# Economic evaluation of bio-based supply chains with $CO_2$ capture and utilisation

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## Abstract

Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) are acknowledged as important R&D priorities to achieve environmental goals set for next decades. This work studies biomass-based energy supply chains with $CO_2$ capture and utilisation. The problem is formulated as a mixed-integer linear program. This study presents a flexible supply chain superstructure to answer issues on economic and environmental benefits achievable by integrating biomass-coal plants, $CO_2$ capture and utilisation plants; i.e. location of intermediate steps, fraction of $CO_2$ emissions captured per plant, $CO_2$ utilisation plants' size, among others. Moreover, eventual incentives and environmental revenues will be discussed to make an economically feasible project. A large-size case study located in Spain will be presented to highlight the proposed approach. Two key scenarios are envisaged: (i) Biomass, capture or utilisation of $CO_2$ are not contemplated; (ii) Biomass, capture and $CO_2$ utilisation are all considered. Finally, concluding remarks are drawn.

*Keywords*: Mathematical modelling, MILP, NPV, biomass co-combustion, coal power plants, bio-based CCU supply chain

## Glossary

| | |
|---|---|
| AWR | Agricultural woody residues |
| BD | Bulk density |
| CCS | Carbon capture and storage |
| CCU | Carbon capture and utilisation |

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| CDU | Carbon dioxide utilisation |
| DM | Dry matter |
| EOR | Enhanced oil recovery |
| ETS | Emission's trading system |
| EU | European Union |
| FWR | Forest wood residues |
| GHG | Greenhouse gas |
| LHV | Lower heating value |
| MC | Moisture content |
| MEA | Monoethanolamine |
| MILP | Mixed Integer Linear Program |
| SC | Supply chain |
| UTM | Universal Transverse Mercator |

## 1 Introduction

The $CO_2$ emissions from oil, natural gas and coal for any use have changed from 15 500 $MtCO_2$/y in 1973 to 32 200 $MtCO_2$/y in 2013 (IEA, 2015) In spite of advances in the use of energy sources, coal is still the main fossil fuel used worldwide (EC, 2014). The contribution of fossil fuels to the energy share in Europe will continue to be higher than renewable and nuclear power in the short and medium term (European Commission, 2011). Moreover, process industries like cement, iron and steel, aluminium, pulp and paper, and refineries, have inherent $CO_2$ emissions as a result of their raw material conversion. Beyond different alternatives, carbon capture is needed to lower $CO_2$ emissions.

According to the Energy Roadmap 2050 (European Commission, 2011), CCS will have to be present in 7-32 % of the fossil fuel energy generation share in 2050, depending on the modelling scenario considered, to meet a 80-95 % greenhouse gas (GHG) emissions reduction by 2050 with 1990 as reference year. The 2030 Climate and Energy Policy Framework (General Secretariat of the Council, 2014) proposes a GHG reduction of at least 40 % of the 1990 level by 2030 in order to meet the 2050 objective. Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) have been acknowledged as important research and development priorities of the European Energy Union if it is to reach its 2050 climate objectives in a cost-effective way (European Commission, 2015a). Moreover, CCS and CCU are research priorities of the Strategic Energy Technologies (SET) Plan of the European Union (European Commission, 2015b). The new financing instrument of the Emissions Trading System from the European Union (EU ETS) is the Innovation Fund ([1]). Among other characteristics, it dedicates EUR 400 million allowances to support innovation, plus EUR 50 million from the allowances that remain unused in 2013-2020 to remove a total of 450 million of $CO_2$ emissions from the current emission's share. The EU ETS is the EU carbon market and works on a cap and trade principle. From 2013, all power generators have to buy all their $CO_2$ allowances ([2]).

Carbon dioxide utilisation (CDU) processes are not only relevant to the energy generation or to the heavy industry sectors, but also in a number of other policy areas such as: GHG emissions, transport sector emissions, waste disposal, chemical industry and technological development. The capability of CDU as a $CO_2$ abatement option and as a competitive advantage for the chemical industry is acknowledged. Its potential has been estimated in about 10 % of today's global $CO_2$ emissions (Zimmermann and Kant, 2015). The major interest for CDU processes is on carbon footprint reduction if compared to the benchmark fossil fuel route, as well as in fossil fuel savings that are not used as raw material (von der Assen et al., 2013). The $CO_2$ stream for CDU processes may come from other sources rather than power plant flue gases; i.e. captured in heavy industry, produced as by-product, generated in the natural gas industry, or captured from the atmosphere. Therefore, different commercial synergies (as for captured $CO_2$ "management") may be possible to develop feasible business cases (Pérez-Fortes and Tzimas, 2016; Zimmermann and Kant, 2015).

Biomass can provide a larger energy share than the one that provides nowadays. At large scale, it can be properly co-used with fossil fuels, while at small scale 100 % biomass systems can be appropriate for residential uses and rural electrification (Puigjaner et al., 2015). Biomass alternative and renewable systems must be sustainable and provide a better $CO_2$ emissions balance than the reference situation with fossil fuels usage. A better $CO_2$ balance will result from (i) responsible resource exploitation by balancing source availability with the capacity of the plant that uses biomass, and from (ii) an efficient supply-distribution network. Biomass can be considered as carbon neutral if there exists the appropriate time delay between emissions and biomass growth (Zanchi et al., 2012). This means that new biomass growth may offset $CO_2$ emissions caused by biomass consumption for energy purposes if the consumption rate is smaller than the harvesting rate. $CO_2$ emissions from biomass can be even

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[1] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2015:337:REV1

[2] http://ec.europa.eu/clima/policies/ets/index_en.htm

negative in specific situations as demonstrated in Tilman et al. (Tilman et al., 2006) for the production of biofuels through high diversity grassland biomass. In biorefineries, the overall conversion of biomass can be increased if combined with CDU utilisation processes with a noticeable lower $CO_2$ emissions impact (Sharifzadeh et al., 2015). The use of woody biomass to replace fossil fuel in heat and power generation indicates better environmental performance. A lower environmental impact is reported if biofuels are the objective (Steubing et al., 2011). As well as with CDU processes, the consumption of less fossil fuel is an important added value of biomass processes.

The purpose of the paper is to identify the economic optimal supply chain (SC) configuration for a bio-based – CCU SC under an emissions abatement condition. Conventional coal power plants are to be adapted to decrease their overall emissions by (i) co-combustion of biomass and by (ii) carbon capture and utilisation in $CO_2$-based methanol plants. The article is organised as follows: after a brief overview, the mathematical model used for SC optimisation and the case study are described. The model considers SC long-term strategic decisions, such as selection of biomass sources, establishment of pre-treatment units and their location, disposition of distribution centres, coal power plants adapted with co-combustion and carbon capture, and coal power plants equipped with $CO_2$-based methanol plants. Therefore, the results of this exercise are the network structure design, the selection of the processes' location based on an exclusive list of candidates, the estimation of the needed investment and the monthly flows of mass and energy along the different sites.

## 2 Overview

The current energy sector needs to reduce its $CO_2$ emissions. The available options are more efficient conversion processes, renewable sources and smart grids, with the consequent change of business model. Customised and tailor-made solutions to the conditions of each particular site will allow the profitability and feasibility of the business case. As a transition solution towards carbon-free energy generation, biomass can be co-used with fossil fuels in already existing power plants. The use of biomass waste, which entails disposal problems, can be an alternative source of organic matter for power production. The alternatives to centralised and conventional sources of energy should be sustainable in the time, which implies responsible resource exploitation, by balancing source availability with electricity demand, and thus with the plant capacity. That is the reason why the SC optimisation is crucial towards a new energy sector (Puigjaner et al., 2015).

Any type of industry or process can take benefit of modelling and optimisation of SC's, where not only operations are considered, but also business functionalities or market/operation dynamics (Laínez-Aguirre and Puigjaner, 2012). Mathematical programming is an appropriate tool to assist in the quantitative evaluation of bio-based systems, where points of biomass generation may be far from consumption or demand points, local available biomass may not match the biomass demand, and different generation/pre-treatment technologies may be available. The biomass SC problem may be addressed using a wide range of decision-maker outlooks: economic (Bowling et al., 2011; Caputo et al., 2005), environmental (Damen and Faaij, 2006; Perry and Rosillo-Calle, 2008), or both (Ayoub et al., 2009; Bojarski et al., 2009; Mele et al., 2011). Other attempts have been recently done to add the social criterion to the economic and environmental points of view, as the creation of places of job (Pérez-Fortes et al., 2012; You et al., 2012). The optimisation of bio-based SCs under sustainability issues, encompasses many approaches, from the selection of raw material(s) (location, characteristics, and treatments) and/or products to be synthesised, to the selection of synthesis processes (Ba et al., 2016; Cambero and Sowlati, 2014).

