Design of regional and sustainable bio-based networks for electricity generation using a multi-objective MILP approach

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Abstract

Biomass energy systems can be employed to meet the requirements of distributed energy systems in rural and urban contexts, in electrification and microgeneration projects. This work describes a supply chain management (SCM) approach applied to bio-based supply chains that use locally available biomass at or near the point of use, or pre-treated biomass, that can come from an established market, to produce electricity or any other bioproduct. The subject is set out as a multi-objective mixed integer linear program (MO-MILP) taking into account three main criteria: economic, environmental and social. The model is applied to a specific region in Ghana to set out the most suitable biomass and electricity networks among the communities. The considered technology to transform the biomass is gasification combined with a gas engine. The model provides data about linkages between providers and consumers, biomass storage periods, matter transportation and biomass utilisation.

Keywords: Supply chain management, sustainability, biomass waste, rural areas development, MILP

1. Introduction

The development of a successful bioenergy sector in both developed or industrialised and developing countries will contribute to a long-term diversity, security and self-sufficiency of energy supply (Sims, 2004). Current challenges emerging in the worldwide energy sector can be summarised in three key topics: diminution of natural sources, climate change and technology development. It is in this context where bioenergy is seen as one of the most appreciated options to mitigate greenhouse gases (GHG) emissions by fossil fuels replacement and to be a sustainable source of energy in vehicles and in electric power generation, certainly by adequately exploiting the resources and the technology options (Faaij, 2006). Bioenergy, as an energy supply alternative, encompasses a broad range of sectors that can be categorised in two big blocks: energy-carrier generation and biomass as a source. Energy-carrier generation deals with the different biomass conversion routes to increase the efficiency of the already existing processes and to expand and research new mature commercial technologies. Biomass as energy source is coupled with two main sectors of the economy: agriculture and waste management. On the one hand, agriculture can be used to produce food, feed, fibre of fuel (the so-called "4F's") leading to a certain controversy and competitiveness for the land use, and therefore, for water use. Land as a resource deals with the pressure of population growth, life styles variations and climate change consequences (Otto, 2009). On the other hand, residues management is also interlinked with other markets. Waste can be used as raw material in certain processes, as feed or as fertiliser, or in other industries that treat them to be further used in other processes. These lead to a complex competitive trade, where obviously prices are fixed by the demand (Faaij, 2006). Is in this context where a supply chain (SC) approach is needed to adequately exploit biomass for energy purposes.

The bioenergy sector is nowadays accepted as having the potential to provide an important part of the projected renewable energy provisions of the future. Nevertheless, it has to overcome technological, economic and social barriers to obtain the needed political and social supports and to be attractive as an investment project (Bridgwater, 2003). Practitioners should dispose of tools to guide this energy sector transformation in industrialised and developing countries, thus, in different contexts. As a result, the efforts are concentrated on developing integrated frameworks to support the decision-making process. This work proposes a multi-objective mixed integer linear program (MO-MILP) for the bio-based supply chain (BSC) modelling, to support the decision-making task. The MILP approach captures the relevant fixed and variable operating costs for each facility and each major product (Graves and Tomlin, 2003).

Supply chain management (SCM) copes with the SC flows, that are materials, cash and information, in a coordinated way, along the different processes to deliver efficiently goods or services. Note that the different SC components can be geographically distributed. This is especially important for biomass to energy projects which are highly geographically dependent and whose profitability can be strongly influenced by the location of the different processes and biomass sources, being the logistic variables of special complexity to manage (Caputo et al., 2005). Commonly, biomass production and transportation account for a significant fraction of the whole bioenergy SC cost (Panichelli and Gnansounou, 2008). Therefore, a tool able to evaluate the possible trade-offs between different feedstock sources, each one with specific properties, i.e. moisture content, energy and bulk densities, and the location of processing and consumption sites, is a requisite to develop efficient bioenergy networks. This work tackles with the SCM problem that is, the strategic-tactical problem associated to the optimal design and operation of a BSC, with biomass as raw material, taking into account a variety of specific considerations.

The chosen objective functions should represent the decision-maker interests. The metrics considered in this work include economic, environmental and social points of view thus, a sustainable criteria. The economic criterion is the most common parameter considered for projects evaluation. The net present value (NPV) is considered here. Distributed energy systems should take into account social and ecological aspects, for resources management and population involvement. No pre-conceived management and rural electrification issues usually works as stipulated solutions for all the scenarios. One main characteristic of social factors is their principally qualitative rather than quantitative nature. Social issues such as population increase, urbanisation problems, changing gender roles or the varying knowledge, may be identified as priorities. Those issues cannot be tackled neglecting their dynamic nature, and without respectful appraisal for local knowledge and experience (Berkes and Folke, 2000). At the design-planning level, the implementation of social-environmental issues is a challenge of a multiple-objective optimisation problem, since qualitative and dynamic concerns are involved. Many design-planning rural projects, take into account the social factor in the light of generation of jobs exclusively; see for instance Ravindranath et al. (2004) or Silva and Nakata (2009). The work by Fleskens and de Graaff (2010) defines a social function based on employment and liveability, as maximum hired labour input that people can pay assuring a minimum level of life. Nidumolu et al. (2007) further include the land use in the analysis. Thus, their social objective seeks to maximise food production. This is an example of a surrogate criterion, where issues that cannot be quantified directly (in this case, m^2 to be used for energy purposes), are modelled through a related effect, i.e. the need of food. Note that social concerns in industrialised and developing countries can involve completely different desired consequences. As described in Bojarski (2010), social criteria concerning process design and operation in industrialised countries are security patterns and working conditions enhancements. In contrast, in developing countries, those social factors aim at reflecting parameters that promote economic development and satisfaction of basic needs.

A life cycle assessment (LCA) is performed in this paper for the environmental point of view. The LCA follows a systematic approach described in a series of ISO documents (ISO14040). It can include the entire life cycle of the process from raw material obtaining since final disposal (from cradle to grave). In an analogous way to the environmental LCA, the papers by Hunkeler (2006) and Dreyer et al. (2006) describe a methodology to determine the societal impact, aiming to define a comparable parameter between the different case studies. Further work is being developed in this field, to be implemented as a robust and standard tool. Human dignity and well-being are proposed as areas of protection. Job creation, local/national recruitment, genereation of employment and conditions of work are some of the issues to be evaluated in this societal LCA. This work considers the creation of jobs in the widest range of communities as a social parameter.

2. State of the art

Biomass as energy source, in comparison with fossil fuels, has a low calorific value as well as intrinsic characteristics that derive into technological limitations. That is the reason why 100% biomass to energy projects typically employs small scale conversion systems, and furthermore, they are placed close to the biomass generation source as well as close to the demand points, in order to avoid high logistic and network infrastructure constraints (Strachan and Dowlatabadi, 2002; Caputo et al., 2005; Gold and Seuring, 2011). Nevertheless, as Bouffard and Kirschen (2008) points out, the electricity generation sector of the future will have to combine the best attributes of both paradigms, the advantages of centralised and those of distributed energy systems. In this context, bioenergy should be equally present in big and small scale conversion systems, therefore co-using biomass with fossil fuels or using it alone, respectively.

The supply chain problem defined in this work includes a specific region, understood as a delimited are where resources and clients are embraced, being self-sufficient. For example, the papers by Cucek et al. (2010) and Lam et al. (2011) identify different regional supply chains according different principles. They use spatial planning and mathematical linear programming, to identify clusters and zones of competition and co-operation. The case study analised here comprises a group of communities that share a common characteristic, as will be explained in Section 7.

Biomass can be transformed into a gas, by means of digestion or gasification, into a liquid, through fast pyrolysis or directly combusted as a solid. In this paper, gasification is the chosen technological option to provide a combustible gas. According to Faaij (2006), large gasification systems are from 10 MW_{th}, and small gasification systems cover the range from less than 100 kW_{th} up to a few MW_{th}. In terms of electricity and in accordance with Siemons (2001), small scale gasification plants enclose plants with a power up to 200 kW_e. These ranges lead to significant value differences in terms of land use for the plant infrastructure, investment, operation and maintenance costs and plant dimensions. Centralised energy systems consist in large power plants that export electricity to the grid and transport the raw material or energy source to the plant; decentralised or distributed energy systems (DES) entail localised electricity generation near the demand points and near the biomass generation places, being appropriate one or other option depending on the conditions of the area. There exists no agreement in the literature about the definition of distributed generation; nevertheless it is usually perceived as small scale electricity generation (Mitra et al., 2008). The literature overviews from Bayod et al. (2005) and Mitra et al. (2008), point out that the term can be referred to (i) stand alone or autonomous applications, (ii) standby sources that supply power during grid outages, (iii) co-generation or waste heat recovery installations with power injection to the grid if the DES has a higher power production than the local demand, (iv) DES that support the grid by decreasing power losses and improving the system voltage profile and to (v) energy systems connected directly to the grid that sell the electricity produced. This work uses the term DES as stand alone applications. Centralised systems involve the use of transmission and distribution lines, while DES may use microgrids to connect a limited number of consumers.

The study by Silva and Nakata (2009) remarks that one of the main reasons why renewable energy technologies in modular, or small scale, configuration have not been highly extended in rural areas is the lack of an integrated approach in rural electrification planning. Integrated approaches should include economic, environmental and social criteria, according to each specific case study context. Silva and Nakata (2009) are focused on a specific case study situated in a remote area in Colombia. It evaluates two possible options for energy access: electrification by diesel or renewable sources. The paper uses goal programming to assess a qualitative response in terms of electricity generation cost ($/kWh), employment generation (jobs/kWh), avoided emissions ($kgCO_2$/kWh) and land use (m^2/kWh per year) in terms of interference with land use for agriculture or habitat conservation caused by the plant and place of storage extensions. In a previous work, Silva and Nakata (2008) use linear programming (LP) to deal with the energy planning model. The considered case study is the same rural region from Colombia. The authors demonstrate that such rural electrification projects can be financially sustainable, if taken into account the appropriate data concerning reliable geographical location of sources and clients, income levels and energy demand. The mathematical problem deals with an objective function based on the minimisation of subsidised costs. The mix of possible biomass processing technologies considers electricity generation by diesel engines, biomass boilers, gasification-gas engines and fast-pyrolysis matched with diesel engines. As a result, the technology that minimises costs is the combustion of biomass. The adequate performances of gasification and pyrolysis are penalised by their prices. It suggests that the proliferation of advanced techniques will be derived from environmental policies that should motivate their specific implementation by more environmentally restricted systems. Kanase-Patil et al. (2010) uses LP formulation to assure a reliable integrated renewable energy system, by evaluating the cost of the energy (COE), the costumer interruption costs, and the expected energy not supplied. The renewable mix of technologies takes into account biomass, solar, hydrological and wind resources. Then, four scenarios are considered to meet with the energy demand in domestic, agricultural, community and rural industry areas of an specific zone from India, based on combinations of the abovementioned sources. LINGO and HOMER softwares, which are specific tools for renewable energy mix determination, are used to verify the results of the developed model. The system that combines micro-hydrological power, biomass gasification, biogas production, wind and solar photovoltaic is the best one in terms of reliability and costs.

The work by Kanagawa and Nakata (2008) is also focused on India, and aims at finding quantitative relations between social and economic development by evaluating the literacy rate versus the electrification rate. The paper by Hiremath et al. (2009) takes into account a high number of state-of-the-art evaluating parameters used for decentralised energy planning. Goal programming is the chosen methodology to take advantage from its level of subjectivity. The selected objective functions are cost, system efficiency, petroleum products usage, locally available resources, employing generation, emissions (CO_2, NO_x and SO_x) and reliability on renewable energy systems, subjected to demand and supply constraints. The results show that, in the considered context, biomass-based systems have the potential to meet with rural needs, offering reliability, promoting local participation, local control and creation of skills. Cherni et al. (2007) and Brent and Kruger (2009) develop, describe and use a multi-criteria decision tool called SURE, that aims at choosing the appropriate energy mix of technologies to match with the energy demand of a rural area, reducing poverty at the same time. The tool combines quantitative and qualitative parameters, and allows for changes on the priorities according to the decision-maker criteria. The model analyses the strengths and weaknesses of a community according to five resources: physical, financial, natural, social and human. Then, it tries to find compromise solutions to supply the energy demand. Behind the software, a local survey has been drawn to state the baseline of a rural community in Colombia, to identify its energy needs and the growing tendency. In Brent and Kruger (2009), the Delphi research methodology is used with experienced individuals in the field of energy and poverty. SURE and the developed tool by the Intermediate Technology Development Group (ITDG) are integrated, and compared with the results from the experts panel. It is put into relevance that technology assessment methods should be further developed to formulate more appropriated implementation strategies. The paper by Ferrer-Martí et al. (2009) is an example of modular renewable energy source implementation, concretely wind, that uses MILP to assess the optimal location of wind generators and the appropriate micro-grid extension in a specific community from Perú, by minimising the initial investment.

