSup_{gt}}{TMA_l^{Loc} * TCap_l * LHV_i} \left(\frac{2 * LD_g}{SP_l} + LUT_l \right) \quad \forall\, t \end{aligned} \tag{28}$$

Equation (28) is composed by two terms that correspond to capital investments for regional and local transportation of BioSNG, respectively. TMC_l refers to the capital cost for establishing a new transportation mode l. LUT_l is the load-unload time of the transportation units, e.g. trailers, trucks. $TCap_l$ is the capacity of a new transportation unit. TMA_l^{Reg} and TMA_l^{Loc} are the regional and local availability of transportation mode l expressed in hours per day. SP_l is the average speed of transportation mode l. LD_g and

$AD_{gg'l}$ are the local and regional delivery distances. The calculation of costs is driven by the amount of BioSNG that is being transported either locally or regionally. This is represented by the variable $Q_{biosng,gg'lt}$ which is the flow rate of product BioSNG between regions g and g' via mode l, and the variable $LocSup_{gt}$ which refers to the amount of BioSNG that is produced and supplied within the same region. In order to calculate the local supply, it is assumed that $LocSup_{gt}$ is limited either by the local production $P_{biosng,gt}$ or the local demand $D_{biosng,gt}$. That is, if the local production is higher than the local demand, then $LocSup_{gt}$ is set to be equal to the local demand. Likewise, if the local production is lower than the local demand, then $LocSup_{gt}$ is set to be equal to the local production. These conditions are modelled through Equations (29)and (30):

$$LocSup_{gt} \geq P_{biosng,gt} - LimP * \left(1 - PD_{gt}\right) \quad \forall\, g, t \tag{29}$$

$$LocSup_{gt} \geq D_{biosng,gt} - LimD * PD_{gt} \quad \forall\, g, t \tag{30}$$

Where, $LimP$ is an upper bound for production and $LimD$ an upper bound for demand. PD_{gt} is a binary variable that equals 1 if BioSNG production in region g and time period t is less than the demand in same region and time period. If that is the case, $LocSup_{gt}$is set at the value of $P_{biosng,gt}$, otherwise if $P_{biosng,gt}$ is greater than $D_{biosng,gt}$, the binary variable is equal to 0 and the variable $LocSup_{gt}$ is set at the value of $D_{biosng,gt}$. It is worthwhile to mention that this is an approximation in order to reduce the complexity of the model.

3.4.3 New feedstocks

If plantation of new feedstocks is required, then investments in cultivating areas with new crops should be made. The total capital expenditures, $CAPEX\_EC_t$, in new crops is expressed in Equation (31):

$$CAPEX\_EC_t = \sum_{f \in F^e, g} \left(EstCost_{ft} + PlanRem_{ft}\right) * A_{fgt} \quad \forall\, t \tag{31}$$

$EstCost_{ft}$ and $PlanRem_{ft}$ are parameters that account for costs associated with the establishment of new plantations and plantation removal costs, respectively.

3.5 Operating expenditures

Operational costs consist of cost associated with feedstock production, cost of production in integrated facilities, and corresponding transportation costs.

3.5.1 Feedstocks costs

Equation (32) presents the estimation of total costs FC_t related to procurement of feedstock:

$$FC_t = \sum_{f \in F^a, g} \frac{\lambda * UFC_{fgt} * P_{fgt}}{LHV_f} + \sum_{f \in F^e, g} \lambda * \left(Rent_{gt} + OpCost_{ft}\right) * TArea_{fgt} \quad \forall\, t \tag{32}$$

The first term of the right-hand side of Equation (32) accounts for costs associated with purchasing available feedstocks, e.g., forestry residues and agricultural waste. The second term refers to costs associated with new feedstocks. The parameter UFC_{fgt} represents the unit acquisition cost for available feedstocks ($f \in F^a$). Parameters $Rent_{gt}$ and $OpCost_{ft}$ are the renting costs of land for new plantations and general operational costs, respectively. The latter includes fixed overheads, agrochemicals, harvesting costs and storage costs.

3.5.2 Production costs

Total production costs PC_t are split into fixed and variable costs. Fixed costs are independent of the output level of a plant and often include insurance, rent, salaries, etc. On the other hand, variable costs such as inventory, utilities, packaging, etc. depend proportionally on the actual production of a plant. This is expressed mathematically in Equation (33).

$$PC_t = \sum_{kg} \sum_{f \in F_k} \left(FxOpIN_{fkt} * AvIN_{fkgt} + VrOpIN_{fks} * PIN_{fkg,biosng,t}\right) \quad \forall\, t \tag{33}$$

Parameters $FxOpIN_{fkt}$ and $VrOpIN_{fks}$ correspond to fixed and variable costs of integrated plants. The binary variable that accounts for installation and subsequent capacity expansions, δIN_{fkgts}, is not adequate to calculate the fixed operational costs. Therefore, a new binary variable, $AvIN_{fkgt}$, is introduced which becomes active once a plant is installed. This condition is modelled by means of Equations (34) and (35).

$$AvIN_{fkgt} \geq \sum_{s} \delta IN_{fkgts} \quad \forall\, k, f \in F_k, g, t \tag{34}$$

$$AvIN_{fkgt} \geq AvIN_{fkg,t-1} \quad \forall\, k, f \in F_k, g, t \tag{35}$$

3.5.3 Transportation costs

The total transportation cost TC_t is calculated as the sum of local and regional transportation costs for delivery of feedstocks, and BioSNG as shown in Equation (36):

$$TC_t = TC\_F_t + TC\_SNG_t^{Reg} + TC\_SNG_t^{Loc} \quad \forall\, t \tag{36}$$

Calculation of feedstock transportation costs includes local and regional components. Furthermore, the local and regional costs are divided into two terms, fixed and variable expenses as depicted in Equation (37). The unit fixed cost for local transportation of feedstocks is represented by parameter $FxTC_f^{Loc}$. The total fixed cost is proportional to the production of feedstocks which is denoted by the variable P_{fgt}. On the other hand, the local variable cost is estimated based on the unit local variable cost, $VrTC_f^{Loc}$, the local production of feedstocks, P_{fgt}, and local transportation distance, LD_g.

$$\begin{aligned} TC\_F_t = {} & \sum_{fg} \left(\frac{\lambda * FxTC_f^{Loc} * P_{fgt}}{LHV_f} + \frac{\lambda * VrTC_f^{Loc} * LD_g * P_{fgt}}{LHV_f} \right) \\ & + \sum_{(fgg'l) \in \eta_{igg'l}} \left(\frac{\lambda * FxTC_{fl}^{Reg} * Q_{fgg'lt}}{LHV_f} \right. \\ & \left. + \frac{\lambda * VrTC_{fl}^{Reg} * AD_{gg'l} * Q_{fgg'lt}}{LHV_f} \right) \quad \forall\, t \end{aligned} \tag{37}$$

An equivalent formulation is included to account for regional transportation costs in which parameters $FxTC_{fl}^{Reg}$ and $VrTC_{fl}^{Reg}$ refer to fixed and variable unit regional costs for transporting feedstock f via mode l. The regional distances are represented by parameter $AD_{gg'l}$. Scalar λ is a conversion factor included for consistency of units. Additionally, local transportation costs of BioSNG, $TC\_SNG_t^{Loc}$, associated with new installed facilities are calculated through Equation (38):

$$TC\_SNG_t^{Loc} = \sum_{gl} \left[FP_l \frac{2 \ast \lambda \ast LD_g \ast LocSup_{gt}}{FE_l \ast TCap_l \ast LHV_i} + DW_l \frac{\lambda \ast LocSup_{gt}}{TCap_l \ast LHV_i} \left(\frac{2 \ast LD_g}{SP_l} + LUT_l \right) \right.$$
$$+ ME_l \frac{2 \ast \lambda \ast LD_g \ast LocSup_{gt}}{TCap_l \ast LHV_i} \tag{38}$$
$$\left. + GE_l \frac{\lambda \ast LocSup_{gt}}{TMA_l^{Loc} TCap_l \ast LHV_i} \left(\frac{2 \ast LD_g}{SP_l} + LUT_l \right) \right] \quad \forall\, t, i = \{biosng\}$$

Four main components constitute the local costs due to BioSNG transportation: fuel price FP_l, driver wage DW_l, maintenance expenses ME_l, and general expenses GE_l. Parameter FE_l refers to the fuel efficiency. Finally, an analogous formulation is included to calculate the regional costs for BioSNG transportation, $TC\_SNG_t^{Reg}$, as depicted in Equation (39):

$$TC\_SNG_t^{Reg} = \sum_{(igg'l)|\in \eta_{igg'l}} \left[FP_l \frac{2 \ast \lambda \ast AD_{gg'l} \ast Q_{igg'lt}}{FE_l \ast TCap_l \ast LHV_i} \right.$$
$$+ DW_l \frac{\lambda \ast Q_{igg'lt}}{TCap_l \ast LHV_i} \left(\frac{2 \ast AD_{gg'l}}{SP_l} + LUT_l \right) + ME_l \frac{2 \ast \lambda \ast AD_{gg'l} \ast Q_{igg'lt}}{TCap_l \ast LHV_i} \tag{39}$$
$$\left. + GE_l \frac{\lambda \ast Q_{igg'lt}}{TMA_l^{Reg} TCap_l \ast LHV_i} \left(\frac{2 \ast AD_{gg'l}}{SP_l} + LUT_l \right) \right] \quad \forall\, t, i = \{biosng\}$$

3.6 Model summary

The proposed optimisation framework previously described addresses the long-term strategic design of BioSNG supply chains at regional and national levels. The proposed model relies on an economic component, Equations (1) to (9), that is common to other methodologies presented for different systems. However, there are important considerations particularly relevant to the design of BioSNG supply chains worth of highlighting. One of them is the computation of land used for sustainable energy applications, modelled through Equations (12) and (13), since they allow to contemplate regional and nationwide environmental limits for a sustainable production of BioSNG from energy crops, which is modelled by means of Equations (14) and (15). Energy integration for the cogeneration of heat and power is another important aspect for the economics of

BioSNG supply chains. This has been included as part of the optimisation process by means of Equation (18). The compatibility of BioSNG with natural gas makes possible its injection into the gas transmission or distribution system. Certainly, this is a tremendous advantage for the economics of BioSNG production. Accordingly, Equations (20) and (21) account for any existing natural gas transportation network that can supply BioSNG to final consumers. Finally, costs related to the development of new infrastructure for local and regional deliveries of BioSNG from processing plants to injection points should be considered. This is accounted for by Equations (28) to (30) which are included to calculate the capital investments of BioSNG transportation infrastructure, and Equations (38) and (39) which are included to account for the associated operational costs.

4 Model implementation: a UK-based case study

In this section, we discuss the applicability of the proposed optimisation model through the implementation of a UK case study. The optimisation framework requires technical and economic information regarding feedstock cultivation, processing facilities, and transportation modes. In addition, geographically distributed data is necessary in order to quantify demand distribution and location of available and new resources for energy generation. A Geographical Information System (GIS) was used to process this type of information. In general, the information comes in shapefile or raster format; these layers are uploaded in ArcGIS 10.2 [75] in which a pre-processing stage is carried out to generate data that fits the particular features of the case study such as the time horizon and the discretisation of the territory under study. This case study considers a time horizon of 20 years from 2020 to 2040 divided into four 5-year periods. Additionally, the UK map was discretised accordingly to level 2 of the Nomenclature of Territorial Units for Statistics (NUTS2) [76]. A map showing NUTS1 and NUTS2 classification as well as equivalence between NUTS2 codes and the corresponding actual names of the regions is provided in section A.2 of supporting information. In total, 35 regions are included in the case study.

4.1 Resources

In this study, 4 types of resources are included as potential feedstocks for BioSNG production: (1) woody biomass, (2) cereal straw, (3) miscanthus, as a new energy crop, and

(4) residual waste. The potential availability of each feedstock is estimated based on domestic resources.

4.1.1 Woody biomass

Currently, woody biomass is regarded as the most likely feedstock to be used in first commercial plants for production of BioSNG [17]. In this study, the potential of woody biomass available for renewable energy generation is estimated based on 4 sources: (1) forestry residues and stemwood, (2) arboricultural arisings, and (3) sawmill coproducts.

