UNIVERSITY OF TWENTE.

TU Graz
Graz University of Technology

Optimum Technology Network for Ethanol Production and Electricity Cogeneration in Ecuador

Christian Andres Polanco Pacheco
Internship Assignment Report
November 2016

Supervisors:
prof. dr. Maarten J. Arentsen
dr. ir. Michael Narodoslawsky

Sustainable Energy and Society Group
Faculty of Engineering Technology,
Master Sustainable Energy Technology
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Name: Christian Andres Polanco Pacheco
Student number: s1708023
Company name: Institute of Process and Particle Engineering, Graz University of Technology, “Optimal Technology Networks for Regional and Urban Utilization of Renewable Resources” research area
Mentor: Dr. Michael Narodoslawsky
City and country: Graz, Austria
Period: 15/08/2016 – 04/11/2016
University of Twente supervisor: Dr. Maarten Arentsen, “Sustainable Energy and Society” research group

I. Preface

This report is the final assignment of the internship conducted in the Institute of Process and Particle Engineering at the University of Technology in Graz, Austria. Specifically in the "Optimal Technology Networks for Regional and Urban Utilization of Renewable Resources" research area between August to November 2016. This internship was supervised by Dr. Michael Narodoslawsky in conjunction with Dr. Maarten Arentsen as my supervisor in the University of Twente.

I would like to thank Dr. Narodoslawsky whose expertise and feedback were invaluable for the direction of this work and the analysis of the results. Special thanks to Stephan Maier whose experience and insight contributed with valuable ideas and discussions for the execution and improvement of this work. Furthermore I would like to thank to the entire department, whose kindness and cordiality made this experience very satisfying and enriching.

II. Abstract

Mitigation of climate change effects is one of the main tasks of this a future generation. Therefore responsible and sustainable energy planning is needed at every level (national, regional and local). In order to so, is necessary to incorporate in the current vision of planning the following elements: carbon mitigation, provision of energy services as basis of planning, energy conservation and efficiency solution in the demand-side, etc.

In the context of this mindset evolution, Ecuador is committed to transform its energy matrix towards renewable and sustainable energy sources. Specifically in the transportation sector (although being an oil-exporting country) its technological infrastructure is not technically sophisticated enough to satisfy the demand of gasoline and diesel. In order to diminish the importation dependence, Ecuador through concrete policies and planning has encouraged the biofuel market and in 2013 the government set the ambitious goal of replacing the transport sector fuel with mixtures starting in 5% progressively to 10% with biofuels (ethanol and biodiesel).

Therefore, in this work sustainable development, energy planning and technology optimization concepts were combined to find an optimum technology network for ethanol production and cogeneration of electricity at regional level in Ecuador. The goal is to find the best combination and utilization of available resources for ethanol and electricity production. In order to do so, a systematic approach combined with "Process Network Synthesis" algorithms and P-Graph method was applied. For the application of these concepts and methodology, it was selected the Muisne region as case study.

First, data collection was made in order to estimate qualitatively and quantitatively the available resource (biomass and solar energy). It was found that is possible to complement the existing agribusiness model of cultivating and selling premium crops with technology that allowed the utilization of agricultural waste from these crops to produce ethanol and cogeneration of electricity. The production route to ethanol of these individual resources was analyzed and combined in order to generate a "technology network" which produces bioethanol as main product. It can be also obtained electricity and organic fertilizer as by-products that add extra revenue for the project.

Once the process design was established, the "Process Synthesis Network" methodology was applied using the PNS Software Studio. This tool allowed generating the maximum possible structure, following the process design and generated optimal and suboptimal solutions taking into account cost minimization or profit maximization.

Based in the results, it can be concluded that with careful planning is possible to establish a financially attractive energy system for ethanol and electricity production using available bio-resources within a region and at the same time contribute to sustainability national goals. Other scenarios were considered too, in order to test how resilient the technology network is with special focus to profit and resource utilization. The parameters or restrictions applied were: maximum profit, maximum ethanol production, introduction of another renewable energy source, change in current feed-in tariffs and forecast of oil market prices.

The scenarios simulation showed that the obtained technology network is resilient to the variations and restrictions applied ensuring the profitability and viability of the project. Special attention deserves the aspect of social contribution in the Regulation for renewable energy feed-in tariffs in Ecuador. This undoubtedly is a substantial contribution for social and community development projects, this itself can be considered as a “driving force” for encouraging and supporting the implementation of these bio refineries with electricity cogeneration in the country.

Keywords: Renewable energy systems, Regional development, Process network synthesis, Green biorefinery.

III. Table of content

IV. List of Tables

V. List of Figures

1. Introduction

1.1. Sustainable development

Nowadays is widely known that climate change represents a serious threat to human population, wildlife and environment. Its consequences can already be felt with impacts such as: loss of sea ice, stronger hurricanes, accelerated sea level rise, severe heat waves, drought, floods, dangerous forest fires, etc. According to the latest IPCC report, the "global carbon budget" which is the amount of carbon dioxide emissions that can be emitted while still having a chance of limiting the global temperature rise to 2 degrees Celsius (above pre-industrial levels) will be exceeded in about 30 years with the current rate of emissions [1].

In order to adapt and mitigate the effects of climate change is necessary to take action and implement effective strategies [2] against it such as:

- Social, ecological asset and infrastructure development,
- Technological process optimization,
- Integrated natural resources management,
- Institutional, educational and behavioral change or reinforcement,
- Financial services, including risk transfer,
- Information systems to support early warning and proactive planning.

1.2. Sustainable energy planning

Among the strategies to alleviate climate change effects stated before, two of them can be highlighted and combined, "infrastructure development" and "integrated natural resources management" into a concept that in recent years has become more and more important, "Sustainable Energy Planning". The goals of this approach are achieve: optimal energy-efficiency, low or no carbon energy supply and accessible, equitable and good energy service provision to user [3].

Therefore is necessary to incorporate in the current vision of planning the following elements: carbon mitigation as key aspect of future infrastructure projects, provision of energy services as basis of planning and not only revenue, energy conservation and efficiency solution in the demand-side, consider environmental and social cost in the decision making process, clear and straightforward communication with all the actors involved, etc.

If these measures are taken some additional advantages can be obtained such as: improvements in air quality due to reduce air pollution, financial saving due to more efficient and responsible energy consumption, new jobs and new partnerships creation (e.g. utilities, private enterprises, financial institutions and local governments) by the growing sustainable industry and its promotion.

In this sense, Ecuador in its latest constitution [4] in several articles ratifies and explicitly states the following about sustainable energy planning:

Art. 15: The State shall promote, in the public and private sector, the use of environmentally clean and non-polluting alternative energies and low-impact technologies. Energy sovereignty will not be achieved at the expense of food sovereignty, or affect the right to water.

Art. 414. The State shall adopt transversal and appropriate measures to mitigate climate change by limiting emissions of greenhouse gases, reforestation and air pollution; it will take measures for the conservation of forests and vegetation, and protect the population at risk.

From a macro point of view, these goals are achieved through the implementation of the National Good Living Plan (2013-2017) [5]. Among its most important points emphasizes:

Objective 11: To ensure the sovereignty and efficiency of strategic sectors for industrial and technological transformation.

Policy 11.1: To restructure the energy matrix under criteria of transforming the productive structure, inclusion, quality, energy sovereignty and sustainability, increasing the share of renewable energy.

1.3. Ecuador's biofuels situation

Although Ecuador is an oil-exporting country, its technological infrastructure is not technically sophisticated enough to satisfy the demand of gasoline and diesel. Therefore these derivatives are exported and subsidized for internal consumption. In the table below a statistical description of this problem can be found:

Table 1: Ecuador fuel supply 2014 [6]

	Consumption in 2014 (million gallons)	Production	Imports
Diesel	1,506	31%	69%
Gasolines	1,396	40%	60%

In order to diminish this importation dependence, Ecuador through concrete policies and planning has encouraged the biofuel market. In 2010 a pilot plan in Guayaquil (most populated city in Ecuador) successfully substituted traditional gasoline for transportation with a 5% ethanol blend. In 2013 the government's ambitious goal of replacing the transport sector fuel with mixtures starting in 5% progressively to 10% with biofuels (ethanol and biodiesel) was proposed.

Nowadays the installed capacity for ethanol and biodiesel production is 36 and 85 million liters per year respectively, however in order to reach the ethanol and biodiesel production target is necessary to increase the production up to 400 and 240 million liters per year respectively [7].

In order to impulse the ethanol production sector, the governmental strategy consists of:

- Fostering of niches and associations
- Increase of cultivable area throughout the national territory.
- Support through the National Irrigation Plan.
- Reconversion of plantations with preferential credits.
- Promotion of associative agribusiness for the establishment of collection centers and distilleries.
- Support for private industry through incentives and tax deductions, etc.

Since Ecuador is a country with great biodiversity and protected natural areas, any technological development is heavily regulated within an environmental management framework trough several laws, regulations and decrees. In a general sense the institutions involved in this legal framework that regulates the biofuel production activity in Ecuador are the following:

- Coordinating Ministry of Production, Employment and Competitiveness
    - Ministry of Agriculture, Livestock and Fishing
    - Ministry of Industry and Productivity
- Coordinating Ministry of Strategic Sectors
    - Ministry of Electricity and Renewable Energy
    - Ministry of Hydrocarbons
- Ministry of Culture and Heritage
    - Ministry of Environment

Therefore in this context, it can be seen that sustainable production of energy (in all its forms) is encouraged, established as a national goal and environmentally regulated in Ecuador. This establishes a secure environment which combined with responsible energy planning will allow the development of energy projects that provide welfare and progress to the country.

2. Background

2.1. First and second generation bioethanol integration

Within the biofuels field in general, is widely known that they are generally grouped into three generations. The first generation biofuels are obtained from typically “food” crops (like corn, sugar, vegetable oil, etc.) therefore, discussion revolved around food competition and security with this energy source. Then, the second generation appeared differing from the first one because, instead of using food sources, this feedstock is composed of waste from the first generation or from crops that are not used for human or animal consumption anymore. Finally, the third generation comprises biofuel production using algae, which has demonstrated much higher yields with lower resource inputs however the technology is still in lab scale.

Given the fact, that specifically second generation bioethanol has obstacles regarding investments cost for its implementation at large scale. The aim is to integrate the second generation into the existing and mature first generation process, in order to maximize the ethanol production. For first generation bioethanol exist two main production processes: wet milling and dry milling. The only difference between them is the initial treatment of the feedstock.

In the dry milling process, the feedstock (grains generally) is milled and slurried with water to form a “mash”, then enzymes are added to decompose the organic matter into more simple sugars. Next is transferred to fermenters where yeast is added for converting the sugar into ethanol and carbon dioxide. Finally the mix is transferred to traditional distillation columns, where the ethanol is recovered from the stillage and concentrated to the desired grade. The difference in the wet milling process, is that the feedstock is previously soaked in water and diluted with sulfurous acid in order to facilitate the separation process, then the subsequent steps are the same that the dry milling process.

For the second generation bioethanol, the conversion process is a biochemical one that uses biological agents such as: specific enzymes, acids or micro-organism. To deconstruct the lignocellulose component of the feedstock, into cellulose and hemicellulose. And then into more simple sugars following the same process than the first generation bioethanol [8]. This is a significant contribution to ethanol production, given the fact that most crop residues have a low economic value, or they are discarded without even being used, incurring in additional disposal cost. In the figure below a typical lignocellulose ethanol production scheme is shown:

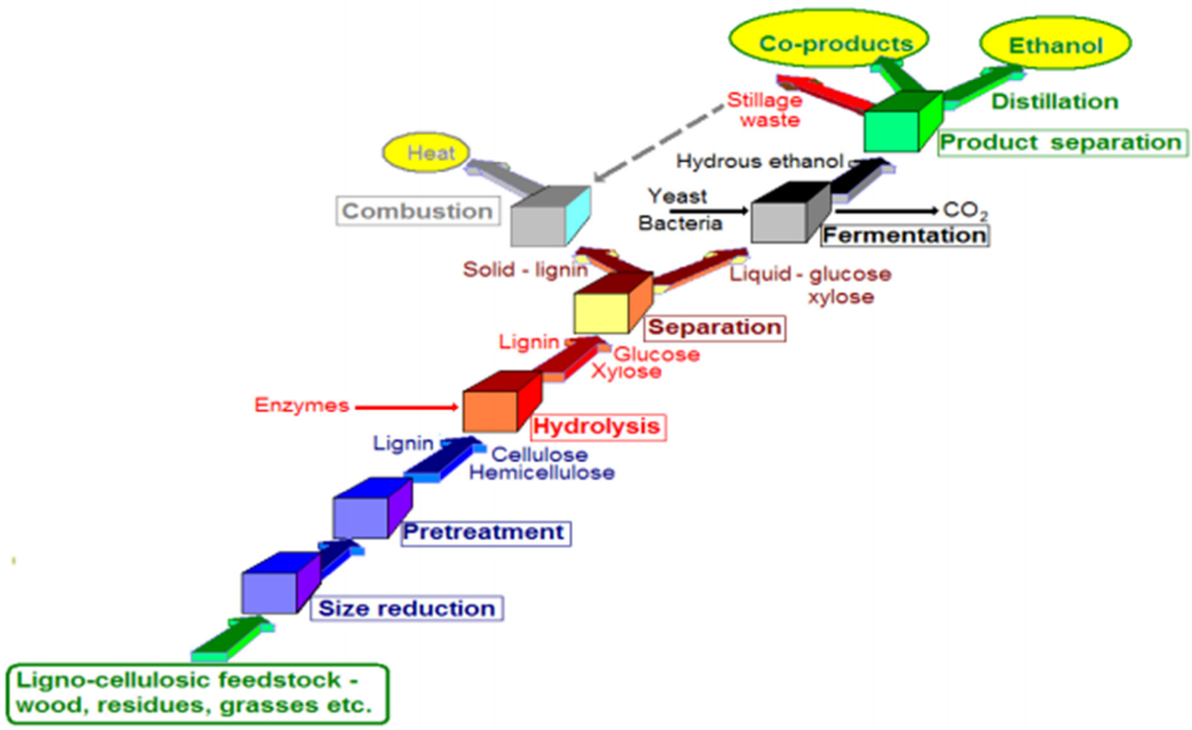


Figure 1: Lignocellulose ethanol production scheme [8]

2.2. Design of integrated processes

In order to design concurrent or integrated processes, it was found in the available literature that the application of systematic methodologies has raised more and more interest and importance. This type of methodology focuses in: the problem definition, descriptive tool to find trade-off in design and evaluation or feasibility (technical and economic).