Janssen et al. (2009) promotes the sustainable use of the African land to produce bioenergy, stating that the country has an important extension of marginal and degraded land that can be suitable for a socio-economic development based on biomass trade and use. The study assesses the suitable areas for bioenergy, excluding all regions used for food and with severe water, terrain or soil constraints. This land use needs from appropriated policies and development plans, dealing at the same time with rural development, sustainable production, community participation in the projects, modernisation of agricultural policies, creation of standards and fuel-food conflicts avoiding. Hamimu (2009) promotes biomass trade from biomass waste in Sub-Saharan countries. Biomass should be used not only for exportation, but also for own consumption, to assure independence from fossil fuels. This work reveals the land tenure issue in some countries from Africa, where they cannot be property of the farmers. Therefore, governments should avoid speculation with this matter and promote fair partnership between local farmers and foreign investors. Otto (2009) distinguishes between biofuels production for exportation and biofuels production for local use through advanced uses of biomass to promote the emergent business models in the sector, dealing with the connection among the two markets.

Summing up, LP and goal programming are well extended approaches for solutions selection in DES problems, but they do not take into account allocation. New trends such as biomass sharing between communities and bioenergy trade need from the allocation problem resolution. There is a lack of systematic energy models that promote biomass trade and use in developing or rural areas. Those new approaches should take into account a wide range of issues, i.e. economic, environmental and social.

3. Small scale gasification

Small scale gasification systems are employed to meet the specific requirements of DES using biomass available at or near the point of use, or pre-treated biomass, such as pellets, bought from an established market. Small scale gasification systems can be employed in rural or urban contexts in both, industrialised or developing areas. In the first context presented, the main system requirements are sustainability. In the second context, the main target is to save energy consumption from the grid and/or to be self-sufficient. This option belongs to residential building programs. Both options contribute to mitigate climate change by using clean and efficient systems.

The case study of this paper exemplifies a rural electrification problem. The chosen technology for micro-generation is gasification linked to an internal combustion engine (ICE) to supply a specific electricity demand. According to Kirkels and Verbong (2011), gasification application is still having problems regarding tar, operation, maintenance and economic feasibility. Research on coal and/or biomass gasification proliferated during oil crisis (world wars) and climate change regulations, mainly in Japan, China, USA and India. It is a recurrent technology that has not been definitely incorporated into the energy share of the different countries and is highly dependent on government regulation and assistance. Kirkels and Verbong (2011) conclude that small scale biomass gasification has been successful in a few niche markets, even if it is still in an early commercial step. The biomass gasification market is characterised by a lack of focus and proper impetus.

In the same line, the work by Verbong et al. (2010) points out a strategic niche management of biomass gasification, based on the Indian experience. The management of gasification projects should deal with the social network composition of actors, for instance private and/or public actors, consumers as clients or as active actors, and with the proper expression of expectations. Lessons learnt from real case studies reflect the need of improving the technology and enhancing economic efficiencies (need of subsidies, since positive cash flows are difficult to obtain), as well as the finding of appropriate application domains. There is a lack of well trained technicians in the field, as well as of monitoring and evaluation programs of biomass gasification small scale plants. In Mechanical wood products branch (1986) the most important concerns with a biomass gasifier include ashes, soot, slag and tarry condensates, safety rules, equipment failures caused by design mistakes, the choice of inadequate materials and incomplete instructions on O&M.

Current challenges on small scale gasification plants are raw material characterisation and homogenisation, better gasification operation results (concerning tars and producer gas composition), more efficient cleaning units and an overall optimal performance. A standard biomass gasifier combined with an ICE layout is used in this work to characterise the main parameters to be included in the MILP model.

The layout of the plant follows standard process description and the specific flowsheet of the pilot plant built at UPC, and financed by VALTEC08-2-0020 project. The main characteristic introduced in this new design is a dry method to clean the gas, avoiding water pollution by means of a venturi scrubber. This unit uses a reactor with CaO as catalyst, for tars and, to a low degree, for any sulphur removal. The outline of the plant is shown in Figure 1 by the considered blocks. The performance of the plant has been calculated with Aspen Plus©. The gasifier operates with 100% biomass. This is an Imbert downdraft gasifier working at atmospheric pressure. The moisture content (MC) is assumed here of 8.5%. The equivalence ratio (ER) is between 0.25 and 0.9 using the oxygen-based definition. The pilot plant at UPC is designed to work with 15 kg/h of wood pellets. Therefore, the amount of air ranges between 20.4 kg/h and 73.5 kg/h. The most important parameter in the biomass gasifier, which influences the producer gas composition, is the amount of inlet air (therefore, the ER). The second is the MC.

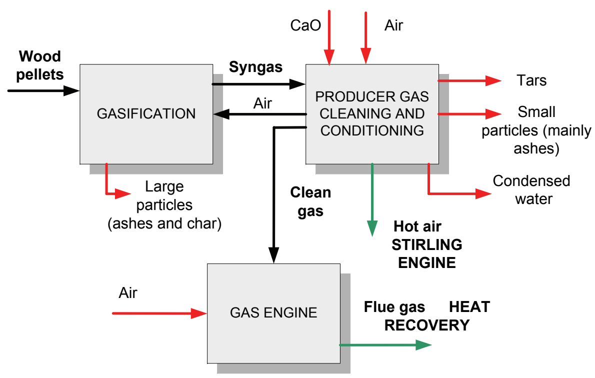

Figure 1: Gasification-ICE plant layout, with waste heat recovery options in bold and capital letters.

The most important results are summarised in Table 1: T_{gasif}, as the temperature of the producer gas at the gasifier outlet, producer gas composition and LHV, power and heat outputs, as well as partial (cold gas efficiency, CGE) and overall (η) efficiencies of the system.

4. Problem statement

The proposed sustainable SC design problem is focused on the specific needs of the target market. The identified drawbacks reveal the difficulty of scaling-up the biomass gasification technology for high dissemination: variations in the energy need among the different users groups, availability and

Table 1: Principal output values.

Parameter	Values
T_{gasif} (°C)	702
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
Power (kW_e)	15.80
η (%)	17

type of biomass, financial, human and institutional resources, economies of scale difficulty. Thereby, the approach is highly application-specific or tailor-made (Ghosh et al., 2006). The problem can be stated as follows.

Inputs:

1. Process data
    - A set of materials; raw matters, intermediates and final products.
    - A set of demands.
    - Efficiencies of the considered technological options in the SC.
    - A proposition of SC layout, mainly focused on biomass pre-treatments. Consequently, a set of biomass materials as raw, pre-processed and processed matter, characterised by their main properties. For further details see Section 5.
    - A set of providers, intermediates and consumers locations.
2. Economic data
    - A time horizon and a specific interest rate.
    - Investment, fixed and variable costs associated to all the technological options involved.
    - Products and consumables prices.
3. Environmental data
    - Raw material production environmental interventions.

- Each process environmental interventions.
- Transportation environmental interventions.

4. Social data
   - Number of communities and number of processes able to be installed into each community.

Outputs:

1. Selection of the most suitable pre-processing units, with their corresponding capacity.
2. Connections between providers, pre-processing sites and consumers.
3. Biomass storage periods.
4. Matter transportation flows.
5. Biomass utilisation.
6. The detail of the economic parameters and environmental impacts for all the SC echelons.

5. The bio-based supply chain

The bio-based supply chain (BSC) has special features that distinghish it from a conventional SC problem: the use of multiple biomass sources that can be from different locations, and the subsequent necessary pre-treatment to get it homogeneous in terms of mass and energy. These features imply the combination of different moisture contents (MC), dry matters (DM), lower heating values (LHV) and bulk densities (BD), that result on a "new" product, different from the original one(s). Biomass high MC, low BD, low LHV and fibrous nature, lead to a necessary biomass improvement in order to optimise its transport, handling and processing. These are the main reasons why a BSC should deal with changes on raw material properties. It should be noted that the biomass market is still an emergent market. Depending on the scale of the BSC, transportation is in more or less degree the bottleneck.

The outline of a BSC to produce electricity is depicted in Figure 2. The sequence of pre-treatment, storage and transportation may change depending on the biomass type, the specific case study conditions and the chosen supply strategy. Nevertheless, it is convenient to store and transport biomass in an upgraded state to avoir costs and non-desired effects, such as MC gaining.

The major steps in the BSC are:

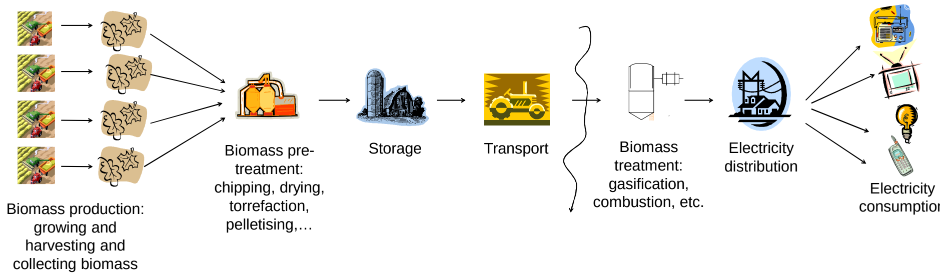

Figure 2: A BSC to produce and distribute electricity. Based on Gold and Seuring (2011).

- *Biomass growing, harvesting and collecting* are involved in a biomass production category. This step aims at recovering biomass waste or at using energy crops. Usual processes at this stage are drying, i.e. natural drying in the land field, and baling or chipping, to diminish the volume and reduce the risk of deterioration (Van Belle et al., 2003). The harvesting or collection period depends on the seasonality of the resource, thus the amount of fuel can be discontinuous during the year. Moreover, different biomass sources can be mixed in a central gathering point, allowing for seasonality impact mitigation.

- *Biomass pre-treatment* includes all the necessary steps to produce an upgraded fuel. The main objective is the reduction of costs for treatment, storage, transportation and handling activities, through an homogeneous fuel without impurities and denser in terms of matter and energy. Pre-treatment techniques can be briquetting, pelletisation, torrefaction and pyrolysis, being the last two still under development. The work by Uslu et al. (2008) states that only upgraded biomass can be used for international trade. Torrefaction, pelletisation, torrefaction combined with pelletisation process and pyrolysis are evaluated in terms of mass yield, energy yield and process efficiency. Economies of scale are also analysed. In the line of biomass pre-treatments, Panichelli and Gnansounou (2008) contemplate forest wood residues from final cuttings to produce torrified wood that supplies a gasification unit to provide electricity. Magalhaes et al. (2009) are focused on biomass pre-treatment options, i.e. torrefaction and fast pyrolysis, evaluating prices, forest yield, transportation distances, investment and operating costs. The analysed case study is situated in The Netherlands, with importation of biomass. The paper by Wu et al. (2010) evaluates the SC of bioslurry, which is a mixture formed by bio-oil and biochar, taking into account the trade-off between the chain cost increment due to the distributed pyrolysis units investment, and the chain cost reduction due to the diminution on transportation costs.

- *Storage* can be considered throughout the BSC. This is crucial when there is a time gap between production and consumption, thus when there exists a biomass seasonality. This stage is often used taking advantage of the drying phenomenon that takes place here, even if some dry matter loss occurs (Rentizelas et al., 2009). *Handling systems* are needed to transport the biomass from the point of delivery or storage to the next step. These techniques are for instance wheel loaders, cranes, belt conveyors, chain conveyors, screw conveyors, hydraulic piston feeders and bucket elevators (van Loo and Koppejan, 2008). Storage costs depend on its location and the type of storage, i.e. open air, roof covered, air fan, indoor storage; that in turn depends on the climate, shape and volume of biomass and time of storage (Gold and Seuring, 2011). The work by Rentizelas et al. (2009) emphasizes the multi-biomass seasonal availability combined with the biomass storage problem, being the most exhaustive contribution on storage effects among the literature consulted. The stages considered before the conversion plant include harvesting and collection, handling in field and transportation, storage, loading and unloading, transport, and biomass pre-treatment. This last stage can be included in any of the abovementioned stages, and it can optimally precede the transportation stage. Storage can be equally located at biomass origin, in an intermediate step or at the power station site.

- *Transportation* of biomass represents a relevant cost issue due to the low energy density of the energy carrier. Costs depend on travel-time, which is a function of distance, speed, tortuosity, hauliers capacity and amount to be transported. Moreover, operating costs such as driver remuneration or fuel costs, as well as social and environmental impacts should be evaluated (Gold and Seuring, 2011). The work by Forsberg (2000) sets out the transportation problem in terms of environmental viability and ecological sustainability, by trailer, truck, train, ship or pipeline, depending on the distance and the state of the feedstock. In the transportation echelon, optimisation passes through an appropriate match between the amount of disposable biomass near the plant and the plant size. The paper by Yu et al. (2009) evaluates a mallee residues SC focused on the transportation costs. It uses a discrete mathematical model for mallee production, harvest, on-farm transportation and road haulage modelling. Their case study reveals that on farm transportation for central biomass gathering during the first stage of the BSC, can be more expensive than biomass road transportation. The reason is the strong influence of feedstock collection area in costs. In turn, the studies by Pootakham and Kumar (2010a) and Pootakham and Kumar (2010b) compare transportation of bio-oil by pipeline and by truck through a LCA. The two works provide with specific energy consumptions, emissions and costs of each one of the alternatives. It is seen that the transportation media election depends on the distance to be displaced and the source of energy that is used to pump the bio-oil or to run the trucks.