Forestry residues are mainly composed by tips and branches (56%), poor quality stemwood (30%), and foliage (14%) [77]. The European Environmental Agency (EEA) estimated that in the UK the total potential that can be used without impacting the environment is 3450 kTon/yr for 2020 and 2532 kTon/yr for 2030 [78]. As the information is reported at national level, a map for the geographic distribution of forestry lands across UK [79] (see section A.4 in supporting information) is used as proxy for the calculation of available forestry residues at NUTS2 level. Arboricultural arisings include stemwood, branches, wood chips, and foliage from harvesting, pruning and safety operations in urban and semi-rural areas. The contribution of arboricultural arisings for energy generation is 332 kTon/yr [80]. In order to distribute this potential into the 35 regions (NUTS2), a Land Cover Map of Great Britain published in 2007 (LCM2007) was used [81]. With respect to sawmill coproducts, the fraction available for energy generation is set to 10% of the total sawmill coproducts since most of the production is sold to wood processing industries [80]. The total production of sawmill coproducts in the UK for 2020 was projected to be 120 kTon/y [77]. The sawmill coproducts potential at NUTS2 level was estimated based on a map of active sawmills in the UK (see section A.4 in supporting information).

In total, the resources of woody biomass that can be used for energy generation are estimated in 3902 kTon/y by 2020. As the woody resources are composed by different types of biomass, an average cost of 65 £/Ton was used for all the regions [82]. This cost was kept constant for all the planning periods.

4.1.2 Cereal Straw

Agricultural residues are an additional source of biomass for renewable energy generation. For this case study, cereal straw, from wheat and barley, is considered to be a suitable feedstock for future projects in BioSNG production. The Department for Environment Food and Rural Affairs (Defra) estimated that the total straw production in the UK in 2007 ranged between 9 and 10 million tonnes per year. Nonetheless, a significant fraction of these resources are recycled for activities such as animal bedding (56%), animal feed (19%), and used as fertilizers and organic matter supplements [83]. After considering these figures, Defra estimated the total production of cereal straw available for bioenergy production to be 3000 KTon/yr [84]. The price of cereal straw was fixed at 60 £/Ton which is the average of the monthly price reported by Defra for pickup baled wheat straw in 2014 [85].

4.1.3 Miscanthus

Specialised energy crops can play an important role in the development of renewable supply chains. Miscanthus is a perennial energy crop with great potential for sustainable energy generation, which could have environmental advantages if its cultivation is carried out in marginal land areas avoiding land competition and woodland or grassland replacement [86]. In this study, miscanthus is included as a potential new feedstock. In this case, the availability is defined in terms of the crop productivity and available marginal land for energy crops cultivation across the UK. The miscanthus yield potential for current and future climate conditions across Great Britain was investigated by Hastings et al. [87]. Miscanthus yield maps were generated for 2020, 2030 and 2050 in which three scenarios were considered; low, medium and high productivity. In this study, the high productivity scenario was used as it seems to be the path the UK is committed to for the foreseeable future (The School of Biological Sciences, The University of Aberdeen. Personal communication). Additionally, Lovett et al. [88] studied the potential available land for cultivation of new perennial crops for energy generation. A rigorous land classification was implemented in order to exclude territories from the final land availability estimation such as: Urban areas, main roads, rivers, lakes, natural and seminatural areas, areas with slope greater than 15%, high organic carbon soils, existing woodland, cultural heritage, natural parks, and areas of outstanding natural beauty. Finally, a potential availability of 8.1 Mha was estimated for new specialised energy crops, which is equivalent to 35% of the Great Britain territory. The interception of the potential miscanthus yield map and the available land map is shown in Figure 4.

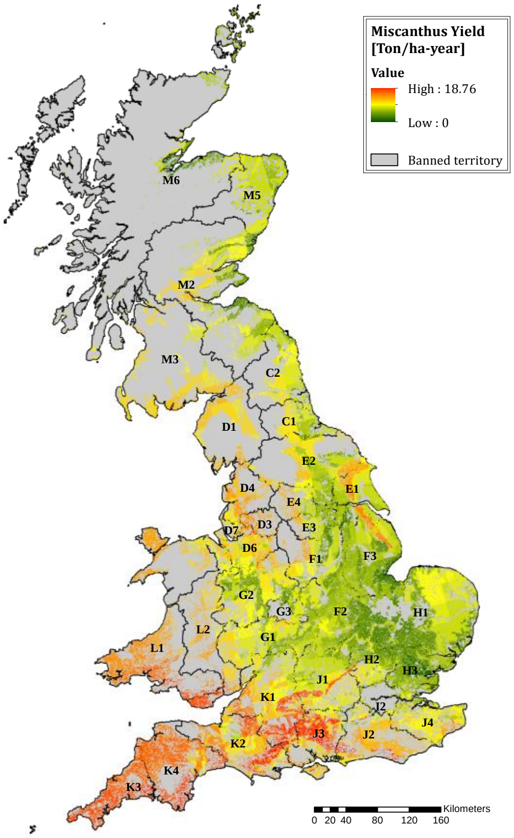


Figure 4. Miscanthus yield estimation for high productivity scenario in 2020. (Map generated with data from [87] and [88])

The European Environmental Agency (ECA) published the report "Estimating the environmentally compatible bioenergy potential from agriculture" [72] where they established feasible limits of land usage for energy crops without risking aspects such as sustainability, and food security due to possible land competition. The maximum limits were estimated to be 824 kha in 2010 and 1584 kha for 2030. Although these limits refer to arable land, they were implemented in the current case study in order to prevent possible over utilisation of available land exclusively for miscanthus cultivation.

Regarding the economic aspects, plantation of new energy crops requires initial investment related to establishment and removal activities; additional operational costs are also considered which correspond to activities such as fixed overheads, agrochemicals, harvesting costs and storage. This information was taken from the work published by Bauen et al. [71].

4.1.4 Residual Waste

The waste management hierarchy places waste prevention at the top, followed by reuse, recycle/compost, then energy recovery, and finally disposal as the last option [89]. The UK has adopted a policy framework that gives priority to recycling, while limiting the percentage of waste that can be treated in waste-to-energy facilities. Some of the relevant policies are detailed in section A.3 of supporting information. Three categories were included for the estimation of available waste for energy production: MSW, commercial sector, and industrial sector.

In Wales, MSW availability is estimated to be 531 kTon/year and 128 kTon/year available for 2020 and 2040, respectively [90] and [91]. The available resources from commercial and industry sectors for energy generation are 497 kTon/year and 596 kTon/year in 2020, and decrease to 132 kTon/year and 148 kTon/year in 2040, respectively [92] and [93]. In Scotland, the available resources for energy generation by 2020 from MSW, commercial, and industrial sectors are estimated in 706 kTon/year, 1058 kTon/year, and 405 kTon/year, respectively [94]. The resource availability decreases around 69% by 2040. In England, the total available resources are estimated in 7,344 kTon/year, 5911 kTon/year, and 5971 kTon/year for MWS, commercial sector, and industrial sector, respectively [95], [96], [97], and [98].

In total, available residual waste for energy generation the UK is around 23,020 kTon/yr in 2020 and decreases to 7,544 kTon/yr by 2040, around 67% less availability than at the beginning of the planning horizon. Figure 5 presents information regarding the distribution of MSW, commercial waste, and industrial waste for 2009 and the steps involved to estimate available residual waste resources for energy generation in 2020. These figures were subsequently distributed across the UK at NUTS2 using as proxy projections of population per region [99].

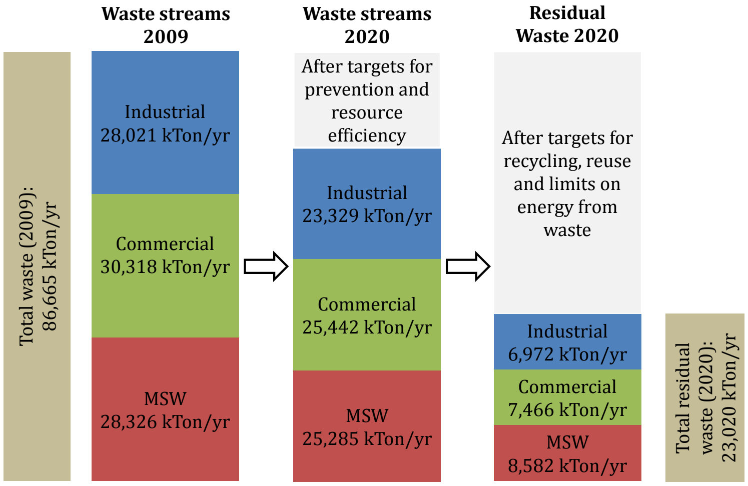
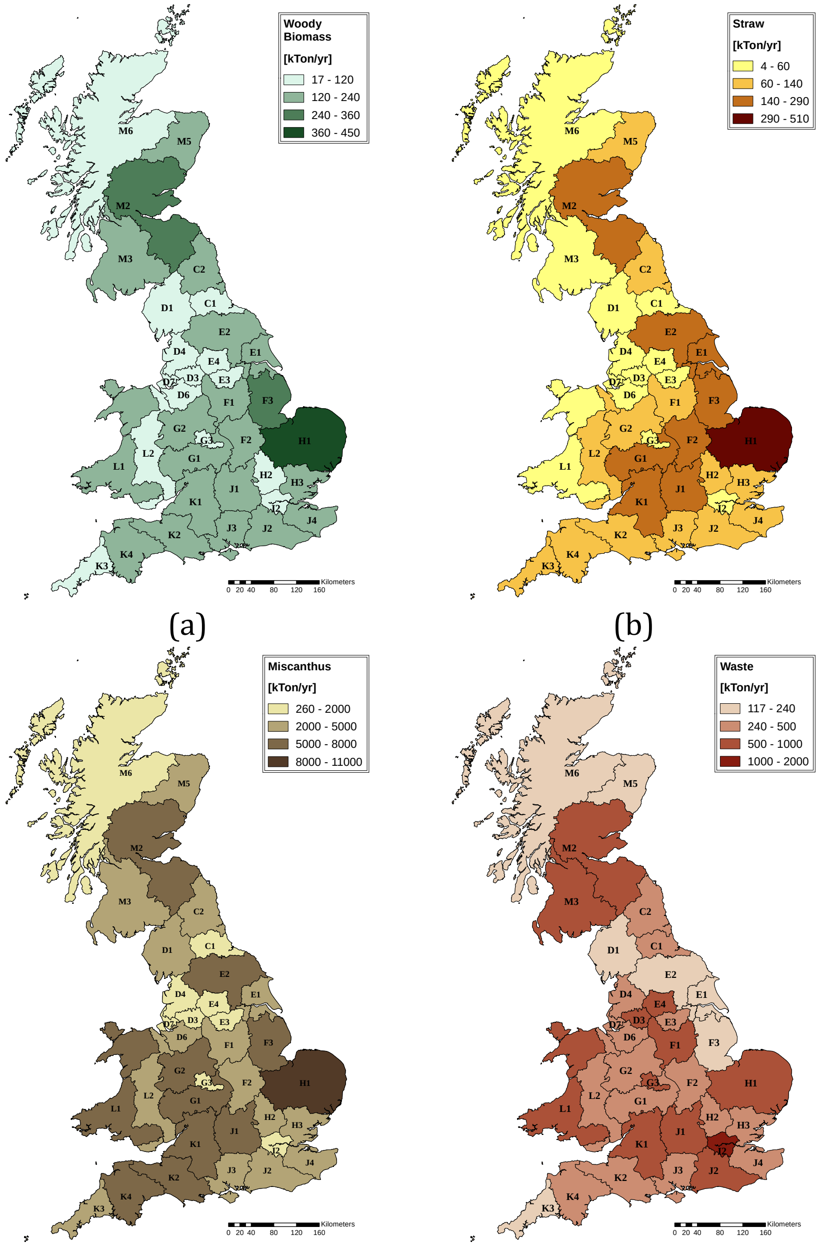


Figure 5. Estimation of available residual waste resources in the UK for 2020

In 2014, the landfill tax was set at 80 £/Ton, this means that local authorities have to pay £80 for every ton of waste sent to landfill. Alternative technologies that can process waste for lower costs would gain rapid acceptance since they can represent a cheaper option to treat waste. Many gate fees are reported for waste [100,101], in this work an average for the cost of waste was initially set at -35 £/Ton for the first planning period. This represents an important incentive for companies involved, especially considering that the use of waste as feedstock is comparatively more challenging than woody biomass or perennial crops. However, as the usage of waste for energy generation increase, it is expected major competition for residual waste which will likely increase gate fees [38]. Unfortunately, the prediction of gate fees for residual waste has not been reported for the UK, therefore, in order to take this into account at some extent, a steady increment of gate fees was carried out along the planning horizon.