The work by (Yue et al., 2014) reviews the major pathways for biomass to bioenergy and biofuel. Biorefineries and CCS and CDU processes are also included. The concept of superstructure is exploited for the selection of the best technologies in each echelon. A superstructure approach, for first and second biomass conversion technologies is also applied in the design of a bioethanol SC in (Miret et al., 2016). With regard to the SC of $CO_2$ emissions, once emissions are produced  they are considered as a material and  goes through four echelons/activities: carbon sourcing, capture, transport and storage or sequestration. $CO_2$ can be used to synthesise fuels, chemicals or materials. The captured $CO_2$ may be utilised and/or (permanently) stored in geological formations depending on the $CO_2$ flowrate and on the purpose of the overall SC. $CO_2$ sources and technological options for capture, transport by pipeline or ships, storage sites location and/or multiple CDU choices configures an interesting superstructure, and business model. To the best of our knowledge, several works have been devoted to the SC optimisation of $CO_2$ utilisation. In US, enhanced oil recovery (EOR) is the $CO_2$ utilisation option that has been in practice for many decades, with $CO_2$ from natural gas processing. A US SC is the subject of study in (Hasan et al., 2015, 2014), where a superstructure is considered for the economic optimisation of the whole country taking into account large $CO_2$ stationary sources, saline formations and non-mineable coal areas for $CO_2$ storage, and oil and gas reservoirs for EOR. In (Roh et al., 2016a, 2016b) the superstructure approach aims at considering the most convenient conversion of $CO_2$ according to the demand to be supplied, $CO_2$ reduction and economic feasibilities.

The current paper studies the combination of co-combustion of biomass and coal with carbon capture for $CO_2$ utilisation in the synthesis of methanol. As for the carbon capture technology, it is a technology already used in industry segments such as natural gas processing, hydrogen production, and in a portion of flue gas from a power plant (Rubin et al., 2012). However, carbon capture at fully commercial scale for a power plant still remains opened: the only existing large scale CCS project is Boundary Dam in Canada which incorporates a coal power plant of 110 MW (MIT, 2016). Currently, the most effective and well-known method to capture $CO_2$ from flue gas is the chemical absorption with an aqueous MEA (monoethanolamine) solution in a post-combustion configuration. The use of $CO_2$ as raw material is seen in Europe as a factor of chemical industry rejuvenation (CEFIC, 2009). These processes are currently under different levels of development, ranging from the most basic research, up to first commercial plants, as for instance Carbon Recycling International ([3]). The CDU processes receive the attention of intermittent renewable plants (i.e. wind, solar), that see $CO_2$ conversion, and more specifically, the synthesis of $H_2$ via electrolysis, a way of electricity storage (Jallouli and Krichen, 2012; Jurgensen et al., 2014). It turns out that the conversion of $H_2$ into a liquid chemical through its combination of $CO_2$ is attracting the attention of companies that aim at the liquid storage of hydrogen carriers, instead of the high volume and relatively dangerous storage of gaseous $H_2$ (Dalebrook et al., 2013; Dutta, 2014). It has been recently demonstrated that, to represent net $CO_2$ emissions reduction if compared to the benchmark situation, CDU processes that consume $H_2$ produced ad hoc by an electrolyze, need renewable sources to power it (Pérez-Fortes and Tzimas, 2016). The current paper aims at connecting the renewable share of electricity production by biomass in a co-combustion configuration with partial $CO_2$ capture plants that send the $CO_2$ to inside $CO_2$-based methanol plants, in order to evaluate the potential benefit on the $CO_2$ emissions balance.

## 3 Problem statement

This paper deals with the strategic and tactical decisions associated with the optimal design and planning of bio-based SC network where co-combustion of biomass and coal is the main alternative technology to fulfil the market demand of electricity. One of the main

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[3] http://carbonrecycling.is/

decisions to evaluate is the inclusion of CCU, delivering $CO_2$ for the production of methanol (i.e. no other utilisation or storage option is considered), fed by the electricity produced by the portion of coal feedstock replaced by biomass (considered here as "zero" $CO_2$ emission source). It is assumed that incorporating $CO_2$ capture technologies causes a reduction in the efficiency of a co-combustion plant. In this paper, methanol production from carbon utilisation fulfils the required methanol demand. A process using natural gas as feedstock is the benchmark layout for methanol production.

The current approach has as starting points:

- The SC depicted in (Pérez-Fortes et al., 2014). The case study comprises coal power plants from the Spanish electricity system, and the local woody biomass waste available as assessed in (A Gómez et al., 2010) through a square geographical discretisation. The SC has been expanded to include CCU.
- The mass and energy balances and economic data from the $CO_2$-to-methanol process and evaluated in (Pérez-Fortes and Tzimas, 2016).
- A superstructure of biomass pre-treatment systems (Pérez-Fortes et al., 2014), and the investment and operating costs for coal power plant adaptation to co-combustion and $CO_2$ capture (European Commission, 2014a).

The optimisation problem is based on an economic criterion and has to meet (i) the electricity demand, (ii) the methanol demand and (iii) the required $CO_2$ emissions reduction. The emissions reduction and the economic criterion are relative towards a reference case which considers that no action to further decrease $CO_2$ emissions is taken.

In general, at the strategic level decisions include selecting the network nodes (suppliers, producers, storage locations) through which intermediates and final products are processed and distributed to finally reach the final consumer. Additionally, the strategic decisions include the selection of those technologies to deploy in the different nodes as well as their corresponding capacity. The most common approach is to formulate this problem as a large-scale Mixed Integer Linear Program (MILP) that captures the relevant fixed and variable operating costs for each location and each relevant product (Graves and Willems, 2003). The tactical decisions are related to the amount of the different materials and energy that flow along the network.

The considered SC network consists of a number of potential locations where either a processing site or distribution centre or both of them can be located, and suppliers at fixed locations which have available biomass waste with different characteristics. Energy can be generated at several plants located at different locations using the different biomass waste and coal; while methanol can be produced using $CO_2$ captured at the co-combustion power plant. It is assumed that the $CO_2$ captured is used at the same site; thus, no $CO_2$ transport is needed. The characteristics of the biomass can be changed by using the pretreatment units (e.g., chipping and drying) so that the treated biomass (i) meets the characteristics required to be used in the coal power plant or (ii) increases bulk density to facilitate distribution. Materials flow between any pair of locations may appear if selecting such flow allows improving the performance of the SC.

A general schematic of the bio-based – CCU SC is shown in Figure 1. It is comprised by six main blocks: (i) sourcing, (ii) pre-treatment, (iii) biomass distribution, (iv) biomass storage, (v) energy generation in power plants and (vi) carbon capture and utilisation in the methanol plant. The sourcing block consists in collecting the different biomasses (BM) from different regions and suppliers. After BM being collected in residues piles, the model selects the appropriate location and size of the storage sites where moisture content is decreased due to natural effects. The pre-treatment block considers those activities that modify the quality (primarily moisture content) and/or shape of the biomass, i.e. chipping and drying. Biomass is then transported and stored in silos to be later delivered to their respective consumption points. These consumption points are represented by the generation block or power plants, which convert biomass and coal into electricity. The carbon capture and utilisation block integrates $CO_2$ capture to feed the CDU methanol plants. Location and quantity of $CO_2$ capture and CDU methanol plants are decided by the model which is driven by a target decrease of $CO_2$ emissions. For further details about the depicted superstructure, the reader is referred to (Pérez-Fortes et al., 2014).

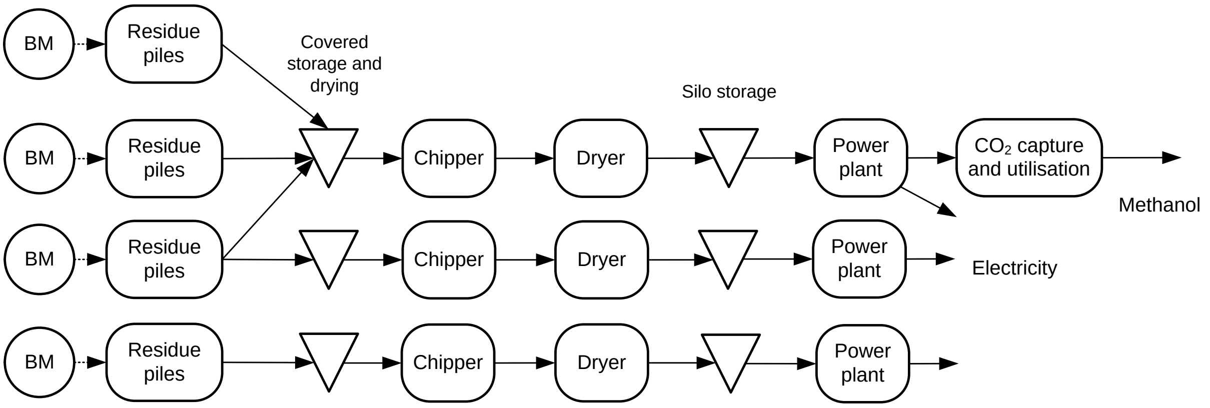

*Figure 1 General scheme of the bio-based – CCU SC considered. BM: Biomass.*

Given the following inputs:

1. Process data

- Biomass waste available for energy purposes: Lower heating value (LHV) and availability (i.e. seasonality).
- Superstructure of pre-treatment and conditions of shape and humidity to meet to enter the power plant.
- Characteristics of biomass storage installations and means of transport for raw biomass and pre-treated biomass.
- Activities efficiencies for the bio-based part: moisture content (MC), dry matter (DM), bulk density (BD), and LHV change into each block. Utilities consumption.
- Activity efficiency for the power plant with CCU: the capture plant has an efficiency penalisation with respect to the coal power plant without capture. Both, $CO_2$ capture and utilisation plants consumption of electricity.
- A set of matter states that quantifies MC, DM, BD and LHV for each flow of mass between the activities up to the power plant.
- A set of demands for (i) the energy required by the co-combustion power plants according to the electricity demand, (ii) the methanol needed.
- A set of biomass providers, intermediates and plants locations.
- $CO_2$ emissions associated to the use of coal and natural gas, and diesel as consumable for biomass transport. $CO_2$ emissions from the EU electricity network and from the CDU plant (direct $CO_2$ emissions).
- Time period, planning horizon, project lifetime and annual working hours.