The methodology consists of three basic steps: generation of the process model, global process optimization and selection of the most interesting process configuration. Specifically for the optimal design of an ethanol production plant with sugarcane in the work of [9] the chosen technique was a multi-variable, bi-objective optimization using and evolutionary algorithms leading to the generation of a Pareto Optimal Frontier (POF) for the optimization problem. This allowed optimizing taking into account two parameters (ethanol production with energy efficiency or with capital costs for example).

However this work is focused more about designing for more than one input resource, turning a usually straightforward problem into a more complex one. The aforementioned methodology did not face the problem of having to select among several inputs to produce the same required product, and at the same time having to optimize the solution in function of an objective (cost minimization or profit maximization for example). This turns this set of individual problems into a network that has to be solved at the same time.

Therefore this methodology is combined with Process Network Synthesis, in order to tackle in a comprehensive and complete way the design of an ethanol plant with more than one resource as feedstock. In recent years, process synthesis method has proven to be the right tool for the task, being implemented in several publications ([10], [11], [12], [13] and [14]).

2.3. Process Network Synthesis (PNS)

Process Network Synthesis is a method to graphically represent the structure of a process which consists of sub-processes which contains in their most simple form the following elements: inputs, outputs and operating units. It uses bipartite graphs called *"p-graphs"* to construct this structure.

The graphical representation of this method assigns horizontal bars to the operating units and solid circles to materials streams (with an arrow in the direction of the flow). An example is shown in the figure below where input materials B and C enter the operating unit O2, resulting in an intermediate who consequently feeds the operating unit O1 to obtain the output material A.

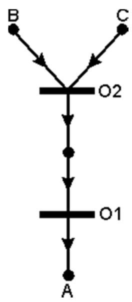


Figure 2: P-graph representation example [15]

Individual processes represented by *p-graphs* obey certain rules or axioms in order to be a feasible solvable-structure of a synthesis problem. The axioms are:

1) Every final product is represented in the graph.
2) A vertex of the M-type (inputs) has no input if and only if it represents a raw material.
3) Every vertex of the O-type (outputs) represents an operating unit defined in the synthesis problem.
4) Every vertex of the O-type has at least one path leading to a vertex of the M-type representing a final product.
5) If a vertex of the M-type belongs to the graph, it must be an input to or output from at least one vertex of the O-type in the graph [15].

Once a process network synthesis problem is formulated, a polynomial algorithm called MSG (maximal structure generation) which is based in the previous axioms, creates the simplest mathematically rigorous maximal structure of the synthesis problem. Which means that the obtained structure is feasible capable of generate the specified product from the materials. In the figure below is shown an example of maximal structure of a complex process network synthesis problem with multiple inputs and outputs.

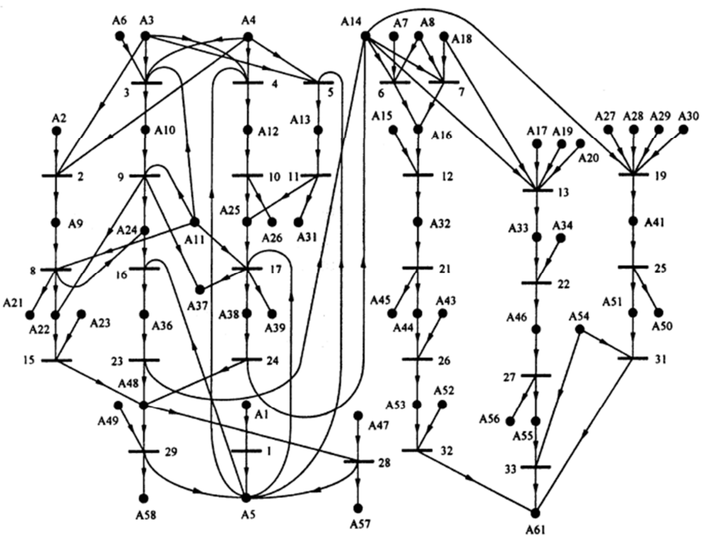


Figure 3: Example of maximal structure [16]

In this maximal structure there are several "pathways" that can be followed to find a feasible solution to the problem, the computational procedure to find all feasible solutions is done by an algorithm called SSG (solution structure generation), however this solutions can be optimized in terms of an objective function.

The optimization is done usually in terms of finding the most reliable process and minimizing cost or maximizing profit. This is done by an algorithm called ABB (accelerated branch-and-bound), this model takes into account: constrains for the operating units, consumption rate of the raw materials and required production rate of the final products are bounded. In the figure below is shown an example of the optimized solution for a PNS problem.

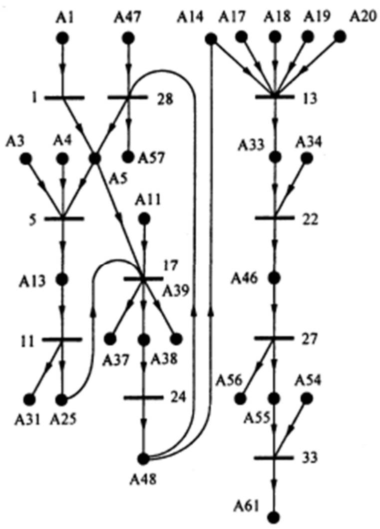


Figure 4: Example of an optimized solution-structure [16]

In the context of sustainable energy and financial optimization, in the following paragraphs a short description and procedure of the tool is shown. This tools use PNS methodology for the solution of Process Network Synthesis problems.

2.3.1.PNS Studio

The previously explained algorithms were implemented in a software called “PNS Studio” which is free and available on the web [17] to computer-aided solve process network synthesis problems. This software is basically composed of a solver and a model analyzer. Easily allows constructing process network synthesis models using a “tree-view” and also editing the properties and units of the materials and operating units, as can be seen in the figure below:

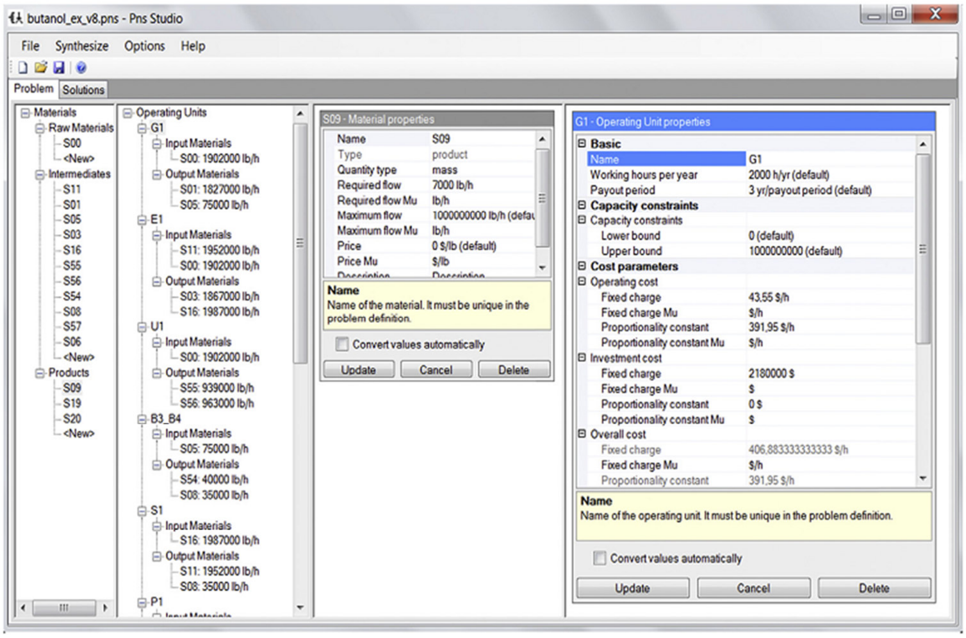


Figure 5: Tree-view and properties edition [18]

After implementing the PNS problem, the solver module generates the maximum possible structure following the combinatorial rule of the specific problem and generates optimal and suboptimal solutions, taking into account cost minimization or profit maximization. If the rates of required product are defined, the solver will minimized the overall cost to achieve the goal, otherwise if the rate of the available materials (with the corresponding price or production cost) is defined, then the profit is maximized (if the optimal cost is negative then the solution is profitable). In the following figure the solver and solution analyzer can be seen:

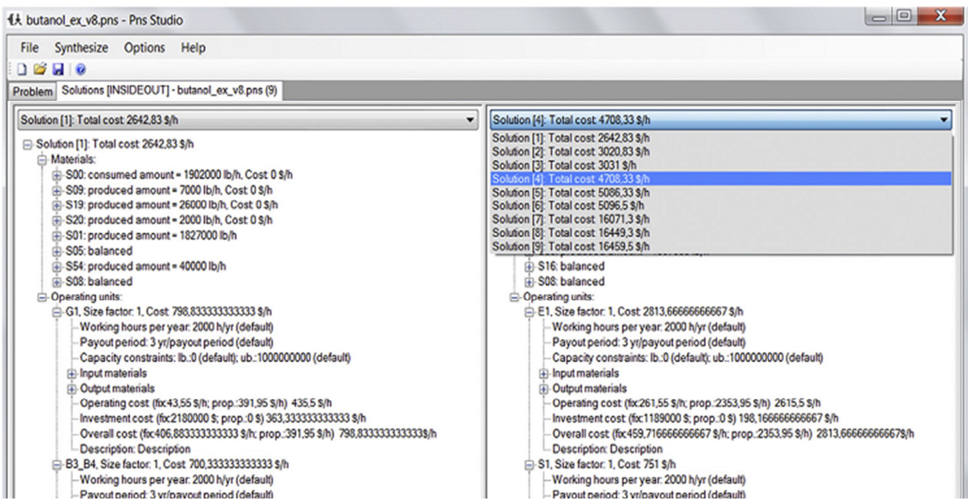


Figure 6: PNS Studio solution view [18]

2.3.2.RegiOpt

RegiOpt in an online tool that supports decision making process in energy planning, by providing optimized technology systems based on the locally available resources. This optimized technology system is evaluated economically and ecologically (through the calculation of the corresponding ecological footprint using the Sustainable Process Index method as well as with the Carbon Footprint) [19].

By changing the quantity and type of input resources (raw materials) and altering several parameters, the tool can calculate the required output products (energy, heating, etc.) and create different scenarios which are useful for example for policy makers, local or regional governments, utilities companies, etc.

The procedure to use the tool is described in the following paragraphs: the first step is to fill a user-friendly questionnaire about the size of the region/settlement, availability of resources, required amount of output products and economic data. The accuracy and validity of the results are bound by the consistency and reliability of the data.

Then the tool enters the data into a pre-defined technology network, which has been previously fed with information and data of conventional and renewable energy technologies. The obtained solution serves as the most economically feasible technology pathway for the region/settlement based on the available raw materials.

In the final step, the tool calculates the ecological footprint of the selected solution using the Sustainable Process Index (SPI) method. This user-friendly tool allows changing in an easy way the input parameters in order to create different scenarios and technology networks which are valuable tools for the decision-making process in energy planning tasks. In the figure below is shown a scheme of the described process.