The regional distribution of woody biomass, cereal straw, miscanthus, and residual waste is presented in Figure 6. Regions H1 (East Anglia), M2 (Eastern Scotland), and L1 (West Wales and The Valleys) present high availability of woody biomass resources. Cereal straw resources are predominantly located in regions H1 and M2, the eastern part of mid England and regions G1 (Herefordshire, Worcestershire and Warwickshire), and K1 (Gloucestershire, Wiltshire and Bristol/Bath area). The potential for miscanthus cultivation is comparatively higher in regions H1, L1, and K1. It is worth to mention that the distribution shown in the map is calculated with data presented in Figure 4 and no global limit on land utilisation was considered.



(a) (b)

(c) (d)

Figure 6. Forecasted resource availability distribution in UK for period 2020-2024 for different feedstocks: (a) Woody Biomass. (b) Straw. (c) Miscanthus. (d) Waste.

Finally, residual waste distribution is substantially high in regions corresponding to the main cities in the UK, such as London (I2), Birmingham (G3), Leeds and Bradford (E4), Edinburgh (M2), Glasgow (M3), etc.

4.2 Conversion Technologies

In this work, we consider gasification technology as the main route for BioSNG production in integrated plants. Several gasification technologies exist, Entrained Flow, Circulating Fluidized Bed, and allothermal (Indirect) gasification. The overall efficiency to BioSNG is usually higher for allothermal gasification [25]. Before the gasification step, feedstocks may need to be dried depending on the moisture content, since moisture decreases the gasifier performance. The net overall efficiencies on LHV basis, including electricity consumption and methanation process, are 54% for Entrained Flow, 58% for CFB, and up to 67% for allothermal gasification [25]. In this study, the design called MILENA, which is based on allothermal gasification and still under development by the Energy research Centre of the Netherlands (ECN), was chosen as the conversion technology for integrated plants. The global efficiency of the process can reach up to 91% if energy integration is considered [31]. The data is reported for woody biomass feedstock; however, due to lack of information the same efficiencies are used for cereal straw and miscanthus. For facilities treating residual waste, plasma gasification was selected since it is more flexible and robust to handle this type of feedstock in comparison to allothermal gasification. The global efficiency for BioSNG production using plasma gasification was reported to be 52% with a potential increase of 10% if heat recovery is implemented [102].

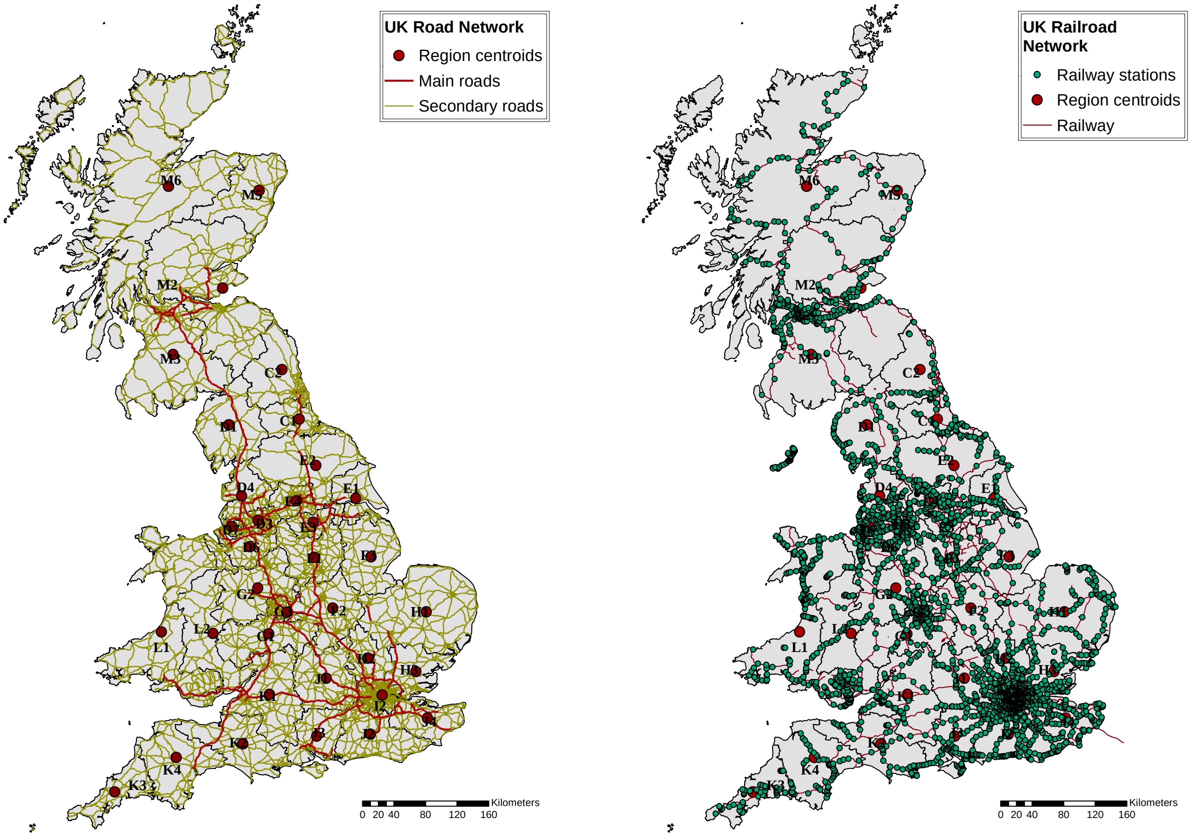
Regarding capital investments, Batidzirai [103] estimated that a “nth-plant” using the MILENA concept with capacity to process 100 MW of woody biomass will require an initial investment of £116m. Taking these figures as a reference and using a scale factor of 0.67, it is possible to generate a curve that relates capital investment with installed capacity that reflects economies of scale. The scale factor was estimated based on the data published in [101]. The maximum capacity of an integrated plant that can be installed in a region was limited to 1000 MW for every period of the planning horizon [104]. Based on this information, the capex curves for straw and miscanthus were obtained by correcting the data with the corresponding LHVs. This is an attempt for considering variations of investments for a specific type of biomass. However, this assumption does not take into account particular technical variations in the process, therefore, more detailed studies are needed to fill this gap. For facilities using plasma gasification, the capital expenditure was estimated to be £95m for an plant with installed capacity of 57 MW [103]. A scale factor of 0.8 was used to generate additional data for different capacities.

The operating costs are composed by two terms, fixed and variable costs. The fixed costs are independent of the operation of the plant whereas the variables costs depend on the throughput of the plant. The fixed cost for processing woody biomass, miscanthus, and cereal straw is set at £3m per year. The variable cost for woody biomass was estimated to be £0.0037m/GWh. This value was used to infer the corresponding variable costs for miscanthus and cereal straw by means of a correction based on LHVs. For facilities operating with plasma technology, the fixed cost was set to £2.8m per year with a variable cost of £0.0236/GWh. The previous data was inferred from available information in literature [101,102]. The data for global efficiencies of the process, capital investments, and operating costs take into account the entire process from raw feedstocks to BioSNG, which involves: (1) biomass reception, preparation and handling, (2) gasification, (3) syngas processing (which includes contaminants removal and hydrogen/carbon monoxide ratio adjustment), (4) syngas methanation, and (5) gas conditioning and compression. A summary is presented in Table 1.

4.3 Transportation infrastructure

Three modes for regional transportation are included in the case study: truck, trailer and railroad. In the case of local transportation only truck and trailer are considered. The transportation costs are divided into fixed and variable costs. The term that accounts for the fixed costs depends on the amount of feedstock transported; similarly, the term for variable costs depends on the mass transported but also on the transportation distance. The transportation cost data for woody biomass and miscanthus for truck and rail modes was taken from Mahmudi and Flynn [105]. On the other hand, BioSNG is transported only by trailers as compressed natural gas (CNG). The fixed and variable costs for truck and rail mode for each feedstock are summarised in Table 2. From the data it can be noticed that fixed costs for truck transportation are lower than for rail transportation, by contrast, variable costs for truck transportation are higher than for rail. This makes transportation by rail more convenient over longer distances, whereas transportation by truck is more appropriate for short distances. Additionally to local and regional transportation costs, it is considered that further investments are required for establishing an adequate transportation network for BioSNG from production plants to injection points. The corresponding information was taken from Almansoori and Shah [106] and Agnolucci et al. [73].

The estimation of distances between the different regions for truck and rail transportation modes was based on two georeferenced maps (see Figure 7) corresponding to the UK Road network and the UK Railroad network [107].



(a) (b)

Figure 7. Transportation infrastructure in the UK. (a) Road network and (b) Railroad network. Contains Ordnance Survey data © Crown copyright and database right 2015 [107].

It is assumed that future plants will be located in the centroids of the regions; the coordinates of each point are calculated with ArcGis 10.2. The distance by road between pair of regions was estimated through a network data set created in ArcGis 10.2 by joining layers containing main roads, secondary roads, roundabouts and interceptions; not shown in the map for convenience. Using the tool "Network Analysis" it is possible to intercept this network with the region centroids, creating an origin-destination matrix (OD Matrix) containing the minimum distance between two regions. The OD Matrix is then filtered to get the connectivity of the regions sharing a common border (neighbourhood). Additionally, a visual inspection was carried out to detect possible connections between regions without a common border whose connectivity is possible due to the dense road and/or rail network. For example, region I2 can be connected to J1, and J1 can be connected to region K1, however, there is a main road between I2 and K1 that makes possible a connection between them despite that the region J1 is in-between. This consideration will allow more flexibility in the final decisions regarding the transportation of feedstocks. An analogous procedure was followed for obtaining the distances by railroad. The local transportation distances were estimated by drawing a circumference around the centroid of a region whose radio represents the average travel distance for taking biomass from any area within the region to its centroid. This approach takes into account the spread distribution of the biomass around the centroid of a region. The same methodology was applied for obtaining the transportation distances between a plant and the injection points available locally.

4.4 Demand Data

The Gas Ten Year Statement 2013 (GTYS) published by the National Grid [108] reports the gas and power annual demand forecasted until 2027. The GTYS deals with the associated uncertainty by analysing 2 different scenarios; GoneGreen and SlowProgression. In GoneGreen scenario, it is assumed that the environmental targets set for 2020, 2030 and 2050 are met. By contrast, in SlowProgression scenario the progress in renewables is slow, therefore, the target for 2020 is actually met between 2020 and 2025, and the target for 2030 is not achieved. This is reflected on a higher future demand for electricity and gas in SlowProgression scenario in comparison to GoneGreen scenario. For this study, the gas demand is fixed based on the GoneGreen scenario. No demand for heating is considered, therefore, all the heat recovered from the BioSNG production can be converted into power assuming an efficiency of 40%. The future gas and power demand as well as their corresponding forecasted prices are shown in Figure 8.

