Chapter 24
Efficient Design of Biomass-Based Supply Chains: A Key Component of a Sustainable Energy System

J.M. Laínez Aguirre, M. Pérez-Fortes and L. Puigjaner

Abstract This chapter describes the use of mathematical programming as the tool for the design of biomass-based supply chains. This tool is helpful to devise the most appropriate manner of integrating conversion and pretreatment technologies with the channels required to convert the raw biomass, available in the collection areas, into energy in the demand points. The project analysis should be carried out adopting a holistic view. The formulation described in this chapter does so by tackling the problem from a multiple objective approach which considers financial, environmental as well as social aspects. The problem is formulated as a mixed integer linear program (MILP). The insights gained by using this approach are demonstrated through three literature case studies. The first case study comprises an illustrative hydrogen supply chain, where hydrogen is synthesised from biomass and coal gasification. The second one considers regional electrification in rural areas by using gasification combined with gas engines. In this case, a social criterion is introduced. The third case study is a biomass-based supply chain designed to partially fulfil the demand of processing coal plants existing in Spain.

Notation

Indices

a	mid point environmental impact categories
e	suppliers
f, f'	facility locations
g	end point environmental impact categories

J.M. Laínez Aguirre
University at Buffalo, 342 Bell Hall, Amherst, NY 14260, USA
e-mail: jmlainez@gmail.com

M. Pérez-Fortes
Institute for Energy and Transport Energy Technology Policy Outlook, Westerduinweg 3, 312/001, 1755 LE Petten, Netherlands
e-mail: Maria-Del-Mar.PEREZ-FORTES@ec.europa.eu

L. Puigjaner (✉)
Universitat Politècnica de Catalunya, Avda. Diagonal 647, 08028 Barcelona, Spain
e-mail: Luis.Puigjaner@upc.edu

G.M. Kopanos et al. (eds.), *Advances in Energy Systems Engineering*,
DOI 10.1007/978-3-319-42803-1_24

i tasks
j equipment technology
s materials (states)
t, t' planning periods

Sets

A_g set of midpoint environmental interventions that are combined into endpoint damage factors g
FP set of materials s that are final products
$\bar{I}$ set of tasks i with variable input
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
NTr set of production, or non-transport, tasks
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

$FCFJ_{jft}$ [$/h] fixed cost per unit of technology j capacity at location f in period t
i_r [adim.] discount rate
$NormF_g$ [adim.] normalising factor of damage category g
$Price_{sft}$ [$/MJ] price of product s at market f in period t
$Water_s$ [adim.] Moisture for material s
$Water_{ij}^{max}$ [adim.] Maximum moisture for task i performed in equipment j

Greek symbols

α_{sij} [adim.] mass fraction of task i for production of material s in equipment j
$\bar{\alpha}_{sij}$ [adim.] mass fraction of task i for consumption of material s in equipment j
ζ_{ag} [adim.] g end-point damage characterisation factor for environmental intervention a
$\psi_{ijff'a}$ [points/kg] a environmental category impact CF for task i performed using technology j receiving materials from node f and delivering it at node f'
ψ_{ija}^{T} [points/(kg km)] 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

$DamC_{gft}$ [point]	normalised endpoint damage g for location f in period t
$DamC_{g}^{SC}$ [point]	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
HV_{s} [MJ/kg]	lower heating value for material s
IC_{aft} [point]	midpoint a environmental impact associated to site f which rises from activities in period t
$Impact_{overall}^{2002}$ [point]	total environmental impact for the whole SC
NPV [$]	economic metric, net present value
$P_{ijff't}$ [kg]	specific activity of task i, by using technology j during period t, whose origin is location f and destination is location f'
$Profit_{t}$ [$]	profit achieved in period t
Pv_{sijft} [kg]	input/output material of material s for activity of task i with variable input/output, by using technology j during period t in location f (This must be a production activity)
$Sales_{sff't}$ [$]	amount of product s sold from location f in market f' in period t
S_{sft} [kg]	amount of stock of material s at location f in period t
SoC [unit]	surrogate social metric

24.1 Introduction

Late last century a survey on energy efficiency in industrial processes CEC (1988) warned a general trend that favours flexibility in the use of facilities dedicated to process manufacturing. This is an obvious requirement with the present fluctuations and the uncertain economic situation that characterizes today's market demand. This survey made reference essentially to the chemical process industries (CPI) as the most representative sector, although it also was of relevance to other flexible manufacturing industries which employ a network configuration. As a consequence, in the following years an intensive effort was dedicated to multi supplier operations, looking for strategies, management practices and techniques for improving the performance of supply and distribution chains. Increasing benefits made clear the importance of the subjacent energy supply chain. Additionally, economic, environmental and social factors questioned the dependence on a single source of energy based on fossil fuels which imposed energy prices subject to the increasing market uncertainty.

The panorama described above has resulted in a mounting pressure to explore alternative sources of energy that reduce environmental footprint at competitive cost. Nowadays, residual biomass is emerging as a preferred feedstock candidate Puigjaner et al. (2015). Bioenergy, or energy from biomass, from different sources (woody biomass, agricultural and land use biomass, industrial and municipal biodegradable wastes) has an important role in the future low-carbon society to replace fossil fuels for the production of heat, electricity, transportation fuels, and to synthesize different types of chemicals. It is worth noting that while global energy demand is expected to grow by 37 % by 2040 Pérez-Fortes (2011), the European Union has established a target of 20 % share of renewable energy out of the total European energy consumption by 2020 Tchapda and Pisupati (2014). The 2030 Climate and Energy Policy Framework EU (2014) proposes the reduction of Greenhouse Gas (GHG) emissions to at least 40 % of the 1990 level by 2030 in order to meet the 2050 goal. Moreover, renewable energy source is one of the research priorities of the Strategic Energy Technologies (SET) Plan of the European Union Puigjaner et al. (2015); Commission (2015) as well as a research theme in the Integrated Roadmap of the SET Plan, whose aim is to consolidate the updated technology roadmap and to propose research and innovation actions EU (2014). In this context, bioenergy is not only relevant to the energy generation sector, but also in a number of other areas such as greenhouse gas control (as a potential zero and even negative emissions source), biofuels and waste disposal.

As a consequence, the energy sector is moving towards a new paradigm. More efficient conversion processes, renewable sources and smart grids are all encompassed by this new approach. It develops customized solutions, adapted to the particular needs and resources of each area. In this context, as an immediate and transition solution biomass can be properly co-used with fossil fuels, where technology is already mature; while 100 % biomass systems at small scale can be appropriate for residential uses and rural electrification in emerging countries. Notwithstanding, in the long term it is foreseen that there will not be a single technology or renewable source with massive implementation, but a combination of various conversion technologies to meet the energy demand. The alternatives to centralised and conventional sources of energy should be sustainable in the time, which implies a responsible resource exploitation, by balancing source availability with electricity demand, and therefore with the plant capacity Puigjaner et al. (2015).

Common challenges facing biomass to become a viable option are:

- Energy generation: Affordable biomass conversion technologies for fuel or energy production
- Sourcing: Conflict with agriculture (land and water use) and other uses of waste
- Link between technologies and site of use: Efficient supply-distribution network

Biomass can provide a larger energy share than the one that represents nowadays. For that to become a reality, technological, economic and social barriers need to be overcome. As a result, efforts are concentrated on developing integrated frameworks to support the associated decision-making process. This chapter explores the interactions between technology energy efficiency, consumption, environment, and social impact to help identify pathways toward a sustainable biomass-based energy system. In particular, we review holistic models developed to support decisions regarding the network configurations required to move towards approaches that address simultaneously the multiple dimensions of the de-carbonisation problem. This chapter is principally focused on gasification and combustion technologies.

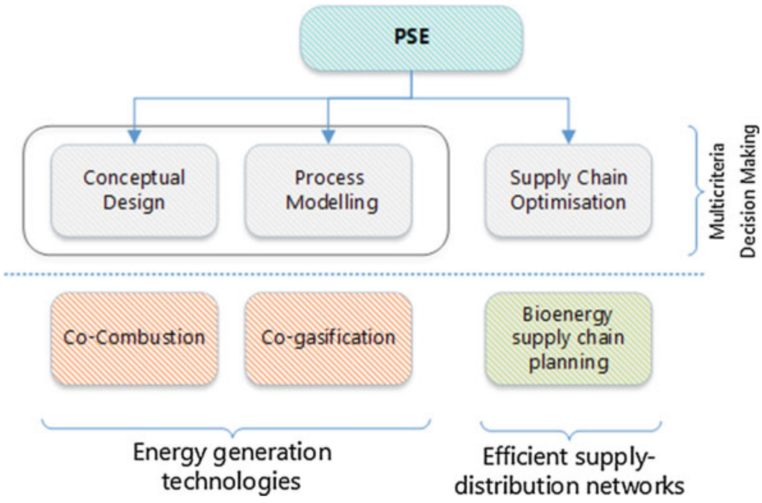

Fig. 24.1 PSE approach to bioenergy systems

As we shall see, a Process Systems Engineering (PSE) approach, depicted in Fig. 24.1, provides tools to address most of the aforementioned challenges. The first two blocks are related to developing process technologies for biomass exploitation; while the third one deals with the efficient supply-distribution networks needed to deploy such technologies. The focus of this chapter is on the latter block.

In the following, and after a brief literature review of the state of the art, this chapter focuses on the necessary integration of the entire supply/delivery chain for efficient and sustainable design of these emerging biomass energy systems, which includes the assessment of economic as well as social and environmental impacts. Moreover, emphasis is given to a rigorous approach that uses Process Systems Engineering, mathematical programming. First, a holistic framework is presented for modelling the energy and biomass, which contains a generic mathematical model. As motivating example is considered the supply chain for pure hydrogen generation from solid biomass. Then, biomass supply chains in developing economies are considered. The mathematical programming approach is applied to bio-based supply chains that use locally available biomass at or near the point of use in order to produce electricity or other bio-product. Here, a social impact metric is introduced. Next, biomass supply chains are examined in development economies. Here, the model considers the supply chain long-term strategic decisions, such as the selection of biomass sources, establishment of pre-treatment units and their location, and disposition of distribution centres, including an estimation of the potential of woody residues to supply the coal power plants that exist in the country. This model considers the possibility of collecting biomass/intermediates with different properties along the supply chain. To approach the computational expense of medium scale problems is the focus of the following section, where the mathematical model is supporting the decision-making associated with the strategic and tactical design of biomass supply chains.

As conclusions and outlook of this chapter, further work is also underway to devise efficient strategies to decrease computational time and to add the additional constraints in the objective functions in order to tackle the mono-objective optimizations required in the multi-objective case.