2. Economic data

- Investment, fixed and variable operating costs for the technologies comprised into all the blocks.
- Unit transportation costs per km and volume of biomass that is moved.
- Base capacity size and associated economies of scale for pre-treatment, storage, co-combustion and utilisation plants. Capture power plant investment cost is lineal.
- Prices of raw biomass, coal, electricity, fuels needed for transport, water, methanol, oxygen and natural gas. Current market price also for the tonne of $CO_2$ in the EU ETS.

Determine:

- The biomass network structure: location, number and capacities of the pre-treatment units, size of the volume transported, storage sites and their corresponding dimensions, and connections among them.
- Percentage of coal replaced by biomass into each power plant.
- The number of CCU installations and the percentage of $CO_2$ captured into each power plant.
- Raw biomass utilisation and schedule, i.e. suppliers operation per month. Inventory levels per month.
- Breakdown of investment and operating costs.

Subject to:

- Electricity and methanol demand satisfaction.
- $CO_2$ emissions reduction.

Objective:

- Economic optimisation through the metric net present value (NPV).

## 3.1 Indicators

To evaluate the performance of the proposed network, the NPV is optimised. The $CO_2$ emissions reduction condition is driving the replacement of coal and the installation of CCU plants. It is important to point out that the NPV and the $CO_2$ emissions reduction compare the so-called base case with the researched optimum SC. The base case considers that (i) power plants are uniquely fed by coal, (ii) conventional synthesis of methanol (the benchmark synthesis process) is used to meet the market demand of methanol and (iii) biomass waste is burnt (biomass disposal in Figure 2). The two metrics, NPV and $CO_2$ emissions reduction, evaluate (i) incremental costs due to new units installed related to the base case, and (ii) emissions decrement due to the use of biomass and to the $CO_2$ capture, as well as the prevented natural gas and coal to produce methanol and electricity, respectively. Figure 2 depicts both cases.

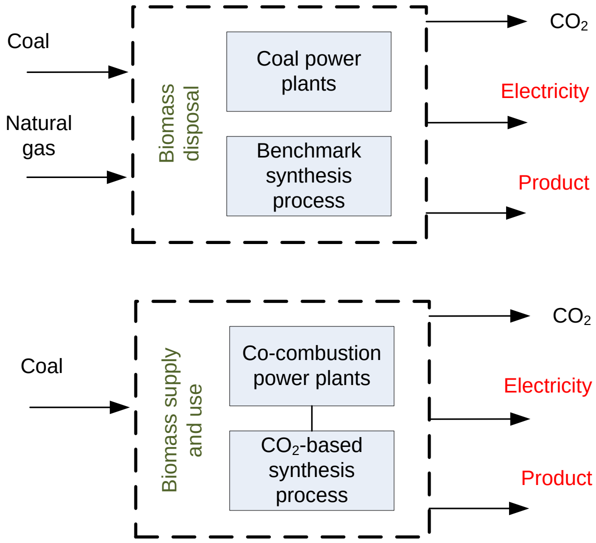

Figure 2 Boundaries for Case I - baseline case (top graph) and Case II - optimum SC configuration (bottom graph). Both of them produce the same amount of electricity and product (methanol). The main differences are: (i) consumption of natural gas (Case II does use $CO_2$ instead of natural gas to synthesise methanol), (ii) biomass final destination and (ii) use of and change on $CO_2$ emissions.

### 3.1.1 Net Present Value (NPV)

Here, in order to compute the NPV, operational costs include those associated with production, distribution and raw materials (i.e. coal, natural gas and biomass) acquisition. Revenue is obtained from the sales of methanol, oxygen (as byproduct of hydrolysis) and electricity. Investments on facilities and technologies are assumed to occur at the beginning of the project.

## 4 Mathematical model

The model is formulated using a multi objective MILP (moMILP) approach. The mathematical formulation is briefly described next. The interested reader is referred to Pérez-Fortes et al. (2014) for further details. The variables and constraints of the model can be roughly classified into three groups. The first one comprises the process operations constraints, while the second group deals with the environmental model. Finally, third group describes the equations required to evaluate the economic metric.

### 4.1 Design - Planning Model

The design-planning model is adapted from the work of Laínez et al. (2009). The model most important variable is $P_{ijff't}$; which represents the specific activity of task $i$ performed using technology $j$ receiving input materials from site $f$ and “delivering” output materials to site $f'$ during period $t$. This variable is employed for both production and distribution activities. In order to model a production activity, it must receive and deliver material within the same site ($P_{ijfft}$). In case of a distribution activity, facilities $f$ and $f'$ must be different. The model's equations are briefly described in the next paragraphs.

Materials mass balance must be satisfied at each one of the nodes (*f*). Equation (1) expresses the mass balance for each material (state in the STN formulation) $s$ at each potential facility $f$ in every time period $t$. Parameter $\alpha_{sij}$ represents the mass fraction of material $s$ that is produced by task $i$ performed using technology $j$ and the set $T_s$ refers to those tasks that have material $s$ as output, while parameter $\bar{\alpha}_{sij}$ and set $\bar{T}_s$ refers to tasks that consume material $s$.

$$S_{sft} - S_{sft-1} = \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_{f})} \bar{\alpha}_{sij} P_{ijff't} \qquad \forall s, f, t \tag{1}$$

The model assumes that process parameters are fixed (i.e. reactions conversion, separation factors and moisture characteristics). This assumption is acceptable for the majority of the activities: covered storage, chipping, drying, power plant conversion, $CO_2$ capture and $CO_2$ conversion. There are activities for which the model should suggest the mixture of inputs in order to achieve a given value for a specific biomass property (i.e., moisture content). For such activities the proportion of the different possible feedstock should be variable. In order to account for those activities, the mass balance shall be modified as shown in Equation (2).

$$\begin{aligned} S_{sft} - S_{sft-1} = {} & \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_{f})} \bar{\alpha}_{sij} P_{ijff't} \\ & + \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} Pv_{sijft} - \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_{f})} Pv_{sijf't} \\ & \forall s, f, t \end{aligned} \tag{2}$$

For these flexible activities, it is necessary to make sure that the energy balance is achieved. This is done by introducing Equation (3). Here, $HV_{si}$ is the heating value for material *s* in activity *i*. Notice that heating values for feedstock are fixed and given.

$$\sum_{s \in S_i} HV_{si} Pv_{sijft} = \sum_{s \in \bar{S}_i} HV_{si} Pv_{sijf't} \qquad \forall i \in \bar{I}, j, f, t \tag{3}$$

Let us consider that a flexible activity must accomplish total moisture content. In that case, constraint (4) must be satisfied. Parameters $Water_s$ and $Water^{max}{}_{ij}$ indicate the moisture content for material $s$ and the maximum moisture content allowed for task $i$ performed in equipment $j$. Silo storage is a flexible activity in the current case study.

$$\sum_{s \in S_i} Water_s Pv_{sijft} \leq Water_{ij}^{\max} \sum_{s \in \bar{S}_i} HV_{si} Pv_{sijf't} \qquad (4)$$

$$\forall i \in \bar{I}, j, f, t$$

Equation (5) models capacity expansions. The model is able to consider either a pure design or a retrofit of SCs. Equation (6) defines the total capacity ($F_{jft}$) accounting for the expansion during planning period $t$ ($FE_{jft}$).

$$V_{jft} FE_{jft}^{L} \leq FE_{jft} \leq V_{jft} FE_{jft}^{U} \qquad \forall f, j \in \tilde{J}_f, t \qquad (5)$$

$$F_{jft} = F_{jft-1} + FE_{jft} \qquad \forall f, j \in \tilde{J}_f, t \qquad (6)$$

Equation (7) ensures that the total production rate in each plant is greater than a minimum desired production rate and lower than the available capacity. In this equation, parameter $\beta_{jf}$ defines a minimum utilisation rate of technology $j$ in site $f$, while $\theta_{ijff'}$ indicates the capacity utilisation rate of technology $j$.

$$\beta_{jf} F_{jft-1} \leq \sum_{f'} \sum_{i \in I_j} \theta_{ijff'} P_{ijff't} \leq F_{jft-1} \qquad \forall f, j \in \tilde{J}_f, t \qquad (7)$$

Equation (8) forces the amount of raw material $s$ obtained from site $f$ at each time period $t$ to be lower than an upper bound given by physical limitations ($A_{sft}$). Also, the model assumes that part of the demand can actually be left unsatisfied because of limited production or supplier capacity. Thus, Eq. (9) expresses that the sales of $s$ carried out in market $f$ during time period $t$ must be less than or equal to demand.

$$\sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in J_i} P_{ijff't} \leq A_{sft} \qquad \forall s \in RM, f \in Sup, t \qquad (8)$$

$$\sum_{f'} \sum_{i \in T_s} \sum_{j \in J_i} P_{ijff't} \leq Dem_{sft} \qquad \forall s \in FP, f \in Mkt, t$$

(9)

## 4.2 Environmental Model

The application of the LCA methodology to a SC includes four steps, namely (i) goal setting, (ii) life-cycle inventory (LCI), (iii) life-cycle impact assessment (LCIA), and (iv) results interpretation towards improvement.