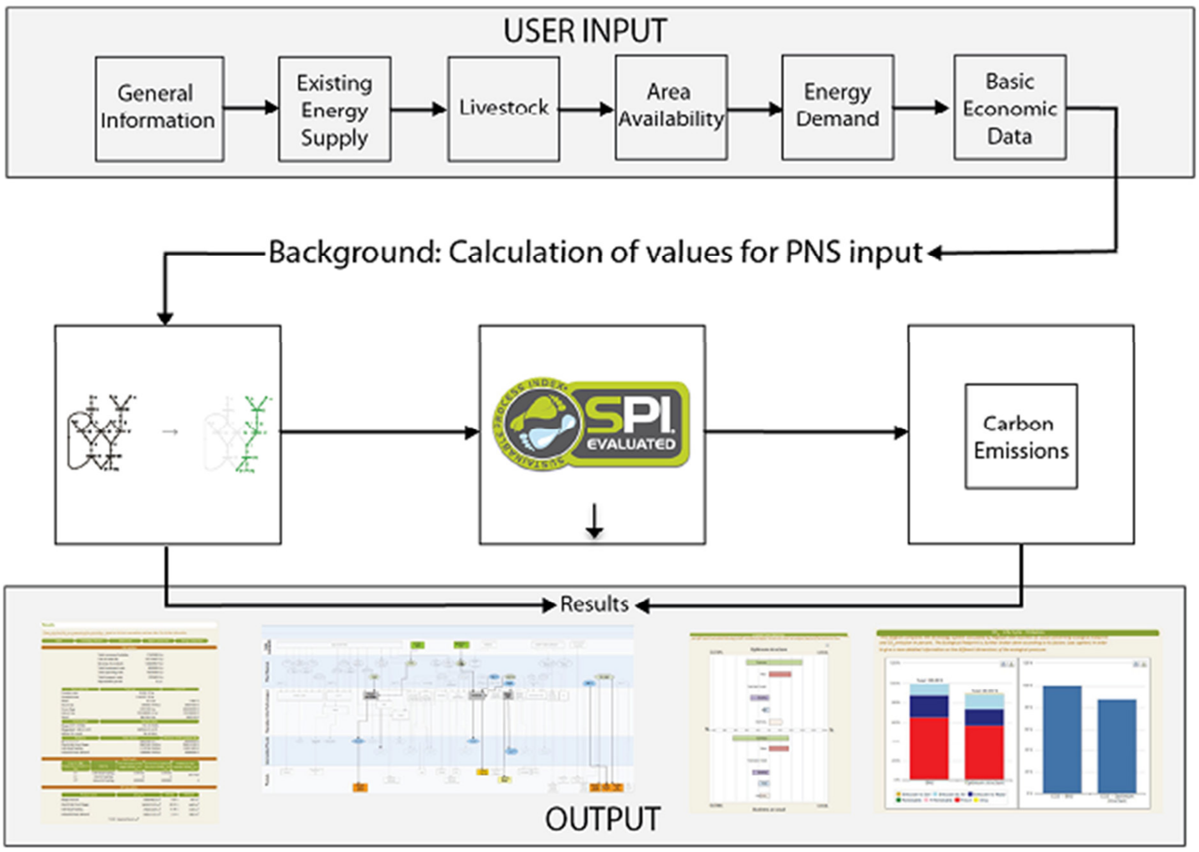


Figure 7: RegiOpt procedure scheme [20]

3. Problem definition

This work has the intention to integrate the aforementioned concepts of: sustainable development, energy planning and technology network optimization into a complete methodology, to design a sustainable technology network for ethanol production with power cogeneration in the Muisne region in Ecuador.

The city of Muisne and the surrounding region located in the Esmeraldas province in Ecuador. This popular beachside city was devastated by an earthquake in July this year, which significantly affected the economic activities in this very important region for tourism. The total area of the region is 1,265 km^2 and the population of the city is 5,925 inhabitants and the main economic activities are agriculture and fishing [21] [22]. Its location can be seen in the figures below:

This study takes into account the availability and quantity of agricultural products and associated waste. The main goal is to produce bioethanol, however electricity production is also desirable and extra revenue from fertilizer as sub-product. The purpose of this work is to stimulate the economic development of this city through the creation of a biorefinery in the region, in order to contribute with high quality products to the growing biofuels market and simultaneously satisfy the energy requirements of the city.

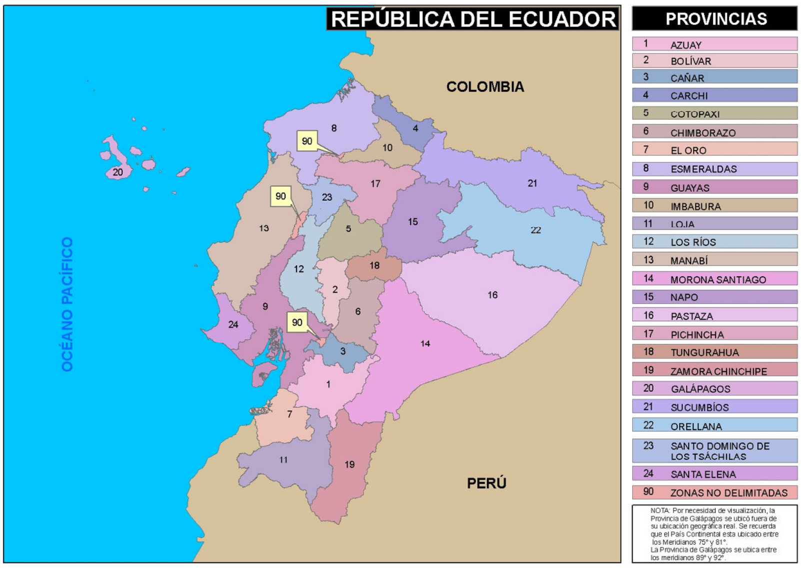


Figure 8: Ecuador political division [23]

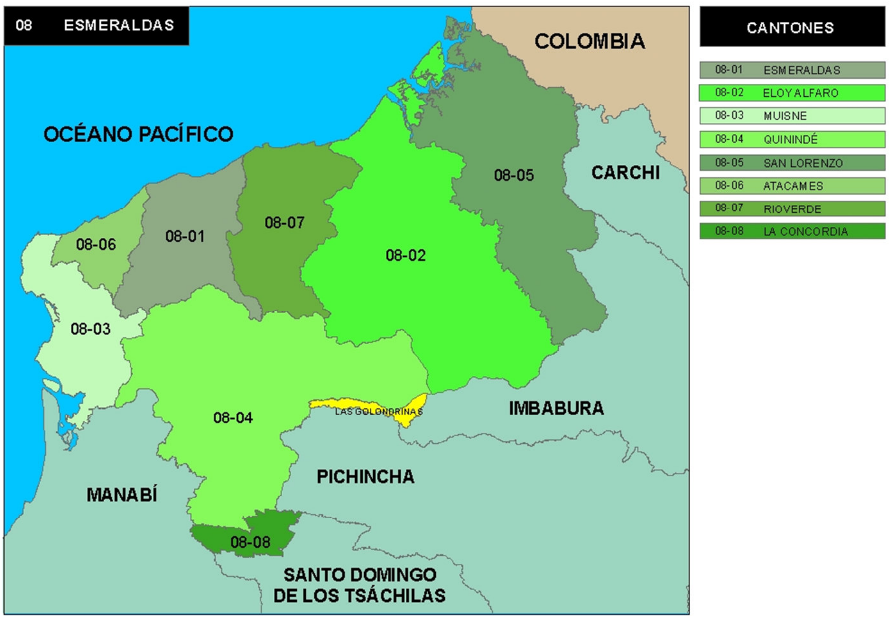


Figure 9: Esmeraldas province regional division [23]

4. Methodology

As mentioned before in the Background section, the methodology applied consists of three major steps. The first step consists of generating the process model which will allow the "thermo-economic" evaluation. Then, the global process optimization is done using the PNS method. And finally in the third step the selection of the most interesting solution and process configuration. In order to find the answer to the research question the following procedure with its corresponding subtasks is applied:

1) Process Model Generation
    - Identification of raw materials and its properties (flows, cost and availability)
    - Identification of required products and its properties (flows and selling price)
    - Definition of the production route and its operating units (capacities, efficiencies and costs)
    - Equipment and supplies cost estimation

2) Process Optimization
    - Preliminary evaluation of the available tools
    - Analysis of preliminary results by trial and error
    - Selection of the applicable tool and case study implementation

3) Process Configuration Selection
    - Baseline scenario solution analysis
    - Application of criteria and constraints to define new scenarios
    - Selection of the optimized solution
    - Discussion and analysis of the results

The implementation of this methodology through the aforementioned procedure, will allow finding the optimal technology network for an integrated first and second generation ethanol production plant with cogeneration of electricity.

4.1. Process Model Generation

4.1.1. Raw materials

The soil in the Esmeraldas state is very fertile allowing the cultivation of many products such as: rice, corn, cassava, banana, cocoa, coffee, sugarcane, African oil palm and several fruits. In the Muisne region there are 87,488 Ha of land which is distributed between different land use categories. The figure below shows this distribution in a visual way:

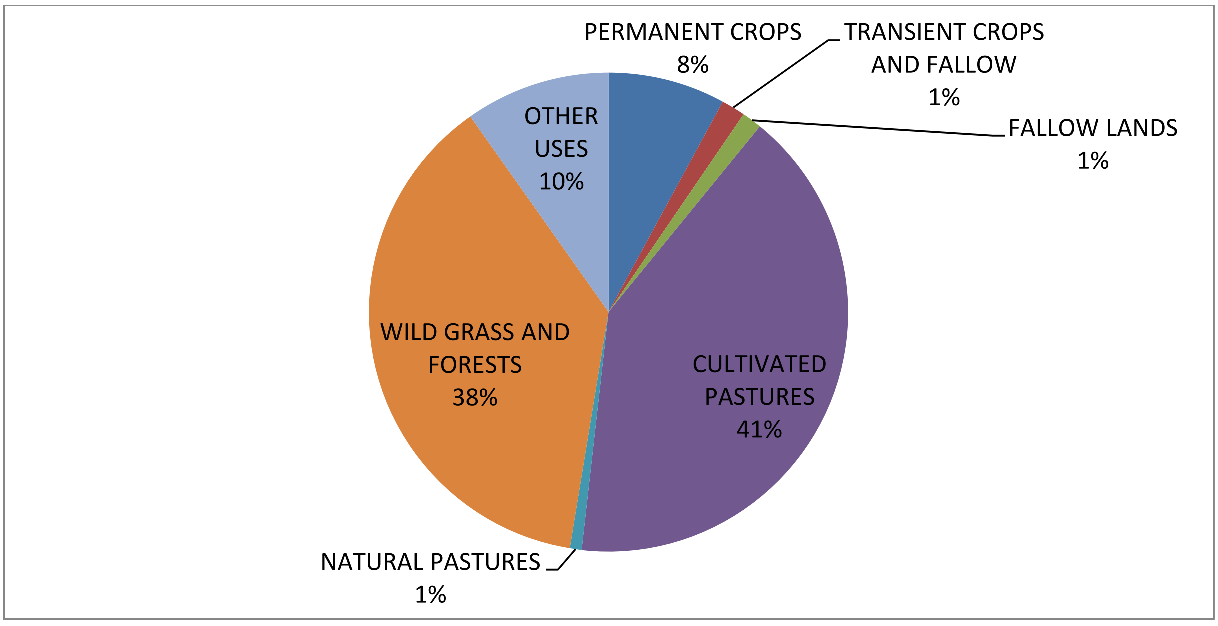


Figure 10: Muisne region land use [24]

In the studied region the most important existing crops are banana, plantain and cocoa. The associated waste to these crops can be used as an alternative for the ethanol and electricity production. A more straightforward way to produce ethanol would be also to use sugarcane in new suitable areas for cultivation. The data is shown in the table below:

Table 2: Feedstock available in the Muisne region [25] [24]

	Harvested surface (Ha)	Production (T)
Banana	4,802	8467
Plantain	1,705	1913
Cocoa beans	3,822	926

4.1.1.1. Banana

Banana is the most important product of exportation in Ecuador, in 2014 exported 27.32% (850,806 T) of the total in the world [26]. This permanent crop grows in tropical humid weather and can be harvested during the whole year. It requires temperatures between 22 to 26 °C and precipitation per cycle of 1,200 to 1,500 mm of water. The cultivated area in the Esmeraldas state represents the 10% of the total in the country [24].

One of the steps before the exportation is the de-handing and selection, where the banana that does not fulfill the required technical and phytosanitary requirements is “rejected”. A portion of the rejected bananas (approximately 17% of the total production) are sold to satisfy the local consumption, another share is used to feed farm animals and in worst case scenario is abandoned in the plantations or in dumpsters [27].

During the processing of the banana a large amount of residues are generated such as: pseudo stem, leafs and peduncles. Especially during the de-handing and cutting operation the peduncle is generated in situ and discarded immediately, as shown in the figure below:

Figure 11: Banana production waste [28]

The juice of the banana peduncle contains carbohydrates, protein and sugars. And it can be extracted through a grinding operation and then used in ethanol production. The peduncle accounts for the 18% in weight basis of the whole fruit. The remaining fiber can be used as input of anaerobic digestion for the production of biogas [29].

The idea behind using banana as feedstock for ethanol production consists of buying the “rejected” bananas from the local farmer and collects all the peduncles from the banana processing (which includes the exportation and rejected ones). In 2014 the production cost for one hectare of banana was USD 8,786.85 where 50.16% represents labor work, 25.25% phytosanitary control, 15.44% harvesting and 9.15% fertilization. Considering the national yield of 37.09 T/Ha, the production cost is 237 USD/T [26]. The summarized data of this resource is shown in the table below:

Table 3: Banana as feedstock

	Production (T/year)	Cost (USD/T)	Remark
Exported Banana	7,070	237	-
Rejected Banana	1,397	237	-
Peduncle	1,533	-	18% of the total Muisne region production [29]

4.1.1.2. Plantain

Despite of belonging to the same family of banana, the plantain is not consumed as a fruit. Is a highly desired product in the local gastronomy due to its salty or sweet flavor (depending on its state of maturation) and can be consumed fried, boiled, baked or broiled. Plantain is grown and harvested in the same way that the banana, also producing a rejected product and peduncles as waste.

Due to plantain is used in the same way than banana, the fruit and the peduncles are combined with the banana in one productive chain. In 2014 the production cost for one hectare of plantain was in average USD 1,615.4 where 33.16% represents cultivation, 29.55% fertilization, 18.6% labor work and 18.69% harvest and phytosanitary control. Considering the national yield of 7.2 T/Ha, the production cost is 224 USD/T [26]. The summarized data of this resource is shown in the table below:

Table 4: Plantain as feedstock

	Production (T/year)	Cost (USD/T)	Remark
Exported Plantains	1,597	224	-
Rejected Plantains	316	224	-
Peduncle	346	-	18% of the total Muisne region production [29]

4.1.1.3. Cocoa

Since the independence days of Ecuador cocoa production was already an important source of income and it was known locally as the "black gold". Ecuador was the world's largest exporter of cocoa until the beginning of the 20th century and nowadays its cocoa is considered the highest quality raw material for chocolate [30].