24.2 State of the Art

Mathematical programming is a promising tool to assist in the quantitative evaluation of new approaches in the area of electricity generation. It is especially adequate for bio-based systems where sites of biomass generation may be far from consumption or demand points, biomass available locally may not match the biomass demand, and different generation/pre-treatment technologies may be available. Bio-based supply chains can be whether regional, i.e. concerning a community or small area with local needs to be fulfilled, or they can be global, i.e. when biomass to be supplied is required to satisfy the needs of a centralised energy system. In the medium and short term, the use of waste, which entails disposal problems, may be a continuous source of organic matter for power production Puigjaner et al. (2015).

Modelling and optimisation of SC's is becoming more popular, not only for biomass. Any type of industry or process can take benefit of this approach. Laínez and Puigjaner (2012) reviewed the application of SC optimisation in the chemical process industry. SC modelling derives from classical approaches that only consider operations, and goes a step forward by integrating business functionalities or market/operation dynamics. Supply chain decision-making tools, and tailor made approaches, will allow to appropriately exploiting the potential of biomass in power generation, heat and cooling applications, and as a transportation fuel. The optimisation of bio-based supply chains encompasses various decisions such as raw materials selection, facility location, selection and sizing of pre-treatments, products to be synthesised, and connectivity in the supply/delivery network, among others.

The biomass SC problem may be addressed using a wide range of decision-maker outlooks. As example, Caputo et al. (2005) evaluate the net present value (NPV) of 100 % biomass projects, focusing on transportation. Bowling (2011) look for an optimal SC for a biorefinery, considering overall sales and costs optimization to discern between a distributed or centralized structure with special attention on transportation costs. Ayoub et al. (2009) focus on costs and environmental impact through emissions to air, water pollutants and solid wastes. Damen and Faaij (2006) perform a life cycle inventory to compare co-combustion and combustion of only coal and Perry and Rosillo-Calle (2008) focus on CO_2 emissions along the whole SC. A more recent work from Mele et al. (2011) combines the use of mathematical programming with LCA, to perform a multi-objective optimization based on the NPV and the LCA, to produce bioethanol from sugar cane in Argentina. Environmental evaluations often take into account a LCA Cherubini and Stromman (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 You et al. (2012). The bio-based works combine multi-objective optimization and mathematical programming (MILP, mixed integer non-linear program, MINLP, with and without uncertainty and risk consideration) or scenario-based optimization with geographic information systems (GIS) for spatial data analysis. The literature review from An et al. (2011) exposes that bioenergy is approaching to an important growth and needs to integrate strategic, tactical and operational decisions (i.e. the operations research point of view) to enhance and secure their viability, even if planning models have not been fully required (and therefore, developed) yet. Different works can be found that go in depth into a specific SC echelon: (i) feedstock production (growing, harvesting and collection), or waste generation, (ii) biomass pre-treatment, (iii) storage, (iv) biomass treatment, (v) electricity distribution and (vi) electricity consumption.

The work by Yue et al. (2014) reviews the major pathways for biomass to bioenergy and biofuel products. Biorefineries and carbon capture and storage are also included. The concept of superstructure is also exploited for the selection of the best technologies. The authors point out the challenges of including sustainability and uncertainties into the optimisation of the supply chain. The review by Cambero and Sowlati (2014) remarks that the use of biomass has an important potential to substitute fossil fuel, while all three aspects of sustainability (economic, environmental, and social) have to be considered in the optimisation problem. Uncertainty has been increasingly considered when modelling biomass supply chains: in Osmani and Zhang (2014) a stochastic mixed-integer linear program (MILP) model is developed which considers uncertainty in the supply of biomass-to-bioethanol, demand of biofuel, biomass and biofuel prices. The purpose of this model is to determine the location and the efficiency of the biorefineries, storage sites and selling points of bioethanol. Gebreslassie et al. (2012) also develop a stochastic MILP to address the optimal design of a biorefinery supply chain under supply and demand uncertainties. Miret et al. (2016) in their design of a bioethanol supply chain took into account the optimisation of a superstructure of first and second generation biomass conversion technologies.

High complex and computational demanding programs are resulting from the development of MILPs for the evaluation of biomass related supply chains, thus calling for decomposition methods that can attenuate the heavy computational load that is needed for the solution of stochastic programs. For example, Balaman et al. (2014) designed an anaerobic digestion supply chain, under cost and environmental criteria optimisation. Their model considers uncertainties by employing a Fuzzy multi-objective MILP. Osmani and Zhang (2014) employed a decomposition based on the Sample Average Approximation method. Gebreslassie et al. (2012) utilised the Multicut L-shaped method, while the work by Shastri et al. (2011) employed a decomposition scheme together with a distributed computing approach.

24.3 Energy/Biomass Supply Chain Modelling

This section describes the generic problem associated with the optimal design and operation of Biomass SC networks. In general, the SC strategic level determines the network through which the final product is manufactured/generated and distributed to finally reach the final consumer. The goal of a SC network design problem is to determine the optimal sourcing, manufacturing and distribution configuration for the different product lines of an enterprise. The most common approach is to formulate a large-scale Mixed Integer Linear Program (MILP) that captures the main revenue channels as well as the relevant fixed and variable operating costs for each facility and each major product Graves and Tomlin (2003). Specifically, a Biomass SC network consists of a number of potential geographical locations where either a conversion/pre-treatment site and/or distribution centre can be opened, and suppliers at fixed locations which have available biomass with different properties. The characteristics of the biomass can be changed by using the pretreatment units (e.g., drying or torrefaction) so that the treated biomass meets the characteristics required to be used in further steps. Even more, such pre-treatments increase the energy content and bulk densities of the biomass. Material flows between any facilities may appear if selecting such flow allows improving the performance of the SC. A market demand may be served by more than one site.

The mathematical model supports managers on planning decisions such as:

- The active SC nodes and links among them;
- The facilities capacity expansion in each time period;
- The product portfolio per plant, production amounts, utilization level, and transportation links to establish in the network alongside with material flows;
- The amount of final products to be sold in each market;
- The environmental impact associated to each SC node or activity.

A general schematic of the biomass energy SC is shown in Fig. 24.2. Notice that it is comprised by four blocks: (i) sourcing, (ii) pretreatment, (iii) generation, and (iv) distribution. The sourcing block consists in collecting the different biomass that may be available from different regions and suppliers. Each type of biomass has its own characterizing properties such as moisture content and heating value that determines its energy conversion efficiency. The pretreatment block considers those activities that modify the quality (primarily moisture content) and/or shape of the biomass. Examples of this kind of processes are the chipping, pelletising, drying, and torrefaction. These activities may be necessary, provided that there may be a technology in use which requires feeding material having a maximum moisture content and/or some shape requirements. The generation block converts the biomass into energy or any biofuel. Finally, the distribution block comprises those activities aiming at delivering the final product to the consumption points.

In a first approach, the SC decisions will be taken such that an economic indicator, i.e., Net Present Value (NPV), and an environmental impact metric, are optimized at the end of a predefined planning horizon.

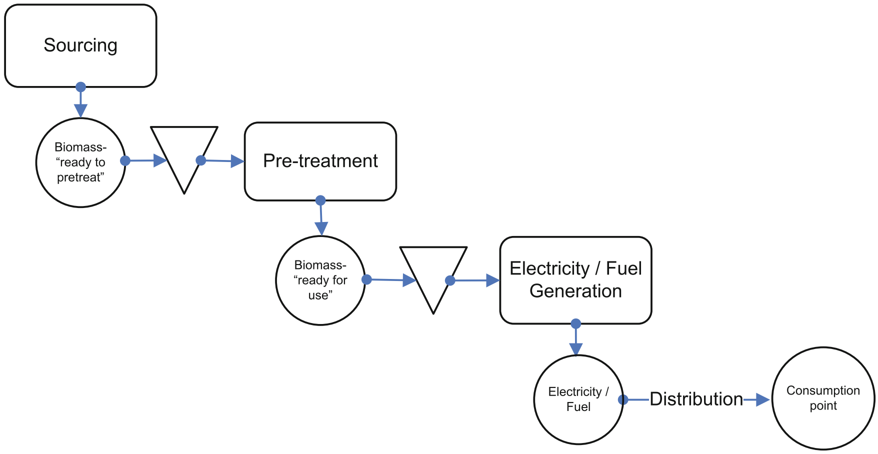

Fig. 24.2 General schematic of the biomass SC

The environmental metric selected for this model is the IMPACT 2002+ Humbert et al. (2005). This methodology proposes a feasible implementation of a combined mid-point/damage-oriented approach. It relates all types of Life Cycle Inventory results via 15 mid-point impacts (e.g., human toxicity, respiratory effects, iphoto-chemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, global warming) to four end-point categories (human health, ecosystem quality, climate change-global warming potential and resources).

24.3.1 The Mathematical Formulation

The mathematical formulation of the biomass-based SC problem is briefly described next. This is a MILP formulation based on the works of Laínez-Aguirre et al. (2009) and Bojarski et al. (2009). In this chapter, the most relevant parts of the formulation are briefly explained. The interested reader is referred to the previous references for the complete formulation. The variables and constraints of the model can be roughly classified into three groups. The first one concerns process operation constraints. The second one deals with the environmental model, while the third refers to the economic formulation.

24.3.1.1 Operations Model

The design-planning model selected is adapted from the work of Laínez-Aguirre et al. (2009). This model translates the State-Task-Network (STN) formulation Kondili et al. (1993) to the SC context. This facilitates the consideration of pretreatment activities and their outputs. The SC material balances can be modelled by means of a single equation set for all materials and echelons. This is possible since the formulation is centred around tasks i in contrast to the traditional product-based formulations. Thus, the most relevant variable of the model is $P_{ijff't}$, which represents the magnitude of a particular task i, performed using technology j during period t, whose origin is location f and destination is location f'. In the case of production activities, they must receive and deliver material within the same location (P_{ijfft}), while a distribution activity have different facilities f and f'. This mathematical formulation assumes that an activity consumes and produces certain materials with determined properties and can be performed in different equipments.