Regarding goal setting, it is important to define the boundaries of the system under study, and the corresponding functional unit (FU). Commonly, a certain amount of production is considered as the FU. In this sense, it is advisable to compare different SCs in terms of the fulfilled amount of sales or portion of demand satisfied (Bojarski et al. 2009).

The LCI step requires the estimation of SC environmental interventions (emissions or natural raw material consumptions) which can be collected using LCI databases. Finally, the results of the LCI step can be interpreted by means of different environmental metrics. As aforementioned, we will focus on $CO_2$ emissions (i.e., climate change damage category) in this work.

The equations of the environmental model are briefly described next. Equation (10) evaluates $IC_{aft}$ which represents the mid-point $a$ environmental impact associated with site $f$ in period $t$; $\psi_{ijff'a}$ is the $a$ environmental category impact CF for task $i$ using technology $j$, receiving materials from node $f$ and delivering them at node $f'$. Note that $\psi_{ijff'a}$ is a negative factor for those activities that "consume" $CO_2$ emissions.

$$IC_{aft} = \sum_{j \in \tilde{J}_f} \sum_{i \in I_j} \sum_{f'} \psi_{ijff'a} P_{ijff't} \qquad \forall a, f, t$$

(10)

It is assumed that $\psi_{ijff'a}$ is fixed and constant, provided that all environmental impacts are directly proportional to the activity performed in that node ($P_{ijff't}$). This issue is common practice in LCA, where all direct environmental impacts are considered linear with respect to the FU (Heijungs and Suh 2002). In the case of distribution, the FU commonly considered is the amount of material shipped a given distance [kg·km]. Consequently, the value of $\psi_{ijff'a}$ can be calculated by Eq. (11) in the case of transportation, which considers the distance between sites ($distance_{ff'}$) and where $\psi^{T}_{ija}$ represents the $a$ environmental category impact CF for the transportation of a mass unit of material over a length unit. It should be noted that environmental impacts associated with distribution activities are allocated to their source node.

$$\psi_{ijff'a} = \psi^{T}_{ija} distance_{ff'} \qquad \forall i \in Tr, j \in J_i, a, f, f' \tag{11}$$

Equation (12) introduces $DamC_{gft}$ which is a weighted sum of all mid-point environmental interventions combined using $g$ end-point damage factors $\zeta_{ag}$ and then further normalized with $NormF_g$ factors. Equation (13) is used to compute the $g$ normalized end-point damage along the whole SC ($DamC^{SC}_{g}$). In this work, the set $g$ is comprised of one single element: the climate change damage category.

$$DamC_{gft} = \sum_{a \in A_g} NormF_g \zeta_{ag} IC_{aft} \qquad \forall g, f, t \tag{12}$$

$$DamC^{SC}_{g} = \sum_{f} \sum_{t} DamC_{gft} \qquad \forall g \tag{13}$$

CO2 emissions that are prevented are computed as shown in Eqns. (14) and (15). The set $ISV$ represents those activities which allow, by using biomass as energy source or CCU technologies, to avoid tasks that generated CO2 emissions (e.g., biomass sourcing vs. coal purchasing). Here $\overline{\psi}_{iff'\,a}$ is the $a$ environmental category impact CF avoided by performing task $i$ using technology $j$, receiving materials from node $f$ and delivering them at node $f'$; while, $\overline{IC}_{aft}$ and $\overline{DamC}^{SC}_{g}$ are the mid-point $a$ environmental impact *savings* associated with site $f$ in period $t$ and the $g$ normalized end-point damage *savings* along the whole SC , respectively.

$$\overline{IC}_{aft} = \sum_{j \in \hat{J}_i} \sum_{i \in ISV} \sum_{f'} \overline{\psi}_{iff'\,a} P_{ijff'\,t} \qquad \forall a, f, t \tag{14}$$

$$\overline{DamC}_g^{SC} = \sum_{a \in A_g} \sum_{f} \sum_{f} NormF_g \varsigma_{ag} \overline{IC}_{aft} \qquad \forall g \tag{15}$$

Equations (16) aggregate the environmental damage category results for the whole SC.

$$Impact = \sum_g \left( DamC_g^{SC} - \overline{DamC}_g^{SC} \right) \tag{16}$$

## 4.3 Economic Model

As previously stated, the NPV will be used for the economic evaluation. We are dealing with a network design problem. One of the characteristics of this type of problems is that they are capital intensive. Profit or cost do not take into account the capital needed for the investments associated with the new SC design or SC retrofit. However, NPV does and is commonly used to assess this kind of projects.

Operating revenue is calculated by means of net sales which are the income related to the normal SC activities. Thus, the total revenue incurred in any period *t* can be easily computed from sales executed in period *t* as shown in Eq. (17).

$$ESales_t = \sum_{s \in FP} \sum_{f \in Mkt} \sum_{f' \notin (Mkt \cup Sup)} Sales_{sff't} Price_{sft} \qquad \forall t \tag{17}$$

In order to calculate overall operating cost an estimation of indirect costs and direct costs are required. The total fixed cost of operating a given SC network can be obtained using Eq. (18). $FCFJ_{jft}$ represents the fixed unitary capacity cost of using technology *j* at site *f*.

$$FCost_t = \sum_{f \notin (Mkt \cup Sup)} \sum_{j \in \tilde{J}_f} FCFJ_{jft} F_{jft} \qquad \forall t \tag{18}$$

The cost of purchases from supplier *e*, which is computed through Eq. (19), includes raw materials purchases, transport, production resources and cost avoidance due to the use of biomass as energy source or carbon capture and utilisation technologies.

$$EPurch_{et} = Purch_{et}^{rm} + Purch_{et}^{tr} + Purch_{et}^{prod} - Purch_{et}^{ISV} \quad \forall\, e,t \tag{19}$$

The purchases ( $Purch_{et}^{rm}$ ) associated with raw materials from supplier *e* can be computed through Eq. (20). Parameter $\chi_{est}$ represents the cost associated with raw material *s* purchased from supplier *e*.

$$Purch_{et}^{rm} = \sum_{s \in RM} \sum_{f \in F_e} \sum_{i \in \overline{T}_s} \sum_{j \in J_i} P_{ijfft}\, \chi_{est} \qquad \forall e \in E_{rm}, t \tag{20}$$

The costs of production and distribution are determined by Eqns. (21) and (22), respectively. Here, $\rho_{eff't}^{tr}$ denotes the *e* provider unitary cost associated with shipping materials from location *f* to location *f'* during period *t*. $\tau_{ijfet}^{ut1}$ represents the unitary production cost associated with task *i* using technology *j*, whereas $\tau_{sfet}^{ut2}$ represents the unitary inventory costs of material *s* stored at site *f*, both of them using provider *e* during period *t*.

$$Purch_{et}^{tr} = \sum_{i \in Tr} \sum_{j \in J_i \cap \overline{J}_e} \sum_{f} \sum_{f'} P_{ijff't}\, \rho_{eff't}^{tr} \qquad \forall e \in \overline{E}_{tr}, t \tag{21}$$

$$Purch_{et}^{prod} = \sum_{f} \sum_{i \notin Tr} \sum_{j \in (J_i \cap \hat{J}_f)} P_{ijfft}\, \tau_{ijfet}^{ut1} + \sum_{s} \sum_{f \notin (Sup \cup Mkt)} S_{sft}\, \tau_{sfet}^{ut2}$$
$$\forall e \in \tilde{E}_{prod}, t \tag{22}$$

The cost avoidance achieved by substituting some activities in the supply chain by biomass based energy generation and carbon capture and utilisation technologies is accounted in Eq. (23).

$$Purch_{et}^{ISV} = \sum_{j \in \hat{J}_i} \sum_{i \in ISV} \sum_{f'} P_{ijff't}\, \tau_{iffet}^{ISV} \qquad \forall e \in \widetilde{E_{ISV}}, t \tag{23}$$

Finally, the total investment on fixed assets is computed through Eq. (24). This equation includes the investment made to expand the technology's capacity *j* in facility site *f* in period *t* ($Price^{FJ}_{jft} FE_{jft}$). A piece-wise linear function can be used to model economies of scale.

$$FAsset_t = \sum_f \sum_j Price^J_{jft} FE_{jft} + I^J_{ft} JB_{ft} \qquad \forall t$$

(24)

Equation (25) is to evaluate the profits in period *t*. It is assumed that the prices of raw materials, utilities, products and byproducts are constant along the selected time horizon. To conclude, NPV is computed by means of Eq. (26).

$$Profit_t = ESales_t - (FCost_t + \sum_e EPurch_{et}) \quad \forall t$$

(25)

$$NPV = \sum_t \left( \frac{Profit_t - FAsset_t}{(1+rate)^t} \right)$$

(26)

Finally, the SC network design-planning problem whose objective is to optimise the NPV can be mathematically posed as follows:

$$Max_{X,Y}\, NPV$$

subject to

Eqns. (1) to (26)

$$\mathcal{X} \in \{0,1\}; \mathcal{Y} \in \mathbb{R}^+$$

Here *X* denotes the binary variables set, while *Y* corresponds to the continuous variables set.

## 5 Case study: a bio-based – CCU SC located in Spain

The aim is to retrofit selected plants of the coal combustion plants in Spain with biomass co-use and CCU. Given a set of biomass collection sites and power plants, the SC model will provide solutions for the location-allocation problem, flows of matter among sites and percentage of $CO_2$ captured per plant, by optimising an economic criterion under a restriction of $CO_2$ emissions.