In 2014 the national production was 228,000 tons and exported 198,776 tons which means that Ecuador is the 3rd world exporter with a 5.58% share [26]. Cocoa is also a permanent crop that can be harvested several times in the year. It requires temperatures between 18 to 34 °C and precipitation per cycle of 1,200 to 3,000 mm of water.

The production process starts with the recollection by hand of the pods twice per year. The pods are split open and the beans (which are covered by a white pulp) are carefully peeled and collected. The empty pods and the pulp are considered waste and are usually left in the open field to rot and nourish naturally the soil as can be seen in the figure, this waste represents 90% of the original waste [31]. From the Cocoa beans, it can be obtained four intermediates products (liquor, butter, cocoa mass and powder) and chocolate as finished product.

Figure 12: Cocoa production waste [32, 33]

The objective is to use this waste to produce ethanol with the pulp combined with the banana and plantain waste in a cellulosic ethanol production process and electricity from the pod husk mixed with banana and plantain waste fiber by direct combustion. In 2014 the production cost for one hectare of Cocoa was in average USD 1,266.54 where 55.36% represents cultivation, 15.22% soil preparation, 12.41% labor work and 17.01% harvest and phytosanitary control. Considering the national yield of 0.57 T/Ha, the production cost is 211 USD/T [26]. The summarized data of this resource is shown in the table below:

Table 5: Cocoa as feedstock

	Production (T/year)	Cost (USD/T)
Cocoa beans	926	211
Pod husk	5,927	-
Pulp	2,408	-

4.1.1.4. Sugarcane

Is widely known that sugarcane is one of the most energy-efficient crop sources for ethanol production. In Ecuador currently exist great support for the massification of this crop for this purpose, in general sugarcane is used for the production of refined sugar and by-products. The sugarcane production in 2014 increased by 16.62% compared to 2013, however the national harvested area decreased by 2.94% although this behavior did not affect production levels due to increased levels of performance 20.14% [26].

This transitory crop grows and can be harvested once a year usually. It requires temperatures between 20 to 32 °C and precipitation per cycle of 1,000 to 2,200 mm of water. The cultivated area in the Esmeraldas is small and does not represent a big economic activity within the state. However is a very interesting resource for ethanol production.

In 2014 the production cost for one hectare of sugarcane was in average USD 2,329.64 where 35.26% represents cultivation, 30.93% labor work, 16.74% fertilization and 17.06% soil preparation and phytosanitary control. Considering the national yield of 85.15 T/Ha, the production cost is 27.36 USD/T [26]. The summarized data of this resource is shown in the table below:

Table 6: Sugarcane as feedstock

	Yield (T/year)	Cost (USD/T)	Remark
Sugarcane	90	27.36	
Trash	-	-	8% of produced sugarcane [34]
Bagasse	-	-	27% of processed sugarcane [34]

4.1.1.5. Solar energy

In recent years it has become more and more common to use solar energy as an energy resource in Ecuador, there are several reasons to justify the use of the solar energy resource in Ecuador, such as:

- Its privileged location close to the equatorial line, receiving radiation perpendicularly which means that the angle of incidence is constant through the year
- The amount of solar radiation is considered moderately high
- Weather conditions are stable and predictable throughout the year, etc.

These reasons support the production of electricity from solar parks as viable and attractive option for the country. Thus, between 2011 and 2012, the CONELEC approved the installation and operation of 17 power generation projects with solar panels in Imbabura, Pichincha, Manabi, Santa Elena, among other provinces for a total of 272 MW of power, which is equivalent to 6% of installed capacity in the country or a quarter of the power of the Paute plant (biggest hydropower plant in Ecuador). The implementation of these projects requires investments of USD 700 million, according to CONELEC's projections [35].

Therefore for the production of electricity in the present study, according to studies and mapping previously conducted on this resource, state that the average global irradiation for Muisne region is 5,250 Wh/m^2/day [36].

4.1.2.Products

Considering the goals of generating income for the region and increasing the production of biofuels, the following desired products were identified: traditional exportation of agricultural products, ethanol, electricity and by-products. In the following paragraphs the selling price and considerations for each product is explained.

4.1.2.1. Exported crops

Following the Ecuadorian agricultural tradition, the preferred market for the commercialization of their crops is the international one, and then in second place satisfies the national consumption. In general terms these products are highly appreciated and widely accepted, each year the share of exported products and the selling price is rising. Therefore in this case study is considered that the premium fruit is exported and the rejected and associated wastes are used for the biofuel and electricity production. The summarized data of the selling prices is shown in the table below:

Table 7: Crops selling price [26]

	Selling price (USD/T)	Remark
Banana	319	-
Rejected banana	210	only 10% can be sold
Plantain	309	-
Rejected plantain	117	only 10% can be sold
Cocoa beans	2,486	-
Refined sugar	33.18	8% of sugarcane in weight

4.1.2.2. Ethanol

In order to stimulate the production of ethanol and the transition to a green economy, in 2015 the Ecuadorian government announced mechanisms for the control and regulation of the biofuel market by law [37]. Among other important points, this law state that progressively gasoline for transportation sector must be replaced by a mix of 10% ethanol and 90% traditional gasoline (hereafter called ECOPAIS), and until the completion of the contract period or until delivery of the contracted volume fixed the ethanol selling price with the following formula:

$$Bioethanol_t = Ethanol\ ARGUS\ USGC\ CIF\ Ecu_{t-1} + K$$

Where:
$Bioethanol_t$: is the price of anhydrous ethanol for the month "t" expressed in United States of America dollars per liter.

Ethanol ARGUS USGC CIF Ecu $_{t-1}$ = average valid daily quotation prices of anhydrous ethanol, fuel grade, for the calendar month before the reception, published in ARGUS, located USGC (US Gulf Coast), plus applicable importation cost of the product to the country, expressed in dollars of the United States per liter.

K: Value defined as an incentive to the productive chain, which considers factors associated with the development production of bioethanol industry, which is eighteen hundredths expressed in dollars of the United States of America per liter.

However it must obey the following conditions:

a) *It shall not exceed the value equals the production costs of gasoline ECOPAIS with production costs of a gasoline with the same octane content without the component anhydrous ethanol, fuel grade (ceiling price).*
b) *It will not be less than a price of USD 0.90 / liter.*
c) *In the event that market conditions present a scenario where the "ceiling price" is below the "floor price", the "floor price" will prevail.*

Considering the aforementioned conditions and the current ethanol market situation, the ethanol selling price for this case study is the following:

Table 8: Ethanol selling price [38]

Ethanol incremental price	USD/liter
Ceiling price	0.5230
ARGUS CIF ECU	0.6427
Floor	0.9
Valid price until July 2016	0.9

4.1.2.3. Electricity

In the same way than ethanol, electricity from renewable sources has a preferential treatment and advantages over traditional energy sources. The government through its regulatory and control agency for energy "CONELEC" stablishes the applicable feed-in tariffs.

The currently one in force is the regulation 001/13 from 2013 which has the distinction to exclude the solar PV one and also set specific capacity for wind, biomass and biogas, solar CSP, ocean energy and geothermal. In 2014, the regulation 014/14 ratifies the aforementioned but stablishes a differentiated tariff for biomass and biogas, and for hydropower smaller than 30 MW. Historical and current tariffs can be seen in the following table:

Table 9: Ecuador Feed-in Tariff scheme [39]

CONELEC Regulation	2000*	2002*	2004*	2006*	2011	2013[$]	2014[$$]
	008/00	003/02	004/04	009/06	004/11	001/13	001/13c***
Tariff[$$$] (USD/MWh)[$$$$]							
Wind	100.5	100.5	93.1	93.9	91.3	117.4	X
Solar PV	136.5	136.5	283.7	520.4	400.3	X	X
CSP	X	X	X	X	310.2**	257.7	X
Biomass	102.3	102.3	90.4	96.7	110.5 (<5 MW) 96 (>5 MW)	110.8	96.7
Ocean	X	X	X	X	447.7**	324.3	X
Biogas	102.3	102.3	90.4	96.7	110.5 (<5 MW) 96 (>5 MW)	110.8	73.2
Geothermal	81.2	81.2	91.7	92.8	132.1	138.1	X
Hydro 30-50 MW	X	X	X	X	62.1	65.1	X
Hydro 10-30 MW	X	X	X	X	68.8	68.6	65.8
Hydro 5-10 MW	X	X	50	50	71.7	78.1	65.8
Hydro < 5 MW	X	X	50	50	71.7	78.1	65.8
* Max Power per project was 15MW for all technologies except for small hydro.							
** Added in 2012 by CONELEC Resolution 017/12							
*** As modified by Resolution CONELEC 014/14							
[$] Max total installed capacity per technology: wind - 100 MW; solar CSP -10 MW; ocean - 5 MW; biomass and biogas (combined) – 100 MW; geothermal – 200 MW; small hydro – no limit.							
[$$] Max total installed capacity per technology: biomass and biogas (combined) – 100 MW; small hydro – no limit.							
[$$$] The Galapagos Islands had differentiated tariffs, for the last feed-in tariff in force it was: Biomass USD 106.4/MWh, Biogas USD 80.5/MWh.							
[$$$$] All amounts expressed in USD in original legislation							

Also the current regulation states that the energy projects that were granted with feed-in tariff must contribute to social and community development projects, the fixed amounts are: biomass $23.8 USD/MWh, hydropower (<30MW) $18.9 USD/MWh, wind $23.9 USD/MWh, solar PV $118 USD/MWh, CSP $87.4 USD/MWh, ocean energy $127.7 USD/MWh, and geothermal $33.6 USD/MWh.

4.1.2.4. Fertilizer

Due to the organic nature of the input one of the most common by-products of bio refineries is organic fertilizer. In the present case study is assumed that this final by-product has the appropriate characteristics to be used safely as fertilizer, quality can be improved by mixing it with waste fiber, leafs or other agricultural waste. In order to stablish a selling price, research for the current prices of commercial fertilizer in the Esmeraldas state was done.

The considered commercial fertilizers are: urea, muriate of potash and diammonium phosphate. Their prices fluctuate between 26 to 38 USD per bag of 50 kg, which represents an average price of 613 USD/T [40]. For this case study has been considered a reduced price of 100 USD/T in order to stablish it as an attractive option for the local farmer and win a share of the market.

4.1.3. Production routes

In order to establish the relationships between the raw materials and the required products is necessary to define the production routes of each raw material and combine them. The goal is to identify among the different production chains common elements (operating units and intermediate products) that can be merged, in this way a “network” can be created which is the input for the PNS Studio implementation phase.

Considering the chemical characteristics of the banana, plantain and cocoa feedstock, which is classified as lignocellulosic biomass, therefore they need a pretreatment process known as hydrolysis (process to breakdown complex sugar chains into smaller and simpler sugars) to be converted first into glucose and then fermented to produce ethanol [41].

The figure shows a schematic diagram of the production network for ethanol, electricity and by-products production: the first step is the recollection on site and transportation to the central facility of the banana/plantain (peduncles and rejected fruit), cocoa (pulp and pod husk) and sugarcane (in scenarios different than the baseline). It has been assumed that the 100% of the peduncles were able to been recovered and after the juice extraction 30% are generated residues.

Latter the feedstock go through a cutting and grinding previous the hydrolysis; according to some research and literature review, the hydrolysis can be done using organic enzymes or inorganic acids. An economic study about the feasibility of these two methods from cassava bagasse (which is also lignocellulosic biomass) shows that the acidic route is cheaper and has similar yield than the enzymatic route [41] [42]. For this step an efficiency of 96% based in lab-scale experiments from [33] was considered.

The next step is the fermentation of the peduncle and fruit juice into ethanol, this process has a global efficiency of 90% [41]. The ethanol is recovered through a distillation process with a yield of 2.7 kg of ethanol from 38 kg of wet biomass [33]. In the case of the sugarcane the fermentation contemplates 90% efficiency.

The pretreatment step generate fiber residues (banana/plantains peduncles, sugarcane trash and bagasse) that can be mixed with the cocoa pod husk to be burned in a CPH unit that produce electricity and heat (in form of superheated steam) to fulfill the steam and electricity consumption of the facility, any excess and be sold to obtain extra revenue. This CPH unit considers energy-to-electricity and energy-to-heat efficiencies of 30% and 47% respectively according to [43]. Specifically in the hydrolysis sub-process, organic waste (with a rich organic value) is generated that can be mixed with the ashes of the CPH combustion and fed into a composting unit to produce fertilizer that can be sold for extra revenue.

In the fermentation and distillation step organic residues and vinasse are generated, and can be processed in a digester in order to produce biogas which can be fed in the previous CPH unit.

Experimental data obtained in average 2,340 liters of biogas (with a 70% content of methane) per ton of wet biomass [33]. In the case of the sugarcane the distillation contemplates 7.2% efficiency and generates 10 liters of vinasse per liter of ethanol produced [34].