Mass balance is one of the main building blocks of the formulation and must be satisfied at each node of the network. The expression for the mass balance for each type of material s (raw material, pre-processed biomass, final product) processed at each potential site f in every time period t is presented in Eq. (24.1). Parameter α_{sij} is defined as the mass fraction of material s that is produced by task i using technology j. T_s is a set that refers to tasks that produce s, while $\bar{\alpha}_{sij}$ and $\bar{T}_s$ sets, are associated with tasks which consume s.

$$S_{sft} - S_{sft-1} = \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_f)} \bar{\alpha}_{sij} P_{ijff't} \forall s, f, t \quad (24.1)$$

For biomass SC, it is particular important to include an *energy balance* equation. If we considered that biomass properties are fixed along the different process in the network, the energy balance is satisfied directly by the definition of the streams. However, we would like to relax this assumption. For that purpose, we defined the set of activities ($\bar{I}$) for which it is convenient to let the model specify the mixture of inputs required in order to achieve a given value of a specific biomass property; for instance, a specific moisture content. For such activities, the combination of feedstock and, therefore, the proportion of each feedstock is *variable*. In order to model this feature, the mass balance is modified as shown in Eq. (24.2). Note that Eq. (24.1) is a particular case of Eq. (24.2).

$$\begin{aligned} S_{sft} - S_{sft-1} = & \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'})} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_f)} \bar{\alpha}_{sij} P_{ijff't} \\ & + \sum_{i \in (T_s \cap \bar{I})} \sum_{j \in (J_i \cap \tilde{J}_{f'})} Pv_{sijft} - \sum_{i \in (\bar{T}_s \cap \bar{I})} \sum_{j \in (J_i \cap \tilde{J}_{f'})} Pv_{sijft} \quad \forall s, f, t \end{aligned} \quad (24.2)$$

With regard to the variables $P_{ijff't}$ [kg] and Pv_{sijft}, the former is used in the mass balance (Eq. (24.2) coupled with the parameter α_{sij} or $\bar{\alpha}_{sij}$ which specify a fixed proportion of material produced or consumed for a task i. On the other hand, Pv_{sijft} is modelling flexible tasks which allow the proportion of the material produced or consumed to vary so as to provide more degrees of freedom for biomass mixing to the model. Consequently, Pv_{sijft} is not multiplied by such parameters in Eq. (24.2).

The energy balance for "flexible" activities is represented by Eq. (24.3). Here, HV_s [MJ/kg] is the heating value of material s. Each type of biomass has a different heating value. A specific activity changes the heating value of the output stream if (i) it is a pre-treatment task that modifies explicitly the calorific value of the biomass, or (ii) it is a task whose main objective is the change of shape, but it is fed with a mixture of biomasses.

$$\sum_{s \in T_s} HV_s Pv_{sijft} = \sum_{s \in \bar{T}_s} HV_s Pv_{sijft} \qquad \forall i \in \bar{I}, j, f, t \tag{24.3}$$

In case the flexible activities must be fed by an input stream with a given moisture content (MC), constraint (24.4) is enforced. The parameters $Water_s$ and $Water_{ij}^{max}$ represent the MC for material s, and the maximum MC allowed for task i performed in equipment j, respectively.

$$\sum_{s \in S_i} Water_s Pv_{sijft} \leq Water_{ij}^{max} \sum_{s \in \bar{S}_i} Pv_{sijf't} \qquad \forall i \in \bar{I}, j, f, t \tag{24.4}$$

The previous equations are the most relevant for biomass SC models compared to a traditional supply chain. The complete operations formulation includes capacity and market related equations that are common to most strategic network configuration models which can be found in Laínez-Aguirre et al. (2009).

24.3.1.2 Environmental Formulation

The application of the life cycle assessment (LCA) methodology to the SC model allows the implementation of the environmental formulation, which uses the IMPACT 2002+ as metric. Here, environmental interventions for each activity i are translated into metrics related to impact as end-points or mid-points metrics by the usage of characterisation factors. Equation (24.5) calculates IC_{aft} which represents the mid-point environmental impact a associated with site f, as a consequence of carrying out activities in period t. In turn, $\psi_{ijff'a}$ is the a characterisation factor of the environmental category impact for task i performed using technology j, receiving materials from node f and delivering them at node f'.

$$IC_{aft} = \sum_{j \in \tilde{J}_f} \sum_{i \in I_j} \sum_{f'} \psi_{ijff'a} P_{ijff't} \qquad \forall a, f, t \tag{24.5}$$

Equation (24.6) introduces $DamC_{gft}$ [points], which is a weighted sum of all mid-point environmental interventions. They are combined using g end-point damage factors ζ_{ag} [adim.], normalised with $NormF_g$ factors. Moreover, Eq. (24.7) calculates g normalised end-point damage along the SC ($DamC_g^{SC}$ [points]).

$$DamC_{gft} = \sum_{a \in A_g} NormF_g \zeta_{ag} IC_{aft} \qquad \forall\, g, f, t \tag{24.6}$$

$$DamC_g^{SC} = \sum_f \sum_t DamC_{gft} \qquad \forall\, g \tag{24.7}$$

Equation (24.8) aggregate the end-point environmental damages for the whole SC.

$$Impact_{overall}^{2002} = \sum_f \sum_g \sum_t DamC_{gft} \tag{24.8}$$

For further details regarding the environmental formulation the interested reader is referred to Bojarski et al. (2009).

24.3.1.3 Economic Formulation

The expressions required to compute the operating revenue, the operation costs, the total capital investment, and NPV are included in the economic formulation.

For instance, the *operating revenue* is expressed in Eq. (24.9) as the product sales during period t.

$$ESales_t = \sum_{s \in FP} \sum_{f \in Mkt} \sum_{f' \notin (Mkt \cup Sup)} Sales_{sf'ft} Price_{sft} \qquad \forall t \tag{24.9}$$

General speaking, the *operating costs* include fixed ($FCost_t$) and variable ($EPurch_{et}$) costs. The latter usually includes the cost of purchases from supplier, transport cost and production cost. Another important piece of the economic formulation is the *total capital investment* on fixed assets ($FAsset_t$), which must consider the investment made to expand the technology's capacity j in facility site f in period t.

Equation (24.10) represents the profit in period t, as operating revenues minus fixed and variable operating costs. The NPV can be calculated as in Eq. (24.11).

$$Profit_t = ESales_t - (FCost_t + \sum_e EPurch_{et}) \qquad \forall\, t \tag{24.10}$$

$$NPV = \sum_t \left(\frac{Profit_t - FAsset_t}{(1 + i_r)^t} \right) \tag{24.11}$$

The overall optimisation problem can be posed mathematically as follows:

$$\underset{\mathscr{X},\mathscr{Y}}{\text{Min}} \left\{-NPV, Impact^{2002}_{overall}, -SoC\right\}$$
$$\text{subject to}$$
$$\textit{Operations, Environmental and Economic formulation};$$
$$\mathscr{X} \in \{0,1\}; \mathscr{Y} \in \mathbb{R}^{+}$$

where, $\mathscr{X}$ denotes the binary variables set, while $\mathscr{Y}$ corresponds to the continuous variable set.

24.3.2 A Hydrogen Supply Chain

This case study illustrates the basic concepts behind the biomass SC design-tactical model outlined in the previous section and was first presented in Laínez et al. (2011). It compares the generation of electricity and H2 from two different kinds of feedstock: (i) different biomass wastes and (ii) coal.

24.3.2.1 Case Study

A simplified potential network is proposed and restricted to Spain (see Fig. 24.3). Lugo (F1), Ciudad Real (F2) and Burgos (F3) are considered to be possible facilities location nodes. The feedstock is supposed to be available at Cordoba (LA), Lugo (LB), Cuenca (LC), Santander (LD) and Oviedo (LE). This last site is the one supplying coal. Hydrogen is supposed to be sold at three market places located at Madrid (M1), Valencia (M2) and Barcelona (M3), while electricity is fed to the Spanish electricity network at their respective generation places. Different biomasses are modelled considering that each of them possesses different energy content and humidity. Here, coal has been considered as a dry material which does not require any pretreatment.

The biomass may be pretreated before being finally processed. Figure 24.4 depicts the different pretreatment processes that may be applied to the biomass (BM) so that it achieves the adequate shape and properties (energy content and humidity) for later processing. In this case study bulk density has not been considered for the sake of simplicity. The pretreatment options considered here are: chipping, drying, torrefaction and pelletising. It is assumed that the condition for biomass to pass through torrefaction is to have a LHV lesser than 15 MJ/kg, while to be pelletised biomass must have a humidity equal to or lower than 7 %. The parameters associated with the pretreatment processes are listed in Table 24.1.

The technology that is employed to provide the final product is gasification and a gasification plant with Carbon Capture and Storage (CCS) for the H2 generation. Efficiencies of 40 % and 30 % are assumed for each plant respectively. Other

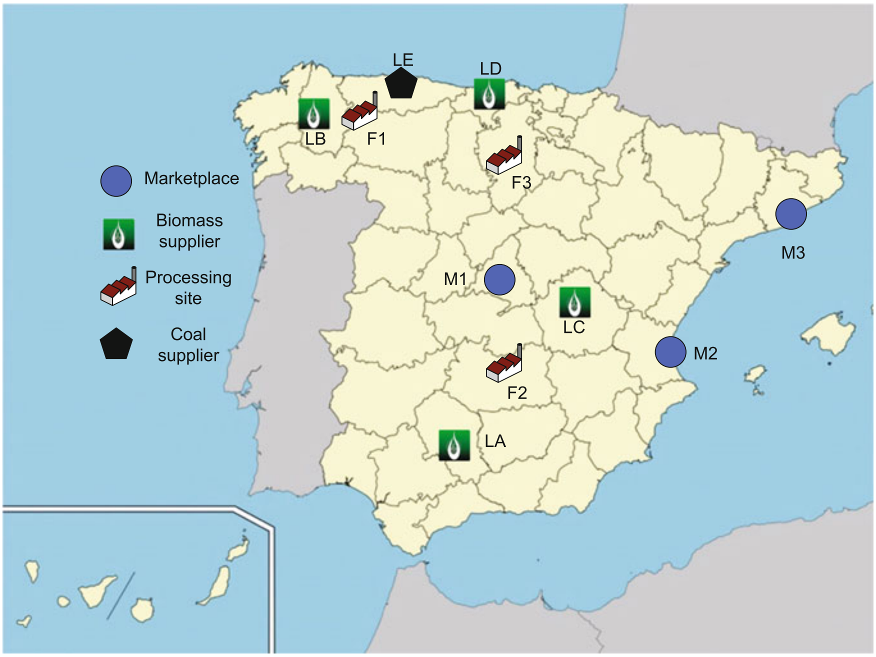

Fig. 24.3 Location map for the potential SC network

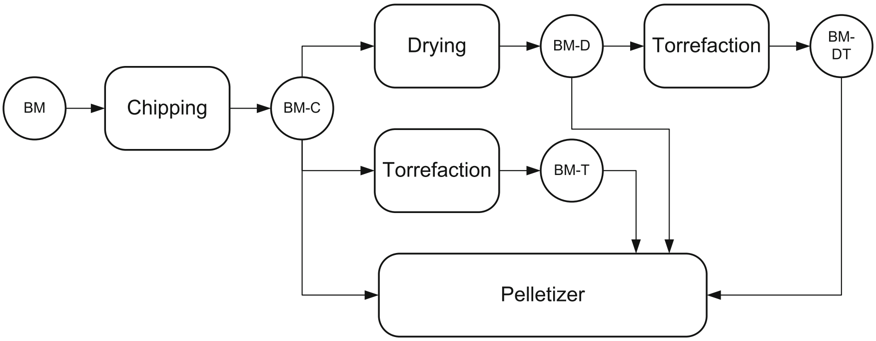

Fig. 24.4 STN representing the pretreatment activities for a generic biomass

relevant information concerning these technologies is presented in Table 24.2. In order to assess the environmental impact associated with the energy SC, the available LCI values were retrieved from the LCI database EcoinventV2.0 using SimaPro 7.1.6 SIMAPRO (2004) and converted directly to the IMPACT 2002+ mid-point indicators. For those activities which were not available, the impacts were assumed based on similar products or activities. The project is evaluated along a planning horizon

Table 24.1 Pretreatment processes and their main modelling assumptions

Activity/ equipment	Moisture losses (%)	Dry matter losses (%)	Operating cost (EUR/t)	Capacity (t/h)	Investment (1×106 EUR)	Electricity consumption (MWh/t)
Chipper	0	0.17	2.5	30	0.37	5
Dryer	88	0.08	55	100	5	20
Torrefactor	55	19	40	20	0.1	37
Pelletizer	0	0	3.5	6	0.485	30

Table 24.2 Parameters for the processes for electricity and H2 generation

Technology	Operating cost (EUR) (1×106EUR)	Capacity	Investment	Product price (EUR)	Total monthly demand
Electricity	34.2/MWh	300 MW	860	0.151/ kW-h	75000 MWh
H2	1880/t	33.6 t/h	1500	3/kg	650 t

of 25 years, considering monthly planning decisions. The model was implemented in GAMS which is algebraic modelling software.