- The coordinate system Universal Transverse Mercator (UTM) is used. Linear distances among sites are calculated and corrected by a tortuosity factor of 1.4 (A. Gómez et al., 2010). The centre of the square areas for biomass sites and the specific power plant locations are considered.
- Boundaries are set from cradle-to-gate (see Figure 2). Distribution and use of electricity and methanol are outside the scope of this paper. The natural gas and coal cradle-to-gate emissions and LHV, and the emissions associated to the European electricity grid are from (European Commission, 2014b).
- The currency used is $EUR_{2014}$. The Chemical Engineering Plant Cost Index CEPCI published monthly in the Chemical Engineering Magazine is used to actualise each unit purchase cost to 2014 ("Economic indicators," 2014). European Power Plant Capital Cost Index ([4]) and the Dollar-EUR currency conversion are also taken into account (Eurostat, 2016).
- $CO_2$ equivalent emissions are taken into account.
- The average of working hours is 7 800 h/y for all the plants considered in the SC. The time horizon is 10 years.
- The interest rate is 5% (inferred from (Pérez-Fortes and Tzimas, 2016) and taking into account the interest rate tendency of Spain ([5])), and the capital expenditure happen the first year.

We refer the reader to (Pérez-Fortes et al., 2014) for further details about the bio-based case study.

## 5.1 Raw materials and coal combustion plants

The types of biomass waste used are forest wood residues (FWR) and agricultural waste residues (AWR) from (A Gómez et al., 2010; A. Gómez et al., 2010). Only the areas (60 x 60 km for AWR, and 80 x 80 km for FWR) producing more than 50 t/y are considered in this case study. The candidate locations to place a pre-treatment unit are those where biomass average waste production is above 95 t/y. These thresholds have been established to take into account a 90% of the forest residue produced. These thresholds are also based on the fact that

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[4] https://www.ihs.com/Info/cera/ihsindexes/index.html

[5] https://ycharts.com/indicators/spain_long_term_interest_rates

to benefit from economies of scale, is better to focus on those areas where biomass is more concentrated. The amount of available biomass (according to the criteria described in (A Gómez et al., 2010; A. Gómez et al., 2010)) is further reduced to take into account other potential users, and to only meet the needs from the combustion coal power plants. Figure 3 depicts the yearly energy profile of biomass supply and of the maximum demand of biomass energy from the selected coal power plants (15 % coal replacement, in LHV terms), based on the energy profile of 2014 in Spain (Red Eléctrica de España, 2015). On the one hand, the available biomass has been reduced to meet the needs: 15 PJ/y are provided by FWR and 13 PJ/y by AWR. The ten plants that provided most energy during year 2014, delivered 27 957 GWh. This amount is, taking into account a plant efficiency of 45 % (European Commission, 2014a) and a coal replacement of 10 % (as a problem condition), 23 PJ/y. The problem condition establishes that 10 % of the coal inlet energy has to be replaced by biomass, ranging from 0-15 % individually per plant. See in Table 5, Table 6 and Table 7 the detail of the monthly biomass provision and power plants energy demand.

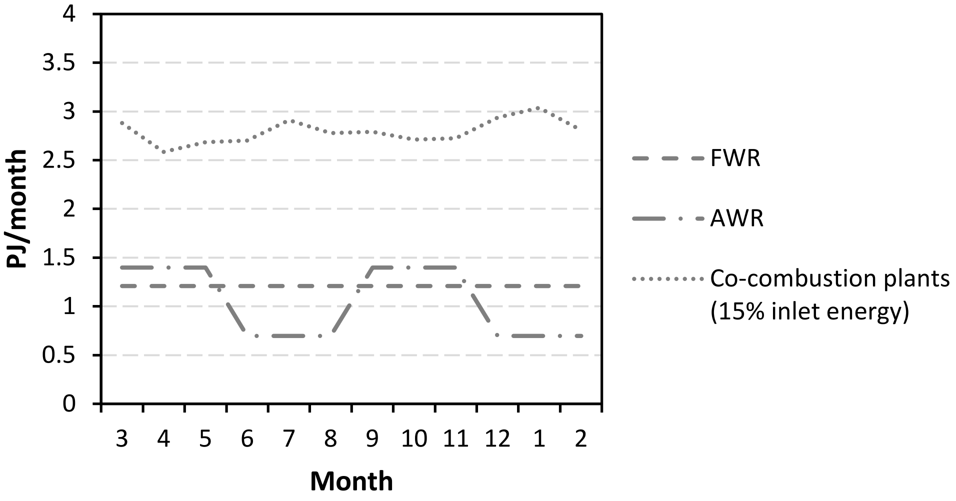

*Figure 3* *Biomass seasonal availability and seasonal power plants demand. The energy demand is calculated as a 15 % of the coal inlet thermal value (LHV), which is assumed to be replaced by biomass (Pérez-Fortes et al., 2014).*

## 5.2 Biomass pre-treatment units, storage and transportation

Biomass storage is allowed after harvesting or collection and after the pre-treatment (before combustion plants). Open air covered storage is considered from raw material (for a maximum of two months) and storage of pre-treated biomass in silos. In the first case biomass properties could change and they were modelled as biomass states. In the second case, the activity was modelled as flexible (see (Pérez-Fortes et al., 2014) for further information). The pre-treatment possibilities taken into account are chipping and drying. Firstly, biomass is converted into chips of 240 kg/m$^3$. Secondly, its moisture content is reduced to 5 or 10 %. The chipper consumes electricity and the drier's energy is supplied by diesel. Transport by trucks also consume diesel.

## 5.3 Carbon capture and $CO_2$-based methanol plant

The most important parameters taken into account for the CCU modelling are summarised in Table 1 and Table 2. The economic data for input and output streams of the case studies are summarised in Table 8 and Table 9. The case study takes into account that the electricity available for the CDU plant is limited to the amount of electricity equivalent to the coal replaced by biomass, so as to achieve the required condition of being powered by renewables and thus emit less than the benchmark process (Pérez-Fortes and Tzimas, 2016). This electricity consumption directly determines the size of the CDU plant that can be installed in the specific co-combustion plant. At the same time, the size of the CDU plant determines the consumption of $CO_2$, thus, determines the fraction of $CO_2$ captured, in each specific co-combustion plant.

*Table 1 Capture plant modelling* (European Commission, 2014a)

| | | |
|---|---|---|
| Investment | 941 | EUR/kWe |
| Fixed cost | 2.4% | of CAPEX |
| Production | 840 | t $CO_2$/kWe |

*Table 2 Methanol plant modelling* (Pérez-Fortes and Tzimas, 2016)

| | | |
|---|---|---|
| Production | 440 000 | tMeOH/y |
| Investment (CAPEX) | 565 | MEUR |
| Fix cost | 5.5% | of CAPEX |
| Scale factor | 0.6 | |
| *Utilities* | | |
| Electricity consumed | 12 | MWh/tMeOH |
| *Inputs and outputs* | | |
| $CO_2$ consumed | 1.46 | t/tMeOH |
| Water consumed | 1.99 | t/tMeOH |
| Methanol produced | 1 | t/tMeOH |
| Oxygen produced | 1.59 | t/tMeOH |

With regard to the environment, we will focus on a $CO_2$ emission trading scheme. Therefore, we compute the equivalent $CO_2$ amount associated with each optimal network configuration. However, it is used in the model as a constraint instead of an objective.

### 5.3.1 Reduction of $CO_2$ emissions

One important figure in the case study is the reduction of $CO_2$ emissions. This considers: the emissions prevented from coal and natural gas extraction, transport and consumption, the emissions captured and used, the emissions from biomass transport and pre-treatment and from the CDU process.

Two cases are presented next: the baseline and the carbon capture and utilisation case. They have been modelled in GAMS and solved using the CPLEX solver on an Intel Xenon at 2.3 GHz with 64 GB computer. The model consists of 5994112 continuous variables, 998 discrete variables and 66118 equations. The total CPU time using 20 threads in parallel with an optimality gap of 2.5% is 41957 s and 37308 s for Case I and Case II, respectively.

## 5.4 Case I: Baseline case

Firstly, the supply chain has been optimised with no consideration of carbon capture and utilisation. A schematic of the optimal network configuration is shown in Figure 4. The model proposes to activate 45 pre-treatment sites which are represented as black dots in Figure 4. All of these pre-treatment sites were provided chipping technology with a capacity between 10 and 15 t/h. However, dryers were installed in only seven pre-treatment sites where biomass is collected and dried. This allows taking advantage of dryer's capacity since such pre-treatment technology demands a significantly higher capital investment in comparison with chippers. All installed dryers have a capacity of 40 t/h. In this network, eight combustion plants receive biomass to cover their respective energy demand and are modified in order to co-fire coal and biomass. The total demand share that is satisfied by using biomass is 10%. The investment needed to deploy this network configuration is listed in Table 3.