- *Biomass treatment* in the processing plant to produce electricity, in this case gasification combined with a gas engine.

6. Mathematical model

A general outline of the modelled BSC is shown in Figure 3. It comprises four main blocks: sourcing, pre-treatment, product generation and product distribution.

The BSC is defined as a number of potential locations where processing sites or distribution centers, or both of them can be installed. Suppliers are at fixed locations, where biomass is available. The final product can be produced at several plant sites. The characteristics of the raw biomass are enhanced by means of the pre-treatment units, so as to allow treated biomass to meet the characteristics required to be used in subsequent steps in the SC, and diminishing transportation costs. The production capacity of each processing site is modelled by relating the nominal production rate per activity to the availability of the equipment per year, i.e. the number of working hours per year and equipment. Distribution centres and the distribution or transportation activity are modelled by considering upper and lower bounds

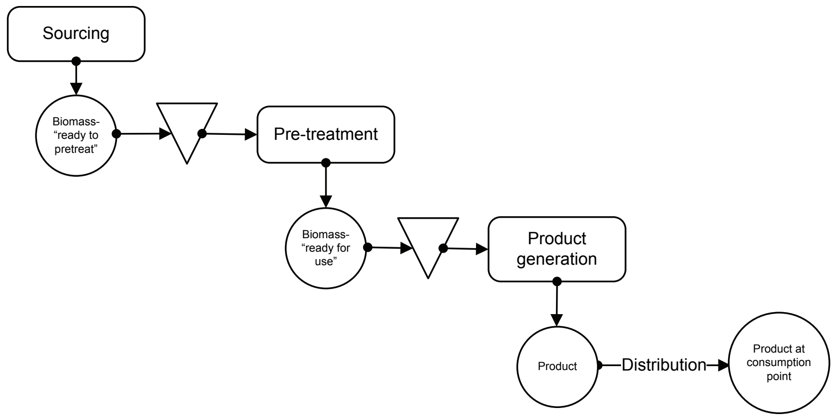

Figure 3: General scheme considered here for a BSC.

based on their biomass handling capacity. Distribution centres can be supplied from more than one pre-treatment plant. Given the way the problem is modelled, materials flow between facilities may appear if selecting such flow improves the performance of the SC. The market demand of electricity, can be satisfied by more than one site.

All the abovementioned decisions will be taken by considering the optimisation of an economic (NPV), an environmental impact (Impact 2002+) and a social metric along a pre-defined planning horizon.

Next, the mathematical formulation is described. The resulting model is solved by using a MO-MILP algorithm, which allows assessing the trade-off among the environmental impact, the economic and the social indicator. The model variables and constraints can be categorised into four groups: (i) process operations constraints given by the design-planning sub-model, (ii) the economic metric formulation ,(iii) the environmental sub-model and (iv) the surrogate social metric.

6.1. Design-planning model

The design-planning model selected to deal with the Biomass based SC network is adapted from the work of Laínez-Aguirre et al. (2009). This model translates the state task network (STN) formulation (Kondili et al., 1993), which is a widely known approach for scheduling, to the SC context. One of the most relevant features of such a formulation is that it can collect all the

SC nodes activities information through a single variable. On the one hand, this eases the economic and environmental metrics formulation. On the other hand, it facilitates the consideration of pretreatment activities and their outputs. The SC material balances are modelled by means of a single equation set, since manufacturing nodes, distribution centres, production and distribution activities as well as final products, raw material and intermediates are treated indistinctively . Therefore, the most relevant variable of the model is $P_{ijff't}$, which represents the particular activity of 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 site (P_{ijfft}). In contrast, in a distribution activity, facilities f and f' must be different. This mathematical formulation assumes that an activity consumes and produces certain materials with determined properties and can be performed in different equipments. Using the activities as the core of the formulation rather than using products-materials renders a flexible formulation which can be easily extended to deal with different case studies. The equations are described in the following paragraphs.

Mass balance must be satisfied at each node of the network. The expression for the mass balance for each type of material s (that can be raw material, pre-processed biomass), processed at each potential site f in every time period t is presented in Eq. (1). Parameter α_{sij} is defined as the mass fraction of material s that is produced by task i using technology j. T_s set refers to tasks that produce s, while $\bar{\alpha}_{sij}$ and $\bar{T}_s$ set, are associated with tasks which consume s.

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

The model assumes that process parameters such as conversions, separation factors or temperatures, are fixed for each activity to enforce the linearity of the problem. In this sense, the parameters α_{sij} and $\bar{\alpha}_{sij}$ give the "recipe" for a specific activity. Nevertheless, there are activities for which it is desirable to let the model specify the mixture of inputs ($\bar{I}$) in order to achieve a given value of a specific biomass property, for instance, a specific MC. For such activities, the combination of feedstocks and, therefore, the proportion of each feedstock is variable. In order to take into account such activities, the mass balance is modified as shown in Eq. (2). Note that Eq. (1) is a particular case of Eq. (2)

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

For the activities that work with fixed biomass properties, the energy balance is satisfied directly during the definition of the streams. However, it is necessary to verify that the *energy balance* is satisfied for the flexible activities. The energy balance is represented by Eq.(3). Here, HV_s is the heating value of material s. Notice that each different 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 receiving a mixture of biomasses as input.

$$\sum_{s \in T_s} HV_s Pv_{sijft} = \sum_{s \in \bar{T}_s} HV_s Pv_{sijft} \quad \forall i \in \bar{I}, j, f, t \tag{3}$$

In case the flexible activities must accomplish a MC for the input stream, constraint (4) must be satisfied. 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.

$$\sum_{s \in S_i} Water_s Pv_{sijft} \leq Water_{ij}^{max} \sum_{s \in \bar{S}_i} Pv_{sijf't} \quad \forall i \in \bar{I}, j, f, t \tag{4}$$

Another important extension of this model is the consideration that storage is capable of changing biomass properties (e.g., moisture content, dry matter, heating value). In order to do so, storage should be considered as an actual activity. Let us define the subsets J_{stor} and S_{stor} which will represent the storage "equipment" and those materials that when kept in storage change their properties, respectively. Notice that the mass balance has been decomposed in this case so as to deal with the one period delay necessary for the properties change to occur. As expressed by Eqs. (5) and (6), a storage activity places inventory in the actual period t and takes inventory from the previous period $t-1$.

$$S_{sft} = \sum_{f'} \sum_{i \in T_s} \sum_{j \in (J_i \cap \tilde{J}_{f'} \cap J_{stor})} \alpha_{sij} P_{ijf'ft} \ \forall s \in S_{stor}, f, t \tag{5}$$

$$S_{sft-1} = \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in (J_i \cap \tilde{J}_f \cap J_{stor})} \bar{\alpha}_{sij} P_{ijff't} \ \forall s \in S_{stor}, f, t \tag{6}$$

Eqs. (7) and (8) represent the temporal change in the equipment technology installed in the potential facility locations. We will considered economies of scale by using a piecewise linear approximation in K different intervals and a so-called SOS2 variable type (ξ_{jfk}). Such variables are positive and at most two consecutive variables are non-zero. FE_{jfk}^{limit} is the limit of capacity for interval k. V_{jft} is a binary variable indicating whether or not capacity of technology j is expanded at site f in period t. This formulation will be recalled in the economic metric section for computing the investments associated with capacity expansions. Eq. (9) is used for total capacity F_{jft} bookkeeping taking into account the capacity augment during the planning period t (FE_{jft}) for equipment technology j in facility f. This equation considers the case of the initial design of a SC ($FE_{jf0} = 0$) as well as a SC retrofit scenario ($FE_{jf0} \neq 0$).

$$\sum_k \xi_{jfkt} FE_{jfk}^{limit} = FE_{jft} \qquad \forall f, j \in \tilde{J}_f, t \tag{7}$$

$$\sum_k \xi_{jfkt} = V_{jft} \qquad \forall f, j \in \tilde{J}_f, t \tag{8}$$

$$F_{jft} = F_{jft-1} + FE_{jft} \qquad \forall f, j \in \tilde{J}_f, t \tag{9}$$

Eq. (10) is used to ensure a utilisation greater than or equal to a minimum value established by the decision maker and that the utilized capacity is lower than or equal to the available one. Parameter β_{jf} defines a minimum utilisation of technology j in site f as a proportion of the total available capacity. Parameter $\theta_{ijff'}$ represents the resource utilisation factor. This is the capacity utilisation rate, in terms of capacity units (e.g., machine-hours), of technology j by task i whose origin is location f and destination location f'.

$$\beta_{jf} F_{jft-1} \leq \sum_{f'} \sum_{i \in I_j} \theta_{ijff'} P_{ijff't} \leq F_{jft-1} \qquad \forall f, j \in \tilde{J}_f, t \tag{10}$$

The capacity is expressed as equipment j available time during one planning period, then $\theta_{ijff'}$ represents the time required to perform task i in equipment j per unit of produced material. Thus, once operation times are determined, this parameter can be readily approximated.

Eq. (11) guarantees that the amount of raw biomass s purchased from site f at each time period t is lower than an upper bound given by physical availability A_{sft} (e.g., seasonality, crop/plantation yield in a specific region).

$$\sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in J_i} P_{ijff't} \leq A_{sft} \qquad \forall s \in RM, f \in Sup, t \tag{11}$$

Eq. (12) establishes that flows of energy exist only if locations f' and f are interconnected. $Z_{f'f}$ is a binary variable which takes a value equal to one if f' and f are interconnected, 0 otherwise, while M represent a big positive number. By Eq. (13) sales of final product $s \in FP$ carried out from facility location f' to market $f \in M$ are estimated. Eq.(14) is used to express that the demand can be partially satisfied, due to biomass production or supplier capacity limitations: the sales of product s carried out in market f during the time period t should be less than or equal to the demand.

$$P_{ijf'ft} \leq M Z_{f'f} \qquad \forall s \in FP, i \in (T_s \cap Tr), f \in Mkt, t \tag{12}$$

$$Sales_{sf'ft} = \sum_{i \in (T_s \cap Tr)} \sum_{j \in (J_i \cap \hat{J}_f)} P_{ijf'ft} \qquad \forall s \in FP, f \in Mkt, f' \notin Mkt, t \tag{13}$$

$$\sum_{f' \notin M} Sales_{sf'ft} \leq Dem_{sft} \qquad \forall s \in FP, f \in Mkt, t \tag{14}$$

Here, it is important to emphasize two aspects. One is that for this sort of networks the final product is the energy delivered to the different regions (MkT). Thus, for those tasks that carry out the energy generation their corresponding parameter α_{sij} is determined as a function of the heating value of the input materials and the efficiency of the equipment. Finally, the energy consumed by the equipment along the SC should be discounted from the energy available to satisfy the demand once the network reaches "steady state".

6.2. Economic model

The expressions required to compute the operating revenue, the operation costs, the total capital investment, and NPV are next described.