The final products of this production network are: ethanol, electricity and fertilizer as a by-product. A schematic drawing can be seen in the figure below:

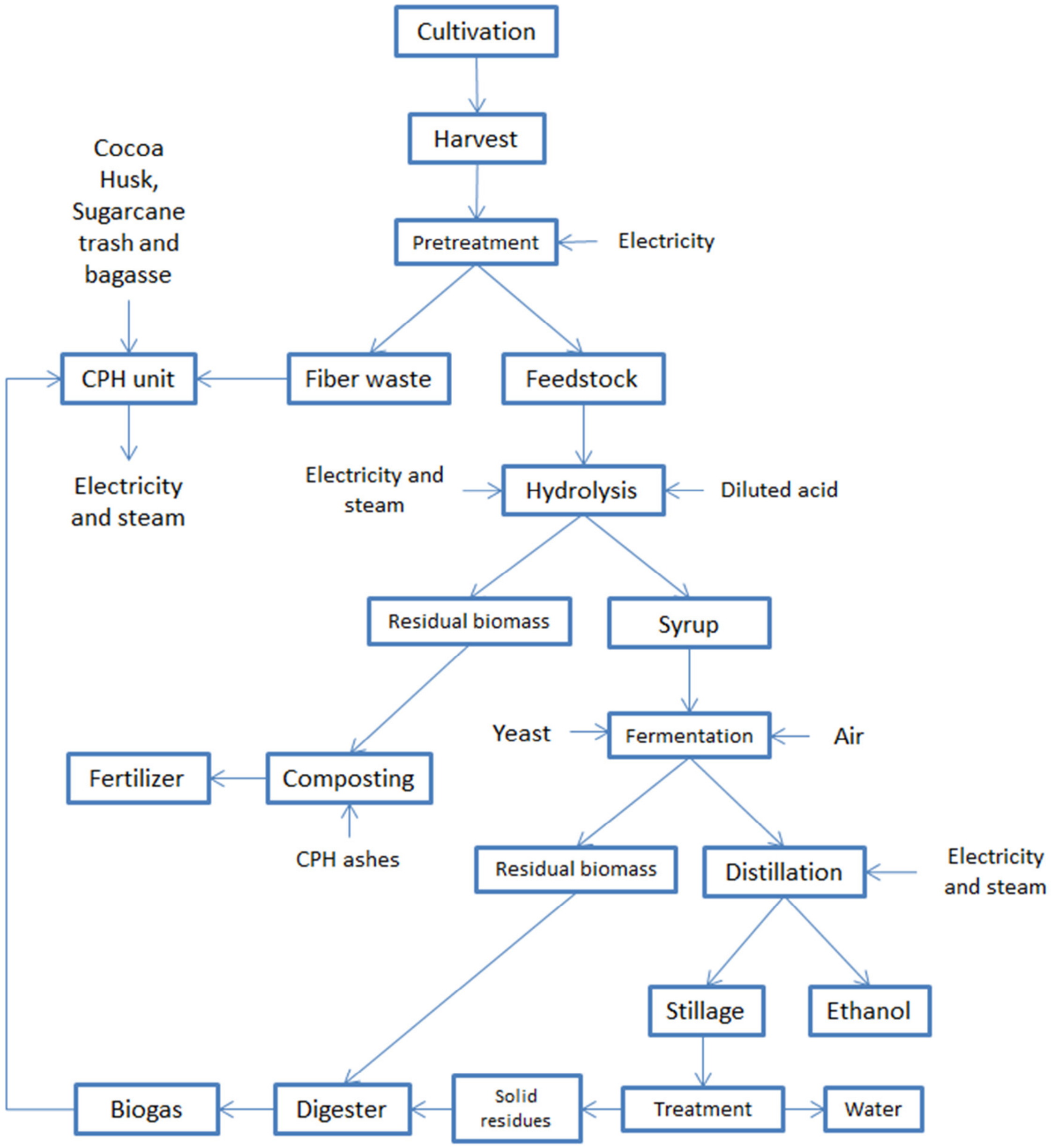


Figure 13: Schematic production network

4.1.4. Costs estimation

Given the fact that the lignocellulosic ethanol process is still in its development and the yields of the different products are based in publications, simulations and bench-scale experiments. Is not possible to find exact cost for the required equipment (also called operating unit) of this facility at commercial scale, therefore is necessary to make an estimation of this cost with the best judgement and reasonable assumptions.

The costing methodology is based in prices for similar equipment (obtained from different public sources or similar studies) corrected for inflation, scaled to the actual capacity of this work and then, their cost scaled using the following exponential correlation:

$$New\ cost = Original\ cost * \left(\frac{New\ size}{Original\ size}\right)^{0.6-0.7}$$

The following assumptions were taken for the estimation of the total cost of the project:

- The plant life is 10 years.
- Baseline scenario plant size is considered as an economically feasible one, with the inputs of the three aforementioned crops to process an estimated capacity of 6,000 ton per year of wet feedstock.
- The plant is new and installed in a greenfield (unused land)
- The online time of the plant is 8,400 hours per year.
- Operating cost are 2% of the equipment cost.
- Fixed indirect costs are 25% of the equipment cost and include: engineering and construction.
- Total cost is the sum of investment, operating and indirect costs per piece of equipment.
- Exported crops transportation costs are included as operating costs in the "selling" operating unit.
- Associated crop waste transportation costs are included as operating costs in the "harvest" operating unit.
- The process needs for electricity and steam per ton of ethanol are 747 kWh and 5,859 kg respectively.
- Chemical costs included in operating cost in the "acid hydrolysis" operating unit.
- Solar PV contemplates a total installed system cost of $2,300 USD/kW for investment cost and 1% for operating costs and a capacity factor of 0.5 due to its exact location in the equatorial zone [44].

Considering the assumptions stated before and the available equipment information from [45], the proportional costs to capacity were calculated and are shown in the table below:

Table 10: Equipment costs

Name	Prop. Oper. cost [$/yr]	Prop. Inv. cost [$]	Prop. Overall cost [$/yr]
harvest_banana	6,339.00	0	6,339
harvest_plantain	1,432	0	1,432
harvest_cocoa	8,616	0	8,616
harvest_sugarcane	1,123	0	1,123
grinder_1	2,746	171,460	19,892
grinder_2	1,044	65,274	7,571
grinder_4	2,746	171,460	19,892
processor_1	8,724	545,278	63,252
processor_2	3,318	207,366	24,055
processor_3	8,912	556,974	64,609
acid_hydrolysis_1	111,166	158,303	126,996
acid_hydrolysis_2	10,298	60,202	16,318
acid_hydrolysis_3	116,595	161,698	132,765
fermentation_1	2,533	158,303	18,363
fermentation_2	963	60,202	6,983
fermentation_3	2,587	161,698	18,757
fermentation_4	2,533	158,303	18,363
distillation_1	3,254	203,392	23,593
distillation_2	1,238	77,349	8,973
distillation_3	3,324	207,755	24,100
distillation_4	3,254	203,392	23,593
composting_1	3,254	203,392	23,593
composting_2	1,238	77,349	8,973
composting_3	3,324	207,755	24,100
composting_4	3,254	203,392	23,593
stoker_chp_1	12,328	770,520	89,380
stoker_chp_2	4,688	293,024	33,990
stoker_chp_3	12,593	787,048	91,298
stoker_chp_4	12,328	770,520	89,380
pv	7,547	754,688	83,016
digester_1	1,754	109,614	12,715
digester_2	667	41,685	4,836
digester_3	1,791	111,965	12,988
digester_4	1,754	109,614	12,715
sell_banana	77,945	0	77,945
sell_banana_rejected	5,776	0	5,776
sell_plantain	26,419	0	26,419
sell_plantain_rejected	1,305	0	1,305
sell_cocoa	13,785	0	13,785
sell_cocoa_rejected	1,532	0	1,532
sell_sugar	4,036	0	4,036

4.2. Process Optimization

4.2.1. Objective function

The objective function selected for the optimization problem is maximizing the profitability of the technology network and as second parameter, the facility ethanol production rate. This choice is supported by the fact that profitability is the best way to convince all the stakeholders involved in this initiative, such as: local government, farmers, local industry, inhabitants and central government.

The installation of this facility will create employment and boost the local economy. At the same time it will provide income security to the farmers, because besides selling their premium fruit in the traditional way, they will obtain extra revenue from the selling of their "rejected" fruit. The region will be benefited with energy security because the surplus of produced electricity can satisfy the whole demand. The government will be benefited by the significant contribution of ethanol to the nation's plant for gasoline substitution initiative.

4.2.2. Tool selection

Applying the defined methodology, and the available data (for resources and the required products). A first attempt of modelling was made using the online tool RegiOpt, in order to obtain: preliminary sizing and composition of the technology network and gross profit.

However the tools proved not to be appropriate from the start, because its user interface is fixed and certain parameters that were required are not applicable in our case study. In the figures below are some examples of the type of information requested is displayed and it is not applicable or relevant to this study:

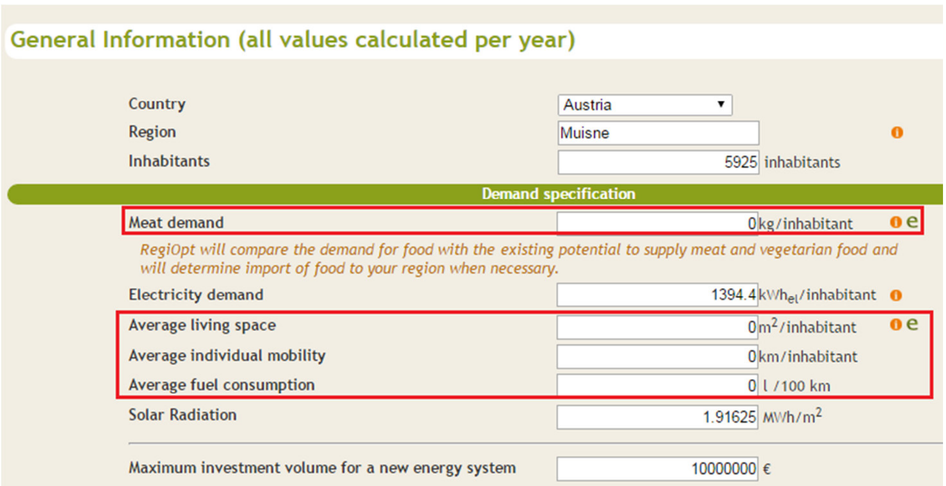


Figure 14: RegiOpt data collection (A)

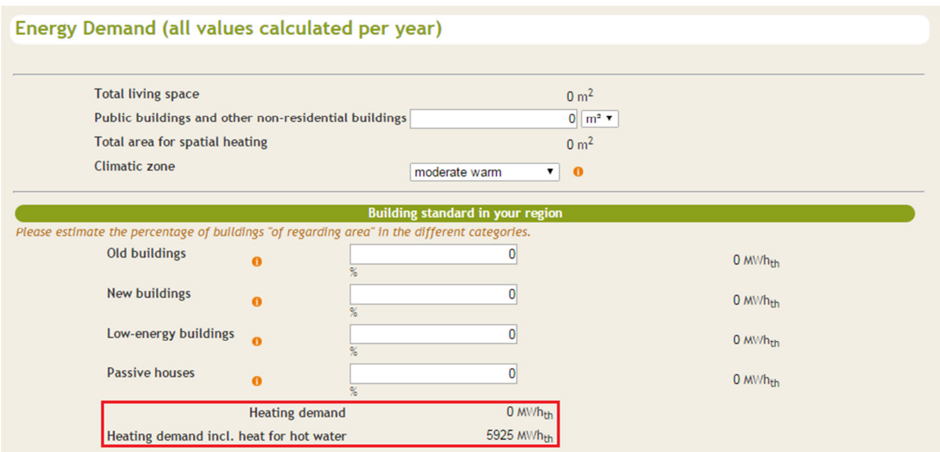


Figure 15: RegiOpt data collection (B)

In the previous figures for example can be appreciated that, the tool requires that “meat demand” is defined so later the amount of pastures needed, for feeding the necessary cattle to satisfy this demand is calculated. In the same figure can be noted that the transportation aspect are also required. It can also be noted how the requirement of heating is set to zero (considering that Ecuador is a country where heating is not needed at all) and nevertheless the total is not reflecting this situation, and instead is fixing a not desired amount.

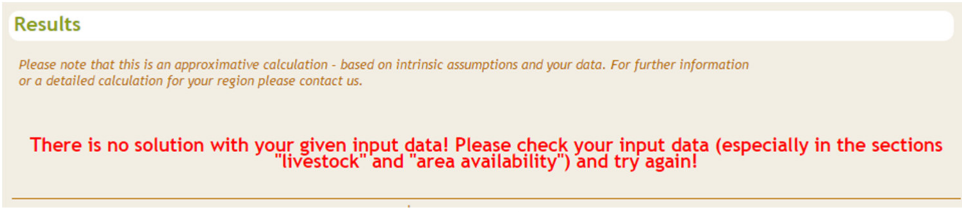


Figure 16: RegiOpt results

These are examples of the complications encountered when trying to use RegiOpt, which ultimately did not allow the tool to find a solution to the problem, as can be seen in the previous figure. Therefore it was concluded that RegiOpt is not the suitable tool for the task.

Another important reason why RegiOpt was not the right tool, it was the fact that is more focused for in a “European” context with a more or less structured technology network and availability of “typical” resources. This argument was reached after trial and error with deliberately varying certain parameters and information in order to try to make the tool work.

Once RegiOpt was discarded, the other available option for modeling the case study was PNS Studio, which is a tool without a fixed structure. This proved to be advantageous in order to implement this specific process network synthesis problem. However more specific information was needed given the fact that RegiOpt in its background had pre stablished technologies with fixed capacities, costs and yields.

4.3. Process Configuration Selection

The last step of this procedure is the selection of the most interesting process configuration, which is a function of the tradeoff between ethanol production rate and profitability. In the following paragraphs a breakdown of the factors that influence these two parameters is mentioned.