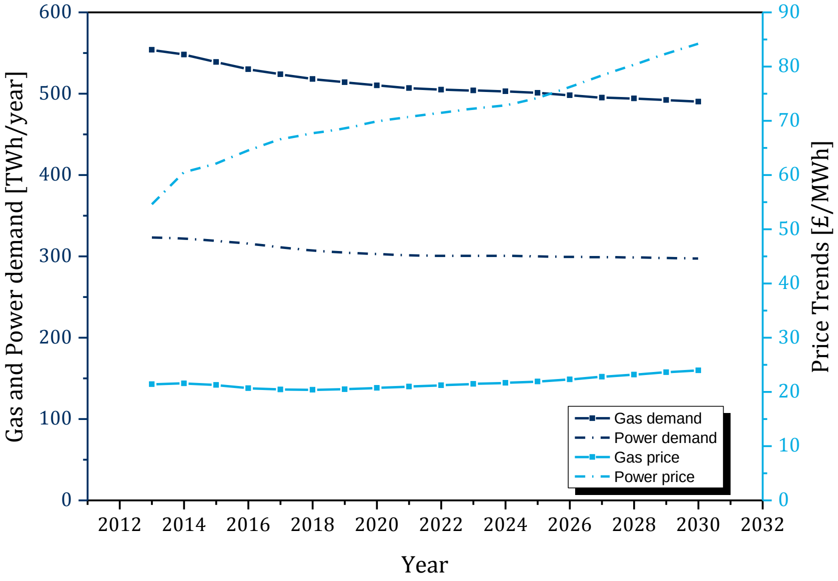


Figure 8. Forecasted gas demand for GoneGreen scenario [108,109]

Future gas and power prices were assigned based on the report UK Future Energy Scenarios published by the National Grid [109]. Gas prices vary from 20.7 £/MWh in 2020 up to 24.0 £/MWh in 2030. In the case of power, the prices are considerable higher starting from 69.9 £/MWh in 2020 and increasing up to 84.1 £/MWh in 2035. As a mean to supply the BioSNG to the demand centres, the BioSNG is sent to the gas transmission system (GTS), specifically to offtake points that connect the GTS with the GDN. The GDN is divided into 13 LDZs with the objective of delivering natural gas taken from the GTS to the final consumers. On average, the LDZs supply around 65% of the total gas demand in the UK. The LDZs supply 100% of the domestic demand and part of the demand from industrial and commercial customers. The rest of the demand (35%) is supplied through the GTS since some customers require operate at high pressure, such as power generation plants and some industries. The GDN is operated by 4 companies:

- Southern Gas Networks is in charge of Scotland (SC), Southern England (SO) and South East England (SE).
- Northern Gas Networks operates Northern England (NO) and North East England (NE).

- National Grid Gas operates North West England (NW), West Midlands (WM), East Midlands (EM), East Anglia (EA) and North Thames (NT).
- Wales & West Utilities is in charge of Wales North (WN), Wales South (WS) and South West (SW).

The GTS map published by the National Grid, and the LDZ distribution is shown in Figure 9. This map was updated by including 97 offtake points based on the information published in [108]. The dotted regions correspond to NUTS2 classification.

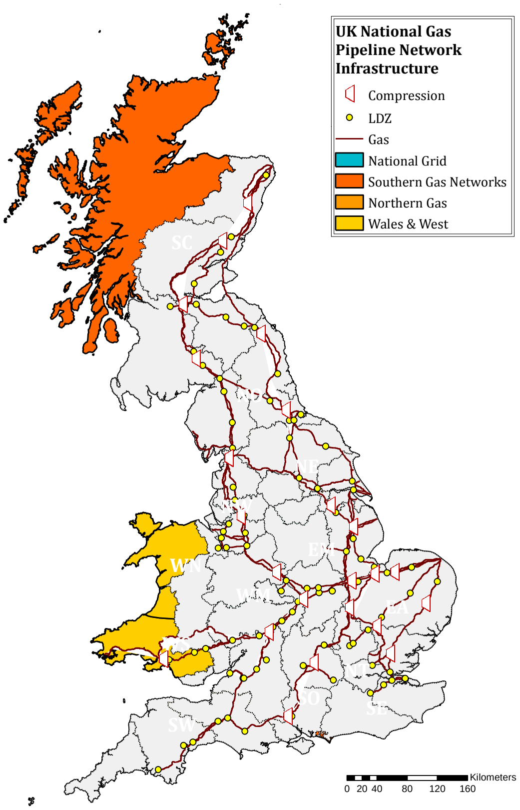


Figure 9. UK Gas pipeline network and Local Distribution Zones (LDZs) (map generated based on [110] and [111])

As the forecast demand correspond to the entire country, the demand per LDZ is assigned by calculating the demand fraction for each of the 13 LDZs based on historical information [112]. It is worth to mention that in some cases, a region of the NUTS2 can supply BioSNG to two or more LDZs, for example region L2 can supply West North (WN) and Wales South (WS). Finally, it was assumed that all of the electricity generation is sold locally; therefore no power transmission system is included in this case study.

4.5 Economic Parameters

Two different factors are used to discount the cash flow, CF_t, and capital expenditures, $CAPEX_t$, terms in the objective function. It is considered that the investments are made at the beginning of every 5-year period. The capital expenditures are discounted on a five-year basis which corresponds to the time resolution chosen for the case study. Accordingly, the discount factor is calculated as follows:

$$DfCA_t = \left(\frac{1}{1+i}\right)^{5*(t-1)}$$

Where i refers to the interest rate. The cash flow depends on terms such as operating costs, income, taxes, etc. These costs should be discounted periodically; therefore it is considered that the cash flow is discounted annually. Taking into account that the period t corresponds to a 5-year period, the equation is modified as follows:

$$DfCF_t = \frac{\sum_{j=1}^{5}(1+i)^{(j-1)}}{(1+i)^{5t}}$$

An average value of 10% was used for the interest rate i. For estimating the depreciation of the investments, it is assumed a 100% of depreciation in the first 7 years of the time horizon [113]. For the tax rate, Tr, a typical value of 35% was chosen.

In addition, the rate for possible incentives for BioSNG production, denoted by parameter Inc_{pt}, is fixed based on the Renewable Heat Incentive programme. This incentive applies only for gas production, its average value is around 70 £/MWh. In case of power generation, Renewable Obligation Certificates (ROCs) are included as part of the income. For this case study, ROCs were set to 45 £/MWh.

5 Results and discussion

In this section we present computational results for the case study described previously in section 4. Two instances of the same case study are considered: Case A, and Case B. The instances differ in the number of commodities (BioSNG and/or power) that are allowed as final products. In Case A we investigate the economic performance of the BioSNG supply chain in UK in which only BioSNG is allowed as final product. Case B aims to quantify the economic impact of cogenerating power along with BioSNG. The relevance of Case B stems from the fact that it is uncertain if the current regulation regarding the generation of renewable electricity could apply to gasification-based processing facilities. A regulation framework would not only facilitate the interconnection with the National Grid, making power sales to the system achievable, but also it would provide access to government incentives such as the Renewable Obligation Certificates (ROCs) programme. Unlike the gas transportation system and the electricity network in the UK, the heat district network capacity is not fully developed, which greatly restricts the centralised generation and distribution of heat to the demand centres. In consequence, the percentage of heat demand supplied by heat district networks is marginal and largely surpassed by the supply of electricity and natural gas. Therefore, it is considered that residual heat is used completely in electricity cogeneration, and not as an additional commodity. Finally, a parametric analysis based on Case B is carried out in which the economic performance of the BioSNG supply chain is addressed with respect to the percentage of total incurred costs subsidised by the government.

The optimisation problems were solved using GAMS 24.4.1. The MILP problem was solved with CPLEX 12.6.1. All runs were performed on a Dell OptiPlex 9010 with Intel® Core™ i7-3770 CPU @3.40 GHz and 16 GB RAM running Windows 7® Enterprise (64-bit operating system). The optimality gap was set to less or equal to 1% for all cases. The corresponding statistics for Case A and Case B are presented in Table 3.

5.1 Case A: Production of BioSNG

The total cost breakdown for Case A is shown in Figure 10a.The values for Capex, Opex, and taxes are discounted to the first period. The main component in the total costs is the operating expenditures with a share of 56.8%, followed by the capital expenditures with a share of 28.7%, and finally 14.5% of the total costs correspond to tax payments. The results indicate that the operational expenditures are the dominant component in the development of a BioSNG supply chain. Therefore, uncertainties in economic, technology, and crop parameters would likely impact the operation of the BioSNG supply chain.

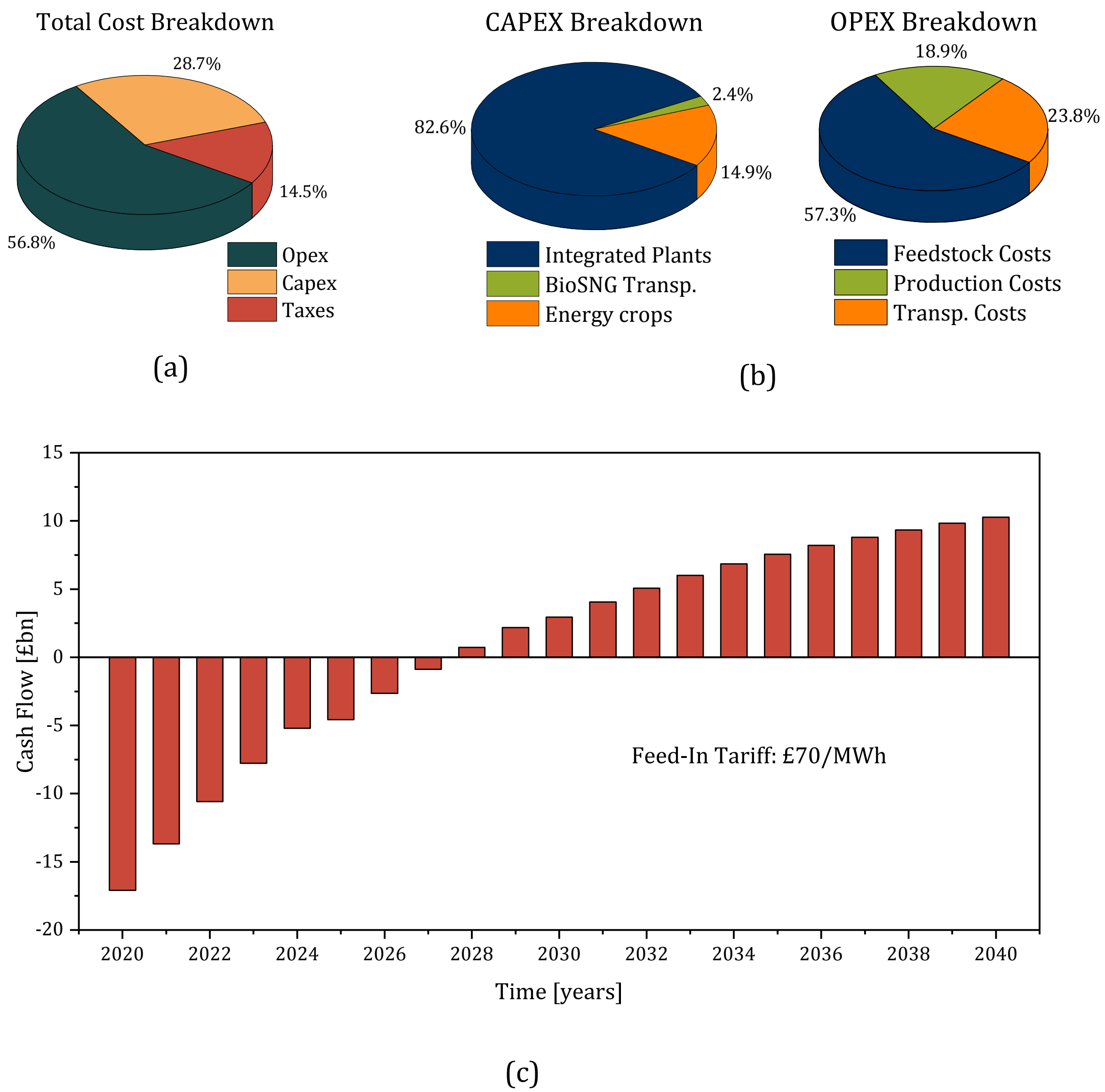
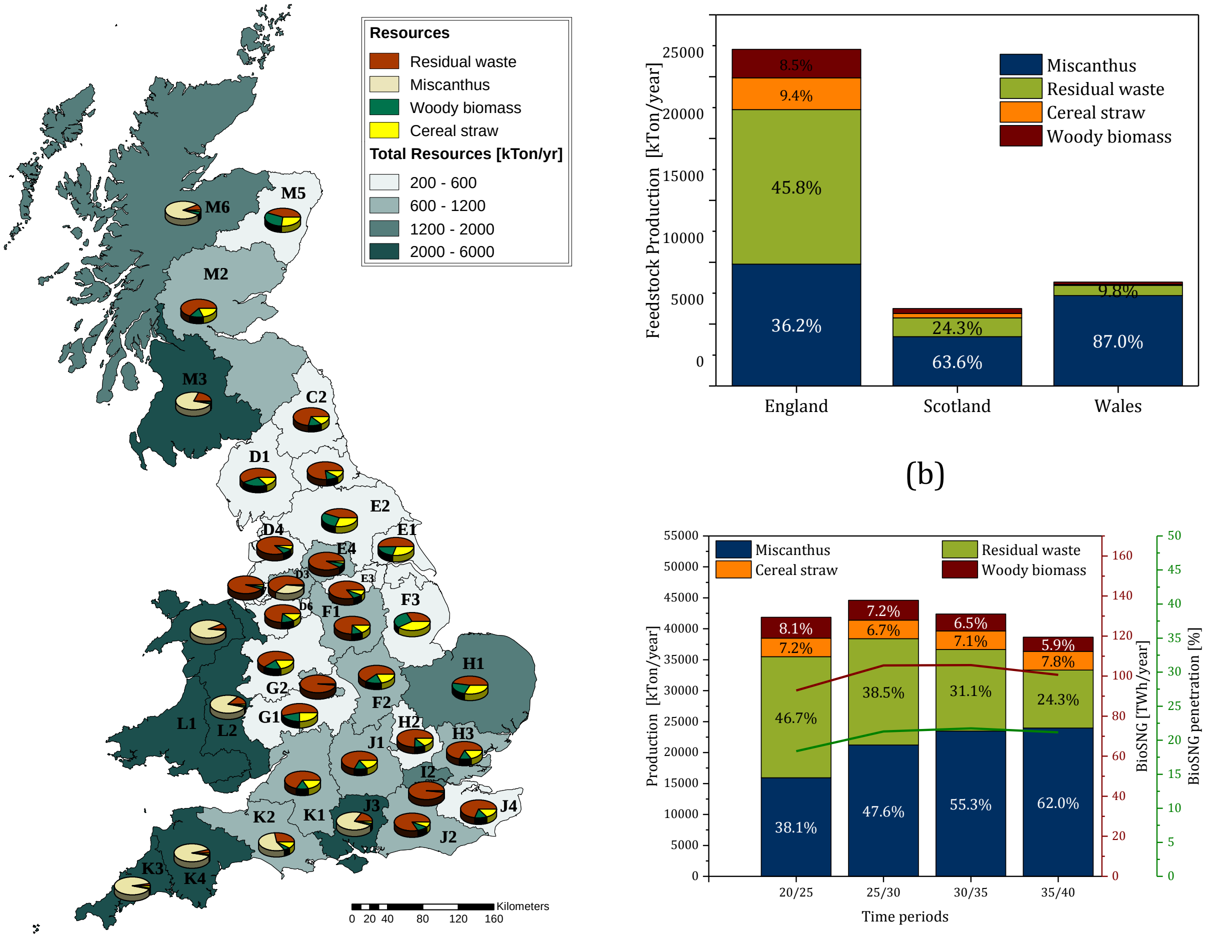