The *operating revenue* is expressed in Eq. (15) as the product sales during period t.

$$ESales_t = \sum_{s \in FP} \sum_{f \in Mkt} \sum_{f' \notin (Mkt \cup Sup)} Sales_{sf'ft} Price_{sft} \qquad \forall t \qquad (15)$$

The *operating costs* include fixed and variable costs: Eq.(16) describes the total fixed costs of operating the SC network. $FCFJ_{jft}$ is the fixed unitary capacity cost of using technology j at site f.

$$FCost_t = \sum_{f \notin (Mkt \cup Sup)} \sum_{j \in \tilde{J}_f} FCFJ_{jft} F_{jft} \qquad \forall t \qquad (16)$$

In turn, as variable costs, the cost of purchases from supplier e, includes raw material procurement, transport and production resources, as shown in Eq. (17). The purchases of raw materials ($Purch_{et}^{rm}$) made to supplier e are evaluated in Eq. (18). We will assume a different supplier for each component of the variable costs. This assumption can be easily relaxed to account for the specifics of the problem being dealt with. The variable χ_{est} represents the cost associated to raw material s purchased to supplier e. Transportation and production variable costs are determined by Eqs. (19) and (20), respectively. $\rho_{eff't}^{tr}$ denotes the e provider unitary transportation cost associated to material distribution from location f to location f' during period t. τ_{ijfet}^{ut1} represents the unitary production cost associated to perform task i using technology j, whereas τ_{sfet}^{ut2} represents the unitary inventory costs of material s storage at site f. The parameter τ_{ijfet}^{ut1} entails similar assumptions to the ones considered with regard to α_{sij} and $\bar{\alpha}_{sij}$, namely, the amount of utilities and labour required by an activity are proportional to the amount of material processed.

$$EPurch_{et} = Purch_{et}^{rm} + Purch_{et}^{tr} + Purch_{et}^{prod} \qquad \forall e, t \tag{17}$$

$$Purch_{et}^{rm} = \sum_{s \in RM} \sum_{f \in F_e} \sum_{i \in \bar{T}_s} \sum_{j \in J_i} P_{ijfft} \chi_{est} \qquad \forall e \in E_{rm}, t \tag{18}$$

$$Purch_{et}^{tr} = \sum_{i \in Tr} \sum_{j \in J_i \cap \bar{J}_e} \sum_{f} \sum_{f'} P_{ijff't} \rho_{eff't}^{tr} \qquad \forall e \in \bar{E}_{tr}, t \tag{19}$$

$$Purch_{et}^{prod} = \sum_{f} \sum_{i \notin Tr} \sum_{j \in (J_i \cap \hat{J}_f)} P_{ijfft} \tau_{ijfet}^{ut1} + \sum_{s} \sum_{f \notin (Sup \cup Mkt)} S_{sft} \tau_{sfet}^{ut2} \qquad \forall e \in \tilde{E}_{prod}, t \tag{20}$$

The *total capital investment* on fixed assets is calculated by means of Eqs. (21) and (22). These equations include the investment made to expand the technology's capacity j in facility site f in period t. The investment required to connect two different locations f and f' by using a medium voltage network is just accounted in the first planning period. Recall that economies of scale for technologies capacity is considered using a piecewise linear approximation in K intervals. Here, $Price_{jfk}^{limit}$ is the investment for a capacity expansion equal to the limit of interval k (FE_{jfk}^{limit}).

$$FAsset_t = \sum_{f} \sum_{j} \sum_{k} Price_{jfk}^{limit} \xi_{jfkt} + \sum_{f} \sum_{f'} Invest^{MV} distance_{ff'} Z_{ff'} \qquad \forall t = 0 \tag{21}$$

$$FAsset_t = \sum_{f} \sum_{j} \sum_{k} Price_{jfk}^{limit} \xi_{jfkt} \qquad \forall t > 0 \tag{22}$$

Finally, Eq. (23) calculates the profit in period t, as operating revenues minus fixed and variable operating costs. The NPV is calculated as in Eq. (24).

$$Profit_t = ESales_t - (FCost_t + \sum_e EPurch_{et}) \qquad \forall\ t \qquad (23)$$

$$NPV = \sum_t \left(\frac{Profit_t - FAsset_t}{(1+i_r)^t} \right) \qquad (24)$$

6.3. Environmental model

The application of the life cycle assessment (LCA) methodology to the SC model requires four steps: goal definition and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and results interpretation. Environmental interventions are translated into metrics related to environmental impact as end-points or mid-points metrics by the usage of characterisation factors. Eq. (25) calculates IC_{aft} which represents the mid-point environmental impact a associated to 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'.

$$IC_{aft} = \sum_{j \in \tilde{J}_f} \sum_{i \in I_j} \sum_{f'} \psi_{ijff'a} P_{ijff't} \qquad \forall\ a, f, t \qquad (25)$$

Analogously to α_{sij} and $\bar{\alpha}_{sij}$, the value of $\psi_{ijff'a}$ is fixed and constant, since all environmental impacts are considered linearly proportional to the activity performed in the node (variable P_{ijfft}) (Heijungs and Suh, 2002). Environmental impacts associated to transportation, has as a common functional unit (FU), the amount of kg of transported material over a given distance (kg·km). Consequently, the value of the mid-point environmental impact $\psi_{ijff'a}$ associated to transport, is calculated as in Eq. (26), where $\psi^T_{ijff'a}$ represents the a characterisation factor of the environmental category impact for the transportation of a mass unit of material over a unit of length. Note that the impact is assigned to the origin node. The environmental impacts associated to production (Eq. 25) or transportation (Eq. 26), can be performed by setting the indices summation over the corresponding tasks ($i \in Tr$ or $i \in NTr$). A tortuosity factor may be employed to correct the estimated distance between nodes.

$$\psi_{ijff'a} = \psi^T_{ija} distance_{ff'} Tortuosity \qquad \forall\ i \in Tr, j \in J_i, a, f, f' \qquad (26)$$

Eq. (27) introduces $DamC_{gft}$, which is a weighted sum of all mid-point environmental interventions. They are combined using g end-point damage factors ζ_{ag}, normalised with $NormF_g$ factors. Moreover, Eq. (28) calculates g normalised end-point damage along the SC ($DamC_g^{SC}$).

$$DamC_{gft} = \sum_{a \in A_g} NormF_g \zeta_{ag} IC_{aft} \qquad \forall\ g, f, t \tag{27}$$

$$DamC_g^{SC} = \sum_f \sum_t DamC_{gft} \qquad \forall\ g \tag{28}$$

Eqs. (29) and (30) sum the end-point environmental damages for each site f and for the whole SC, respectively.

$$Impact_f^{2002} = \sum_g \sum_t DamC_{gft} \qquad \forall\ f \tag{29}$$

$$Impact_{overall}^{2002} = \sum_f \sum_g \sum_t DamC_{gft} \tag{30}$$

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

6.4. Social model

The proposed approach consists in a criterion that counts 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 sites. Therefore, the social criterion SoC should be maximised (see Eq.31). This criterion assigns a value of 1 to each unit installed per site f. V is the binary variable that characterises the number of units installed per site. This is not applied for storage.

$$SoC = \sum_j \sum_f \sum_t V_{jft} \qquad \forall\ j, f, t \tag{31}$$

SoC can be used as objective function along with the NPV and $Impact_{overall}^{2002}$ in the MO-MILP formulation. An ϵ-constraint approach will be used to tackle the MO-MILP.

The overall optimisation problem can be posed mathematically as follows:

$$\underset{\mathscr{X},\mathscr{Y}}{\text{Min}}\{-NPV, Impact^{2002}_{overall}, -SoC\}$$
$$\text{subject to}$$
$$\text{Eqs. (1)-(31);}$$
$$\mathscr{X} \in \{0,1\}; \mathscr{Y} \in \mathbb{R}^+$$

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

6.5. Biomass representation

The main limitation of biomass modelling in a MILP model, is that the different combinations of biomass coming from different periods, different pre-treatment or treatment units, should be defined and characterised a priori. It means that the biomass MC, BD, DM and LHV should be calculated and introduced in the model as biomass states or materials. This leads to a problem delimitation.

6.6. Multiobjective strategy

The approach followed to solve the problem, has three main steps: finding of extreme points, intermediate points calculation and Pareto front (PF) generation. The multiple-criteria decision making process aim at finding the most suitable solution to the decision-maker point of view. Decision problems usually present multiple and conflicting criteria to evaluate alternatives. It is then necessary to make compromises or trade-offs regarding the results of the different possible choices. The solution is given by a ranking of alternatives from the best to the worst one, or by an alternative selection. This last selection can be referred as the best, preferred or satisfying solution: the chosen alternative meets or surpasses the decision-maker criteria. But, if the criteria of the decision-maker is not specific or concise, i.e. no prioritisation of the objective functions, instead of giving one specific solution, a set of feasible solutions may be possible, the so-called PF. A Pareto optimal solution is also called a non-dominated solution or efficient solution, and this is an alternative that is not dominated by any other feasible solution. Therefore, for a Pareto solution, an increase or improvement in the value of a criterion implies at least one decrease or decline in the value of any other decisive factor (Turban et al., 2005). In this work, it is assumed that the decision-maker priorities are not known, therefore, the analysis is focused on a general perspective based on the characteristics of the PF and the most important features of the scenarios that optimise each one of the selected objective functions.

- Extreme points are represented by the three set of values (NPV, Impact 2002+ and *Soc*) that optimise each objective individually, i.e. that maximise NPV, minimise Impact 2002+ and maximise *SoC*. Those points are used to set the range of *SoC*. As more than two objectives are considered, the representation of iso-lines is contemplated to graphically perform the three objectives in two dimensions. The *SoC* is selected due to its discrete nature. Once the *SoC* range is established, for each *SoC* value, NPV is maximised and Impact 2002+ is minimised.

- Each social iso-line counts with two extremes, corresponding to the two optimal values coming from economic and environmental criteria optimisations. The PF points should be determined; the Pareto solutions are found through the ϵ-constraint method, which involves solving a set of cases of single objective optimisation, in this case, of NPV maximisation, while the remaining objective, Impact 2002+, is set as a constraint, with lower and upper limits determined by the two extreme points. In this specific case study, 10 points between upper and lower limits, are determined. Each solution found gives information about the network.

- The PF is determined by filtering the points found in the previous step; the dominated solutions are disregarded. Finally, the PF for each *SoC* level is drawn. The decision-maker selection will be a point of the PF.

The mathematical model was been written in GAMS and solved with MILP model solver CPLEX 11.0 processor, on a PC Intel(R) Core(TM) i7-2620M CPU of 2.70GHz, and 4.00Gb of RAM. The optimisation model contains 27122 equations and 819330 continuous and discrete variables. The CPU time spent to find a single Pareto solution ranges between 33 and 30858s.

7. Case study: a bio-based supply chain located in Ghana using gasification

For this case study resolution, the generic BSC considered in the mathematical formulation and depicted in Figure 2, has been adapted as in Figure 4. Two blocks can be distinguished in the layout depicted in Figure 4, i.e. the biomass block and the energy block. The BSC comprises sourcing, pre-treatment, product generation and product distribution. The biomass attributes modelled and characterised along the SC are MC, DM, BD and LHV. Modifications represent characteristics of the scale of the problem:

- Taking advantage of the local biomass wastes needs short or negligible distances between clients and sites where raw material is generated. A regional BSC is performed, using biomass waste.

- Because of the rural configuration, no long distances should be overcome; chipping and drying are the pre-treatment units considered. Biomass waste is pre-processed before gasification to obtain the adequate shape, LHV and MC. The homogeneisation of biomass shape is important to reduce volume for transportation and a required characteristic for the raw material entering the gasification plant. Storage serves as a biomass reservoir, matching productions from several sites, or when the storage is needed as a buffer for the periods when biomass waste is not produced. Fast pyrolysis, torrefaction and pelletisation are disregarded since the small biomass quantities required for rural electricity demand satisfaction does not allow to take profit from economies of scale. Moreover, those are too complicated technologies for rural areas in developing countries.

- Biomass gasification combined with ICE is the transformation technology used here. It is introduced in the model by means of its efficiency to produce electricity.

- It is assumed that no grid exists. Thus, the customers can be interconnected to a low voltage (LV) or medium voltage (MV) microgrid. The LV distribution line has as objective the intra-community distribution and the MV line, of 36 kV, connects different communities. The investment needed for its construction is contemplated.

- Each community represent one consumer. The estimation of the electricity demand for each consummer takes into account the needs of the community population.

This design of a BSC contemplates a specific rural area of a developing country, Ghana (Africa). Nine communities in Atebubu-Amantin or Atebubu district, in Brong Ahafo Region (see Figure 5) are of concern. The

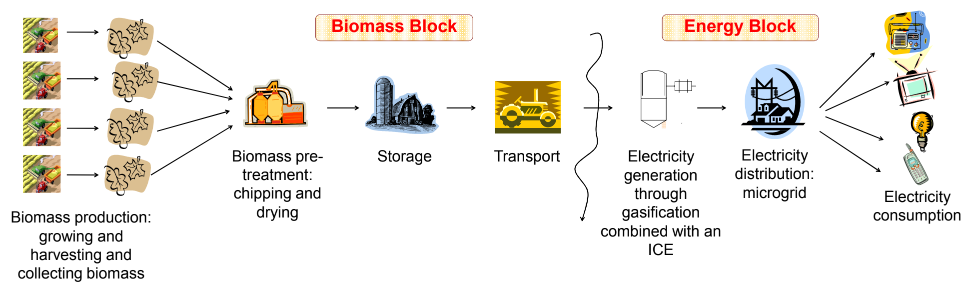

Figure 4: BSC echelons considered for the case study located in Ghana, for rural electrification.

communities, from the highest to the lowest populated are Kumfia, Fakwasi, Abamba, Old Kronkompe, Boniafo, Bompa, Trohye, Seneso and Nwunwom. The biomass considered as raw material is cassava waste. Cassava is a tropical crop highly extended in the country, used to provide food. The most important economic activity in the area is agriculture, producing mainly cassava, yam and maize. Dressmaking, groundnut harvesting and traditional production of charcoal from dried trees are also found in the district. Farmers seldom own the lands. They usually pay a rent. Charcoal, dresses and food can be sold in the same district, in Kumasi and/or in Accra, which are the two biggest cities of the country. The cassava crop is commercialised to produce principally fufu or gari, both of them for food purposes. Women are usually in charge of trading activities, playing therefore a key role in the development of the zone.