Besides maximizing the profitability, the other objective taken into account is the ethanol production. However a trade-off must be done between these two. Changing the ethanol production rate influences directly the size of the whole plant, therefore increasing investments and operating cost sacrificing profitability to cover these extra costs. At the same time the profitability is influenced by the selling price of the ethanol and surplus electricity. These two products have changing selling prices in function of the market, incentives, feed-in tariffs, etc. For the final process configuration selection these two parameters are carefully assessed and discussed.

5. Results and discussion

Considering the schematic production network above a technology network was implemented in solved with PNS Studio (version 3.0.4, 2011). The optimal energy system produces crops selling, bioethanol, electricity and fertilizer. The maximum structure is shown in the Appendix 1.

Without any alteration or restrictions, the business as usual scenario (A1) generates a gross benefit of $1,646,793 USD/year (14.1% net income), calculated considering as the region operates and one big company, paying the production cost of the crops and selling the products at market price (including incentives and feed-in tariffs) considering capital cost spread among a life span of 10 years as well operating cost proportional to the capacity of the equipment (operating units). This gross benefit is a clear sign of the viability and the benefits for the region of this energy system.

The table below shows the input of resources consumption and the yield of the products and by-products. From the results of this first solution, it can be clear right away that selling to the international market the products of the crops is still part of the best solution for the region and the production of: ethanol, electricity and fertilizer for extra revenue.

The surface sowed for these crops accounts for 11,914 hectares of land, which represents only the 14% of available land in the Muisne region. Leaving aside the sold portion of crops, the baseline solution has agricultural resource consumption efficiency of 70.9%. Without the implementation of the bio refinery, all this agricultural waste is simply discarded, and the profit of the region (discounting production and transportation cost) in this scenario (A0) is $ 1,061,820 (10.5% income) which represents the 64.5% of the baseline solution.

Table 11: Baseline inputs and outputs

Category	Item	Flow rate (T/year)
Resource	Banana harvested	8,467
	Plantain harvested	1,913
	Cocoa beans harvested	926
	Agricultural waste	8,332
Products	Banana exported	7,070
	Banana rejected	139.7
	Plantain exported	1,597
	Plantain rejected	31.6
	Cocoa beans exported	833
	Cocoa beans rejected	92.6
	Ethanol	149
	Electricity (biomass)	8,302 MWh
	Fertilizer	1,090

An interesting fact is that, without the feed-in tariff for the sale of surplus electricity and extra revenue from the fertilizer. For the same production of ethanol the revenue decreases to $ 1,071,440 which is still in the same range that the traditional business where only crops are sold and no biorefinery is implemented and nothing is done with the associated waste. This means that the selling of ethanol and electricity at average generation cost (37.62 USD/MWh) still assure the viability of an ethanol production project from agricultural waste.

Adding the selling of 8,302 MWh surplus electricity with the feed-in tariff of 96.7 USD/MWh to the grid, allows the profit to be increased 31% ($ 490,470) and the inclusion of 1,090 T/year of fertilizer in the local market allows to increase the profit a 6.6% ($ 109,006). It is also important to highlight that a big social contribution of 12% ($ 197,581) to local development is generated.

Therefore this solution (scenario A1 in the next table) is established as a baseline because it has demonstrated the viability of the project (with current available resources), which allows further analysis and create scenarios with different restrictions and considerations in order to elaborate a more realistic project and foreseen possible risks that may affect the execution of the project in the future. The optimum structure can be found in the Appendix 2.

In the following graphs a breakdown of the cash flow of the baseline is shown for further analysis. The first thing that stands out is the high participation of the banana and cocoa resources, however they also have a high participation in the profit. The differentiating factor is the fact that in the technology network, cocoa contributes with a remarkable amount of agricultural waste for electricity production. Electricity has a participation of 6.9% against 1.5% for ethanol. Which mean that electricity production and selling is necessary to support ethanol production projects. It should be noted also that in this scenario a 3.7% participation is used for paying investment and operating cost of the whole facility.

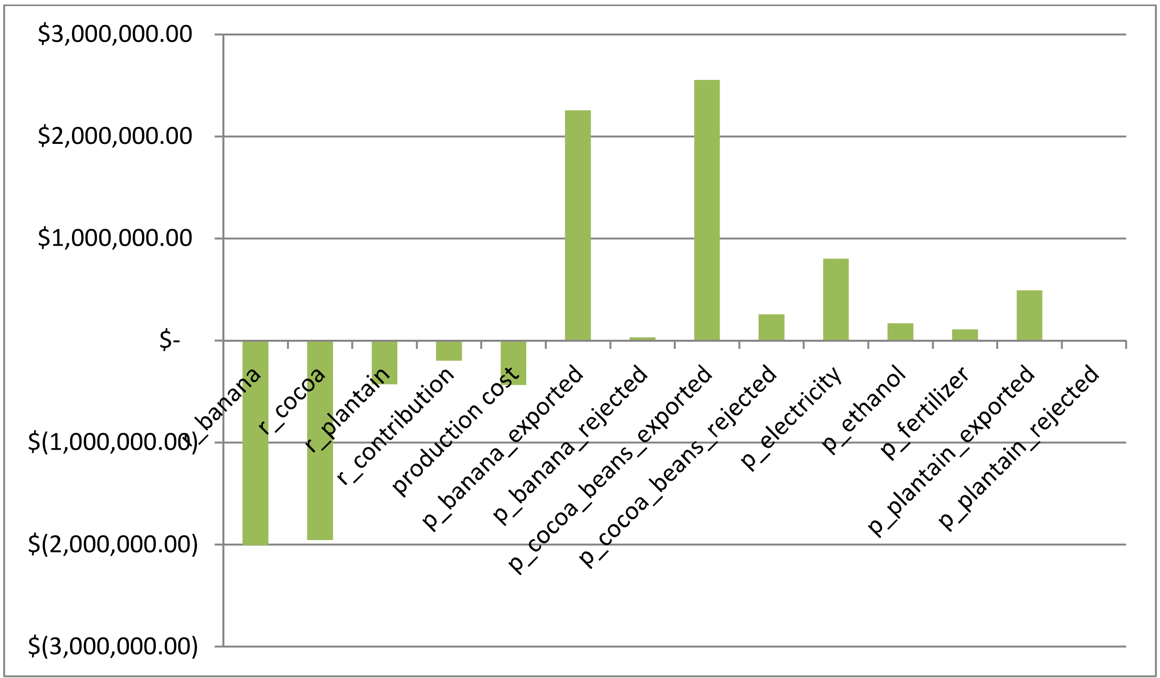


Figure 17: Baseline costs of inputs and outputs

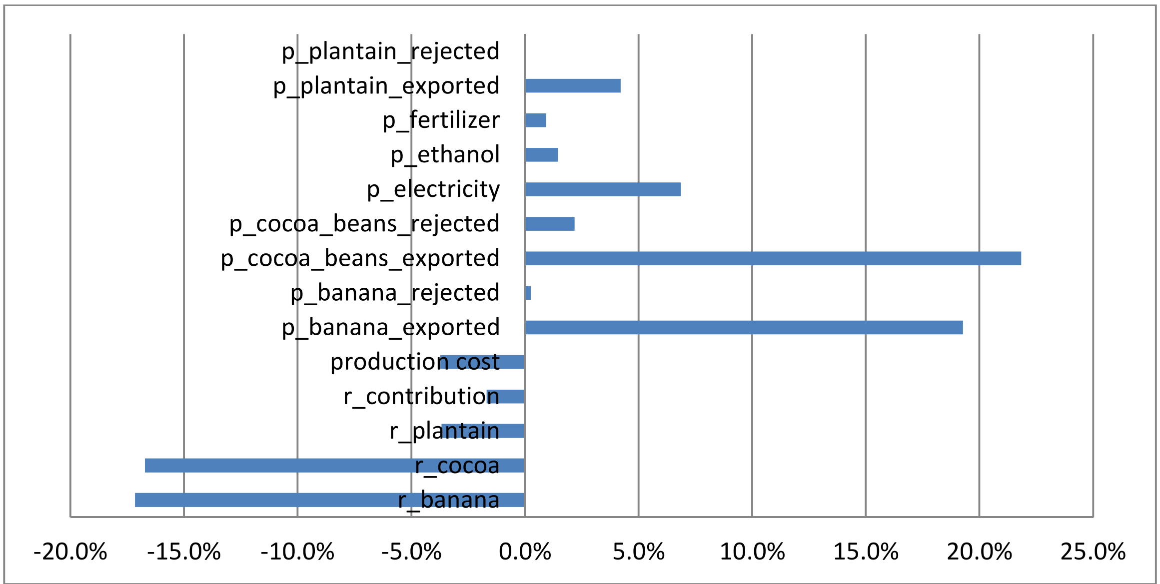


Figure 18: Baseline costs of inputs and outputs in percentage

In the next paragraphs scenarios and results are discussed. The main premise for scenarios definition revolves around increasing the available cultivable area. Then the effect of varying individual parameters was assessed. This was made in order to test how resilient the technology network is with special focus to profit and resource utilization. These parameters or restrictions are: maximum profit, maximum ethanol production, introduction of another renewable energy source, change in current feed-in tariffs, forecast of commodity prices, etc. The following table shows an overview and main results of the different scenarios.

Table 12: Scenarios summary

No.	Description	Resource consumption					Products		Social contribution	Profit		Ethanol	Electricity
		Banana	Plantain	Cocoa	Sugarcane	Area	Ethanol	Electricity		USD	%	%	%
A0	Crops only: sell of premium products to the international market and 10% of the rejected product in the domestic market.	72%	72%	10%	0%	100%	0	0	$ -	$ 1,061,820	10.5%	0.0%	0.0%
A1	Baseline: A0 with production of ethanol and electricity and extra revenue from fertilizer selling.	83%	74%	88%	0%	100%	149	8,302	$ 197,588	$ 1,646,793	14.1%	1.5%	6.9%
A2	Extra revenue excluded: no selling price for fertilizer	83%	74%	88%	0%	100%	149	8,302	$ 197,588	$ 1,561,894	16.2%	1.4%	6.7%
A3	Maximum profit: 100% of the rejected crops are sold in the national market	95%	86%	88%	0%	100%	149	8,302	$ 197,588	$ 1,937,733	16.2%	1.4%	6.7%
A4	Maximum ethanol: 100% of the rejected crops are used for ethanol production	95%	95%	100%	0%	100%	337	8,161	$ 194,232	$ 1,475,360	12.1%	3.2%	6.5%
B1	Available area increased in a 50% and introducing the possibility of using sugarcane combined with the existing crops	95%	95%	81%	64%	150%	273	19,585	$ 466,111	$ 3,782,464	18.6%	1.5%	9.3%
B2	Maximum ethanol: B1 increased available area exclusively for sugarcane for ethanol production	95%	95%	100%	80%	150%	22960	49,163	$ 1,170,087	$ 1,065,192	1.4%	33.7%	6.1%
C1	Past feed-in tariff for solar PV: B1 increased available area and introducing the possibility of using solar PV with the previously eliminated FIT.	85%	71%	100%	64%	150%	5545	876,000 (only solar PV)	$ 103,368,000	$ 199,225,970	37.5%	1.2%	65.9%
C2	No feed-in tariff for solar PV: B1 increased available area and PV with referential generation cost ($ 37.62 USD/MWh).	95%	95%	81%	64%	150%	273	19,584.5 (no solar PV)	$ 466,111	$ 3,782,546	18.6%	1.5%	9.3%
C3	Reduced feed-in tariff for solar PV: B1 increased available area and PV with FIT in agreement with the market.	95%	95%	81%	64%	150%	273	19,584.5 (no solar PV)	$ 466,111	$ 3,782,546	18.6%	1.5%	9.3%
C4	Increased feed-in tariff for solar PV: B1 increased available area and PV with increased FIT ($176 USD/MW).	95%	95%	81%	64%	150%	258	18,478 (biomass) 843,733 (solar PV) 862,211 (total)	$ 100,000,270	$ 3,802,558	1.2%	0.1%	47.1%
D1	Modified ethanol pricing rules: B1 increased available area without current “floor” price for ethanol	95%	95%	81%	64%	150%	273	19,585	$ 466,111	$ 3,755,710	18.5%	1.4%	9.3%
D2	Modified ethanol prices: B1 increased available area without incentive in the price for ethanol	95%	95%	81%	64%	150%	273	19,585	$ 466,111	$ 3,693,440	18.3%	1.1%	9.4%
D3	Forecast ethanol prices: B1 increased available area in low oil price scenario	95%	95%	81%	64%	150%	273	19,585	$ 466,123	$ 3,721,478	18.4%	1.2%	9.3%
D4	Forecast ethanol prices: B1 increased available area in high oil price scenario	95%	95%	81%	64%	150%	273	19,585	$ 466,123	$ 3,725,136	18.4%	1.3%	9.3%
E1	Worst case scenario: A1 available area without: feed-in tariffs for electricity, ethanol incentive and extra revenue.	83%	74%	88%	0%	100%	149	8,302	$ 197,588	$ 1,220,432	11.3%	1.1%	2.9%
E2	Worst case scenario: B1 available area without: feed-in	85%	85%	74%	64%	150%	273	19,495	$ 463,981	$ 2,904,421	15.9%	1.2%	4.0%

5.1. Interpretation of results of the scenarios

Now the baseline is already stablished, the following paragraph describes and analyzes comprehensively the impact of variating parameters in the profit, ethanol and electricity production in order to test the resilience of the technology network. The detailed scenarios data can be found in Appendix 3.