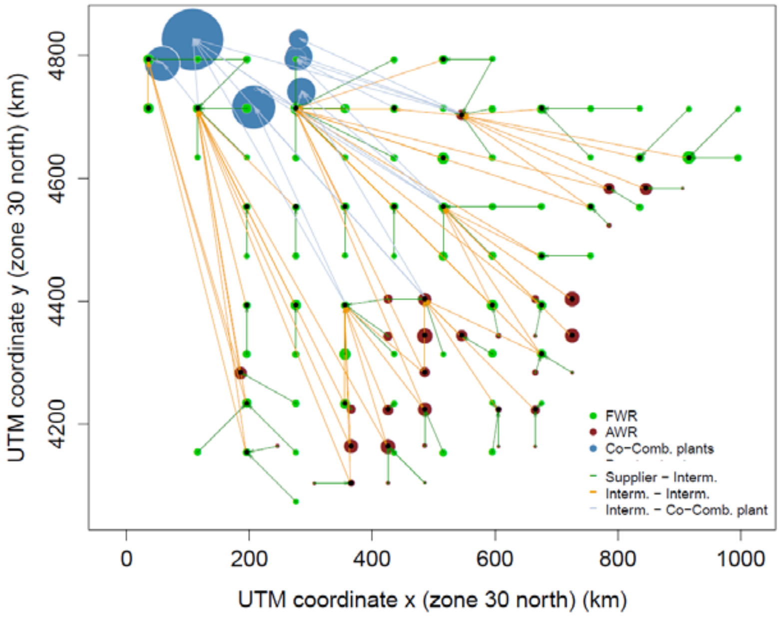

*Figure 4 Optimal network configuration for the baseline case which does not consider CCU technology*

*Table 3 Investments for the baseline case*

| *Equipment* | *Investment (M EUR $_{2014}$)* |
|---|---|
| *Chipping* | 7.7 |
| *Drying* | 26.7 |
| *Co-firing* | 173.5 |
| *Total* | *207.9* |

The baseline configuration results in a negative NPV equal to -353.8 M EUR, meaning that the incoming revenues do not offset the costs and investment needed using a 5% return rate, as detailed in the following lines. Every year, revenue due to biomass-based energy sales amounts to ~ 127.5M EUR, while the biomass purchases contribute 118.2 M EUR to the direct cost. Biomass transportation also represents a significant direct cost and results in approximately 57 M EUR per year. This case prevents the utilisation of approximately 1.4 Mt of coal. That means that for each t of coal that is saved, the project generates a loss of about 25 EUR under the hypothesis and assumptions of this case study.

As one can infer, biomass pre-treatment and co-firing technologies cost should decrease to make a project of this nature viable, which is only achievable (if possible) through more R&D and better integrated processes. Decentralised energy generation could also alleviate part of the distribution costs that are incurred to bring the biomass to centralised co-combustion plants. Yet another alternative is to look for other income sources to compensate the relatively high investment and operating costs. In the next case, we explore carbon capture and its utilisation to produce methanol for this purpose.

## 5.5 Case II: Carbon capture and utilisation with additional energy requirements fulfilled using the European electricity grid

In this case, we consider the possibility of installing carbon capture technology in the co-combustion plants. The captured carbon could be then utilised to generate methanol. We assume that the overall extra requirement of energy due to the installation of these two technologies can be obtained from the European electricity grid. The network is constrained to mitigate at least 1% of the overall Greenhouse Emissions (GHG) generated by the traditional network and to cover at least 5% of the energy demand with renewable resources. In addition, a minimum methanol production of 100k t/y is imposed as minimum demand to be satisfied. The relative reduction in GHG is based on the $CO_2$ emissions generated to deliver 100% of the energy demand by using coal-based combustion and the methanol demand using natural gas as raw material.

The network configuration that results from the optimisation of this case is depicted in Figure 5. The solution activates the constraint that forces that at least 5% of the demand must be satisfied using biomass. This reduces the investment dedicated to biomass pre-treatment technologies and co-firing adaptation in the combustion plants. In this case, there are only four sites which have a dryer installed. Again, each of the dryers has a capacity of 40 t/h. Chippers are installed in the same number of locations compared with the baseline case. Similarly to the baseline, the investment associated with chippers installation is favoured over transportation of high volume biomass along the ten-year planning horizon. Co-firing adaptation is proposed to be carried out in three combustion plants. Table 4 summarises the investment associated with this configuration. This supply chain has a capture and utilisation capacity equivalent to 100 kt MeOH (i.e., 22.8 MW) which has been located next to plant “La Robla” (*m9*).

This configuration generates again a negative NPV of -1148.6 M EUR, thus obtaining an economically unfeasible case with revenues that can not offset the costs and investment required, as explained next. Annual revenue is equal to 113.2 M EUR. Note that this figure is lower than the one in the baseline. The revenue due to methanol and oxygen sales are just about 43.6 M EUR per year, however the considered methanol production technology requires about 12 MWh/t which causes an imbalance in the demand /supply that must be compensated by using energy from the grid. This brings the total direct costs to 253.3 M EUR each year. In this network 3.5% of the total $CO_2$ emissions are recovered or saved by using biomass-based energy. Due to the CCU technology, the network can save around 231 kt $CO_2$/yr. Nevertheless, the extra energy requirement generates around 609.5 kt $CO_2$/yr. As the reader can see, in order to make carbon capture and its utilisation to produce methanol feasible under the assumptions of this case study, methanol technologies should benefit from being more energy efficient, and methanol prices that are higher than the ones currently in the market.

*Table 4 Investments for the baseline case*

| *Equipment* | *Investment (M EUR $_{2014}$)* |
|---|---:|
| *Chipping* | 7.8 |
| *Drying* | 21.1 |
| *Co-firing* | 84.1 |
| *CCU* | 106.6 |
| *Total* | *219.6* |

Let us assume that the extra energy requirements can be obtained from a renewable source. This would reduce the footprint of the network in 609.5 kt $CO_2$/y. Assuming that the network could claim cost reductions by using the ETS and that the right to emit 1 annual t $CO_2$ is currently about 5.5 EUR, the optimal network can be configured such that resulting NPV value is -605.5 M EUR. Still, it does not make this type of project feasible. For the considered CCU technology to make this project viable, it should generate an annual inflow of about 74.5 M EUR. This may be achieved through a price increase or a cost reduction. Under this scenario, we are saving around 2.6 Mt$CO_2$/y. Assuming that this inflow results from the ETS, the right to emit 1 annual t $CO_2$ must be increased by around 27 EUR. Otherwise, if this inflow is to come from methanol sales this would mean an increase of 745 EUR/t (a 120% increase from its current price) since the network is producing 100 kt of methanol per year. On the other hand, in order to make the baseline case financially feasible an extra annual inflow of 44 M EUR is needed. This is an increase of ~ 31 EUR per t $CO_2$ emitted, provided that the baseline is saving only 1.4 Mt $CO_2$/y.

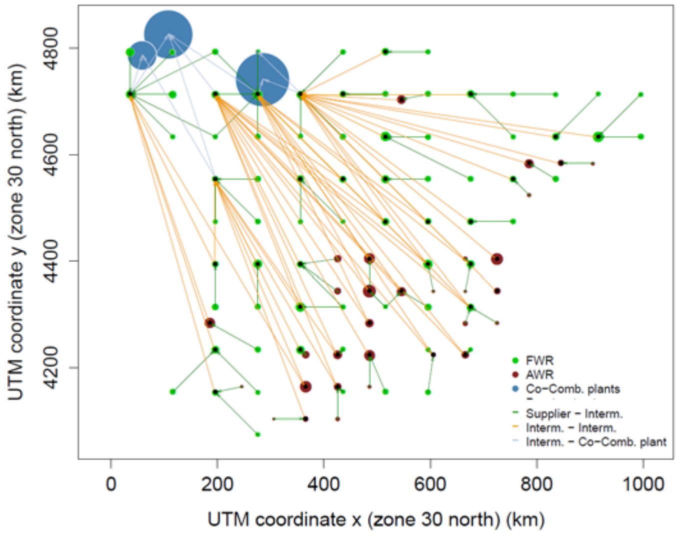

*Figure 5 Optimal network configuration for Case II*

## 6 Conclusions

In this work, we demonstrated how a generic supply chain design-planning formulation can be easily extended by adding new process blocks. In this particular case, a carbon capture and a utilisation block have been added. The utilisation part considers the production of methanol by having carbon dioxide and water as inputs. It has been highlighted how a model of this type can not only support decision-making about typical design questions such as the capacity and location of technology but also be exploited to address regulatory concerns. In the presented case study, it has been shown how this type of economic evaluation could suggest changes in the emission trade structure so as to induce the industrial changes needed to achieve regulatory expected goals.

With regard to the specific case study, the carbon capture technology analysed in this work, under the postulated assumptions, does not allow a biomass-based centralised energy supply chain to be viable or to improve from an economic standpoint. A block for the utilisation of $CO_2$ which is not energy intensive may be an alternative. Under the hypotheses of this study, promising methanol production technologies which are not based on hydrolysis, or cheaper hydrolysis, may create a financial feasible scenario. As for the condition imposed to the problem to mitigate at least 1% of the overall Greenhouse emissions, various tests were carried out to find a proportion that provided a feasible optimisation problem. This proportion could be escalated as technologies mature; however, under the current technologies and market conditions even with this low value significant challenges become apparent to make this type of projects financially viable as demonstrated in the case study.