The objective is to supply the electricity demand of the selected communities that currently share a common characteristic: all are equipped with a multi-functional platform (MFP) that supplies the electricity needs, mainly for cell phone's battery charge, water refrigeration, lighting, radio, TV, computer and machines for maize and cassava processing. Data for the BSC characterisation is provided by Dr. Ahmad Addo, from the Energy Center, in Kwame NKrumah University of Science and Technology (KNUST), in Ghana, and Mr. Ishmael Edjekumhene and Mr. Clement Nartey from the NGO Kumasi Institute of Technology, Energy and Environment (KITE) (Ghana). The MFP's matter in Atebubu district has been executed in collaboration with KITE, and the local NGO called Women and Children Support

Organisation (WACSO). The contact person here is Mr. Jacob Salifu. Prices for transportation and utilities valorisation, as well as specific information about the cassava crop, have been obtained during an on-field travel. The boundaries considered are from cradle-to-gate. The currency is $\$_{2010}$. The applied currency conversion is 1 Ghana cedi = US$0.65946[1].

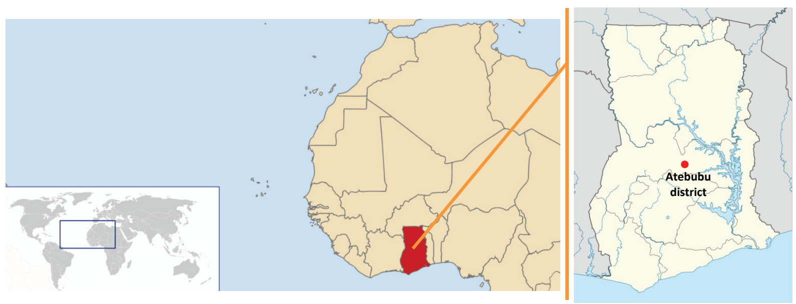

Figure 5: Location of Atebubu district.

Figure 6 represents the 9 communities according to their relative population. The biggest community is Kumfia with 2834 people, and the smallest one is Nwunwom with 122 people.

7.1. Raw material

One of the premises of this work is to use biomass waste as raw material, that does not imply a matter competition for other purposes. According to Encinar et al. (2008), most of the biomass residues can represent an environmental problem when stored or land filled without control; the cause is the anaerobic fermentation that takes place, and its subsequent formation of methane.

Cassava is also called manioc, manihoc, yuca, mandioca, aipin, catelinha, macaxeira and tapioca (Pattiya, 2010). This is a basic food source in tropical countries. According to Serpagli et al. (2010), this is important for food security and for poverty alleviation in rural areas. It has a future strategic dimension, to feed the growing population. Five markets are identified for cassava: traditional food market, feed market, food-grade food market, starch and derivatives market and ethanol market.

[1] www.oanda.com

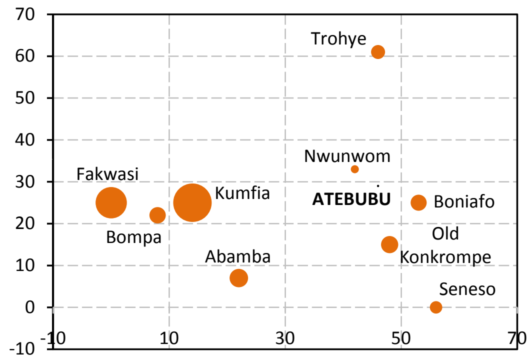

Figure 6: Location map of the 9 modelled communities from Atebubu district, represented according to their relative size (estimated population for year 2010). Axes in km. Data provided by KITE.

The cassava waste is pilled in the farms and used for fertilisation or to feed pigs or poultry. Leaves from cassava crops are used for food (soups). The stalk is used to replant the crop. The underground cassava plant can be divided into rhizome and root. In turn, the root has three main components: the pulp, starch and peels. Starch is used as food. The most extended uses for cassava residues is ethanol production (pulp) and biogas and activated carbon production (peels) (Ubalua, 2007; Pattiya, 2010).

The cassava waste considered in this case study is cassava rhizome. The cassava is planted once a year, in April, during the rainy season[2] and does not need any special care. It takes 3 to 6 months to grow, depending on the type. The harvesting period is assumed to be from June to October. The raw material has 42.5% MC and 10.61 MJ/kg LHV in ar basis. 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 assumed to be zero. See in Table 2 a summary of the main properties. The last column sums up the total amount of cassava waste produced by the 9 communities. It has been considered that from the total amount of cassava rhizome that is produced in Atebubu district according to the cassava production estimated value, from Serpagli et al. (2010), only a 20% is taken for electricity purposes.

[2]Conversation with people from Seneso.

Table 2: Feedstock properties.

Biomass	Cost ($/t)	LHV_{ar} (MJ/kg)	MC (% wt)	BD (kg/m^3)	Seasonality	Yearly available (t)
Cassava waste	0	10.61	42.50	340	June-October	1666.13

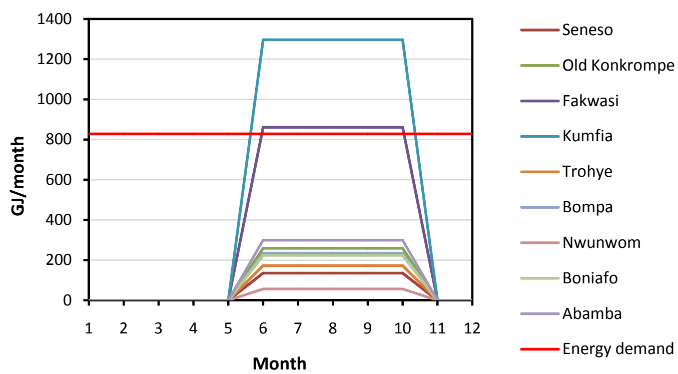

Figure 7: Seasonal cassava waste production and thermal power demand.

It represents an overall value of 17667.6 GJ/yr.

Figure 7 shows the assumed production of cassava waste per community, in GJ/month. It has been estimated proportional to the population of each community based on the 264649 t of cassava produced during 2009 in the whole Atebubu district (Serpagli et al., 2010). The agricultural activity is assumed evenly divided among the communities. The cassava waste disposal is assumed to take place at the same generation place. See also in Figure 7 the aggregated demand estimated for the nine communities. This is expressed in terms of thermal demand, considering a gasification efficiency of 17% (see Section 3).

7.2. Technologies used and electricity demand

Biomass that goes to the gasifier must meet shape (chips) and MC requirements (20%), involving pre-treatment prior to use. The pre-treatment actions considered are drying and chipping. It is assumed that the only possible biomass storage is carried out before chipping and gasification, as on-field storage, being the cheapest and simplest option. Figure 8 shows the layout of the different pre-treatment options applied to the biomass (BM). The biomass properties that change along the network are MC, shape and LHV.

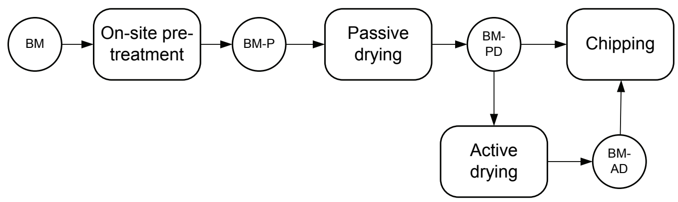

Figure 8: Pre-treatment activities layout.

The main issues of each pre-treatment site as well as the main characteristics concerning transportation, by means of MC, DM and LHV, are summarised below. The reported percentages and proportions are used to linearly model the activities in the mathematical formulation, or to calculate the biomass states. It is assumed that the chipper and the dryer works an average of 8h/day. In contrast, the gasifier is assumed to work 16h/day according to an hypothetical daily demand distributed along 16h. The project has a lifespan of 10 years (Stassen, 1995). The range of unit's capacity have been fixed by taking into account the processed maize in a MFP during one day and the total production of cassava estimated per year. The investment and O&M costs are taken from the bibliography. Economies of scale are considered.

- On-site pre-treatment. In this task the biomass waste is generated. Here, the cassava is harvested. The place of generation also serves as a place for on-site storage. Therefore, open air storage, in open air piles, is considered here.

- Drying. This stage contemplates passive or active drying. Passive drying is a consequence of the abovementioned open air storage. According to Hamelinck et al. (2003), storage at the roadside is free and has negligible O&M cost. If the raw biomass has a MC higher than 20%, DM loss per month is 3%, and MC loss per month is 2%. Figure 7 reveals the need of cassava storage. It is assumed a maximum period of storage of 12 months. Active drying takes place into a rotatory drum. This unit is used to decrease the inlet MC to 20%, which is the humidity required before the gasification process. Biomass changes its MC and its LHV according to the tonnes of water evaporated. This unit has an energy efficiency of 99%. It consumes diesel as utility. The available capacities are between 0.1-5 t/h.

- Chipping. Chipping is placed after drying. It is assumed to consume electricity from gasifiers-ICE systems. This unit has an energy efficiency of 96%. The available capacities are in the range of 0.1-5 t/h.

- Gasification combined with ICE system. The microplant has an efficiency of 17% as calculated in Section 3. The gasification units work in the range of 5 to 100 kW_e according to the enterprise *Ankur*.

- Transportation. Solid biomass can be displaced from its point of generation to a common storage place or to a pre-treatment node by tractors, within a capacity of 10 t for biomass[3]. Lineal distances are assumed between sites and they are expressed in km. A tortuosity factor of 1.8 is taken into account.

- LV and MV networks. LV line is used if the electricity is produced and used at the same community. A MV line is used if the electricity is provided by a plant installed in another community. The LV distribution implies 5% losses in energy terms. It is assumed that there exists 1% additional energy loss. The MV distribution line takes into account losses estimated by Merino (2003), which are proportional to the power demand. See Appendix A for further details.

The economic evaluation is based on estimations of investment and annual O&M costs. It is assumed that the total capital requirement is spent only at the beginning of the project. Table 3 lists the parameters for costs estimation, including pre-treatment units, gasification-ICE plant and transportation. The diesel price is \$1133.31/t[4]. This case study assumes an electricity price of \$0.233/kWh, as the value that the communities are willing to pay. It has been calculated by taken into account the consumption of diesel and batteries, with the subsequent prices, based on the community of Seneso.

[3]On-field data and conversations with Mr. Jacob Salifu (WACSO).

[4]On-field data.

Table 3: Economic parameters for pre-treatment units, gasification-ICE plant, transportation and utilities consumption. Data from Hamelinck and Faaij (2002), Hamelinck et al. (2003), (TTA), Ankur, KITE and WACSO.

	Base scale	Base investment	O&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 microplant[2]	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[3]		$5000/km			

[1] LV network costs are included here.
[2] CaO consumption is disregarded.
[3] Transformer cost is 1000€.

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 demand estimate takes into account residential, community and commercial electricity requirements. See additional details in Appendix A. The highest gross demand is 448.65 kWh/day in Kumfia community, while the lowest is 21.17 kWh/day in Nwunwom community, taking into account the LV microgrid losses. Figure 9 depicts the nine communities represented by their relative GJ/yr of demand. The black points mark the locations selected for pre-treatment and treatment. Note that all the communities are considered as potential places. Four more intermediate sites have been also defined as potential locations.

7.3. Environmental impact

The environmental impact is calculated from Impact 2002+ metric, evaluated in points (pts). LCI values are retrieved from LCI database Ecoinvent-V1.3 (2006) using B.V. (2004), and they are directly converted into Impact 2002+ mid-point indicators, which is the LCIA step. The BSC associated and evaluated tasks are biomass production without transportation, transporta-

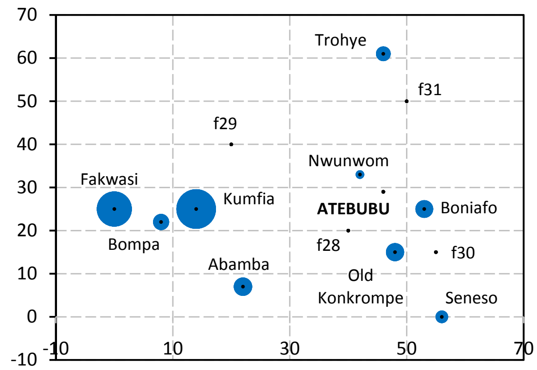

Figure 9: Communities representation by means of their relative energy demand. Black points mark the possible pre-treatment and treatment sites locations. Axes in km.

tion by tractors, pre-treatment technologies and generation of electricity by means of biomass gasification, as listed in Table 4. The last column has been adapted from a large scale gasification plant, according to the difference in efficiencies between an IGCC plant and the gasification-ICE plant. Large gasification impacts have been previously estimated by evaluating the plant output streams impacts separately.

Concerning model parameteres, the time period t is a month. According to the number of biomass status s has 40 different states. In turn, j has 6 different states (in accordance with the different pre-treatment and treatment technologies, and transportation). i has 79 states depending on the couple biomass-activity (including transportation). f considers sites location, being overall 31 of them, by considering suppliers, pre-treatment and treatment possible locations and markets. This case study works with biomass mass. The project is evaluated for a planned horizon of 10 years, with yearly planned decisions. The interest rate is assumed at 15%[5].