Complementing the baseline A1 scenario, it is interesting removing or imposing new restrictions in this scenario, for example the A3 scenario allows selling the entire “rejected” fruit into the national market to obtain maximum profit. And in the opposite sense the A4 scenario uses all this “rejected” fruit to maximize the production of ethanol. The A3 scenario has an agricultural resource consumption efficiency of 84% generating $ 1,937,733 profit and 149 T/year of ethanol, however the A4 scenario uses 95% of the resources and doubles the ethanol production with a 23.9% profit reduction.

Scenarios in the group B simulate the possibility of increasing the cultivable available area for the current crops and sugarcane. According to the government’s plan for large scale production of ethanol, is planned at national level an increase of 67,500 hectares for 2016. Stablishing a geographical proportion to the Muisne region (represent 8% in area) the minimum area to be increased is 5,400 hectares. In the Muisne region the real possibility to increase the cultivable area is using a share of the area categorized as “natural grassland” which accounts for 16,452 Ha. Therefore for the purposes of the following scenarios, the current cultivable area was increased in 50% or 5,957 hectares.

The B1 scenario shows that, allowing the expansion of existing resources (banana, plantain and cocoa) and the introduction of new sugarcane crops. The obtained yield of ethanol is 273 T/year and an electricity production of 19,585 MWh/year almost doubling the results obtained in the baseline scenario with a combined profit of $3,782,464 USD/year. This was achieved by increasing the share of cocoa up to 235% and planting 2,049 new hectares of sugarcane (considered now on as 100%). This scenario has an agricultural resource consumption efficiency of 67%. The optimum structure can be found in the Appendix 2.

For research purposes the scenario B2 shows the maximum potential of ethanol production, sacrificing profitability and increasing the agricultural resource consumption efficiency to 80% it can be produced up to 22,960 T/year of ethanol (154 times more than the baseline) and 49,163 MWh/year of electricity (6 times more than baseline). This scenario contributes with 29.1 million liters of ethanol per year, which means a contribution of 7% to the national goal.

The group C considers the increased area of the previous scenarios, but allows the introduction of solar energy as source for electricity production. The current feed-in tariff scheme does not consider an advantage for the use of solar PV, however is interesting to simulate different tariffs (past, current and possible future one) and their effect in the results.

In the C1 scenario the previous feed-in tariff of $440.2 USD/MWh was applied, it is clear and obvious that this really “high” tariff shifts the use of almost all the available area for solar PV deployment reaching the maximum quota of 876, 000MWh/year with a record profitability of $199,225,970 USD/year. The remaining area is used for cocoa and sugarcane expansion in order to produce 5,545 T/year of ethanol. This scenario no matter how good performs, is not realistic to implement.

With the current feed-in tariff scheme in scenario C2, the production cost of solar PV electricity is higher than its revenue (applying the standard cost of electricity generation, $37.62 USD/MWh). Therefore no solar PV is deployed, and the results obtained in the technology network are the same that the ones obtained in the B1 scenario.

In the final scenarios of this group, the feed-in tariff parameter was varied until the technology network allowed deploy of solar PV (tipping point). The starting tariff applied in scenario C3 was the highest one found during research, the German system one at $100-140 USD/MWh tariff was applied. However this tariff did not allowed solar PV deployment for the same reason than scenario C2.

In scenario C4, the tariff was progressively increased until the balance was found at $176 USD/MWh which is still high in comparison to the German tariffs. The reason that causes this difference in rates is the fact that under the current Ecuadorian feed-in tariff law, solar PV electricity must pay a social contribution of $118 USD/MWh which considerably reduces competitiveness. The results in this scenario were the same to the one obtained in C1 scenario but the profit was highly reduced to $3,802,558 USD/year mainly because of the social contribution that must be paid, which make it not financially attractive and therefore not viable. The scenarios in this group have an agricultural resource consumption efficiency of 77%.

The group D analyzes the influence of changing the current rules that set the price of ethanol for the increased area scenarios. The current regulation stablishes different types of prices and is interesting to simulate how the results can be affected by factors such as market trends and increasing or decreasing oil prices. Starting with the D1 scenario where the floor price is removed, the applicable ethanol price is $1,042.7 USD/T ($0.8227 USD/liter). In comparison with the B1 scenario the ethanol and electricity production remain constant and an agricultural resource consumption efficiency of 77%, but the total revenue decreases in less than 1% which mean that there is no significant impact in the technology network or the profit.

Because the removal of the floor price did not cause significant impact, the scenario D2 simulates the elimination of the “incentive” component ($0.18 USD/liter) in the price setting formula. This means that the paid price is the same as the cost of importation and shipment to the country from the US market, the applied price is $814.6 USD/T ($0.6427 USD/liter). Keeping the ethanol and electricity production constant in comparison with the B1 scenario the revenue decreases 4%, which is very positive and satisfying because it shows that the profitability is not directly dependent on ethanol incentives.

Generally ethanol prices are also affected by the influence of the oil market. In scenario D3 and D4 this influence was assessed considering a low and high oil price. According to EIA predictions for the year 2020, the ethanol price will fluctuate between $ 917.4-930.8 USD/T ($ 0.72-0.73 USD/liter) [46]. In the same way than the previous scenario the ethanol and electricity production were remained constant, the profitability only decreased 2-3% compared to the B1 scenario. This means that even in the forecasted low oil price scenario the profitability of our technology network is maintained and ensured.

In the course of this discussion we have been individually assessed the impact of the increase in cultivable area, changes in prices and tariffs for ethanol and electricity respectively. Finally in the group E scenarios, the joint effect of eliminating preferential tariffs, incentives in the price of ethanol and extra income from the sale of fertilizer is simulated. The scenario E1 considers the same area, ethanol and electricity production of the baseline case. Under these conditions the overall profit obtained is $ 1,220,432 USD/year which is 26% less than the baseline scenario but 15% more than the scenario where the biorefinery does not exist and the revenue comes only from selling the crops in the traditional way.

In the same way, the scenario E2 considers the same increased area, ethanol and electricity production of the B1 scenario. These conditions reduce the profit 23% to $ 2,904,421 compared to the original scenario. Is clear that, despite removing incentives and preferential tariffs. The technology network has proven its resilience and remains profitable and viable in adverse conditions.

For better comparison, the results are also shown in a visual way in the figures below:

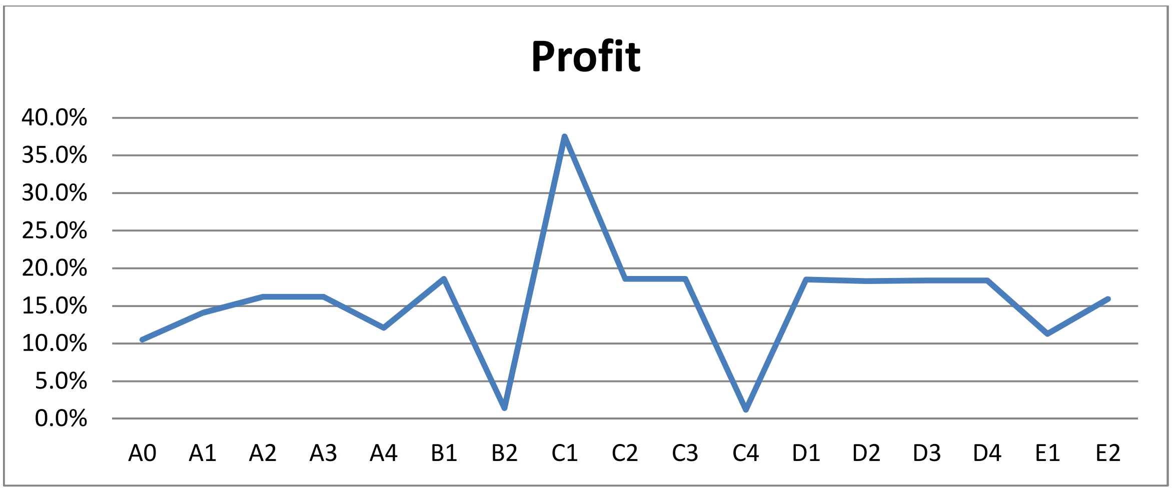


Figure 19: Scenarios profitability

In overall terms the scenarios and their results can be summarized and describes as follow: in group A the optimum process configuration is the scenario A4 because has the best tradeoff between profitability (which is in medium range) and ethanol production is at full capacity. In group B, the B1 scenario is interesting because with the increased area can produce more or less the same amount of ethanol but can almost double the profitability. The group C shows that with current prices of ethanol and market behavior for oil and ethanol, the results are not heavily affected. And finally the E group gives the worst case scenario results, despite the reduce profitability and production of ethanol and electricity nevertheless they are still good for all the stakeholders involved and fulfill the goals of the project.

Special attention deserves the aspect of social contribution in the Regulation for implementing feed-in tariffs for renewable energy in Ecuador. Analyzing the feasible scenarios for short and medium term development, this social contribution for the region varies from $ 194,232 to $ 466,123 per year as can be seen in the figure below.

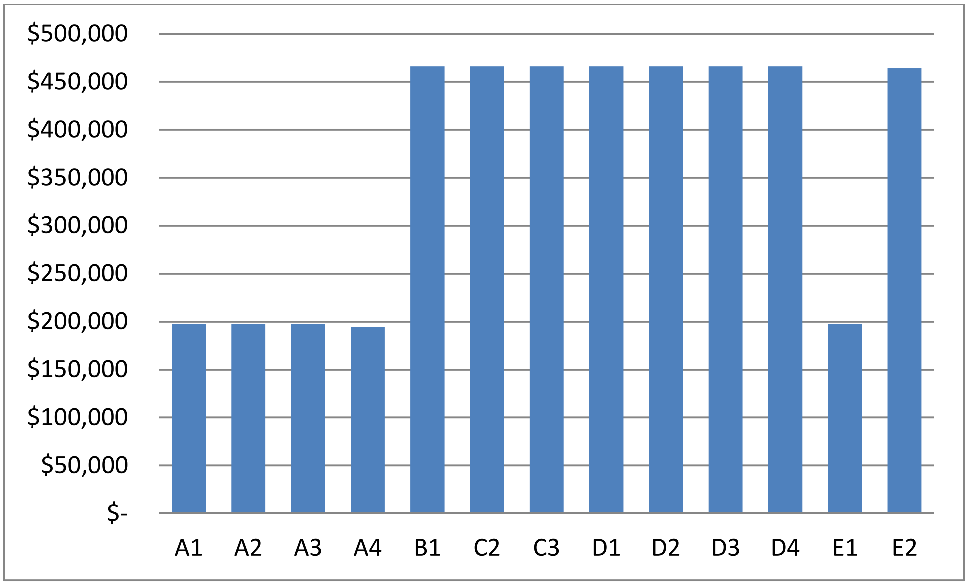


Figure 20: Social contribution

This undoubtedly is a significant amount of money for social and community development projects, this itself can be considered as a “driving force” for encouraging and supporting the implementation of these bio refineries with electricity cogeneration. All elements are in favor: feed-in tariffs, incentives for ethanol production, tax exemptions, central government support, investment protection, etc. Local governments can improve the region economic welfare through these projects and at the same time encouraging social development. However, there are some aspects that still need to be addressed such as: agricultural waste logistics, financing, coordination among stakeholders, etc.

6. Conclusions and recommendations

The results obtained in this work shows that the methodology employed was the correct one. On one hand it allowed an organized and systematic approach to try to answer the research question and at the same time it effectively manage the degree of freedom of the process design, taking into account that the main parameters (resources and final products) were able to be varied significantly producing more than one solution to the problem.

The Process Synthesis Network methodology proved to be very versatile and simple to use, considering all the different configurations that the problem could take. The results were obtained with a short computation time that did not require great computation performance. Therefore is the right tool for one objective optimization when several inputs are considered.

This works shows that is possible with careful planning stablish an energy system using available bio-resources within a region that can fulfill the electricity needs for the urban centers that contain. An interesting fact about this energy system in particular is that it also contributes to a national goal instead of only fulfilling local demands.

It can be concluded that within the framework of this work and the available data, the research question was answered effectively. The generated solutions provided alternative solutions originating an interesting discussion, opening the possibility of taking even further a particular one and elaborate in a more accurate and precise design. The results and particularities of this work give an insight for other regions who wants to assess the possibility of implementing sustainable energy system, or for other design problems that face the same uncertainties of having more than one input available.

The most important conclusion of this work is that this sustainable regional energy system is resilient, profitable and economic feasible. Of course this is linked and influenced by renewable energy policies (feed-in tariffs and incentives), that can make the difference between an economic success or not. Is also important to acknowledge that, by-products of the technology network can influence heavily in the economic success of the project. These products can provide important extra-revenue and provide diversification for the business model of the whole project.

An interesting result about the simulation of the biorefinery is that the electricity cogeneration is major driver in the economic success of the project (attractive feed-in tariff). This work can be framed ideally as a “T shaped” approach, meaning that the positives results obtained so far can be considered “broad” and gives a good indication that this research must continue and deepen in the electricity cogeneration part. Work needs to be done to determine the characteristics and actual feasibility and capacity of the CPH unit, the varied nature of the available biomass is a factor that can greatly influence the design of this part of the system.

This work represents a starting point in the assessment of the feasibility of an ethanol facility with cogeneration. Is strongly recommended to conduct a more detailed process design of the biochemical conversion in order to obtain accurate mass and energy balances. This will allow calculating with more precision the capacities of the individual equipment and their actual cost. This work was limited to ethanol production, however for future work is recommended to assess the oil content of agricultural resources in order to stablish, if it is possible also to produce biodiesel and extent the capacity and diversity of the biorefinery.