24.3.2.2 Results

Figure 24.5 shows the obtained dominant biomass based SC that maximises NPV. It is found that the three potential locations are considered and on each one of them a facility is opened. All pretreatment technologies are installed in location F1 besides the required equipment to produce H2. From this site H2 is delivered to all markets. F1 is collecting all the forest wood residues (FWR) for which larger mass flows are required due to their low LHV. By establishing F1, which is near to the FWR collection site, significant savings in transportation are obtained. The electricity is generated in site F2. In this site; equipments to perform chipping, drying and pelletising are installed. The electricity demand of each market is satisfied from site F2. Site F3 is used just as a distribution centre for pre-treated biomass. Equipment for chipping and drying is installed in such a site. For this configuration there are some inter-site flows, clearly showing the capabilities of the model to tackle with inter-site distribution tasks. For instance, forest wood residues which have been dried and torrefied are being sent from site F1 to F2. By having materials flows of pre-treated biomass the transportation cost is reduced due to their higher bulk density.

The optimal configuration for the environmental impact has also been obtained. Figure 24.6 shows the minimum IMPACT 2002+ configuration for the biomass based SC. This supply chain fulfils with the same demand as the one obtained by optimising NPV. For this case the location F3 is not considered, and all biomass is

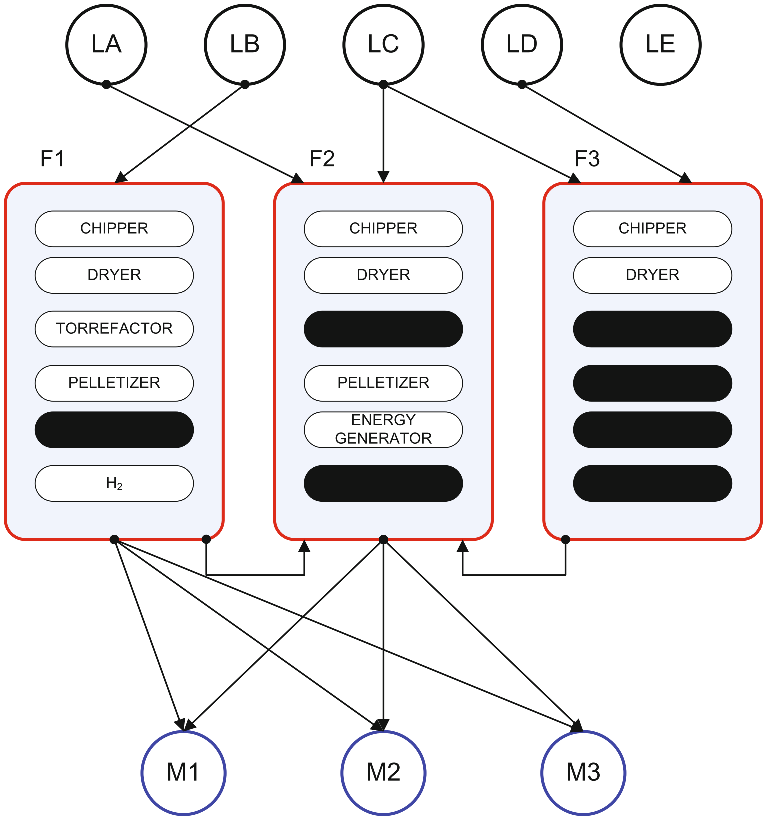

Fig. 24.5 Optimal NPV network configuration for the biomass based SC

sent from the collection sites to locations F1 and F2. This configuration is satisfying the demand of electricity from both locations F1 and F2, whereas H2 is delivered from site F2. This allows to slightly reduce the environmental impact associated with transportation. Recall that we introduce a “flexible” task to account for those tasks for which we would like the model to decide how to better mix different biomasses so as to achieve a given specified biomass property. We have assumed that the pelletizer is one of such tasks for this case study. To give an example, there are periods in which the model proposes to make the following mix: 1.4 % forest wood residues, 30.3 % dried and torrefied forest wood residues, 10.5 % dried pine waste, 14.4 % dried almond tree prunings, and 43.5 % chipped olive pomace (mass basis). This mixture is then fed to the syngas production plant. The values of humidity corresponding to these materials are 10.0 %, 6.0 %, 7.0 %, 7.0 % and 7.5 %, respectively. It can be proved that the humidity of this mix is 7.0 % which is the maximum humidity allowed for the pelletiser input.

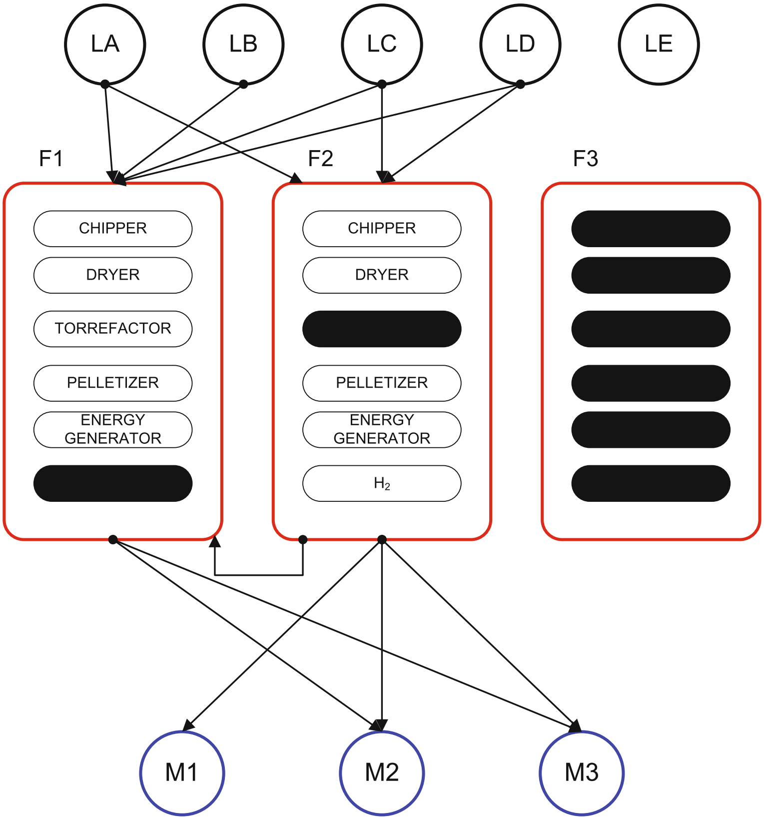

Fig. 24.6 Optimal IMPACT 2002+ network configuration for the biomass based SC

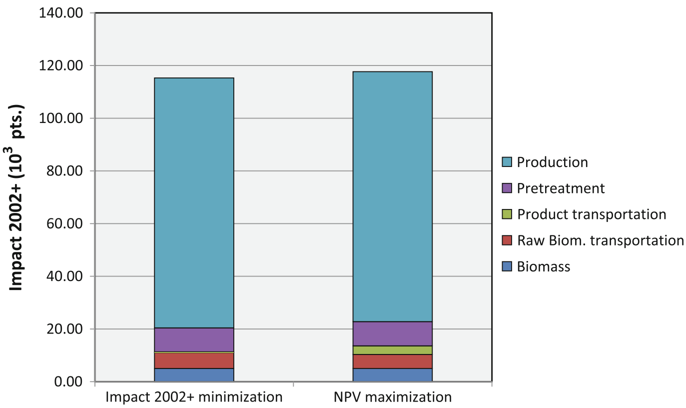

Fig. 24.7 Distribution of environmental impacts for single objective optimization solutions, according to different SC activities

Table 24.3 Environmental impacts arising from the optimisation results [Impact 2002+ pts]

End point impact category	Impact 2002+ optimisation	NPV optimisation	100 % coal-based SC
Human health	16255.29	17267.21	109640.5
Ecosystem quality	3375.79	3610.96	11077.16
Climate change	90383.37	90950.66	95334.48
Resources	5292.64	5852.73	140605.9
Impact 2002+	115307.1	117681.6	356658.1

By deploying the SC configuration corresponding to the more profitable SC configuration, a NPV equal to 228.51 M EUR is obtained. This value is reduced by 3 % when the environmental friendly configuration is established. The main difference between these two configurations is the investment required for installing the proposed capacity in the different sites. With regard to environmental interventions, electricity generation and H2 production are the most important factors contributing to the overall environmental impact in both single objective optimization cases; while biomass sourcing is the least impacting aspect (Fig. 24.7). This clearly shows that activities to reduce environmental impact should be focused on improving the technologies used to produce energy and H2.

For comparison purposes the optimal SC based on coal was also obtained. An NPV improvement of 219 % can be gained by utilizing coal as feedstock when compared to the Biomass based SC. The main difference is from the production cost which is due to the pretreatment activities that are required in the biomass based SC. This fact also makes the investment increase in the Biomass SC. However, the Impact 2002+ is increased in 203 % compared with the biomass based SC (Table 24.3). It is noteworthy that the impact associated with the climate change category is very similar for both cases. We have to bear in mind that CO2 is still emitted when using a Biomass SC, however this biomass is regenerated faster than fossil fuels. Nevertheless, the other categories are significantly increased in the coal based SC, specially for the resources and human health. This fact emphasizes the significance of having an overall impact indicator instead of a partial indicator such as CO2kg.

24.3.3 Biomass Supply Chains in Developing Economies

This second case study contemplates a specific rural area of a developing country, Ghana (Africa) which has been presented in Pérez-Fortes et al. (2012).