7.4. Results

The electrification case study is solved to obtain the PF. The results summarise the performance of the different network configurations obtained (i)

[5]www.bog.gov.gh

Table 4: Environmental impacts in terms of Impact 2002+ metric, associated to SC tasks(Ecoinvent-V1.3, 2006).

Mid-point categories	Cassava rhizome (pts/t)	Chipper (pts/t)	Dryer (pts/t)	Transportation by tractor (pts/t·km)	Electricity generator (pts/GJ)
Carcinogens	$1.96 \cdot 10^{-5}$	$2.16 \cdot 10^{-6}$	$8.64 \cdot 10^{-6}$	$1.66 \cdot 10^{-6}$	0
Non-Carcinogens	$1.53 \cdot 10^{-5}$	$9.28 \cdot 10^{-6}$	$3.71 \cdot 10^{-5}$	$2.78 \cdot 10^{-5}$	0
Respiratory inorganics	$1.08 \cdot 10^{-3}$	$4.18 \cdot 10^{-4}$	$1.67 \cdot 10^{-3}$	$5.81 \cdot 10^{-5}$	$5.16 \cdot 10^{-3}$
Ionizing radiation	$3.12 \cdot 10^{-5}$	$6.03 \cdot 10^{-6}$	$2.41 \cdot 10^{-5}$	$1.78 \cdot 10^{-7}$	0
Ozone layer depletion	$1.00 \cdot 10^{-7}$	$1.23 \cdot 10^{-8}$	$4.93 \cdot 10^{-8}$	$5.38 \cdot 10^{-9}$	0
Respiratory organics	$3.71 \cdot 10^{-6}$	$6.01 \cdot 10^{-8}$	$2.40 \cdot 10^{-7}$	$7.98 \cdot 10^{-8}$	0
Aquatic ecotoxicity	$1.44 \cdot 10^{-6}$	$3.40 \cdot 10^{-7}$	$1.36 \cdot 10^{-6}$	$1.73 \cdot 10^{-7}$	0
Terrestrial ecotoxicity	$5.42 \cdot 10^{-5}$	$6.50 \cdot 10^{-6}$	$2.60 \cdot 10^{-5}$	$7.47 \cdot 10^{-5}$	0
Terrestrial acid/nutri	$1.67 \cdot 10^{-5}$	$5.75 \cdot 10^{-6}$	$2.30 \cdot 10^{-5}$	$9.12 \cdot 10^{-7}$	$1.71 \cdot 10^{-4}$
Land occupation	$2.6 \cdot 10^{-3}$	$1.30 \cdot 10^{-7}$	$5.20 \cdot 10^{-7}$	$1.18 \cdot 10^{-6}$	0
Aquatic acidification	0	0	0	0	0
Aquatic eutrophication	0	0	0	0	0
Global warming	$1.16 \cdot 10^{-3}$	$2.57 \cdot 10^{-4}$	$1.03 \cdot 10^{-3}$	$3.08 \cdot 10^{-5}$	$5.09 \cdot 10^{-2}$
Non-renewable energy	$1.65 \cdot 10^{-3}$	$3.22 \cdot 10^{-4}$	$1.29 \cdot 10^{-3}$	$3.21 \cdot 10^{-5}$	0
Mineral extraction	$6.05 \cdot 10^{-8}$	$2.96 \cdot 10^{-9}$	$1.19 \cdot 10^{-8}$	$1.55 \cdot 10^{-7}$	0

for each objective function optimised individually, (ii) for the loops performed to obtain the points of the PF, and (iii) the PF.

7.4.1. Objective functions optimisation

The networks representation counts with four types of matter flows that connect the different sites, independently of the period (month of the year) where the the flowrate appears:

- In brown, non-stored raw material.
- In green, raw material.
- In orange, dried matter.
- In purple, chipped matter.

Figure 10 depicts the network that maximises the NPV. Three types of matters, i.e. stored and non-stored raw matter and chipped matter are transported between locations. Table 5 lists the calculated capacity of the equipments installed at the sites.

The model recommends to install a plant in each community but dispatches the needed pre-processing facilities in four sites: Old Konkrompe, Fakwasi, Kumfia and Abamba. This shows that even though a gasification installation can provide more than one community, the demand is not high enough to justify the investment on a MV microgrid. The four sites with pre-processing units are strategically located to best handle the biomass of all the communities. The minimum chipping capacity is installed (10t/h) in almost all the communities, which is enough to process all the needed cassava waste. Therefore, Old Konkrompe, Fakwasi, Kumfia and Abamba are centralised processing sites of cassava waste, being four of the five most populated communities. Note that the network is mainly constituted by chipped rather than dried matter. Fluxes of raw material exist to supply the largest communities. The high investment costs associated to an intermediate site ($f28$ to $f31$), since the MV microgrid is needed, prevent their use. The results show that this case study requires from biomass storage in the view of supplying the constant electricity demand. The storage period ranges between 5 and 8 months.

The maximum value of the SoC corresponds to 27. The two extreme cases correspond to the maximisation of the NPV and the minimisation of the environmental impact, therefore, two network configurations are optimum

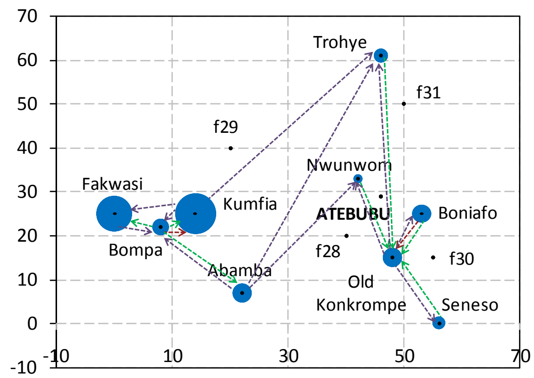

Figure 10: Optimum NPV network configuration. See in brown the non-stored raw matter flow, in green, the raw matter flow, in orange the dry matter flow and in purple the chipped matter flow.

Table 5: Equipment capacity for the optimum NPV BSC.

	Dryer (t/h)	Chipper (t/h)	G-ICE plant (MJ/h)
Seneso			18.00
Old Konkrompe	0.10	0.10	21.44
Fakwasi	0.14	0.10	80.61
Kumfia	0.20	0.11	102.35
Trohye			18.00
Bompa			18.00
Nwunwom			18.00
Boniafo			20.53
Abamba	0.10	0.10	22.04

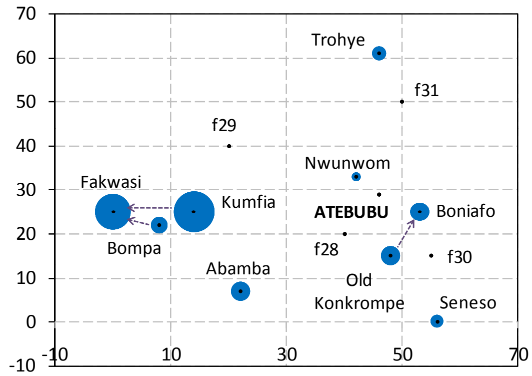

Figure 11: Optimum Impact 2002+ network configuration. See in brown the non-stored raw matter flow, in green, the raw matter flow, in orange the dry matter flow and in purple the chipped matter flow.

for the social criterion optimisation. The environmental objective function optimisation results in a value of 27 for SoC. Therefore, the corresponding network is optimum for the two criteria. As a matter of simplification, the common network configuration is represented for the environmental criterion minimisation, and the other one is associated here to the SoC maximisation.

Figure 11 shows the optimal configuration that minimises Impact 2002+. Table 7 provides the overview of the installed capacities. For this BSC network, material fluxes are again characterised by chipped biomass. The pre-treatment units are installed by means of its minimum capacity at all the sites, except at the two largest, Fakwasi and Kumfia, which relies on adapted dryers and G-ICE units. Old Konkrompe, Boniafo and Abamba also have gasification plants with capacities larger than the minimum. The transportation costs are minimised by means of the environmental impact optimisation. Analogously to the previous case, no MV microgrid is installed. The only flow comes from chipped material, and this network is much more simple than the previous one. The storage period is between 7 and 8 months.

The third network maximises the SoC (and maximises the NPV). The model installs each type of unit at each location, but the capacities are different if compared with the previous case. Note that the network is more complex. All the pre-treatment units' capacities installed correspond to the minimum value, except for Kumfia, that has a larger drier and acts collecting

Table 6: Equipment capacity for the optimum Impact 2002+ BSC.

	Dryer (t/h)	Chipper (t/h)	G-ICE (MJ/h)
Seneso	0.10	0.10	18.00
Old Konkrompe	0.10	0.10	21.44
Fakwasi	0.14	0.10	80.61
Kumfia	0.19	0.10	102.35
Trohye	0.10	0.10	18.00
Bompa	0.10	0.10	18.00
Nwunwom	0.10	0.10	18.00
Boniafo	0.10	0.10	20.53
Abamba	0.10	0.10	22.04

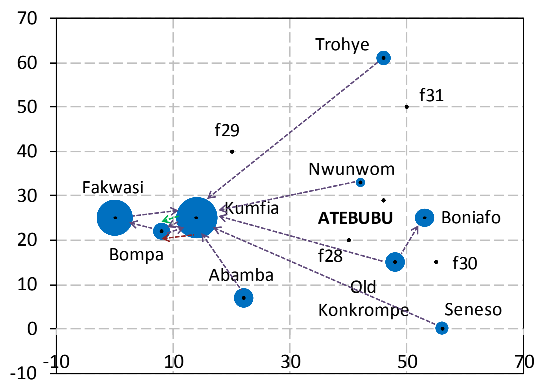

Figure 12: Optimum social network configuration. See in brown the non-stored raw matter flow, in green, the raw matter flow, in orange the dry matter flow and in purple the chipped matter flow.

chipped biomass from other communities. Fluxes of raw material exist only to supply Bompa community. Again, the gasification units are scaled to meet the own demand in all the communities. The storage period is between 5 and 7 months.

As general remarks, note that any of the networks transports dried material. As 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 to use the intermediate sites. The number of storage months change among the optimum situations. Notice that the simplest network comes from the environmental impact minimisation.

Table 7: Equipment capacity for the optimum social BSC.

	Dryer (t/h)	Chipper (t/h)	G-ICE (MJ/h)
Seneso	0.10	0.10	18.00
Old Konkrompe	0.10	0.10	21.44
Fakwasi	0.10	0.10	80.61
Kumfia	0.12	0.10	102.35
Trohye	0.10	0.10	18.00
Bompa	0.10	0.10	18.00
Nwunwom	0.10	0.10	18.00
Boniafo	0.10	0.10	20.53
Abamba	0.10	0.10	22.04

The following results compare the above described optimal solutions. Table 8 summarises the three criteria evaluated for each optimal network. The economic value corresponding to the BSC configuration that maximises the NPV is \$89895.95, which is the maximum number that can be obtained in this case study. This value is decreased by 59% in the environmental friendly network, and by 50% in the social network. The differences are mainly due to higher investment costs arising from the decrease on transportation and from the installation of all the units into each location. For the environmental parameter, it can be deduced that the difference among configurations mainly falls on transportation of pre-processed biomass. The Impact 2002+ value is reduced by 2.3%, if the LCA instead of the NPV is optimised. The environmental impact for the social BSC network is closer to the optimal environmental impact. The maximum value for the social criterion is 27, installing 3 units per site. The comparison between economic and social configurations focuses two extreme scenarios: (i) the capacity of the installed units is adapted to match the demand and, (ii) units are installed and then operated to meet the demand. Thus, a certain centralisation is needed in DES to ensure the sustainability of the network.

Figure 13 depicts the investment and the annual costs breakdown for each BSC optimised. Investment costs are \$284422, \$343187 and \$331967 for NPV, Impact 2002+ and social optimised scenarios, respectively. The utilities costs for each BSC are around \$26000/yr. The reason is the diesel consumption of the dryer. The most relevant features that can be deduced from the breakdown of costs concern the penalisation in costs terms, derived from the installation of more units/capacity than the strictly needed, thus diminishing the transportation costs. Analogous observations can be retrieved

Table 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

Table 9: Environmental impacts arising from single objective function optimisation results, in Impact 2002+ pts (results per year).

End-point impact category	NPV optimisation	Impact 2002+ optimisation	Social optimisation
Human health	13.89	12.95	13.14
Ecosystem quality	5.33	4.48	4.65
Climate change	89.52	89.17	89.24
Resources	4.72	4.34	4.41
Impact 2002+	113.46	110.94	111.43

from Figure 15, where the environmental impact is depicted per SC echelon. The contribution that changes the most among the optimised networks is that of pre-processed biomass transportation. Biomass pre-processing and electricity generation constitute the major share among contributions; the increase of the efficiency of these processes is crucial.

Table 9 lists environmental interventions: the NPV optimum solution has an environmental impact of 113.46 pts, whereas the Impact 2002+ optimum scenario has 110.94 pts and the social optimum network has 111.43 pts. The impacts for each damage category, i.e. human health, ecosystem quality, climate change and resources, are in the same range. The highest impact is on climate change and constitutes 80% of the whole impact.