## Acknowledgements

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# Appendix

## A. Input data for the case study

### A.1 Biomass supply

*Table 5 Availability of FWR for a year (kt)*

| *Location/Month* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *e1* | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 | 6.326 |
| *e2* | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 | 5.371 |
| *e3* | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 | 5.239 |
| *e4* | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 | 5.083 |
| *e5* | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 | 4.994 |
| *e6* | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 | 4.581 |
| *e7* | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 | 4.317 |
| *e8* | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 | 4.298 |
| *e9* | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 | 4.078 |
| *e10* | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 | 4.026 |
| *e11* | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 | 3.772 |
| *e12* | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 | 3.588 |
| *e13* | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 | 3.546 |
| *e14* | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 |
| *e15* | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 | 3.533 |
| *e16* | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 | 3.517 |
| *e17* | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 | 3.463 |
| *e18* | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 | 3.411 |
| *e19* | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 | 3.352 |
| *e20* | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 | 3.330 |
| *e21* | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 | 3.196 |
| *e22* | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 | 2.986 |
| *e23* | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 | 2.978 |
| *e24* | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 | 2.968 |
| *e25* | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 | 2.835 |
| *e26* | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 | 2.807 |
| *e27* | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 | 2.742 |
| *e28* | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 | 2.694 |
| *e29* | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 | 2.685 |
| *e30* | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 | 2.604 |
| *e31* | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 | 2.486 |
| *e32* | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 | 2.476 |
| *e33* | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 | 2.411 |
| *e34* | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 | 2.382 |
| *e35* | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 | 2.370 |
| *e36* | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 | 2.333 |
| *e37* | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 | 2.283 |
| *e38* | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 | 2.277 |
| *e39* | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 | 2.269 |
| *e40* | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 | 2.245 |

| *Location/Month* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *e41* | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 | 2.240 |
| *e42* | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 | 2.221 |
| *e43* | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 | 2.168 |
| *e44* | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 | 2.158 |
| *e45* | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 | 2.155 |
| *e46* | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 | 2.150 |
| *e47* | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 | 2.114 |
| *e48* | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 | 2.046 |
| *e49* | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 | 2.045 |
| *e50* | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 | 2.020 |
| *e51* | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 | 1.935 |
| *e52* | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 | 1.912 |
| *e53* | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 |
| *e54* | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 | 1.845 |
| *e55* | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 | 1.772 |
| *e56* | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 | 1.754 |
| *e57* | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 | 1.681 |
| *e58* | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 | 1.675 |
| *e59* | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 | 1.638 |
| *e60* | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 | 1.634 |
| *e61* | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 | 1.616 |
| *e62* | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 | 1.595 |
| *e63* | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 | 1.584 |
| *e64* | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 | 1.568 |
| *e65* | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 | 1.543 |
| *e66* | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 | 1.518 |
| *e67* | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 | 1.489 |
| *e68* | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 | 1.455 |
| *e69* | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 | 1.422 |
| *e70* | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 | 1.408 |
| *e71* | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 | 1.406 |
| *e72* | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 | 1.355 |
| *e73* | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 | 1.351 |

*Table 6 Availability of AWR for a year (kt)*

| *Location/Month* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *e74* | 6.559 | 6.559 | 6.559 | 3.280 | 3.280 | 3.280 | 6.559 | 6.559 | 6.559 | 3.280 | 3.280 | 3.280 |
| *e75* | 6.043 | 6.043 | 6.043 | 3.022 | 3.022 | 3.022 | 6.043 | 6.043 | 6.043 | 3.022 | 3.022 | 3.022 |
| *e76* | 6.043 | 6.043 | 6.043 | 3.022 | 3.022 | 3.022 | 6.043 | 6.043 | 6.043 | 3.022 | 3.022 | 3.022 |
| *e77* | 5.653 | 5.653 | 5.653 | 2.827 | 2.827 | 2.827 | 5.653 | 5.653 | 5.653 | 2.827 | 2.827 | 2.827 |
| *e78* | 5.172 | 5.172 | 5.172 | 2.586 | 2.586 | 2.586 | 5.172 | 5.172 | 5.172 | 2.586 | 2.586 | 2.586 |
| *e79* | 4.930 | 4.930 | 4.930 | 2.465 | 2.465 | 2.465 | 4.930 | 4.930 | 4.930 | 2.465 | 2.465 | 2.465 |
| *e80* | 4.775 | 4.775 | 4.775 | 2.387 | 2.387 | 2.387 | 4.775 | 4.775 | 4.775 | 2.387 | 2.387 | 2.387 |
| *e81* | 4.641 | 4.641 | 4.641 | 2.321 | 2.321 | 2.321 | 4.641 | 4.641 | 4.641 | 2.321 | 2.321 | 2.321 |
| *e82* | 4.351 | 4.351 | 4.351 | 2.175 | 2.175 | 2.175 | 4.351 | 4.351 | 4.351 | 2.175 | 2.175 | 2.175 |
| *e83* | 3.968 | 3.968 | 3.968 | 1.984 | 1.984 | 1.984 | 3.968 | 3.968 | 3.968 | 1.984 | 1.984 | 1.984 |
| *e84* | 3.809 | 3.809 | 3.809 | 1.904 | 1.904 | 1.904 | 3.809 | 3.809 | 3.809 | 1.904 | 1.904 | 1.904 |

| *Location/Month* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *e85* | 3.257 | 3.257 | 3.257 | 1.629 | 1.629 | 1.629 | 3.257 | 3.257 | 3.257 | 1.629 | 1.629 | 1.629 |
| *e86* | 3.234 | 3.234 | 3.234 | 1.617 | 1.617 | 1.617 | 3.234 | 3.234 | 3.234 | 1.617 | 1.617 | 1.617 |
| *e87* | 3.164 | 3.164 | 3.164 | 1.582 | 1.582 | 1.582 | 3.164 | 3.164 | 3.164 | 1.582 | 1.582 | 1.582 |
| *e88* | 2.978 | 2.978 | 2.978 | 1.489 | 1.489 | 1.489 | 2.978 | 2.978 | 2.978 | 1.489 | 1.489 | 1.489 |
| *e89* | 2.954 | 2.954 | 2.954 | 1.477 | 1.477 | 1.477 | 2.954 | 2.954 | 2.954 | 1.477 | 1.477 | 1.477 |
| *e90* | 2.907 | 2.907 | 2.907 | 1.454 | 1.454 | 1.454 | 2.907 | 2.907 | 2.907 | 1.454 | 1.454 | 1.454 |
| *e91* | 2.719 | 2.719 | 2.719 | 1.359 | 1.359 | 1.359 | 2.719 | 2.719 | 2.719 | 1.359 | 1.359 | 1.359 |
| *e92* | 2.467 | 2.467 | 2.467 | 1.234 | 1.234 | 1.234 | 2.467 | 2.467 | 2.467 | 1.234 | 1.234 | 1.234 |
| *e93* | 2.173 | 2.173 | 2.173 | 1.087 | 1.087 | 1.087 | 2.173 | 2.173 | 2.173 | 1.087 | 1.087 | 1.087 |
| *e94* | 2.172 | 2.172 | 2.172 | 1.086 | 1.086 | 1.086 | 2.172 | 2.172 | 2.172 | 1.086 | 1.086 | 1.086 |
| *e95* | 2.163 | 2.163 | 2.163 | 1.082 | 1.082 | 1.082 | 2.163 | 2.163 | 2.163 | 1.082 | 1.082 | 1.082 |
| *e96* | 2.156 | 2.156 | 2.156 | 1.078 | 1.078 | 1.078 | 2.156 | 2.156 | 2.156 | 1.078 | 1.078 | 1.078 |
| *e97* | 2.141 | 2.141 | 2.141 | 1.070 | 1.070 | 1.070 | 2.141 | 2.141 | 2.141 | 1.070 | 1.070 | 1.070 |
| *e98* | 2.108 | 2.108 | 2.108 | 1.054 | 1.054 | 1.054 | 2.108 | 2.108 | 2.108 | 1.054 | 1.054 | 1.054 |
| *e99* | 2.101 | 2.101 | 2.101 | 1.050 | 1.050 | 1.050 | 2.101 | 2.101 | 2.101 | 1.050 | 1.050 | 1.050 |
| *e100* | 2.068 | 2.068 | 2.068 | 1.034 | 1.034 | 1.034 | 2.068 | 2.068 | 2.068 | 1.034 | 1.034 | 1.034 |
| *e101* | 1.824 | 1.824 | 1.824 | 0.912 | 0.912 | 0.912 | 1.824 | 1.824 | 1.824 | 0.912 | 0.912 | 0.912 |
| *e102* | 1.787 | 1.787 | 1.787 | 0.893 | 0.893 | 0.893 | 1.787 | 1.787 | 1.787 | 0.893 | 0.893 | 0.893 |
| *e103* | 1.702 | 1.702 | 1.702 | 0.851 | 0.851 | 0.851 | 1.702 | 1.702 | 1.702 | 0.851 | 0.851 | 0.851 |
| *e104* | 1.538 | 1.538 | 1.538 | 0.769 | 0.769 | 0.769 | 1.538 | 1.538 | 1.538 | 0.769 | 0.769 | 0.769 |
| *e105* | 1.505 | 1.505 | 1.505 | 0.753 | 0.753 | 0.753 | 1.505 | 1.505 | 1.505 | 0.753 | 0.753 | 0.753 |
| *e106* | 1.406 | 1.406 | 1.406 | 0.703 | 0.703 | 0.703 | 1.406 | 1.406 | 1.406 | 0.703 | 0.703 | 0.703 |
| *e107* | 1.383 | 1.383 | 1.383 | 0.691 | 0.691 | 0.691 | 1.383 | 1.383 | 1.383 | 0.691 | 0.691 | 0.691 |