Figure 10. Summary of the economic performance for Case A: (a) total cost breakdown. (b). Capex and Opex Breakdown. (c) Cumulative net cash flow

The corresponding breakdown for Capex and Opex is shown in Figure 10b. The results show that the economics of the BioSNG supply chain is mainly dominated by feedstock purchases followed by installation of processing facilities. These two components account for 56.2% of the total expenses. Expenses related to transportation of feedstocks come in third place. Comparatively, investment in new infrastructure for BioSNG transportation is marginal. The cumulative cash flow was recalculated in a yearly basis as shown in Figure 10c. The optimal net present value was about £10.27 billion and the breakeven time is reached after approximately 8 years. The breakeven gas price, defined here as the ratio between total expenditures (Capex plus Opex) and total gas production, was found to be 28.5 £/MWh.

The optimal feedstock production distribution across the UK is presented in Figure 11a. The classification shown in the map is based on the summation of average annual tons produced for every feedstock in a specific region. Six regions stand out in terms of feedstock generation for BioSNG production: M3 in Scotland, L1 and L2 which comprise Wales, and K3, K4 and J3 in England.



(a)

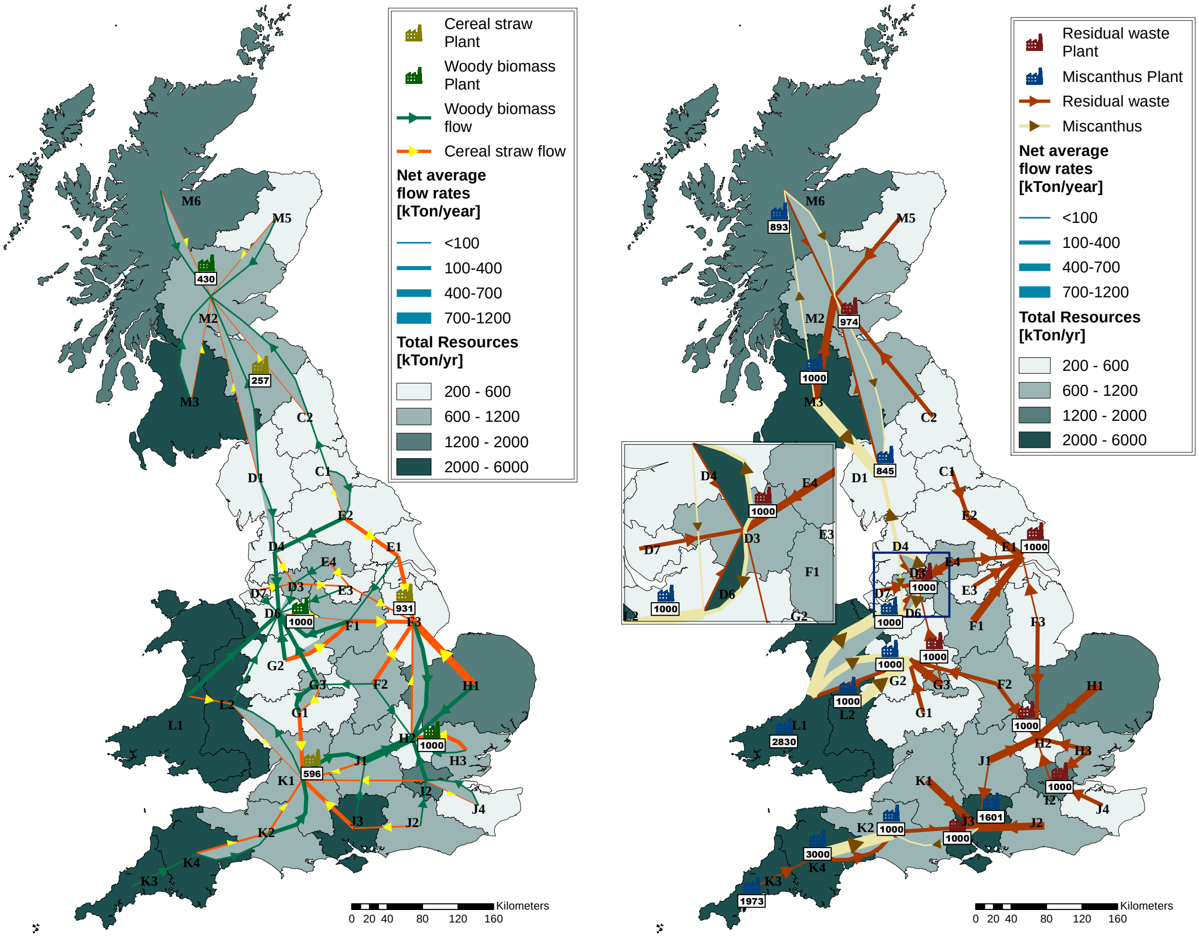
(b)

(c)

Figure 11. Optimal feedstock production: (a) Regional feedstock distribution and composition across the UK. (b) Average feedstock production for England, Scotland, and Wales. (c) Feedstock production and BioSNG penetration along the planning horizon

The use of residual waste for BioSNG production is dominant in most of the regions in England, especially in I2, D7, and G3 in which the cities of London, Liverpool, and Birmingham are located, respectively. The contribution of cereal straw in BioSNG production is comparatively low and fairly sparse between Scotland and England. In the case of woody biomass, its procurement rate for BioSNG production is about the same as the cereal straw. The cultivation of miscanthus has taken place predominantly towards the west part of UK. The regions with the highest feedstock throughput have in common cultivation of miscanthus. Surprisingly, region H1, which has the highest initial potential for miscanthus (see Figure 6), was not selected. The combination of two facts can explain this result. First, due to sustainability reasons, the total land available for miscanthus cultivation is restricted, and second, the yields reported for this region are around the average or below (see Figure 4) which means that the high potential of region H1 comes from the extension of land rather than from the land productivity. Under these circumstances, the optimisation model chooses efficiency of land utilisation over potential, which is confirmed by the fact that the regions selected for miscanthus cultivation coincide with areas with high productivity.

The distribution of feedstock procurement across the countries is summarised in Figure 11b. In average, 65% of the total feedstock production comes from England; Wales contributes with 20%, and finally Scotland with 15%. Miscanthus is the main source of biomass in Scotland and Wales, whereas in England, the predominant feedstock is residual waste. The utilisation of feedstocks along the planning horizon is summarised in Figure 11c. The fraction of woody biomass and cereal straw is nearly constant along the time periods. The utilisation of residual waste decreases along the planning horizon as a repercussion of the policies implemented aiming to a zero waste economy. On the other hand, the importance of miscanthus increases along with time compensating for the reduction of available residual waste. In terms of BioSNG penetration, it is possible to supply 18.4% of the gas demand in the period 2020-2025, and up to 21.2% of the demand in 2035-2040. The feedstock transfers between regions and the final installed capacity for every type of feedstock is presented in Figure 12. The final installed capacity for processing woody biomass is 2430 MW. The facilities are located in the north, centre, and south of UK, exhibiting a centralised production scheme. In the case of Cereal straw, the total install capacity is 2054 MW. Similarly to woody biomass, the distribution of the cereal straw plants across the UK feature a centralised scheme. Despite the high availability of cereal straw in region H1, the optimisation model does not opt for installing a plant in that region; instead, a plant is installed in the contiguous region F3. The reason for this decision lies in the transportation costs. It can be seen that this facility processes cereal from several regions around mid-England, therefore a more central location is preferred in order to reduce the transportation expenses.

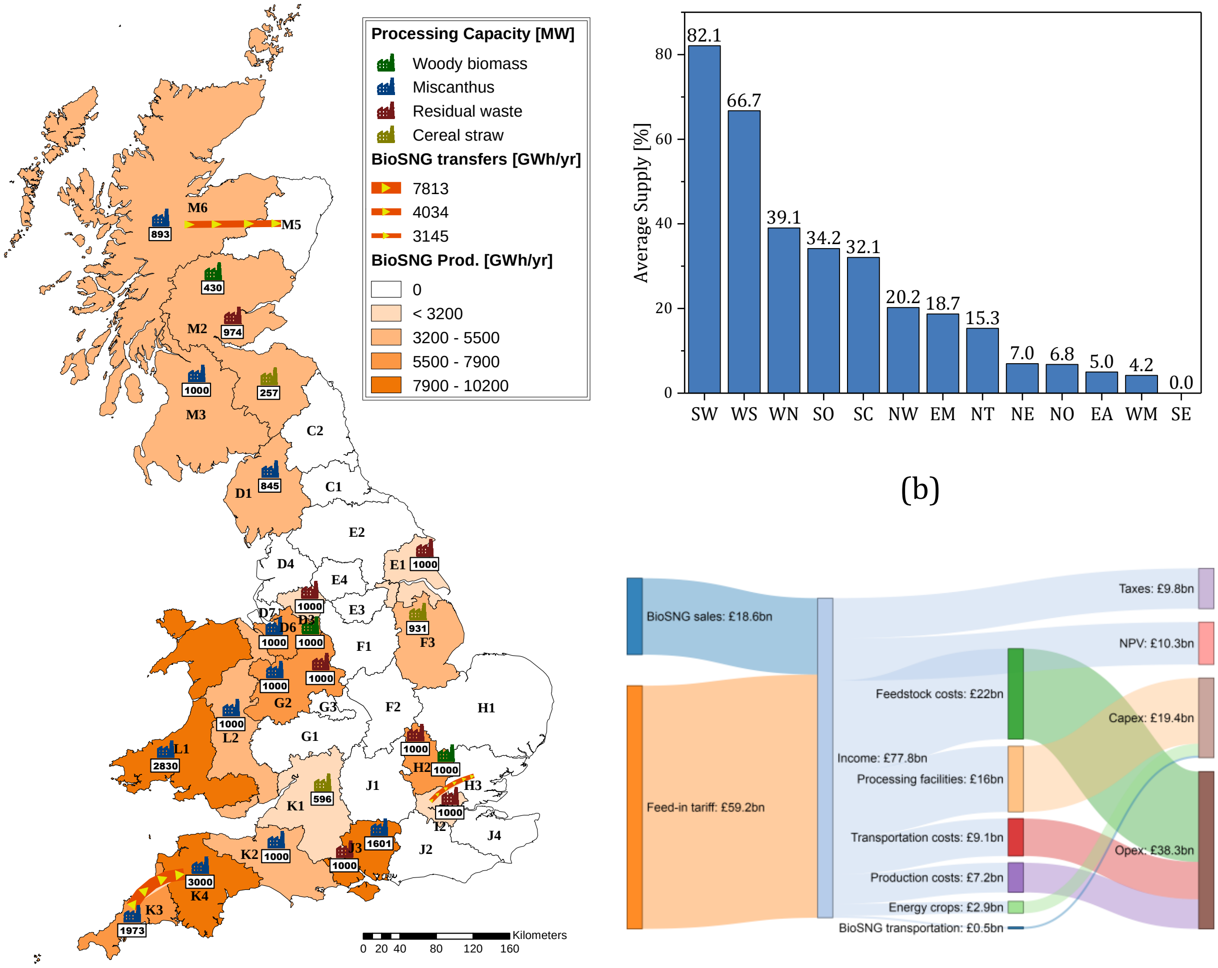


(a) (b)