24.3.3.1 Case Study

Nine communities in Atebubu-Amantin district, in the Brong Ahafo Region (see Fig. 24.8) are part of the analysis. The selected communities form a region with a main characteristic: they are equipped with a multi-functional platform (MFP) that currently supplies the electricity needs; cell phone's battery charging, water refrigeration, lighting, radio, TV, computer and maize mills and cassava graters. Those communities are therefore used to pay for the electricity service. Data for the SC characterisation was provided by the Energy Center, in Kwame NKrumah University of Science and Technology (KNUST), and the NGO Kumasi Institute of Technology, Energy and Environment (KITE) (Ghana). The MFP's project in Atebubu district has been executed in collaboration with KITE and the local NGO called Women and Children Support Organisation (WACSO).

The electricity demand has been estimated on the basis of references from previous experiences on rural electrification projects, in West Africa and South American communities conducted by Arranz-Piera et al. (2011) and the company *Trama Tecnoambiental* Vallvé et al. (2007); Arranz-Piera (2008). The highest estimated gross demand is 448.65 kWh/day in Kumfia community, while the lowest is 21.17 kWh/day in Nwunwom community. Such figures take into consideration the LV microgrid losses. Figure 24.10 depicts the nine communities represented by their relative energy demands (in blue), in a square grid that represents their relative distance in km. Black points mark potential locations for pre-treatment and treatment units; all the communities and four more intermediate sites are considered as potential locations.

Cassava rhizome is the biomass waste considered in this study. Cassava is a well extented tropical crop in the country, mainly used as food (in the form of fufu or gari). Agriculture is the most important economic sector, with cassava, yam and maize as basic products. The cassava is planted once a year, in April, during the rainy season and does not need any special care. A 66.5 % of the tubercle is cassava rhizome Pattiya (2011). As the produced wastes have no current alternative use, the cost of acquisition is considered negligible. Table 24.4 summarises the cassava main

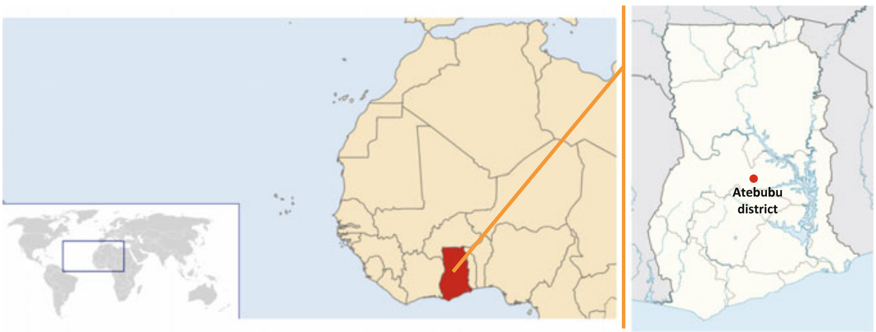

Fig. 24.8 Location of Atebubu district, in Ghana

Table 24.4 Feedstock properties

Biomass	Cost ($/t)	LHV_{ar} (MJ/kg)	MC (% wt)	Seasonality	Yearly available (t)
Cassava waste	0	10.61	42.50	June–October	1666.13

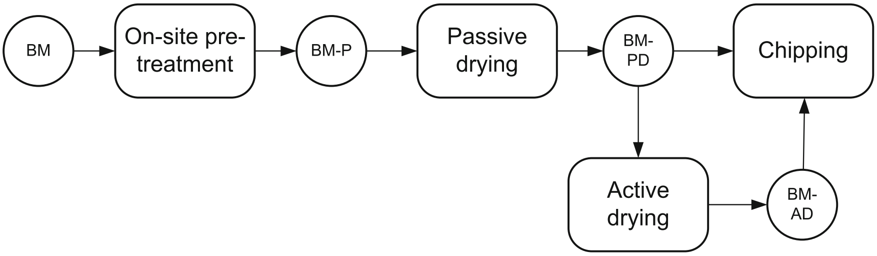

Fig. 24.9 Pre-treatment activities layout

properties. The last column shows the total amount of cassava waste produced by the 9 communities. This value has been calculated by considering that from the total amount produced in Atebubu district, only a 20 % can be taken for electricity purposes. According to Serpagli et al. (2010), 264649 t of cassava has been produced during 2009 in the whole Atebubu district, representing 17667.6 GJ/yr.

Inlet biomass can be fed to a gasifier, however it must be chipped and have 20 % or less of MC. It is supposed that the only possible biomass storage is carried out before chipping and gasification using on-field storage which is the cheapest and simplest option. Figure 24.9 shows the layout of the different pre-treatment options applied to the biomass (BM). MC, DM, shape and LHV change along the network.

The most important parameters in the biomass gasifier are the amount of inlet air (i.e., the equivalence ratio, ER) and the MC. See the main system's parameters in Table 24.5. The gasification units range between 5 and 100 kW_e. Table 24.6 lists the parameters required for cost estimation of the pre-treatment units, the G-ICE plant and transportation. The diesel price is assumed as $1133.31/t.[1]

With regard to the environmental formulation, Impact 2002+ metric is used to evaluate the environmental impact in points (pts). LCI values are retrieved from LCI database Ecoinvent-V1.3 (2006) using SIMAPRO (2004), and they are directly converted into Impact 2002+ mid-point indicators in the so-called LCIA step. The impact of the gasification has been adapted from a large scale gasification plant impact, an IGCC, considering the efficiency difference in energy terms between the two plants.

One important aspect considered in this case study is the *social impact*. The approach proposed to quantify this criterion consists in the number of demand sites that have a treatment or pre-treatment system installed. The aim is to install as many as possible to promote working places in the widest range of communities or demand

[1]On-field data.

Table 24.5 Principal output values

Parameter	Values
T_{gasif} (°C)	702.00
Producer gas composition (on a mole basis)	
CO	23.93
CO_2	10.49
N_2	37.07
H_2	20.88
CH_4	3.58
H_2O	4.03
Flowrate (kg/h)	35.33
LHV (MJ/kg)	6.32
CGE (%)	68.00
Power (kW_e)	15.80
η (%)	17.00

Table 24.6 Economic parameters for pre-treatment units, G-ICE plant, transportation and utilities consumption. Data from Hamelinck and Faaij (2002), Hamelinck et al. (2003), TRAMA (2008), *Ankur Scientific Energy Technologies Pvt. Ltd.*, KITE and WACSO

	Base scale	Base investment	O and M (% of investment)	Utility consumption	Lifetime (yr)
Drying	100 t/h	M$10.5	3	$0.06 \cdot t_{H_2Oev}$ (t diesel)	15
Chipping	80 t/h	M$1.2	20	Bond law 0.15 · t input (kW)	15
G-ICE system	20 kW_e	M$0.05[1]	4		7
Transportation biomass		Tractor full $0.32/km · t	Loading and offloading $1.32/t		
MV network[2]		$5000/km			

[1] LV network costs are included here
[2] Transformer cost is $1000

sites. Therefore, the social criterion *SoC* should be maximised (see Eq. 24.12). This criterion assigns a value of 1 to each unit installed per site *f*. If *V* is the binary variable that characterises the number of units installed per site, this metric can be expressed as follows:

$$SoC = \sum_j \sum_f \sum_t V_{jft} \qquad \forall j, f, t \tag{24.12}$$

24.3.3.2 Results

Three scenarios are obtained by optimizing the individual metrics: NPV, Impact 2002+ and *SoC*. The optimal networks are represented by four types of matter flows that connect the different sites. Those flows are: raw material from harvesting, stored raw material, dried matter and chipped matter, characterised by different colours in Fig. 24.10. Flowrates are obtained in tons/month. All networks distribute dried material. The chipped biomass is the most used alternative. Since it has been assumed that cassava waste is produced into each community, proportional to the population, there is no need to employ a MV microgrid and use intermediate sites. Moreover, the high investment costs associated with an intermediate site prevent their use. The simplest network comes out from the environmental impact minimisation, with only chipped matter being generated. Table 24.7 lists the calculated capacity for the equipments installed at each site for each scenario.

Table 24.8 summarises the three criteria evaluated for each optimal network. If the most environmental friendly option is selected, the decision maker should be willing to compromise around 60 % of the optimum NPV which implies just a 2 % improvement in the environmental metric. In order to decrease the environmental impact, there is a necessity of more decentralised units. This requires a significant greater investment in comparison with the NPV optimum alternative. Notwithstanding, the gain in the environmental impact only results from a reduction in transportation. The environmental impact for the social SC network is closer to the optimal environmental impact. The maximum value for the social criterion is 27, installing 3 units per site. In this case the capacity of the installed units is adapted to match the demand of each community. However, a certain degree of centralisation is needed in network to ensure its financial sustainability.

The needed amount of biomass to satisfy the electricity demand is 1526 t/yr. An 8.4 % of the total available cassava rhizome is not used and can be employed for other purposes. The most important differences among the three selected criteria concern transportation and investment. Due to the cassava waste disposition, which is present in all the communities, no MV microgrid is installed. The smallest communities whose demands are far from the biggest ones, such as Seneso or Nwunwom, are the communities that show more variability along the different scenarios. The largest variability comes from the chipper and dryer installations, since those are the units used to adjust the social factor during the search of optimal scenarios. Even though there is enough biomass to be self-sufficient, biomass from other communities is processed to supply the demand of small communities. By doing so, the investment in pre-treatment technologies is reduced. Such a reduction has a major contribution than the savings in transportation that would be gained if the biomass were pre-treated locally for these small communities. It is also relevant to notice that transportation of raw biomass is carried out from some small communities to other ones with installed pre-treatment capacity in order to face biomass seasonality. Also, it is important to highlight that this type of models can be used to explore the sensitivity of the solutions to important parameters. For example, the effect of the electricity price ($0.233/kWh) on the optimal NPV network can be analysed. It is found that if the

Fig. 24.10 Optimal network configurations for the three selected criteria. See in *brown* the non-stored raw matter flow, in *green*, the raw matter flow, in *orange* the dry matter flow and in *purple* the chipped matter flow. **a** Optimal NPV network configuration. **b** Optimal Impact 2002+ network configuration. **c** Optimal social network configuration