7.4.2. Pareto front

The trade-off among the three selected parameters is represented here. To determine the PF, for the diferent discrete values that the SoC can adopt, which are in the range of 17 (minimum social criterion value from the objective functions' optimisation) to 27 (the maximum one), the net-

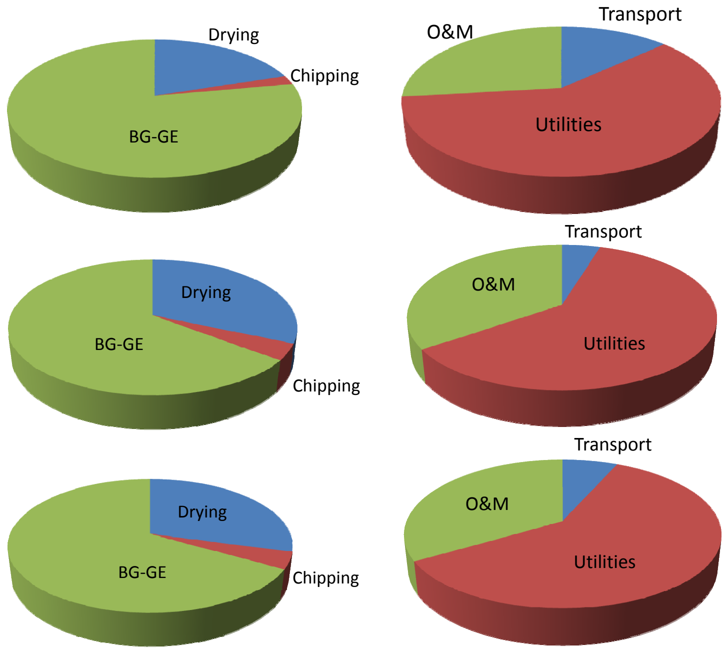

Figure 13: Breakdown of costs for NPV, Impact 2002+ and social optimised networks, respectively. Left side: investment share. Right side: annual costs share.

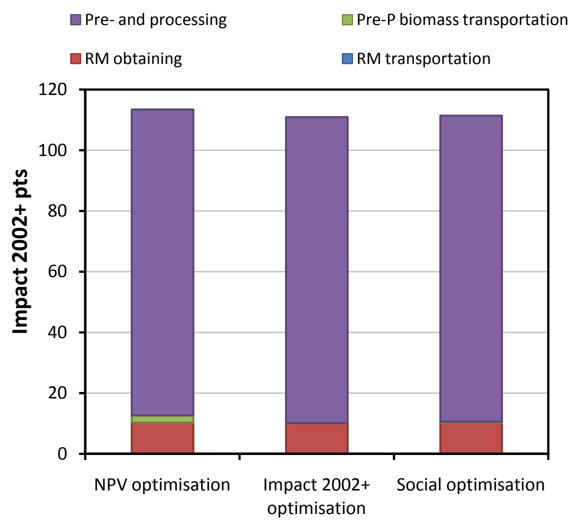

Figure 14: Distribution of environmental impacts for single objective optimisation solutions, according to the different SC activities (results per year).

works that maximise the NPV and minimise the environmental impact are found. Among these two extremes of each social iso-line, 10 networks are set up, using ϵ-constraint methodology for Impact 2002+ value changes, while maximising the NPV. Therefore, overall, 132 networks are considered. See in Figure **??** the representation of the Pareto set of solutions, i.e. the non-dominated solutions, NPV vs. Impact 2002+, for each social iso-line.

It is observed that as the SoC increases, the environmental impact decreases at the expense of compromising the NPV. The curves for SoC equal to 17 and 18, are far from the behaviour of the other level curves. Those are the better options if only regarding the economic criterion. It is seen that in the considered range for the social criterion, the NPV varies in an interval of M$53, while the environmental impact oscillates 1.8 pts. They represent a decrease of 59% and an increase of 2% related to the optimum values.

Remark that due to the shape of the PF, several scenarios share a common NPV value, or share a common Impact 2002+. Nevertheless, each point of the PF represents a different SC configuration with different unit's capacities. To exemplify that, several networks have been compared. See in Figure 16 the resulting SC arrangement for the following three points: the maximi-

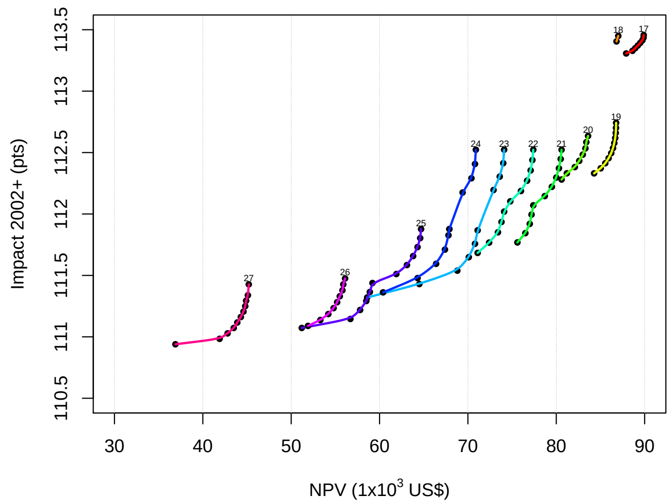

Figure 15: Pareto set of solutions.

sation of the NPV scenario for SoC equal to 22, 23 and 24. They share the same Impact 2002+ value (112.52 pts), the same network but, the installed capacities are different, driven by the social factor value. The issue is in the minimum installed capacity of the chipper installed in Seneso, Nwunwom and Boniafo communities, as shown in Table 10.

In an analogous way, two scenarios that share a common NPV ($70800) are compared. They belong to the PF loops of SoC equal to 23 and 24 (escenarios 4 and 10, respectively). See in Figure 17 the two different networks obtained. They differ in Nwunwom and Seneso installations, as well as in the dryer capacity from Fakwasi, as shown in Table 11.

7.4.3. Sensitivity analyses

The effect of the electricity price ($0.233/kWh) on the optimal network considering the maximisation of the NPV, on the NPV itself, is analysed in Figure 18. See that due to a decrease of the electricity price of 8.5%, the viability of the network breaks down. Therefore, prices lower than around $0.2/kWh would require a subsidy policy.

Figure 19 shown the behaviour of the economic parameter internal rate of return (IRR) when changing the electricity price for the two extreme scenarios, maximising NPV and minimising environmental impact. This parameter

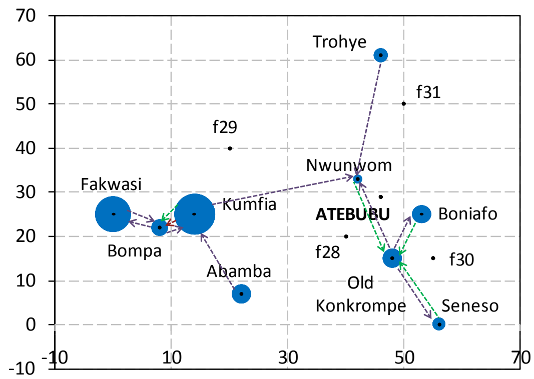

Figure 16: SC configuration for scenarios that share a common Impact 2002+ value: SoC equal to 23, 24 and 25, maximising NPV.

Table 10: Equipment capacity for scenarios that share a common Impact 2002+ value: SoC equal to 23, 24 and 25, maximising NPV.

	SoC 22			SoC 23			SoC 24		
	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		0.10	18.00			18.00		0.10	18.00
Old Konkrompe	0.10	0.10	21.44	0.10	0.10	21.44	0.10	0.10	21.44
Fakwasi	0.10	0.10	80.61	0.10	0.10	80.61	0.10	0.10	80.61
Kumfia	0.13	0.10	102.35	0.13	0.10	102.35	0.13	0.10	102.35
Trohye	0.10	0.10	18.00	0.10	0.10	18.00	0.10	0.10	18.00
Bompa	0.10	0.10	18.00	0.10	0.10	18.00	0.10	0.10	18.00
Nwunwom			18.00		0.10	18.00		0.10	18.00
Boniafo			20.53		0.10	20.53		0.10	20.53
Abamba	0.10	0.10	22.04	0.10	0.10	22.04	0.10	0.10	22.04

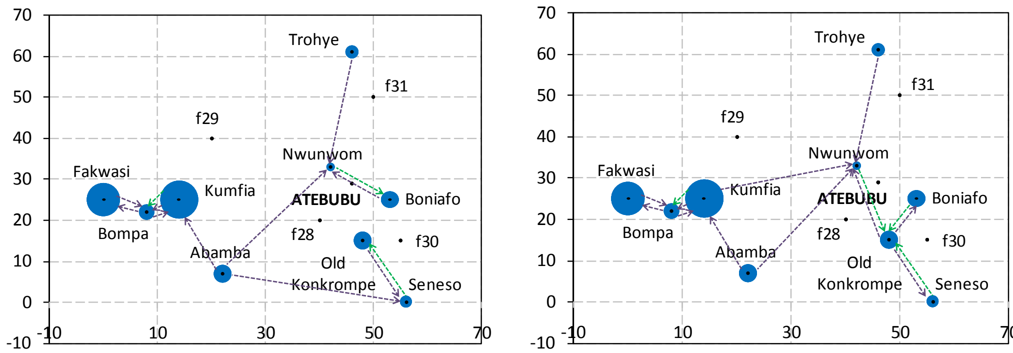

Figure 17: SC configuration for scenarios that share a common NPV value in *SoC* equal to 23 and 24.

Table 11: Equipment capacity for scenarios that share a common NPV value in *SoC* equal to 23 and 24.

	SoC 23			*SoC*24		
	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	18.00
Old Konkrompe	0.10	0.10	21.44	0.10	0.10	21.44
Fakwasi	0.11	0.10	80.61	0.11	0.10	80.61
Kumfia	0.13	0.10	102.35	0.13	0.10	102.35
Trohye	0.10	0.10	18.00	0.10	0.10	18.00
Bompa	0.10	0.10	18.00	0.10	0.10	18.00
Nwunwom			18.00		0.10	18.00
Boniafo	0.10	0.10	20.53		0.10	20.53
Abamba	0.10	0.10	22.04	0.10	0.10	22.04

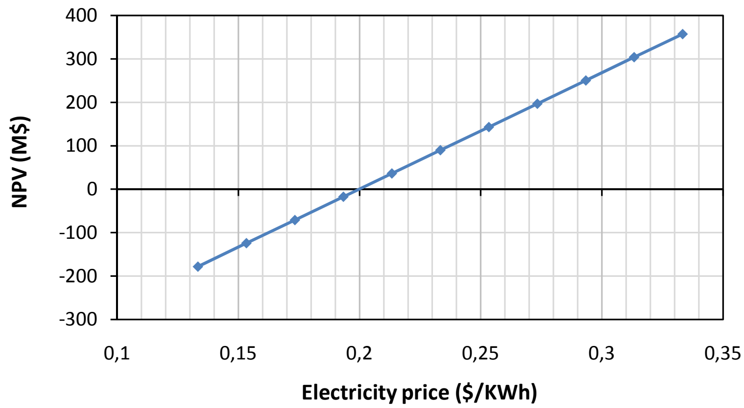

Figure 18: NPV vs. electricity price for the BSC network optimised to obtain the maximum NPV.

is defined as the rate of return that makes the NPV equal to zero. The interest rate considered in this case study is 15%. In general, the IRR of the maximum NPV case, is two points higher than the IRR of the environmental friendly scenario. Therefore, it is appreciated that for the same rate, the economic optimum scenario allows lower electricity prices.

7.4.4. Global remarks

The common traits to all the non-dominated scenarios concern the amount of biomass that is processed to cover all the electricity demand. The needed amount of biomass results in 1526 t/yr. This is a 8.4% of cassava rhizome that is not used and can be employed for other purposes. For the same reason, the utilities cost is in all the networks very similar, around $26000. Therefore, the most important differences concerns transportation and investment. Due to the cassava waste disposition, which is present in all the communities, no MV microgrid is installed. Therefore, the G-ICE plants installed in all the communities, for all the Pareto solutions, are the same. The largest variability comes from the chipper and drier installations: those are the units used to adjust the social factor during the search of optimum scenarios. The smallest communities which are far from the biggest ones, such as Seneso or Nwunwom, are the communities that show more variability along the different scenarios.