## A.2 Coal power plants

*Table 7. Energy demand for each combustion plant in a year (GWh)*

| *Market Notation* | *Plant* | *Month* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| m1 | Puentes García Rodríguez | 655.098 | 587.646 | 609.942 | 613.763 | 661.360 | 631.612 | 634.430 | 616.487 | 619.556 | 667.592 | 690.608 | 637.937 |
| m2 | Meirama | 209.861 | 188.253 | 195.396 | 196.620 | 211.868 | 202.338 | 203.241 | 197.492 | 198.476 | 213.864 | 221.237 | 204.364 |
| m3 | Aboño | 468.602 | 420.353 | 436.301 | 439.034 | 473.082 | 451.802 | 453.818 | 440.983 | 443.178 | 477.539 | 494.003 | 456.327 |
| m4 | Lada | 121.123 | 108.652 | 112.775 | 113.481 | 122.281 | 116.781 | 117.302 | 113.985 | 114.552 | 123.434 | 127.689 | 117.951 |
| m5 | Soto de la Ribera | 125.676 | 112.736 | 117.014 | 117.746 | 126.878 | 121.171 | 121.711 | 118.269 | 118.858 | 128.073 | 132.489 | 122.384 |
| m6 | Narcea | 78.687 | 70.585 | 73.263 | 73.722 | 79.440 | 75.866 | 76.205 | 74.050 | 74.418 | 80.188 | 82.953 | 76.626 |
| m7 | Anllares | 101.538 | 91.083 | 94.539 | 95.131 | 102.508 | 97.897 | 98.334 | 95.553 | 96.029 | 103.474 | 107.042 | 98.878 |
| m8 | Compostilla | 389.743 | 349.613 | 362.878 | 365.151 | 393.469 | 375.770 | 377.447 | 366.772 | 368.597 | 397.176 | 410.869 | 379.533 |
| m9 | La Robla | 143.888 | 129.073 | 133.970 | 134.809 | 145.263 | 138.729 | 139.348 | 135.407 | 136.081 | 146.632 | 151.687 | 140.119 |
| m10 | Guardo | 107.379 | 96.323 | 99.977 | 100.604 | 108.406 | 103.529 | 103.991 | 101.050 | 101.553 | 109.427 | 113.200 | 104.566 |

## A.3 Economic data

*Table 8 Prices corresponding to input streams*

| | | | |
|---|---|---|---|
| Forest Wood Residues | 61 | EUR/ t | Actualisation from values in (Pérez-Fortes et al., 2014) |
| Agricultural Food Residues | 56 | EUR/ t | |
| Water | 1 | EUR/ t | (Pérez-Fortes et al., 2016) |
| Coal | 92 | EUR/ t | (International Energy Agency (IEA), 2014) |
| Diesel | 610 | EUR/ t | (Ministerio de Industría, 2016) |

*Table 9 Prices corresponding to output streams.*

| | | | |
|---|---|---|---|
| Methanol price | 350 | EUR/t | Based on (Pérez-Fortes et al., 2016) |
| Oxygen price | 54 | EUR/t | |
| Electricity | 0.0456 | EUR/kWh | (Red Eléctrica de España, 2015) |
| EU ETS | 5.5 | EUR/t $CO_2$ | (EEX, 2016) |

## B. Notation

**Indices**

| | |
|---|---|
| $e$ | suppliers |
| $f, f'$ | facility locations |
| $i$ | tasks |
| $j$ | equipment technology |
| $s$ | materials (states) |
| $t, t'$ | planning periods |
| $a$ | mid point environmental impact categories |
| $g$ | end point environmental impact categories |

**Sets**

| | |
|---|---|
| $A_g$ | set of midpoint environmental interventions that are combined into endpoint damage factors $g$ |
| $E_{rm}$ | set of suppliers $e$ that provide raw materials |
| $\hat{E}_{prod}$ | set of suppliers $e$ that provide production services |
| $\bar{E}_{tr}$ | set of suppliers $e$ that provide transportation services |
| $F_e$ | set of locations $f$ where supplier $e$ is placed |
| $FP$ | set of materials $s$ that are final products |
| $I_j$ | set of tasks $i$ that can be performed in technology $j$ |
| $\bar{J}_e$ | technology $j$ that is available at supplier $e$ |
| $\tilde{J}_f$ | technology $j$ that can be installed at location $f$ |
| $J_i$ | technologies that can perform task $i$ |
| $Mkt$ | set of market locations |
| $RM$ | set of materials $s$ that are raw materials |
| $Sup$ | set of supplier locations |
| $T_s$ | set of tasks producing material $s$ |
| $\bar{T}_s$ | set of tasks consuming material $s$ |
| $Tr$ | set of distribution tasks |

**Parameters**

| | |
|---|---|
| $A_{sft}$ | maximum availability of raw material $s$ in period $t$ in location $f$ |
| $Dem_{sft}$ | demand of product $s$ at market $f$ in period $t$ |
| $distance_{ff'}$ | distance from location $f$ to location $f'$ |

| | |
|---|---|
| $FCFJ_{jft}$ | fixed cost per unit of technology $j$ capacity at location $f$ in period $t$ |
| $I^{J}_{ft}$ | investment required to establish a processing facility in location $f$ in period $t$ |
| $NormF_{g}$ | normalizing factor of damage category $g$ |
| $Price_{sft}$ | price of product $s$ at market $f$ in period $t$ |
| $Price^{J}_{jft}$ | investment required per unit of technology $j$ capacity increased at facility $f$ in period $t$ |
| $rate$ | discount rate |
| $Water_{s}$ | moisture for material $s$ |
| $Water^{\max}_{ij}$ | maximum moisture for task $i$ performed in equipment $j$ |
| $\alpha_{sij}$ | mass fraction of task $i$ for production of material $s$ in equipment $j$ |
| $\bar{\alpha}_{sij}$ | mass fraction of task $i$ for consumption of material $s$ in equipment $j$ |
| $\beta_{jf}$ | minimum utilisation rate of technology $j$ capacity that is allowed at location $f$ |
| $\zeta_{ag}$ | $g$ end-point damage characterization factor for environmental intervention $a$ |
| $\theta_{ijff'}$ | capacity utilisation rate of technology $j$ by task $i$ whose origin is location $f$ and destination location $f'$ |
| $\rho^{tr}_{eff't}$ | unitary transportation costs from location $f$ to location $f'$ during period $t$ |
| $\tau^{ut1}_{ijfet}$ | unitary cost associated with task $i$ performed in equipment $j$ from location $f$ and payable to external supplier $e$ during period $t$ |
| $\tau^{ut2}_{sfet}$ | unitary cost associated with handling the inventory of material $s$ in location $f$ and payable to external supplier $e$ during period $t$ |
| $\chi_{est}$ | unitary cost of raw material $s$ offered by external supplier $e$ in period $t$ |
| $\psi_{ijff'a}$ | $a$ environmental category impact CF for task $i$ performed using technology $j$ receiving materials from node $f$ and delivering it at node $f'$ |
| $\psi^{T}_{ija}$ | $a$ environmental category impact CF for the transportation of a mass unit of material over a length unit |

**Binary variables**

| | |
|---|---|
| $V_{jft}$ | 1 if technology $j$ is installed at location $f$ in period $t$, 0 otherwise |

**Continuous variables**

| | |
|---|---|
| $DamC_{gft}$ | normalised endpoint damage $g$ for location $f$ in period $t$ |
| $DamC^{SC}_{g}$ | normalised endpoint damage $g$ along the whole SC |

| | |
|---|---|
| $EPurch_{et}$ | economic value of purchases executed in period $t$ to supplier $e$ |
| $ESales_t$ | economic value of sales executed in period $t$ |
| $FAsset_t$ | investment on fixed assets in period $t$ |
| $FCost_t$ | fixed cost in period $t$ |
| $F_{jft}$ | total capacity of technology $j$ during period $t$ at location $f$ |
| $FE_{jft}$ | capacity increment of technology $j$ at location $f$ during period $t$ |
| $IC_{aft}$ | midpoint $a$ environmental impact associated to site $f$ which rises from activities in period $t$ |
| $Impact$ | total environmental impact for the whole SC |
| $LHV_{si}$ | Lower heating value for material $s$ in task $i$ |
| $NPV$ | net present value |
| $P_{ijff't}$ | activity magnitude of task $i$ in equipment $j$ in period $t$ whose origin is location $f$ and destination location $f'$ |
| $Pv_{sijff't}$ | amount of material $s$ for flexible task $i$ in equipment $j$ in period $t$ whose origin is location $f$ and destination location $f'$ |
| $Profit_t$ | profit achieved in period $t$ |
| $Purch_{et}^{pr}$ | amount of money payable to supplier $e$ in period $t$ associated with production activities |
| $Purch_{et}^{rm}$ | amount of money payable to supplier $e$ in period $t$ associated with consumption of raw materials |
| $Purch_{et}^{tr}$ | amount of money payable to supplier $e$ in period $t$ associated with consumption of transport services |
| $Sales_{sff't}$ | amount of product $s$ sold from location $f$ in market $f'$ in period $t$ |
| $S_{sft}$ | amount of stock of material $s$ at location $f$ in period $t$ |

**Superscripts**

| | |
|---|---|
| $L$ | lower bound |
| $U$ | upper bound |

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