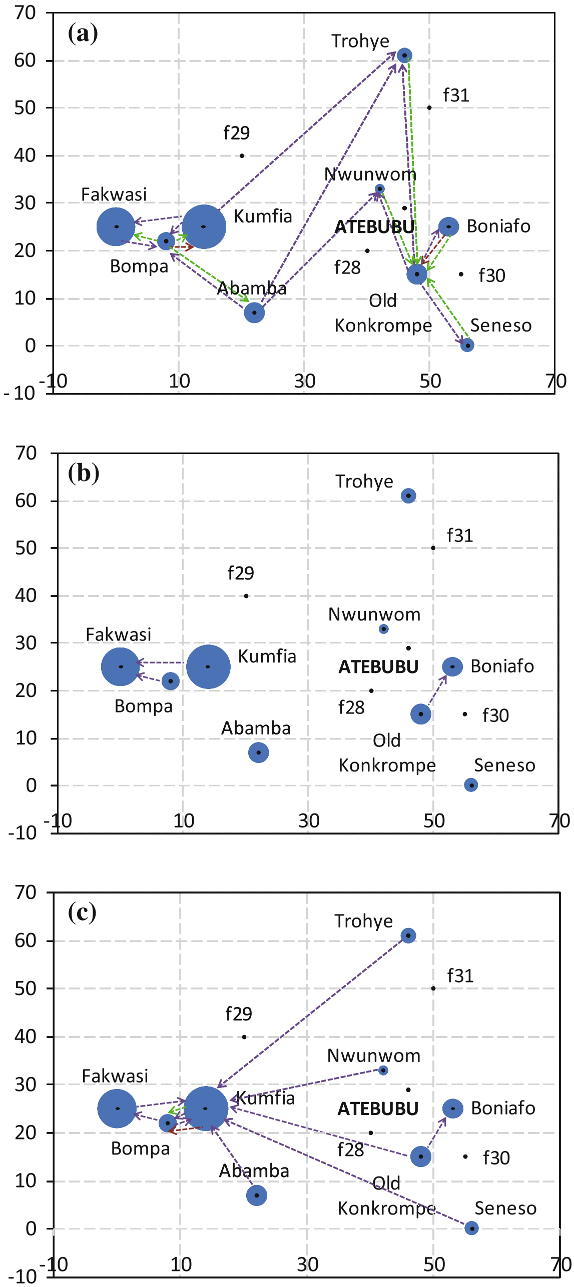

Table 24.7 Equipment capacity for the optimum networks configurations obtained for the three selected criteria

	NPV max			Impact min			*SoC* max		
	Dryer (t/h)	Chipper (t/h)	G-ICE (MJ/h)	Dryer (t/h)	Chipper (t/h)	G-ICE (MJ/h)	Dryer (t/h)	Chipper (t/h)	G-ICE (MJ/h)
Seneso			18.00	0.10	0.10	18.00	0.10	0.10	18.00
Old	0.10	0.10	21.44	0.10	0.10	21.44	0.10	0.10	21.44
Konkrompe									
Fakwasi	0.14	0.10	80.61	0.14	0.10	80.61	0.10	0.10	80.61
Kumfia	0.20	0.11	102.35	0.19	0.10	102.35	0.12	0.10	102.35
Trohye			18.00	0.10	0.10	18.00	0.10	0.10	18.00
Bompa			18.00	0.10	0.10	18.00	0.10	0.10	18.00
Nwunwom			18.00	0.10	0.10	18.00	0.10	0.10	18.00
Boniafo			20.53	0.10	0.10	20.53	0.10	0.10	20.53
Abamba	0.10	0.10	22.04	0.10	0.10	22.04	0.10	0.10	22.04

Table 24.8 Economic, environmental and social aspects for the individual objective functions optimised networks

NPV optimisation ($)	89895.95
Impact 2002+ (pts/yr)	113.46
Social criterion	17.00
NPV ($)	36867.21
Impact 2002+ optimisation (pts/yr)	110.94
Social criterion	27.00
NPV ($)	45155.60
Impact 2002+ (pts/yr)	111.43
Social optimisation	27.00

electricity price falls below $0.2/kWh and equipment investment remains the same then the viability of the network breaks down, i.e. the NPV becomes negative.

24.3.4 Biomass Supply Chains in Developed Economies

This last case study is a retrofitting proposal for coal combustion power plants in Spain that contemplates the use of biomass to replace a fraction of coal. It was first presented in Pérez-Fortes et al. (2014).

24.3.4.1 Case Study

Provided a set of biomass collection sites and the current list of power plants in Spain, the SC model assists on the decisions associated with the technology allocation problem and the flows of materials between sites, while quantifying the performance of the proposed configuration in terms of NPV and environmental impact, IMPACT 2002+.

The types of biomass waste used in this case study are forest wood residues (FWR) and agricultural woody residues (AWR) from Gómez et al. (2010a, b). The amount of biomass available in collection areas is estimated by an approach that integrates physical, geographical and technical limitations, providing an upper bound for the potential availability Gómez et al. (2010b). It is assumed that no transportation cost is charged for biomass assembly inside the collection areas. Table 24.9 sums up the main characteristics of FWR and AWR used for modelling purposes.

The technology considered for biomass usage in a combustion plant is co-firing. According to Basu et al. (2011), the investment is around 192 €/kW$_{th}$ for this technology. Operation and maintenance (O&M) costs represent 4 % of the investment Gómez et al. (2010a). The type of coal used into each plant is specified in López-Vilariño et al. (2003). See Tables 24.10 and 24.11 for further detail about the power plants, their coal origin and power produced.

Table 24.9 Feedstock characteristics Gómez et al. (2010b)

Biomass waste	MC (%wt)	LHV_{ar} (MJ/kg)	BD (kg/m^3)	Yearly available (kton)	Adjusted availability (kton)	Seasonality	Cost (€/ton)
FWR	30	12.5	140	7,748	1,162	None summer	56
AWR	40	10.8	100	3,883	2,718	and winter	52

Table 24.10 Types of coal used in the Spanish power plants. Data for 2010 ENERCLUB (2010); López-Vilariño et al. (2003); REE (2010)

	Type	Origin	LHV_{ar} (MJ/kg)	Cost (€/t)
Coal 1	Sub-bituminous 1	Local	12.57	85
Coal 2	Sub-bituminous 2	Local	17.81	85
Coal 3	Bituminous 1	Local	22.63	85
Coal 4	Bituminous 2	Imported	27.03	80

Biomass storage is allowed after harvesting/collection and after pre-treatment sites. This case study considers open air covered storage for raw material. MC decreases due to natural drying and DM is reduced due to degradation: losses of 2 % MC and 0.25 % DM can be accounted Rentizelas et al. (2009); Maciejewska et al. (2006).

Figure 24.11 shows the general network configuration considered in this case study. After being collected, the biomass waste may be transported to different sites to be stored. Following, there are two mandatory processes before biomass pre-treatment to obtain the mandatory conditions of MC and shape: chipping and drying. Thereafter, torrefied biomass (TOR), torrefied pellets (TOP), pellets (PEL), bio-oil (OIL) or bioslurry (SLU) are produced before being stored if needed, and processed in the power plant. Trucks, adapted to carry solids or liquids are used biomass distribution.

Table 24.12 summarizes investment, O&M costs and utilities consumption for pre-treatment units, storage and transportation echelons. Utilities cost are 1,393 €/t MITYC (2010) for diesel and 0.04463 €/kWh CNEL (2010) for electricity. The electricity sold is bought at 0.03701 €/kWh OMEL (2011).

24.3.4.2 Results

We are going to focus on two scenarios to demonstrate the capabilities of the biomass SC optimization in the context of developed economies. They are proposed to evaluate the trade-offs among the state -of-the-art (SOTA) pre-treatments, i.e. torrefaction, pelletisation, pelletisation of torrefied biomass, fast pyrolysis and fast pyrolysis combined with char grinding:

Table 24.11 Spanish thermal power plants characteristics ordered by region. Installed power (MW) and used capacity (GWh) for 2010 López-Vilariño et al. (2003); REE (2010)

Model name	Name	Power (MW)	Energy (GWh)	Type of coal
m1	Puentes García Rodríguez	1,468	4,955	Coal 1
m2	Meirama	563	856	Coal 1
m3	Aboño	916	3,663	Coal 3
m4	Lada	513	698	Coal 3
m5	Soto de la Ribera	604	927	Coal 3
m6	Narcea	595	1	Coal 3
m7	Anllares	365	0	Coal 3
m8	Compostilla	1,171	209	Coal 3
m9	La Robla	655	29	Coal 3
m10	Guardo	516	63	Coal 3
m11	Pasajes de San Juan	217	487	Coal 4
m12	Cercs	162	516	Coal 2
m13	Escatrón	80	0	Coal 2
m14	Teruel	1,102	1,793	Coal 2
m15	Escucha	159	156	Coal 2
m16	Litoral de Almería	1,159	4,409	Coal 4
m17	Los Barrios	589	2,489	Coal 4
m18	Puertollano	221	255	Coal 3
m19	Puentenuevo	324	590	Coal 3
Total		11,379	22,096	

- Scenario A (SCNA). This option considers as alternatives all the proposed pre-treatments. The model is forced to select at least one SOTA pre-treatment.
- Scenario B (SCNB). This alternative optimizes the SC considering as SOTA pre-treatments only the use of fast pyrolysis and fast pyrolysis with char grinding.

Figures 24.12 and 24.13 illustrate the optimum networks obtained for each criterion and scenario. With regard to SCNA, Fig. 24.12a, b show that the difference between the NPV and IMPACT 2002+ optimisation results is around the distribution among sites. The environmental optimisation does not suggests transportation of intermediates between sites which indeed contributes to reduce the overall impact. Moreover, this is achieved by installing pre-treatment unit in each collection area. Meanwhile, the NPV takes advantage of economies of scale by suggesting equipment of higher capacity at fewer locations.

Figure 24.13a, b depict the optimum networks for fast pyrolysis combined with char grinding. Both networks are very similar. There is mostly transportation of raw biomass from suppliers to intermediate sites despite the biochar being more

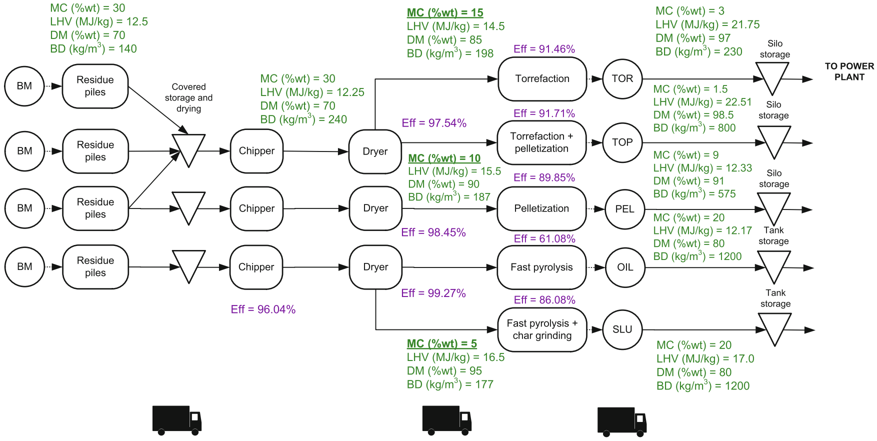

Fig. 24.11 Properties for a FWR stream along the SC. LHV is on *ar* basis. The efficiency (*Eff*) is defined in terms of LHV_{ar}

Table 24.12 Economic parameters of pre-treatment and storage units and transportation Hamelinck et al. (2003); Magalhaes et al. (2009); Uslu et al. (2008)