Figure 12. Regional feedstock transfers and final installed capacity: (a) Net average flows for cereal straw and woody biomass. (b) Net average flows for miscanthus and residual waste

A final installed capacity of 6974 MW is required in order to process residual waste, with 86% of the capacity located in England. In the case of miscanthus, 16142 MW of processing capacity are installed across the UK. The processing of miscanthus is carried out in two facilities in Scotland, seven facilities in England, and two facilities in Wales. Most of the plants are installed in a region where miscanthus have been planted, except in region D6, minimising the transportation distances and therefore the associated costs. A quick inspection of Figure 12b confirms that the transportation network for miscanthus is less complex than for the other feedstocks. It is clear from the results that miscanthus plays a crucial role in the production of BioSNG, especially in Wales and south west of England. Moreover, the production of BioSNG from miscanthus follows a distributed scheme when compared to woody biomass and cereal straw. The final total installed capacity was 27.3 GW, from which facilities for processing cereal straw corresponds to 6.5%, followed by woody biomass (8.9%), residual waste (25.5%), and miscanthus (59.1%). In terms of utilisation of transportation modes between regions, rail is usually the preferred mode although closely followed by truck transportation. For cereal straw, however, truck transportation is the preferred mode. In general, for feedstocks highly distributed and with low availability, the optimisation model prefers installing centralised plants with high capacity rather than small distributed plants. This suggests that the effect of economies of scale is, until certain extent, prevalent over the extra expenses associated with feedstock transportation.

A summary of the regional production of BioSNG, average supply in every LDZ, and net income is presented in Figure 13. In total 18 out of 35 regions are selected for BioSNG production. Figure 13a shows that most of the BioSNG transportation takes place within the regions, from processing facilities to injection points. This is a direct result of considering existing gas networks for injection of BioSNG, which reflects in low investments for BioSNG transportation infrastructure. Only three regional transfers are required due to the absence of injection points. The fact that the installation of facilities takes place in regions with no injection points, suggest that the additional expenses for transporting BioSNG between regions are offset by potential extra expenses of transporting feedstocks if the facilities were installed in contiguous regions with access to the GDN.



(b)

(a)

(c)

Figure 13. BioSNG supply and economic performance: (a) BioSNG production and regional transfers. (b) Average supply per LDZ. (c) Sankey diagram for the global economic performance

The average supply for each LDZ is presented in Figure 13b. South West (SW) and Wales South (WS) can potentially achieve a BioSNG penetration of 82.1% and 66.7%, respectively. A significant supply is also achieved for Wales North (WN), Southern England (SO), and Scotland (SC), varying between 32.1% and 39.1%. The high supply percentages are mainly driven by the cultivation of Miscanthus in the respective areas. 15.3% of the demand in North Themes (including the City of London) can be supplied by BioSNG produced from residual waste and woody biomass. No injection of BioSNG takes place in South East England (SE). Finally, Figure 13c presents a comparison between the main components of the total costs and income from government incentives and BioSNG sales. Notably, tax payments equal the transportation costs and are higher than the production costs. At the tariff of 70 £/MWh, the incentives from the government during 20 years are £59.2bn, which corresponds to 76.1% of the total income. Moreover, the income related to BioSNG production is £18.6bn, which is 23.9% of the total income. The incentives are essentially used to cover operating and capital expenditures, whereas the BioSNG income offsets tax payments, and the surplus corresponds to the optimal NPV of £10.7bn. The fact that the totality of investments and operating costs required to be subsidised, makes less attractive the developing of a BioSNG supply chain from the government perspective. This will be further investigated in section 5.3.

5.2 Case B: Economic impact of power coproduction

As previously discussed, it is unclear how the current regulation in the UK, regarding production of renewable energy, applies to electricity generated as a coproduct of the gasification process. Great efforts have been devoted for the continuous development of an inclusive regulatory framework that contemplates the great variety of sustainable technologies. It is reasonable, then, to consider that coproduction of electricity from gasification will benefit from schemes such as the Renewable Obligation Certificates (ROCs). In this section we investigate this scenario and its potential benefits on the economic feasibility of the BioSNG supply chain. A comparison of the cumulative cash flow for Case A and Case B is presented in Figure 14.

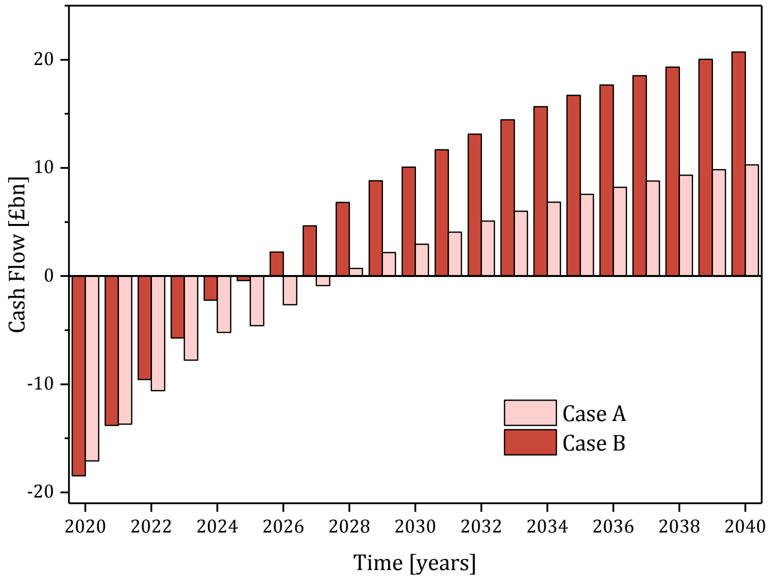
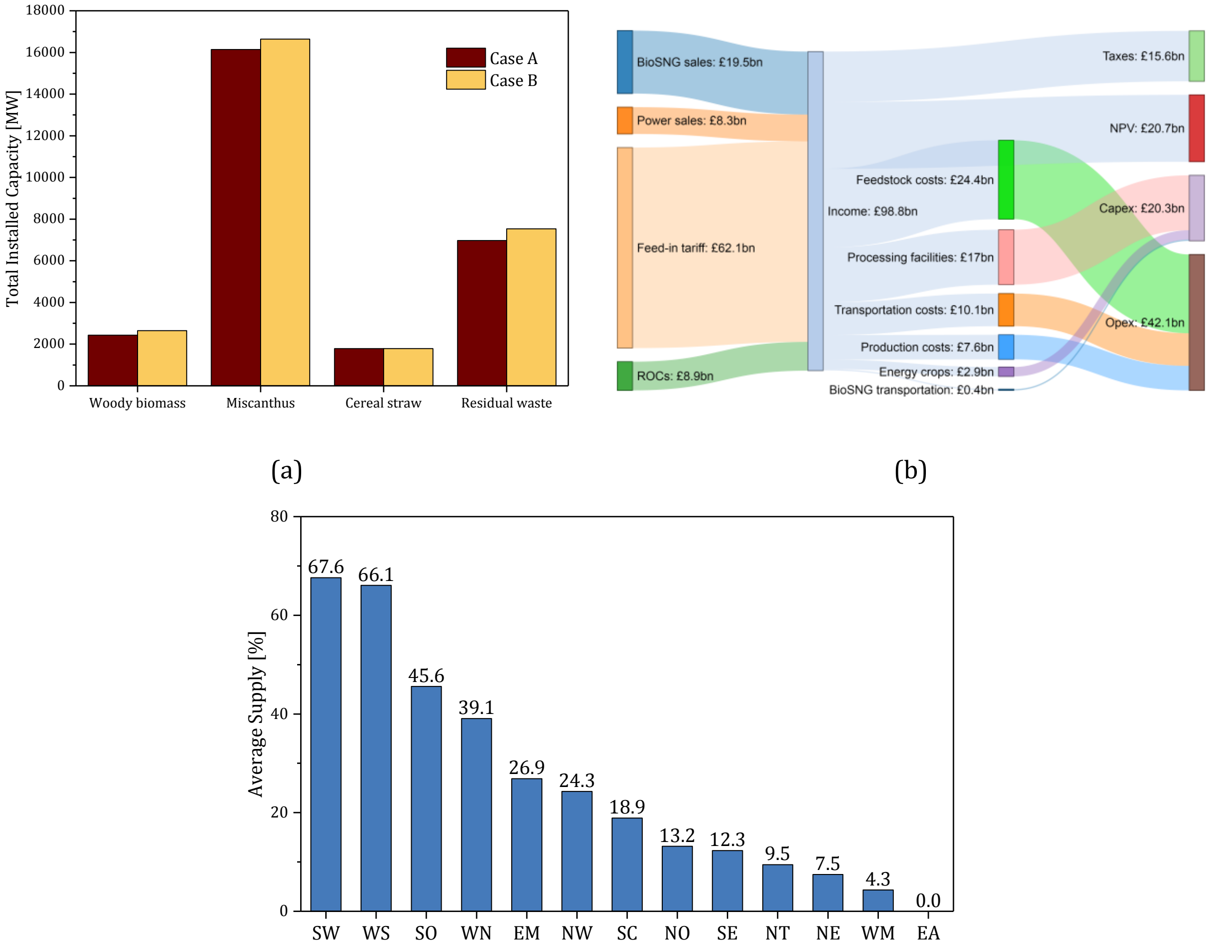


Figure 14. Cumulative cash flow comparison for Case A and Case B

When power sales are included, the breakeven time is 6 years, 2 years less than in Case A. The optimal NPV is £20.7bn, 48.3% higher than in the previous case. The initial investments are fairly higher in Case B than in Case A, this is related to investments in additional processing capacity as shown in Figure 15a. The coproduction of power as extra commodity enables the supply chain to increase the processing of feedstock in order to take advantage of the new source of income. Consequently, the production of woody biomass, miscanthus and residual waste increased 2.6%, 4.6% and 2.6%, respectively.