The calculation time ranges from 32.5s to 30857.2s. The first one corre-

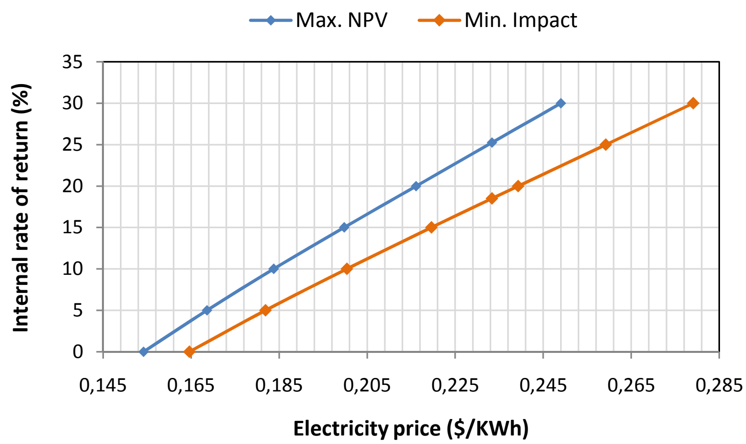

Figure 19: IRR vs. electricity price for the BSC networks optimised to obtain the maximum NPV and the minimum impact.

spond to the extreme scenario that minimises the environmental impact for SoC equal to 27. The highest value is for the environmental impact minimisation scenario for SoC equal to 18. As the social factor increases, the calculation time decreases. In general, it is appreciated that the resolution of the economic criteria is less time consuming than the environmental criteria case.

To end with the BSC problem, the decision-maker should select one of the options represented in the PF, according to his/her criteria. The decision-maker should take into account that the proposed configurations are very sensitive to the input data, principally to the electricity price, biomass characteristics and biomass generation places, and to the pre-treatment units selected.

8. Conclusions

This paper has demonstrated the capabilities for a DES network design of the mathematical model described, with economic, environmental and social concerns. There does not exist any unique and global approach to tackle such a problem: the strategy must be adapted depending on the used raw material, the pre-treatment units and the final energy purpose. The trade-off between quality, understood as a high LHV and a low MC, and seasonality of the used raw material, the involvement of more or less advanced pre-treatment methods and the mitigation of matter degradation governs the capability to satisfy the demand and thus, to determine an optimal solution. Distributed approaches should rely on a certain level of centralisation to be feasible on time, even if they may seek to favour the economy of the areas. Co-generation and tri-generation should be evaluated in future works, as an alternative to enhance the efficiency. The small scale gasification plant should overcome several technological challenges before being highly used.

The capabilities of the proposed model has been exemplified by a case study placed in Ghana. The PF provide crucial data for the design problem, showing the main tendences of the optimal solutions, revealing and evaluating a trade-off between the economic criterion with environmental and social criteria. Each scenario is characterised by biomass flowrates, i.e. values and suppliers-consumers connection, unit's capacities and times of biomass storage.

The energy block is the most versatile part of the model in DES configuration: this part can be easily adapted to other microgeneration sources, such as wind, hydraulics or solar, or even to investigate the use of more than one renewable source in hybrid systems. The present approach can be changed to consider other advanced pre-treatment methods, such as pelletisation, torrefaction or pyrolysis. The biomass modelling should be potentially enhanced to be able to consider the statistical problem derived from different biomass types, from different periods, months of storage and pre-treatment combinations.

The conceived tool is able to support decision-making task of bio-based projects.

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Notation

Superscripts and subindices

ar	as received basis
e	electric
th	thermal

Acronyms

BD	bulk density
BM	biomass
BSC	bio-based supply chain
CGE	cold gas efficiency
COE	cost of the energy
DES	distributed energy systems
DM	dry matter
ER	equivalence ratio
G	gasification
ICE	internal combustion engine
IRR	internal rate of return
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LHV	lower heating value
LP	linear programming
LV	low voltage
MC	moisture content
MFP	multi-functional platform
MO-MILP	mixed integer linear programming
MV	medium voltage
NPV	net present value
O&M	operation and maintenance
PF	Pareto front
SC	supply chain
SCM	supply chain management
SoC	social criterion
STN	state task network

Mathematical formulation

Indices

a	mid point environmental impact categories
e	suppliers
f, f'	facility locations
g	end point environmental impact categories
i	tasks
j	equipment technology
k	intervals for piecewise linear approximation of economies of scale
s	materials (states)
t, t'	planning periods

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
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
J_{Stor}	technologies to perform storage activities
Mkt	set of market locations
NTr	set of production, or non-transport, tasks
RM	set of materials s that are raw materials
S_{stor}	set of materials/biomass that if stored change their properties
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 locationf'

$FCFJ_{jft}$	fixed cost per unit of technology j capacity at location f in period t
FE^{limit}_{jfk}	increment of capacity equal to the upper limit of interval k for technology j in facility f
i_r	discount rate
$Invest^{MV}$	investment required for medium voltage connectivity per length unit
M	a big number
$NormF_g$	normalising factor of damage category g
$Price_{sft}$	price of product s at market f in period t
$Price^{limit}_{jfk}$	investment required for an increment of capacity equal to the upper limit of interval k for technology j in facility f
$Tortuosity$	tortuosity factor
$Water_s$	Moisture for material s
$Water^{max}_{ij}$	Maximum moisture for task i performed in equipment j

Greek symbols

α_{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
β_{jf}	minimum utilisation rate of technology j capacity that is allowed at location f
ζ_{ag}	g end-point damage characterisation factor for environmental intervention a
$\theta_{ijff'}$	capacity utilization 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
τ^{ut1}_{ijfet}	unitary cost associated with task i performed in equipment j from location f and payable to external supplier e during period t
τ^{ut2}_{sfet}	unitary cost associated with handling the inventory of material s in location f and payable to external supplier e during period t
χ_{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'

ψ^{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
$Z_{ff'}$	1 if facilities f and f' are interconnected by a medium voltage line, 0 otherwise

SOS2 variables

ξ_{jfkt}	variable to model the economies of scale for technology j in facility f at period t as a piecewise linear function

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
HV_{s}	lower heating value for material s
IC_{aft}	midpoint a environmental impact associated to site f which rises from activities in period t
$Impact^{2002}_{f}$	total environmental impact for site f
$Impact^{2002}_{overall}$	total environmental impact for the whole SC
NPV	economic metric, net present value
$P_{ijff't}$	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}	input/output material of material s for activity of task i with variable input/otput, by using technology j during period $t$in location f (This must be a production activity)
$Profit_{t}$	profit achieved in period t
$Purch^{pr}_{et}$	amount of money payable to supplier e in period t associated with production activities

$Purch^{rm}_{et}$	amount of money payable to supplier e in period t associated with consumption of raw materials
$Purch^{tr}_{et}$	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
SoC	surrogate social metric

Appendix A. Data for the case study

Three main types of electricity demand are considered. They follow the typical regulated tariffs structure, which is the common reference in demand characterisation for stakeholders involved in the rural electrification sector (Vallvé et al., 2007; Arranz-Piera, 2008; Arranz-Piera et al., 2011).

- Residential. It covers typical household uses of electricity, such as lighting, communications and very small appliances. In rural communities without access to electricity, the majority of households (up to 70% of a community) have a very low electricity demand, in the range of 8 to 20kWh per month (equivalent to 250 to 700 Wh/day), even with access to a 24h service scheme.

- Community. It refers to the use of electricity in community or public premises, for instance schools, health centres, public lighting and water pumping stations.

- Productive & Commercial. It refers to income-generating uses of electricity. Depending on the type of activity, the loads involved may have a higher power demand in comparison to the residential loads, i.e. motors, large fridges or freezers, agro-processing or sawmill equipment. The rationale behind the above distinction of uses of electricity is essentially the resemblance to typical regulated tariff structures, which is the common reference in demand characterisation for stakeholders involved in the rural electrification sector.

Typical electricity consumptions assumed are summed up in Table A.14, for a small rural community without previous access to electricity.

Table A.14: Reference values for electricity demand evaluation.

Type of load	Description	Typical electricity demand (kWh/day)
Lighting	1 Efficient lamp (e.g. compact fluorescent lamps), unit power of 12W, used for 6 hours per day	0.072
Communications	Mobile phone charger, nominal current 65mA (at 220V AC), charging time 2 hours per day	0.029
Entertainment	1 colour TV with DVD player, nominal power 100W, playing time 2 hour per day	0.200
Refrigeration	Compact fridge (60 to 90 litres), low energy consumption (minimum ecolabel rating A), in a hot climate (average temperatures above 25°C)	1.000

The reference community electricity consumptions, are summed up in Table A.16. It belongs to a rural community without previous access to electricity, considering 10 potential users, with 7 households, distributed in the three main types of demand.

Using the reference demand characterisation described in Table A.16, the net demand into each community has been estimated as a proportion to the number of households. Results are shown in Table **??**. The current approach assumes that users will be supplied with a distribution microgrid in each community; hence, the intra-community LV distribution losses have to be estimated to approach the gross demand, that is, the electricity that needs to be supplied to each community. Based on a related International Electrotechnical Comission (IEC) standard (, IEC), the maximum losses in a LV monophasic distribution microgrid would be kept at 5%, plus a 1% of self-consumption due to the installation of meters. The resulting gross demand in each community is shown in Table **??**. Those are the values reported throughout the text of the present paper.

The model performs a comparison with an alternative, which is the interconnection of two or several of these communities so that a centralised generation plant, coupled to a MV distribution grid, could supply more than one community. In order to assess this alternative, the inter-community distribution losses need to be estimated and aggregated to the gross demand in each community. Losses at this stage have been assigned to the use of step-down transformers in each community, for both, load and non-load losses, assuming the use of oil transformers and an average load profile propor-

Table A.15: Base reference for electricity demand estimation in a very small rural community without previous access to electricity (Vallvé et al., 2007).

	Electricity demand (kWh/day)
Residential	
Household 1 (3 lamps + 1 mobile phone charger + TV-DVD player)	0.50
Household 2 (3 lamps + 1 mobile phone charger + TV-DVD player)	0.50
Household 3 (3 lamps + 1 mobile phone charger)	0.25
Household 4 (3 lamps + 1 mobile phone charger)	0.25
Household 5 (3 lamps + 1 mobile phone charger)	0.25
Household 6 (3 lamps + 1 mobile phone charger + TV-DVD player + fridge)	1.50
Household 7 (3 lamps + 1 mobile phone charger + TV-DVD player)	0.50
Community	
Health centre (3 lamps + 1 mobile phone charger)	0.25
Church & Primary school (3 lamps + 1 mobile phone charger + TV-DVD player)	0.50
Productive & Commercial	
Small shop (4 lamps + 3 mobile phone charger + TV-DVD player operating 6h per day+ fridge)	2.0
Total estimated electricity demand	6.5

Table A.16: Estimation of the net and gross electricity demands in each community, taking into account LV and MV microgrids.

Community	Number of households (2010)	Population (2010)	Net demand (kWh/day)	Gross demand LV microgrid (kWh/day)	Gross demand MV microgrid (kWh/day)
Seneso	46	296	42.43	45.00	61.63
Old Konkrompe	95	566	88.60	93.96	119.48
Fakwasi	359	1881	333.20	353.35	393.67
Kumfia	456	2834	423.05	448.64	501.92
Trohye	63	376	58.65	62.20	78.84
Bompa	75	512	69.88	74.11	114.43
Nwunwom	22	122	19.97	21.17	31.57
Boniafo	91	489	84.86	89.99	115.51
Abamba	98	653	91.10	96.61	122.13

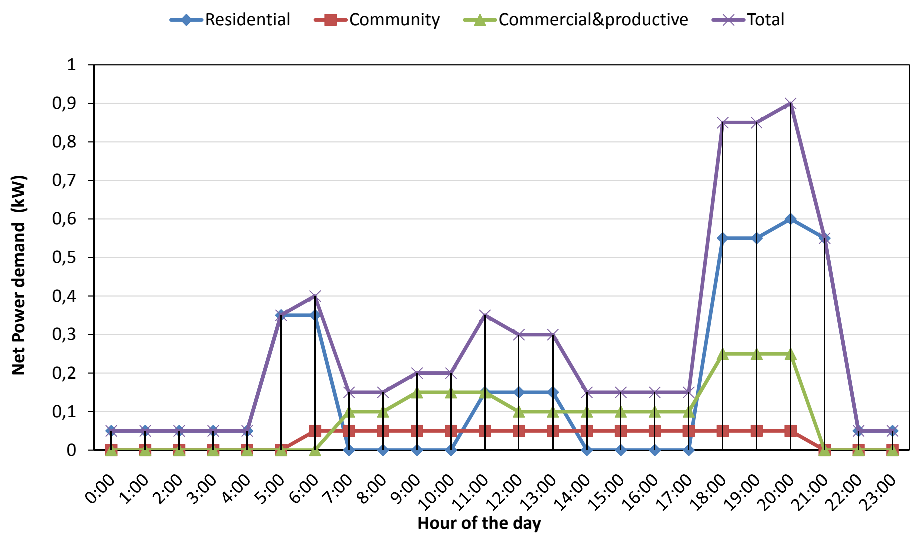

Figure A.20: Estimated power load profile for a reference operation day in a 10 user community, considering the three types of demand and the resulting aggregated demand. It is noticed that the peak power demand remains below 1kW.

tional to the reference shown in Figure A.20. Reference losses are taken from Merino (2003). Table **??** also reports the gross demand of each community if supplied by a MV microgrid.

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