	Base scale	Base investment	O and M (% of investment)	Utility consumption	Lifetime (yr)
Chipping	80 t/h	0.7 M€	20	Bond law $0.15 \cdot t_{input}$ (kW)	15
Drying	100 t/h	6.9 M€	3	$0.06 \cdot t_{H_2Oev}$ (t diesel)	15
Torrefaction	40 $MW_{th_{in}}$	6.2 M€	5	92 kWh/t_{input}	10
Torrefaction +					
Pelletization	40 $MW_{th_{in}}$	7.5 M€	5	102 kWh/t_{input}	10
Pelletization	40 $MW_{th_{in}}$	5.9 M€	5	129 kWh/t_{input}	10
Fast pyrolysis	40 $MW_{th_{in}}$	10.5 M€	4	75 kWh/t_{input}	25
Fast pyrolysis +					
char grinding	5 t/h	4.9 M€	5	95 kWh/t_{input}	25
Open air covered storage			0.53 €/m^3month		
Silo storage	5000 m^3	0.45 M€	3		25
Tank storage	2272 m^3	1.11 M€	3		25
Transportation	130 m^3		0.69 €/m^3		
solid			1.16 €/km		
Transportation	33 m^3		0.69 €/m^3		
liquid			1.70 €/km		

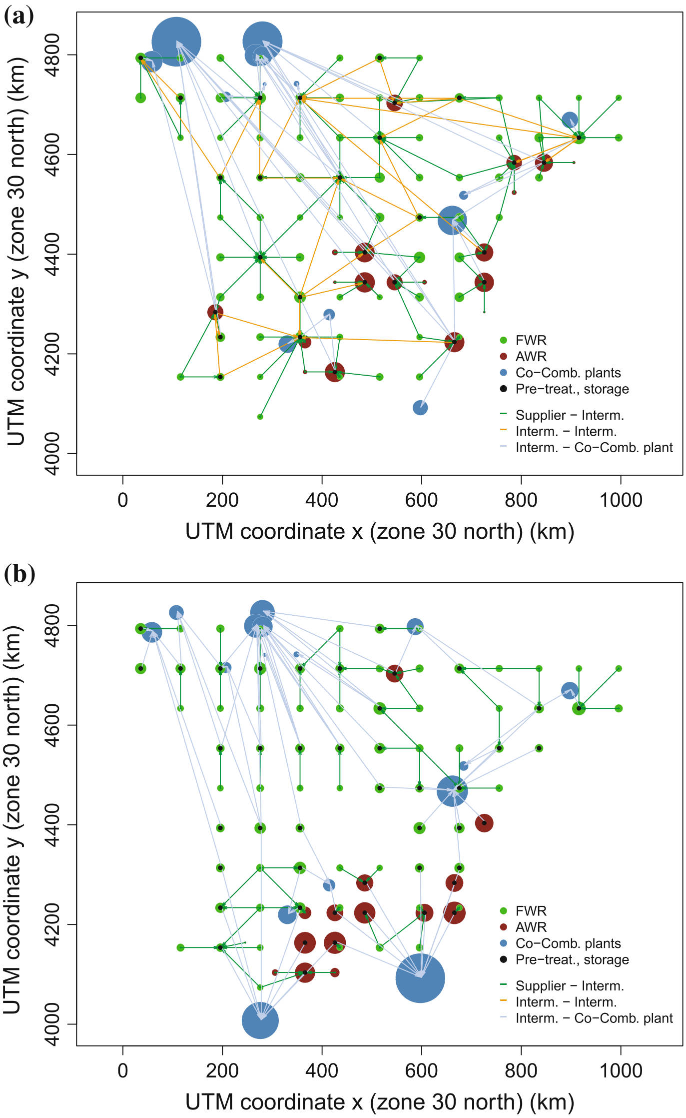

Fig. 24.12 Optimal network configurations for the two selected criteria and mandatory SOTA pretreatments (SCNA). **a** Optimal NPV network configuration for SCNA. **b** Optimal Impact 2002+ network configuration for SCNA

dense. However, observe that liquid product transportation is carried out by trucks of smaller capacity. From the size of the fast pyrolysis plants installed and also considering the efficiencies of chipping and drying (as for example calculated in Fig. 24.11), it can be observed that the minimum capacity available for chipping and drying (for

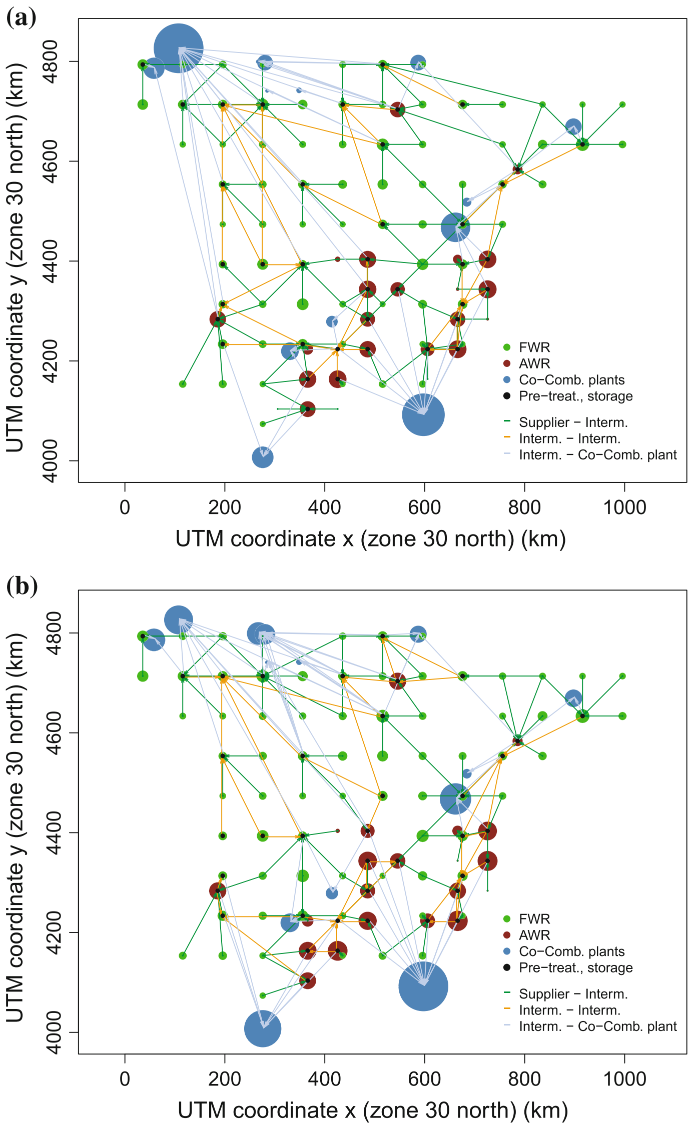

Fig. 24.13 Optimum network configurations for the two selected criteria and production of liquid fuel (SCNB). **a** Optimum NPV network configuration for SCNB. **b** Optimum Impact 2002+ network configuration for SCNB

both scenarios) is larger than input demand. On the other hand, fast pyrolysis units are installed in around 70 % of the candidate nodes at its maximum capacity.

Due the its higher bulk density, liquid biomass is adequate for long distance transportation and for storage in smaller places. Nevertheless, fast pyrolysis is still in a

Table 24.13 Revenues increase to cover the biomass SC

	EcO-SCNA	EnvO-SCNA	EcO-SCNB	EnvO-SCNB
Revenues increase	15.30 %	20.66 %	21.71 %	23.24 %

pre-commercial state and therefore, is more expensive than other alternatives. In addition to that, according to the data for this specific case study, trucks to move liquid biomass are smaller and more expensive than trucks used to transport solid biomass. Under the considered data assumptions, we can concluded that to make liquid biofuels attractive their distribution cost should drop by 30 %, or from another point of view, the distances to be covered should increase by a factor a 1.4–1.5 to justify the conversion into biochar. By comparing the (i) consumed biomass (i.e. efficiency of the process), (ii) overall cost and (iii) investment for the same networks, liquid fuel results in a needed global expense decrease of 5 % to be similarly "attractive". If this reduction is to come only from technology investment, this should decrease by 15 %.

Other type of outcome from this analysis is listed in Table 24.13. It shows the needed increment in electricity price to afford the investment and operation along 10 years for each of the optimal proposed networks. This increase oscillates between 9 and 23 %.

24.4 Conclusions

This chapter has emphasised some of the insights that an optimisation approach for biomass supply chains can provide. These may result useful to move efficiently towards the goals established in the horizon up to 2050. The approach consists of a MILP formulation that considers long-term strategic decisions such as selection of pre-treatment trains of units and their respective location, selection of biomass sources, location of processing sites, and distribution centres. The problem has been formulated with multiple objective functions: the net present value, the Impact2002+ metric to quantify the overall environmental impact, and a surrogate social metric that considers the processing units installed in each location. The latter is especially significant when addressing problems in developing economies, as the electrification problem presented for the communities in the Atebubu-Amantin district in Ghana. Another two distinctive features of the described approach are (i) the model's capability of combining feeds and determining the optimal proportions of each input for the energy generation activity and (ii) the consideration of passive drying during storage. However, further analysis is necessary for determining the benefits of providing these additional degrees of freedom in contrast to assuming a unique source with average properties. For cases where such benefits are significant, exploring the extension of this flexibility to other activities included in the biomass supply chain, such as storage and pre-treatment, may prove worthy. Further work is devoted to envisaging decomposition strategies to reduce the computational cost of solving this type of problems. The capabilities of the mathematical modelling approach were pointed out through the different case studies. These have demonstrated that this formulation can be adapted to address different contexts (e.g., centralised and decentralised, rural or state-wide networks).

Finally, we would like to underscore that efforts to consolidate the research carried out related to pre-treatment/conversion technologies into a repository, which would be available to the PSE community, could facilitate the feasibility evaluation of biomass-based-energy projects.

Acknowledgments The authors are grateful to the CEPIMA members for the support provided. We acknowledge the financial funding received from the Generalitat de Catalunya through the ESF (FI Grants).

Disclaimer This work was performed while the author's main affiliation was the Universitat Politècnica de Catalunya. The authors confirm that this study and all related work were carried out without any conflict of interest. Responsibility for the information and views set out in this work lies entirely with the authors.

References

An, H., Wilhelm, W. E., & Searcy, S. W. (2011). Biofuel and petroleum-based fuel supply chain research: A literature review. *Biomass and Bioenergy*, *35*, 3763–3774.

Arranz-Piera, P. (2008). Development of electricity service operators for poverty alleviation in ecuador and peru. In *4th European Conference PV-hybrid and mini-grid*. Athens, Greece, May 2008.

Arranz-Piera, P., Velo, E., & Horta, F. (2011). Guidelines to introduce biomass systems in decentralised electrification programmes for mdg achievement in the sub-saharan african context. case studies of two reference countries: Ghana & mozambique. In *19th European Biomass Conference and Exhibition*. Berlin, Germany, June 2011.

Ayoub, N., Seki, H., & Naka, Y. (2009). Superstructure-based design and operation for biomass utilization networks. *Computers and Chemical Engineering*, *33*, 1770–1780.