(a) (b)

(c)

Figure 15. Summary of optimisation results for Case B: (a) Final installed capacity. (b) Sankey diagram for the global economic performance. (c) BioSNG supply per LDZ

Nonetheless, the production of cereal straw was the same as in Case A, which indicates that this feedstock is being used at its maximum availability. Additional 215 MW were installed for woody biomass processing in comparison to Case A. For miscanthus and residual waste, the additional capacity was 500 MW and 561 MW, respectively. In the case of cereal straw, the installed capacity was the same as in Case A. The regions selected for installation of facilities in Case B is compared with the results for Case A in Table 4. The decision for location of facilities processing cereal straw remained the same as in Case A. However, some of the regions for processing woody biomass, miscanthus, and waste are different to the previous case. Notably, this coincides with the feedstocks that required additional capacity due to an increment in their production, as discussed previously. The additional production of miscanthus, woody biomass, and residual waste, involves higher transportation activity driving associated costs up. This situation can be mitigated by readjusting the location of the corresponding facilities. A summary of the economic performance of Case B is presented in Figure 15b. The proportions of the different component of total costs are similar to Case A. Regarding the total income, the feed-in tariff increased slightly and continues to be the main source of profit with a share of 62.8%. The BioSNG income increased 4.7% with respect to Case A, reaching £19.5bn (19.7%). Power sales and ROCs contribute with £8.3bn (8.4%) and £8.9bn (9.1%), respectively. Finally, the supply of BioSNG registered a small increment of 0.8%, in comparison to Case A, reaching 21.4%. The coproduction of power is enough to supply 4.4% of the total demand along the planning horizon. The average BioSNG supply in every LDZ is presented in Figure 15c. Although the supply in SW was reduced in 14.5%, this region continues to be the most relevant in terms of BioSNG supply, narrowly followed by WS. By contrast, regions such as SO and SC increased its share of BioSNG supply. These alterations are closely linked to the rearrangement of the facilities across the UK as explained before.

5.3 Case C: Parametric analysis of government incentives

In this section is presented a parametric analysis in which the role of the government in developing a BioSNG supply chain is addressed. Results for Case A and Case B show that the incentives associated to the feed-in tariff scheme surpass largely the income of BioSNG sales and are virtually equal to the capital investments and operating expenses. Consequently, a new constraint was included in the optimisation model in order to limit the fraction of Capex and Opex that can be funded through the feed-in tariff scheme as depicted in Equation (40).

$$\sum_{t}(DfCF_t * IncentiveGOV_t) \leq \theta * \sum_{t}(DfCF_t * OPEX_t + DfCA_t * CAPEX_t) \qquad (40)$$

$IncentiveGOV_t$ is a variable that accounts for economic incentives provided by the government through the Feed-in tariff scheme. The parameter θ corresponds to the fraction of operating and capital expenditures subsidised by the government. Both terms on each side of the constraint are discounted to present value. In addition, variable $IncentiveGOV_t$ will be restricted by the production of BioSNG in every period times the tariff, which for this study is 70 MWh/yr. This condition is modelled by Equation (41):

$$IncentiveGOV_t \leq \sum_{pg} Inc_{pt} * P_{pgt} \quad \forall\, t, p = \{biosng\} \qquad (41)$$

Incentives related to power generation are modelled through the Equation (42).

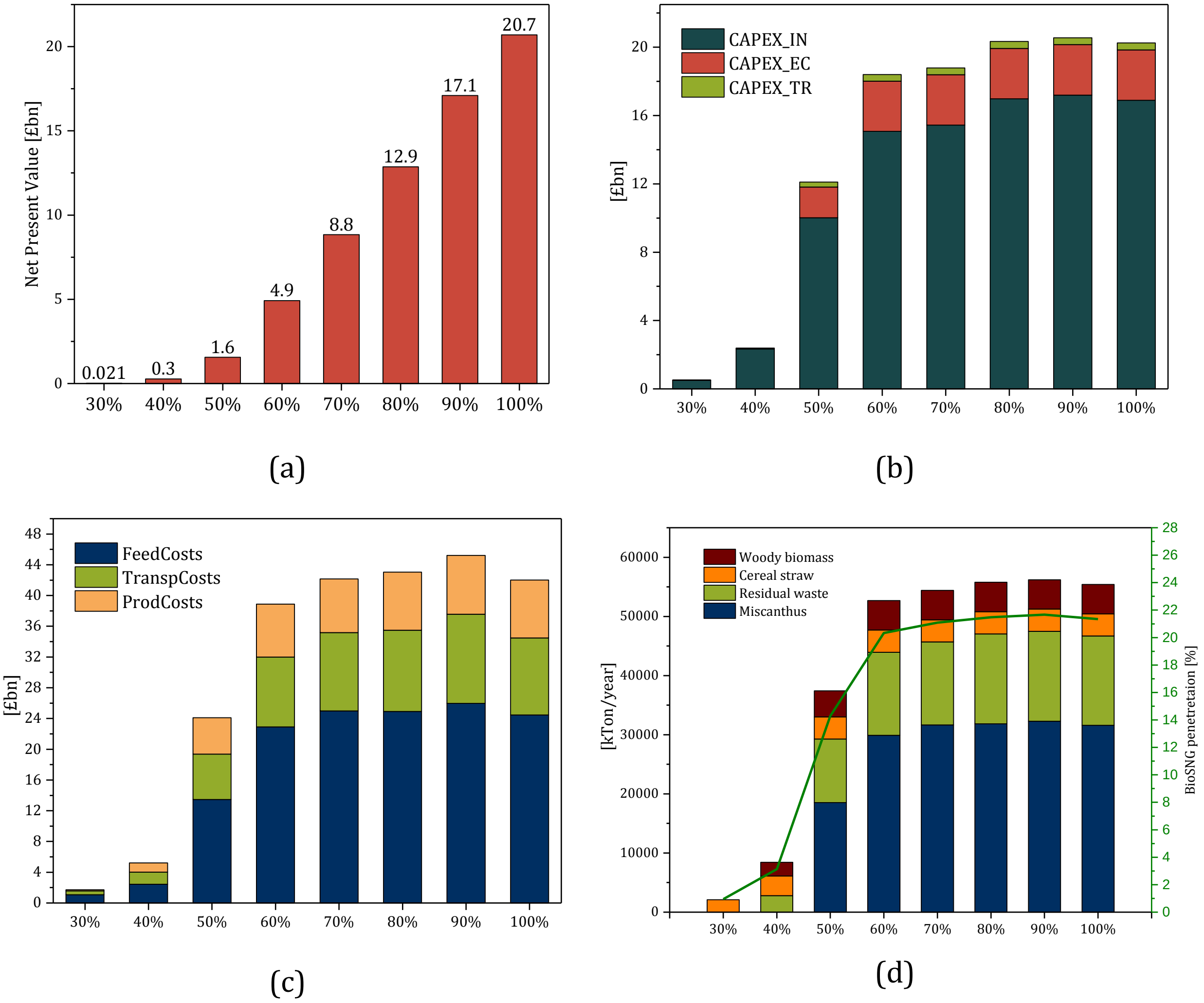
$$IncentiveROC_t = \sum_{pg} Inc_{pt} * P_{pgt} \quad \forall\, t, p = \{power\} \qquad (42)$$

Where $IncentiveROC_t$ is a variable that accounts for economic incentives through ROCs due to power generation. Finally, Equation (5) is modified accordingly in order to take into account the new variables as shown in Equation (43):

$$INCOME_t = \sum_{pg}\left(Price_{pt} * P_{pgt}\right) + IncentiveGOV_t + IncentiveROC_t \quad \forall\, t \qquad (43)$$

The parameter θ was varied systematically from 100% (Capex and Opex can be completely subsidised by the government), down to 0%. The impact of θ on NPV, capital and operating expenditures, and feedstocks procurement rate is presented in Figure 16.

The results show that the development of a BioSNG supply chain is economically feasible if the government supports minimum 30% of the total associated expenses. Nonetheless, this level of subsidisation only achieves a BioSNG penetration of 0.9%. The investments are focused on developing cereal straw as the only feedstock for BioSNG production. The operating costs are almost three-fold of the corresponding Capex. The subsidy is not enough to develop cultivation of miscanthus.



(a) (b)

(c) (d)

Figure 16. Role of government incentives on the BioSNG supply chain: (a) Net present value. (b) Capital expenditures. (c) Operational expenditures. (d) Feedstocks production and BioSNG penetration

At $\theta = 40\%$, woody biomass and residual waste are added to the mix of feedstocks. Consequently, the production of BioSNG can supply 3.1% of the total gas demand. Investments in cultivation of miscanthus start once the government subsidies up to 50% of the total costs. At this point, the NPV is £1.6bn; the investments in facilities as well as the operating costs increased significantly in comparison to the previous case. The cultivation of miscanthus is now the main source of feedstocks. The supply of BioSNG increased remarkably to 14.3%.

An additional increment of 10% in θ drives the investments and operating expenses up in 49.8% and 52.7%, respectively. This is due mostly to installation of new facilities for processing miscanthus. The NPV increased three-fold reaching £4.9bn. The BioSNG supply also increased considerably achieving 20.3% of the total gas demand. After this point, the investments, operating costs, and BioSNG penetration are moderately stable, therefore, the parameter θ has only effect on the NPV. It is worth of mention that there is a slight decrement of investments, and consequently the BioSNG penetration, when θ goes from 90% to 100%. Tax payments are causing this effect. It is expected that the production of BioSNG, and therefore the income, increases along with θ. However, at 100%, the optimal solution led to decreasing slightly the production of BioSNG in order to compensate for the increment of taxes. Additional runs confirmed this. The results revealed that varying the tax rate ±10%, from the base case (tax rate = 35%), the production of BioSNG in the last period increased 0.15% with respect to the base case for a tax rate of 25%. Similarly, for a tax rate of 45%, the production of BioSNG in the last period decreased 0.32% in comparison to the base case. This reaffirms the importance of developing systematic frameworks that assist in disclosing trends that are not evident. Finally, the corresponding breakdown of total cost and income for every θ is presented in Figure 17.

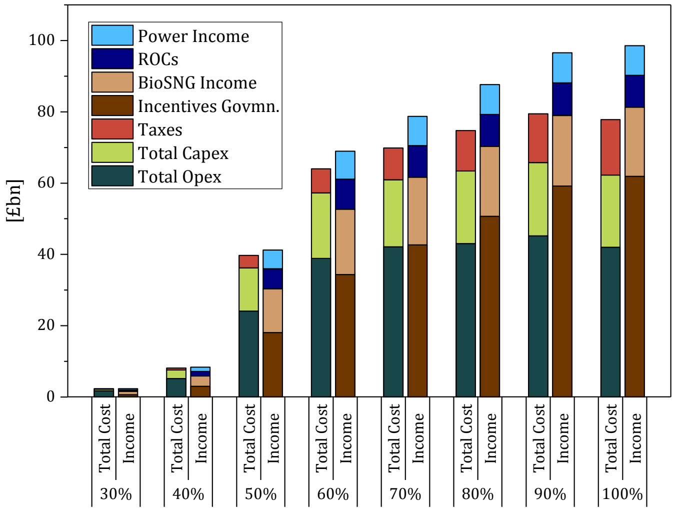


Figure 17. Total cost and income breakdown variation with government incentives

In general, the incentive from the government is the most important source of profit. A supply of 1% of the total demand (θ=30%), requires an investment from the government of £674m. This contribution has to increase up to £18.1bn to achieve a BioSNG penetration of

14.3%. It was found that a support of 60% is a critical point in which a significantly high supply (20.3%) of the total gas demand can be achieved with a financial aid of £34.4bn. In order to increase the supply in 1% (21.3%) it is necessary a financial aid of £61.9bn, around 44.5% more.

6 Conclusions

In this work, a spatially-explicit multiperiod mixed integer linear programming model is proposed to address the optimal strategic design of BioSNG supply chain in a regional and national context. In order to demonstrate the capabilities of the optimisation framework, a UK case study based was implemented. Domestic resources such as woody biomass, cereal straw, residual waste, and miscanthus were included as potential feedstocks for BioSNG production. The availability of these resources considers sustainability criteria and national policies regarding their current and future management strategy. Allothermal gasification and plasma gasification are considered as the main processing routes. The results show that operating costs are the major component in the development of a BioSNG supply chain, followed by investments in processing facilities. In addition, it was found that among four feedstocks, miscanthus is crucial for the production of BioSNG in the UK. On average, England is the highest feedstock supplier with 65% of the total feedstock production; followed by Wales with 20%, and finally Scotland with 15%. The optimisation results show that for the planning horizon (20 years) the production of BioSNG can supply up to 20.6% of the total gas demand. Moreover, the results suggest that the installation of facilities does not necessarily coincide with regions of high potential for feedstocks production. Instead, the transportation cost is a crucial component that can influence the optimal location of a facility.

In addition, It was found that cogeneration of power has a major impact on the economics of the BioSNG supply chain. In this case, the NPV nearly doubles its value and the breakeven time is reduced in two years. Moreover, the production of BioSNG achieved a supply of 21.4%. The coproduction of power can supply 4.4% of the total demand during the planning horizon. In terms of economics, the financial contribution from the government due to BioSNG production is the main source of profit as it is three-fold the income from BioSNG sales. Furthermore, by means of a parametric it was possible to establish that the development of a BioSNG supply chain is economically feasible if the government supports minimum 30% of the total associated expenses. Nonetheless, the BioSNG penetration is marginal and the NPV is significantly low. Therefore, this scenario is not economically attractive for investment from private sectors. It was possible to determine that a contribution from the government of 60% is a critical point in which a BioSNG penetration of 20.3% can be achieved. Further increments in subsidisation do not have a significant impact on the supply.

Finally, the optimal design of a BioSNG supply chain depends strongly on factors such as the geographical distribution of the resources, associated production costs, and market conditions. Therefore, stochastic optimisation techniques should be implemented in order to design robust supply chains in light of uncertainty. In addition, as commercial applications of gasification of biomass and waste are scarce, it is expected that the installation costs would decrease as research continues and more experience is gained (learning-by-doing). Hence, as future work, the optimisation framework can be extended in order to take into account learning curves. Moreover, pre-treatment technologies should be addressed in order to investigate the trade-off between capital investment and reduction of transportation costs, and their impact in the economic performance of a BioSNG supply chain.

Appendix A Nomenclature

Indices

f	Feedstocks
g, g'	Regions
i	Resources
k	Technologies
l	Transportation modes
p	Final products
s	Segments for cost linearisation
t, t'	Time periods
z	Local distribution zone (LDZ)

Sets

F	Set of feedstocks, $F = F^a \cup F^e$
F^a	Set of available feedstocks
F^e	Set of new energy crops
G	Set of regions
I	Set of resources (feedstocks and final products), $I = F \cup P$
K	Set of technologies for integrated facilities
P	Set of final products
S	Set of segments for cost linearisation
T	Set of time periods
Z	Set of Local distribution zones (LDZs)
F_k	Set of feedstocks f that can be processed by technologies k
G_z	Set of regions g with injection points corresponding to a local distribution zone z
$\eta_{igg'l}$	Set of feasible transport links for each resource i between region g and g' via transport mode l

Scalars

Avf	Availability factor for renewable energy plants
Cf	Capacity factor for renewable energy plants
$LimP$	Upper bound for production in regions [GWh year^{-1}]
$LimD$	Upper bound for demand in regions [GWh year^{-1}]
Tr	Tax rate
α	Operating period in a year [hr year^{-1}]
μ	Steam to power generation efficiency
γ, ψ, λ	Conversion factors

Parameters

$AD_{gg'l}$	Actual delivery distance between regions g and g' via transport mode l [km]
aIN_{fks}	Independent term of the linearised capex curve for an integrated plant processing feedstock f with technology k at each segment s [£m]
bIN_{fks}	Slope of the linearised capex curve for an integrated plant processing feedstock f with technology k at each segment s [£m MW^{-1}]
$CMax_{ks}$	Maximum capacity of technology k at each linearisation segment s of the Capex curve [MW]
$CMin_{ks}$	Minimum capacity of technology k at each linearisation segment s of the Capex curve [MW]
Dem_{pzt}	Demand of product p in local distribution zone z in time period t [GWh year^{-1}]
$DepF_{tt'}$	Depreciation factor for investments in t during periods t'
$DfCA_t$	Discount factor for capital costs in time period t
$DfCF_t$	Discount factor for cash flow in time period t
DW_l	Driver wage for transportation mode l [£k h^{-1}]
$EstCost_{ft}$	Establishment costs for energy crops ($f \in F^e$) in time period t [£m ha^{-1}]
FE_l	Fuel efficiency for transportation mode l [Km liters^{-1}]
$FMax_{fgt}$	Maximum feedstock ($f \in F^a$) availability in region g and time period t [ton year^{-1}]
$FMin_{fgt}$	Minimum feedstock ($f \in F^a$) availability in region g and time period t [ton year^{-1}]

FP_l	Fuel price for transportation mode l [£k liters^{-1}]
$FxOpIN_{fkt}$	Fixed costs for operation and maintenance for an integrated plant processing feedstock f via technology k in time period t [£m year^{-1}]
$FxTC_i^{Loc}$	Fixed local transport costs for resources i [£ Ton^{-1}]
$FxTC_{il}^{Reg}$	Fixed regional transport costs for resources i via mode l [£ Ton^{-1}]
GE_l	General expenses of transportation mode l [£k d^{-1}]
Inc_{pt}	Renewable heat incentive for p injection in time period t [£ kWh^{-1}]
$Land_{gt}$	Arable land available in region g and time period t [ha]
LD_g	Actual local delivery distance within a region g [km]
LHV_i	Low heating value for resource i [GJ ton^{-1}]
LUT_l	Load-unload time of transportation mode l [h]
$MaxLand_t$	Maximum total land available for energy crops in time period t [ha]
ME_l	Maintenance expenses for transportation mode l [£k Km^{-1}]
$OpCost_{ft}$	Operation costs related to energy crops ($f \in F^e$) in time period t. It is included fixed overheads agrochemicals harvesting costs and storage costs [£m ha^{-1} year^{-1}]
$PlanRem_{ft}$	Plantation removal costs for energy crops ($f \in F^e$) in time period t [£m ha^{-1}]
$Price_{pt}$	Price of products p in time period t [£ kWh^{-1}]
$Rent_{gt}$	Rent costs for land in region g in time period t [£m ha^{-1} year^{-1}]
SP_l	Average speed of transportation mode l [Km h^{-1}]
$TCap_l$	Capacity of transportation mode l [Kg]
TMA_l^{Loc}	Local availability of transportation mode l [h d^{-1}]
TMA_l^{Reg}	Regional availability of transportation mode l [h d^{-1}]
TMC_l	Capital cost for establishing a transportation mode l for BioSNG [£m]
UFC_{fgt}	Unit feedstock costs of available feedstocks ($f \in F^a$) per region g in time period t [£ Ton^{-1}]
$VrOpIN_{fkt}$	Variable costs of operation and maintenance for an integrated plant processing feedstock f using technology k in time period t [£m GWh^{-1}]

$VrTC_i^{Loc}$	Variable local transport costs for resources i [£ Ton^{-1} km^{-1}]
$VrTC_{il}^{Reg}$	Variable regional transport costs for resources i via mode l [£ Ton^{-1} km^{-1}]
$Yield_{fgt}$	Cultivation yield for energy crops ($f \in F^e$) within region g in time period t [ton year^{-1} ha^{-1}]
βIN_{fkt}	Efficiency of an integrated plant processing feedstock f with technology k to produce p

Positive continuous variables

A_{fgt}	Area occupied by second generation crop ($f \in F^e$) in region g and time period t [ha]
$CAPEX_t$	Total investment cost for the supply chain in time period t [£m]
$CAPEX\_EC_t$	Total investment cost for new energy crops in time period t [£m]
$CAPEX\_IN_t$	Total investment cost of integrated plants in time period t [£m]
$CAPEX\_TR_t$	Total investment cost for new BioSNG transport facilities time period t [£m]
$CAPIN_{fkgts}$	Initial installed capacity for an integrated plant processing feedstock f using technology k in region g and and is available in time period t at segment s [MW]
D_{igt}	Demand for resource i in region g in time period t [GWh year^{-1}]
$DEP_{tt'}$	Depreciation for investments in t during periods t' [£m year^{-1}]
DGZ_{pgzt}	Variable relating the supply of a final product p in region g and the demand of a local distribution zone z for in time period t [GWh year^{-1}]
DIN_{fkgt}	Demand of an integrated plant processing feedstock f with technology k in region g in time period t [GWh year^{-1}]
FC_t	Total feedstock cost in time period t [£m year^{-1}]
$IncentiveGOV_t$	Incentives associated to government subsidies for BioSNG production in time period t
$IncentiveROC_t$	Incentives associated to Renewable Obligation Certificates for power generation in time period t
$INCOME_t$	Total revenues in time period t [£m year^{-1}]
$LocSup_{gt}$	Variable that accounts for the demand of BioSNG met locally in region g and time period t [GWh year^{-1}]
$OPEX_t$	Total operational cost in time period t [£m year^{-1}]

P_{igt}	Production rate of product i in region g in time period t [GWh year^{-1}]
PC_t	Total production cost in time period t [£m year^{-1}]
PIN_{fkpgt}	Production rate at an integrated plant processing feedstock f with technology k to produce p in region g in time period t [GWh year^{-1}]
$Q_{igg't}$	Flow rate of product i via mode l from region g to g' in time period t [GWh year^{-1}]
$TArea_{fgt}$	Total area occupied by second generation crops ($f \in F^e$) in region g and time period t [ha]
TAX_t	Total taxes in time period t [£m year^{-1}]
TC_F_t	Total transportation cost for feedstocks in time period t [£m year^{-1}]
$TC\_SNG_t^{Reg}$	Regional transportation cost for new BioSNG transport facilities in time period t [£m year^{-1}]
$TC\_SNG_t^{Loc}$	Local transportation cost for new BioSNG transport facilities in time period t [£m year^{-1}]
$ToCAPIN_{fkgt}$	Total capacity of an integrated plant processing feedstock f in region g and using technology k that is available in time period t [MW]

Free continuous variables

Cf_t	Cash flow after taxes in time period t [£m year^{-1}]
NPV_t	Net present value [£m]
$PROFIT_t$	Profit after depreciation and operational costs in time period t [£m year^{-1}]

Binary variables

$AvIN_{fkgts}$	1 if an integrated plant processing feedstock f using technology k and located in region g is operating in time period t with a capacity delimited by a segment s, 0 otherwise.
PD_{gt}	1 if BioSNG production in region g and time period t is less than the demand in region g and time period t, 0 otherwise.
δIN_{fkgts}	1 if an integrated plant processing feedstock f using technology k in region g is installed in time period t with a capacity delimited by a segment s, 0 otherwise.

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Table 1. Capex, Opex and technical specifications of processing facilities.

	Allothermal gasification (MILENA)	Plasma gasification
Capacity [MW]	100	100
Capex [£m]	116	149
Fixed cost [£m/y]	3.0	2.8
Variable cost [£m/GWh]	3.7E-03	2.4E-02
Feedstock-to-Biosng efficiency	63.8%	52.0%
Heat recovery efficiency	22.2%	10.0%

Table 2. Fixed and variable costs for feedstock transportation.

	Fixed costs [£/GWh]		Variable costs [£/km-GWh]	
	Truck	Rail	Truck	Rail
Woody biomass	1359.7	2722.2	30.4	8.4
Residual waste	1646.8	3296.9	36.8	10.1
Miscanthus	1190.5	4254.1	32.7	6.9
Cereal straw	1180.5	4218.7	32.5	6.9

Table 3. Model statistics and computational results for Case Study A and Case Study B

	Case study A	Case study B
Total number of variables	15,713	16,553
Continuous variables	12,773	13,613
Binary variables	2,940	2,940
Total number of constraints	11,933	12,245
Non zero constraint matrix elements	54,629	56,589
CPU time [s]	2,483	2,620
Optimal NPV [£bn]	10.27	20.71

Table 4. Comparison for plant installations for Case A and Case B

	Case A	Case B
Woody biomass	D6, H2, M2	D1, F2, J3
Cereal straw	F3, K1, M2	F3, K1, M2
Miscanthus	D1, D6, G2, J3, K2, K3, K4, L1, L2, M3, M6	D1, D4, D6, G2, J2, J3, K1, K2, K4, L1, L2, M3
Residual waste	D3, E1, G2, H2, I2, J3, M2	D3, E1, G2, H3, J1, J2, K2, M2

Table 5. Results comparison for Case A and Case B

	Case A	Case B	Variation [%]
NPV [£bn]	10.7	20.7	48.3
Total Capex [£bn]	19.3	20.4	5.4
Total Opex [£bn]	38.3	42.1	9.0
Taxes [£bn]	9.8	15.6	37.2
Total Income [£bn]	18.6	27.7	32.9
Total Incentives [£bn]	59.2	71	16.6
BioSNG production [GWh/year]	101,109	104,795	3.5
Power production [GWh/year]	-	13,242	-
BioSNG penetration [%]	20.6	21.4	3.7
Power penetration [%]	-	4.4	-
Breakeven cost [£/MMBTU]	28.5	26.5	-7.9