Balaman, S. Y., & Selim, H. (2014). A fuzzy multiobjective linear programming model for design and management of anaerobic digestion based bioenergy supply chains. *Energy*, *74*, 928–940.

Basu, P., Butler, J., & Leon, M. A. (2011). Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. *Renewable Energy*, *36*, 282–288.

Bojarski, A. D., Laínez-Aguirre, J. M., Espuña, A., & Puigjaner, L. (2009). Incorporating environmental impacts and regulations in a holistic supply chains modeling: An lca approach. *Computers & Chemical Engineering*, *33*(10), 1747–1759.

Bowling, I. M., Ponce-Ortega, J. M., & El-Halwagi, M. (2011). Facility location and supply chain optimization for a biorefinery. *Industrial and Engineering Chemistry Research*, *50*, 6276–6286.

Cambero, Claudia, & Sowlati, Taraneh. (2014). Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives? a review of literature. *Renewable and Sustainable Energy Reviews*, *36*, 62–73.

Caputo, A. C., Palumbo, M., Pelagagge, P. M., & Scacchia, F. (2005). Economics of biomass energy utilization in combustion and gasification plants: Effects of logistics variables. *Biomass and Bioenergy*, *28*, 35–51.

Cherubini, F., & Stromman, A. H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, *102*, 437–451.

Club Español de la Energía; Instituto Español de la Energía (Spain). (2010). Retrieved December 2010, from http://www.enerclub.es/es/frontaction.do?action=viewcategory&categoryname=carbón&id=1086.

Comisión Nacional de Energía (Spain). (2010). Retrieved December 2011, from http://www.cne.es/cne/contenido.jsp?id_nodo=423&&&keyword=&auditoria=f.

Commission, European. (2015). *Towards an integrated strategic energy technology (set) plan: Accelerating the european energy system transformation*. Technical report, European Commission.

Damen, K., & Faaij, A. (2006). A greenhouse gas balance of two existing international biomass import chains. The case of residue co-firing in a pulverized coal-fired power plant in The Netherlands. *Mitigation and Adaptation Strategies for Global Change*, *11*, 1023–1050.

Ecoinvent-V1.3. (2006). *The ecoinvent database v1.3*. Technical report, Swiss Centre for Life Cycle Inventories.

Energy efficiency in industrial processes. (1988). Technical report, Report EUR 12046 EN, Commission of the European Communities.

Gebreslassie, Berhane H., Yao, Yuan, & You, Fengqi. (2012). Design under uncertainty of hydrocarbon biorefinery supply chains: Multiobjective stochastic programming models, decomposition algorithm, and a comparison between cvar and downside risk. *AIChE Journal*, *58*(7), 2155–2179.

General Secretariat of the Council. (2014). *Conclusions on 2030 climate and energy policy framework, brussels*. Technical report, European Commission.

Gómez, A., Zubizarreta, J., Rodrigues, M., Dopazo, C., & Fueyo, N. (2010a). An estimation of the energy potential of agro-industrial residues in Spain. *Resources, Conservation and Recycling*, *54*, 972–984.

Gómez, A., Rodrigues, M., Montañés, C., Dopazo, C., & Fueyo, N. (2010b). The potential for electricity generation from crop and forestry residues in Spain. *Biomass and Bioenergy*, *34*, 703–719.

Graves, S. C., & Tomlin, B. T. (2003). Process flexibility in supply chains. *Management Science*, *49*, 907–919.

Hamelinck, C. N., Suurs, R. A. A., & Faaij, A. P. C. (2003). International bioenergy transport costs and energy balance. Technical report, Universiteit Utrecht, Copernicus Institute, Science Technology Society, Utrecht, The Netherlands.

Hamelinck, C. N., & Faaij, A. P. C. (2002). Future propects for production of methanol and hydrogen from biomass. *Journal of Power Sources*, *111*, 1–22.

Humbert, S., Margni, M., Jolliet, O. (2005). *Impact 2002+: User guide draft for version 2.1*. Technical report, Industrial Ecology & Life Cycle Systems Group, GECOS, Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, October 2005.

Kondili, E., Pantelides, C. C., & Sargent, R. W. (1993). A general algorithm for short term scheduling of batch operations. *Computers & Chemical Engineering*, *17*, 211–227.

Laínez, J. M., & Puigjaner, L. (2012). Prospective and perspective review in integrated supply chain modelling for the chemical process industry. *Current Opinion in Chemical Engineering*, *1*(4), 430–445. Biotechnology and bioprocess engineering? Process systems engineering.

Laínez, J. M., Pérez-Fortes, M., Bojarski, A. D., & Puigjaner, L. (2011). *Syngas from waste: Emerging technologies, chapter raw materials supply* (pp. 23–54). London: Springer.

Laínez-Aguirre, J. M., Kopanos, G., Espuña, A., & Puigjaner, L. (2009). Flexible design-planning of supply chain networks. *AIChE Journal*, *55*, 1736–1753.

López-Vilariño, J. M., Fernández-Martínez, G., Turnes-Carou, I., Muniategui-Lorenzo, S., López-Mahía, P., & Prada-Rodríguez, D. (2003). Behavior of fluorine and chlorine in Spain coal fired power plants with pulverized coal boilers and fluidized bed boiler. *Environmental Technology*, *24*(6), 687–692.

Maciejewska, A., Veringa, H., Sanders, J., & Peteves, S. D. (2006). *Co-firing of biomass with coal: Constraints and role of biomass pre-treatment*. Technical report, Institute for Energy and the European Comission (EC).

Magalhaes, A. I. P., Petrovic, D., Rodriguez, A. L., Putra, Z. A., & Thielemans, G. (2009). Techno-economic assessment of biomass pre-conversion processes as a part of biomass-to-liquids line-up. *Biofuels, Bioproducts and Biorefining*, *3*, 584–600.

Mele, F. D., Kostin, A. M., Guillén-Gosálbez, G., & Jiménez, L. (2011). Multiobjective model for more sustainable fuel supply chains. A case study of sugar cane industry in Argentina. *Industrial and Engineering Chemistry Research*, *50*, 4939–4958.

Ministerio de Industria, Turismo y Comercio (Spain). (2010). Retrieved December 2011, from http://www.mityc.es/energia/petroleo/Precios/Informes/Informesmensuales/2010/diciembre2010.pdf.

Miret, C., Chazara, P., Montastruc, L., Domenech, S., & Negny, S. (2016). Design of bioethanol green supply chain?: Comparison between first and second generation biomass concerning economic, environmental and social criteria. *Computers & Chemical Engineering*, *85*, 16–35.

Operador del Mercado Eléctrico (OMEL) (Spain). (2011). Retrieved December 2010, from http://www.omel.es/inicio.

Osmani, Atif, & Zhang, Jun. (2014). Economic and environmental optimization of a large scale sustainable dual feedstock lignocellulosic-based bioethanol supply chain in a stochastic environment. *Applied Energy*, *114*, 572–587.

Pattiya, A. (2011). Thermochemical characterization of agricultural wastes from thai cassava plantations. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *33*, 691–701.

Pérez-Fortes, M. (2011). *Conceptual Design of Alternative Energy Systems from Biomass*. Ph.D. thesis, UPC, Barcelona, Spain.

Pérez-Fortes, M., Laínez-Aguirre, J. M., Arranz-Piera, P., Velo, E., & Puigjaner, L. (2012). Design of regional and sustainable bio-based networks for electricity generation using a multi-objective MILP approach. *Energy*, *44*, 79–95.

Pérez-Fortes, M., Laínez-Aguirre, A., Bojarski, J. M., & Puigjaner, L. (2014). Optimization of pre-treatment selection for the use of woody waste in co-combustion plants. *Chemical Engineering Research and Design*, *92*, 1539–1562.

Perry, M., & Rosillo-Calle, F. (2008). Recent trends and future opportunities in UK bioenergy: Maximizing biomass penetration in a centralised energy system. *Biomass and Bioenergy*, *32*, 688–701.

PRé Consultants, B.V. (2004). SimaPro 6 LCA software. http://www.pre.nl/simapro/default.htm.

Puigjaner, L., Pérez-Fortes, M. & M. Laínez-Aguirre, J. (2015) Coordinated bioenergy supply chain-a process systems approach. Talianisches Kulturinstitut Berlin, Ambasciata d'Italia—Energy Policy and Climate Changes- Präsentation des Sonderhefts der Zeitschrift? Energies? und Podiumsdiskussion mit Prof. L. Puigjaner.

Puigjaner, L., Pérez-Fortes, M., & Laínez-Aguirre, J. M. (2015). Towards a carbon-neutral energy sector: Opportunities and challenges of coordinated bio-energy supply chains - a pse approach. *Energies*, *8*(6), 5613–5660.

Red Eléctrica de España (Spain). (2010). El sistema eléctrico español (2010). Technical report, Red Eléctrica de España (Spain). http://www.ree.es/sistema_electrico/pdf/infosis/inf_sis_elec_ree_2010.pdf.

Rentizelas, A. A., Tatsiopoulos, I. P., & Tolis, A. (2009). An optimization model for multi-biomass tri-generation energy supply. *Biomass and Bioenergy*, *33*, 223–233.

Serpagli, A., Nagori, G. P., Amoriggi, G., & Calvosa, C. (2010). *The use of cassava wastes to produce energy: outcomes of a feasibility study implemented in ghana*. Technical report, International Fund for Agricultural Development (IFAD), Rome, Italy.

Shastri, Yogendra, Hansen, Alan, Rodríguez, L., & Ting., K. C. (2011). A novel decomposition and distributed computing approach for the solution of large scale optimization models. *Computers and Electronics in Agriculture*, *76*(1), 69–79.

Tchapda, A. H., Pisupati, & S. V. (2014). A review of thermal co-conversion of coal and biomass/waste. *Energies*, *7*(3), 1098.

TTA. Trama Tecnoambiental. (2008). *Estudio de base y definición de proyectos piloto para un programa nacional de electrificación rural en paraguay*. Technical report, Inter-American Development Bank, Washingtonn, USA—Asunción, Paraguay.

Uslu, A., Faaij, A. P. C., & Bergman, P. C. A. (2008). Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletization. *Energy*, *33*, 1206–1223.

Vallvé, X., González, S., & Arranz-Piera, P. (2007). *Solar-diesel hybrid options for the peruvian amazon—lessons learnt from padre cocha*. Technical report 111/07, Energy Sector Management Assistance Program (ESMAP).

You, F., Tao, L., Graziano, D. J., & Snyder, S. W. (2012). Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input-output analysis. *Aiche Journal*, *58*(4), 1157–1179.

Yue, D., You, F., & Snyder, S. W. (2014). Biomass-to-bioenergy and biofuel supply chain optimization?: Overview, key issues and challenges. *Computers & Chemical Engineering*. doi:10.1016/j.compchemeng.2013.11.016.