In order to extend the analysis and discussion of the obtained results is also recommended as future work, to perform an ecological evaluation of the most promising ones. In order to support the decision making process by quantifying the ecological impact in the region.

Finally is strongly encouraged to further research and predict how the current feed-in tariff scheme and the mandatory social contribution (for redistribution of wealth through community development projects) can shape communities or even large cities through sustainable energy planning. There is the possibility that this may revolutionize and accelerate the way how renewable energy projects are funded and implemented (thereby contributing to climate change mitigation) not only in Ecuador but also in the world.

VI. References

[1] World Resources Institute, "Understanding the IPCC Reports," [Online]. Available: http://www.wri.org/ipcc-infographics. [Accessed August 2016].

[2] IPCC, "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," in *Response options for adaptation*, Geneva, Switzerland, IPCC, 2014, p. 95.

[3] UN HABITAT, ICLEI and UNEP, "Sustainable Urban Energy Planning," in *Chapter 1 - Why is sustainable energy planning important for your city?*, UN HABITAT and ICLEI, 2009, p. 11.

[4] Constituent Assembly. Republic of Ecuador, Constitution of Ecuador, 2008.

[5] National Secretariat of Planning and Development, Republic of Ecuador, Good Living National Plan 2013-2017, 2013.

[6] Ministerior Coordinador de Sectores Estrategicos, National Energy Balance, Ecuador, 2015.

[7] PRO ECUADOR, Instituto de Promocion de Exportaciones e Inversiones, Biofuels, 2013.

[8] IEA, From 1st to 2nd Generation Biofuel Technologies, OECD/IEA, 2008.

[9] R. Bechara, A. Gomez, V. Saint-Antonin, J. Schweitzer, F. Marechal, "Methodology for the optimal design of an integrated first and second generation ethanol production plant combined with power cogeneration," *Bioresource Technology,* no. 214, pp. 441-449, 2016.

[10] L. Halasz, G. Poveden, M. Narodoslawsky, "Sustainable processes synthesis for renewable resources," *Resources Conservation & Recycling,* no. 44, pp. 293-307, 2005.

[11] M. Narodoslawsky, A. Niederl-Schmiding, L. Halasz, "Utilising renewable resources economically: new challenges and chances for process development," *Journal of Cleaner Production,* no. 16, pp. 164-170, 2008.

[12] K.B. Aviso, C.D. Cayamanda, F.D.B. Solis, A.M.R. Danga, M.A.B. Promentilla, K.D.S. Yu, J.R Santos, R.R. Tan, "P-graph approach for GDP-optimall allocation of resources, commodities and capital in economic system under climate change-induced crisis conditions," *Journal of Cleaner Production,* no. 92, pp. 308-317, 2015.

[13] B. Bertok, I. Heckl, "Process Synthesis by the P-Graph Framework Involving Sustainability," *Sustainability in the Design, Synthesis and Analysis of Chemical Engineering Processes,* no. 9, 2016.

[14] L. Vance, I. Heckl, B. Bertok, H. Cabezas, F. Friedler, "Designing Energy Supply Chains with the P-graph Framework under Cost Constraints and Sustainability Considerations," in *Proceedings of the 24th European Symposium on Computer Aided Process Engineering – ESCAPE 24*, Budapest, Hungary, Elsevier B.V., 2014, pp. 1009-1014.

[15] Department of Computer Science and Systems Technology, University of Pannonia, [Online]. Available: http://p-graph.com/introduction/.

[16] F. Friedler, L.T. Fan, B. Imreh, Process Network Synthesis: Problem Definition.

[17] Department of Computer Science and Systems Technology, University of Pannonia, "P-graph Download," [Online]. Available: http://p-graph.com/download/. [Accessed August 2016].

[18] Gerardo Ruiz-Mercado and Heriberto Cabezas, "Chapter 9: Process Synthesis by the P-

Graph Framework Involving Sustainability," in *Sustainability in the Design, Synthesis and Analysis of Chemical Engineering Processes*, Elsevier, 2016, pp. 203-225.

[19] Institute for Process and Particle Engineering, TU Graz, "RegiOpt," Research group: Process Evaluation, [Online]. Available: http://regiopt.tugraz.at/index.php/en/. [Accessed August 25].

[20] Stephan Maier, Michael Eder and Michael Narodoslawsky, "Regional energy optimisation with RegiOpt Conceptual Planner on web," *Symposium Energieinnovation,* February 2014.

[21] "Muisne region Factsheet," [Online]. Available: https://es.wikipedia.org/wiki/Cant%C3%B3n_Muisne.

[22] "Muisne city Factsheet," [Online]. Available: https://en.wikipedia.org/wiki/Muisne.

[23] INEC, "Political-Administrative Division of Ecuador in Maps," [Online]. Available: http://www.ecuadorencifras.gob.ec/category/cartografia-2/.

[24] Ministerio de Agricultura, Ganaderia, Acuacultura y Pesca, "Censos y Encuestas," 2012. [Online]. Available: http://sinagap.agricultura.gob.ec/resultados-censo-provincial. [Accessed August 2016].

[25] INEC, "Estadísticas Agropecuarias," 2015. [Online]. Available: http://www.ecuadorencifras.gob.ec/encuesta-de-produccion-agropecuaria-continua/. [Accessed August 2016].

[26] Ministerio de Agricultura, Ganaderia, Acuacultura y Pesca, "Boletines Agroeconomicos," [Online]. Available: http://sinagap.agricultura.gob.ec/situacionales-de-cultivo-2015. [Accessed August 2016].

[27] Roberto Gonzabay, "Cultivo del banano en el Ecuador," *Revista AFESE 58,* pp. 113-142, 2013.

[28] Ecuaquimica, "Tips en cosecha y postcosecha de banano," [Online]. Available: http://www.ecuaquimica.com.ec/infoagricola.html. [Accessed August 2016].

[29] Marco Pazmino, "Use of banana peduncle as feedstock for ethanol and biogas production," *Master of Science thesis of the University of Florida,* 2014.

[30] BBC, "Is Ecuador home to the world's best chocolate?," BBC News, 6 June 2013. [Online]. Available: http://www.bbc.com/news/world-latin-america-22733002. [Accessed September 2016].

[31] Beckley Nfor, Osric Forton, Thomas Bemu, Peter Verhaert, "Valorization of the byproducts of cocoa production - towards a more sustainable cocoa value chain in Cameroon," [Online]. Available: http://www.foundation-imagine.org/uploads/media/Valorization_of_cocoa_byproducts_in_Cameroon.pdf. [Accessed September 2016].

[32] Image from the web, "Cocoa," [Online]. Available: https://res.cloudinary.com/yuppiechef/image/upload/v1464635946/blog/yuppiechef/Cocoa-pods_jjkt72.jpg.

[33] Carlos Guevara-Bravo, Jose Acevedo-Ruiz, Carlos Pelaez-Jaramillo, "Biorefineria a partir de banano de rechazo: un sistema integrado para la co-produccion de etanol, proteina unicelular, biogas y compost," *Biotecnologia en el Sector Agropecuario y Agroindustrial,* vol. I, no. 14, pp. 78-86, 2016.

[34] Bruna S. Moraes, Tassia L. Junqueira, Lucas G. Pavanello, Otávio Cavalett, Paulo E. Mantelatto, Antonio Bonomi, Marcelo Zaiat, "Anaerobic digestion of vinasse from

sugarcane biorefineries in Brazil from energy, environmental, and economic perspectives: Profit or expense?," *Applied Energy,* no. 113, pp. 825-835, 2014.

[35] CNACE, "17 new solar photovoltaic projects will be installed in Ecuador until 2015," Ecuador National Anti-Corruption Commission, [Online]. Available: http://comisionanticorrupcion.ec/?p=3455. [Accessed September 2016].

[36] Corporacion para la Investigacion Energetica, Atlas Solar del Ecuador con fines de generacion electrica, CONELEC, 2008.

[37] Presidente Constitucional de la Republica Rafael Correa Delgado, "Decreto Ejecutivo No. 675," in *Constitucion del Ecuador*, 2015.

[38] EP PETROECUADOR, "Ethanol Prices," [Online]. Available: http://www.eppetroecuador.ec/?p=2011. [Accessed September 2016].

[39] IRENA, Renewable Energy Policy Brief, Ecuador, International Renewable Energy Agency, 2015.

[40] SINSAGAP, "Agrochemicals Prices," [Online]. Available: http://sinagap.agricultura.gob.ec/productos/precios-agroquimicos. [Accessed September 2016].

[41] H.I. Velasquez Arredondo, A.A. Ruiz Colorado, S. De Oliveira junio, "Ethanol production process from banana fruit and its lignocellulosic residues: Energy analysis," *Energy,* no. 35, pp. 3081-3087, 2010.

[42] A.L. Woiciechowski, S. Nitsche, A. Pandey, C.R. Soccol, "Acid and enzymatic hydrolysis to recover reducing sugars from cassava bagasse: an economic study," *Brazilian Archives of Biology and Technology,* no. 45, pp. 393-400, 2002.

[43] IRENA, "Biomass for power generation," *Renewable energy technologies: cost analysis series,* no. 1, 2012.

[44] IRENA, Renewable Power Generation Costs in 2014, International Renewable Energy Agency, 2015.

[45] F.K. Kazi, J. Fortman, R. Anex, G. Kothandarman, D. Hsu, A. Aden, A. Dutta, "Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol," *Technical report NREL/TP-6A2-46588,* 2010.

[46] EIA, "ANNUAL ENERGY OUTLOOK 2016," [Online]. Available: http://www.eia.gov/forecasts/aeo/. [Accessed October 2016].

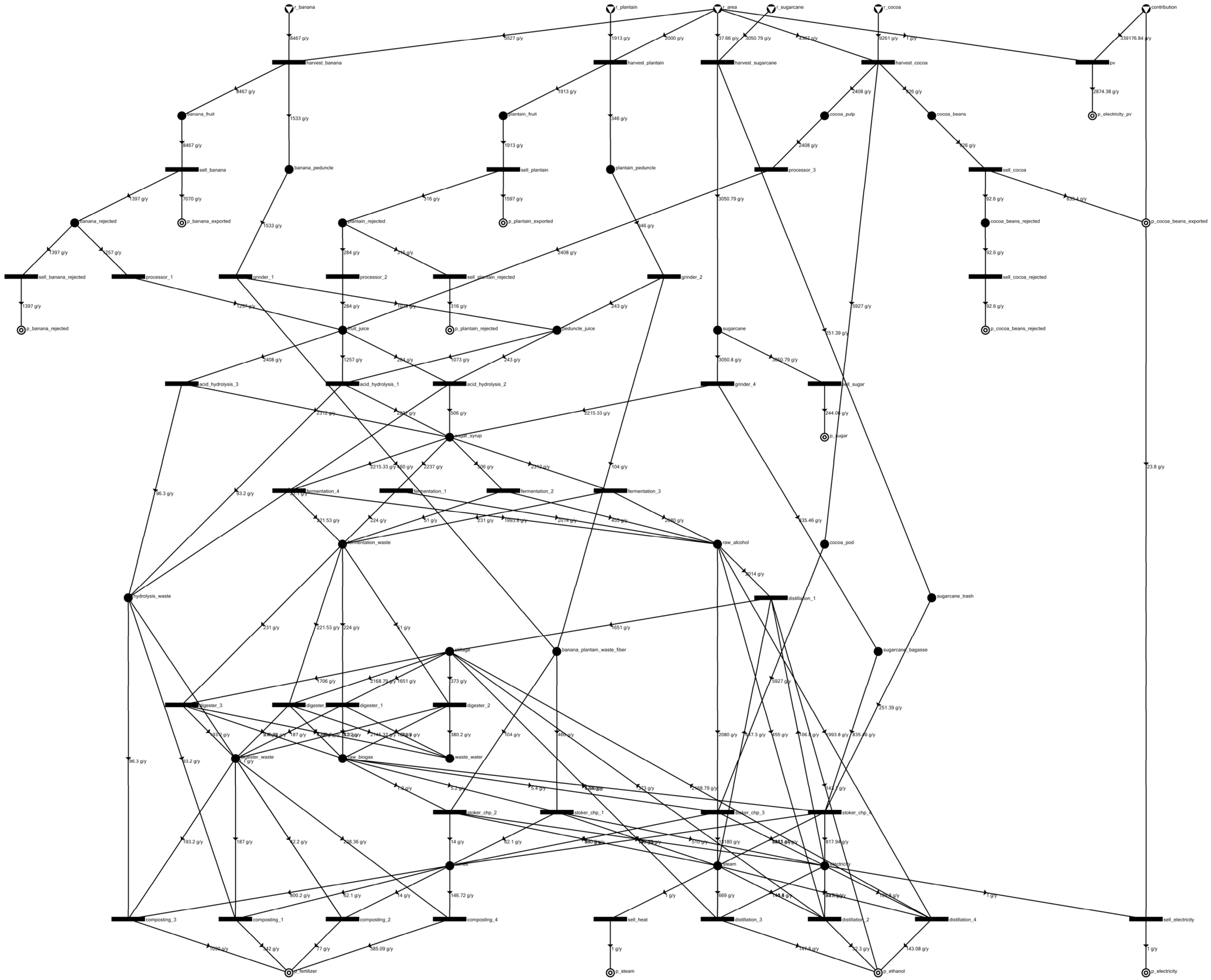
[47] Global Footprint Network, "Footprint Basics," Global Footprint Network, [Online]. Available: http://www.footprintnetwork.org/en/index.php/GFN/page/footprint_basics_overview/. [Accessed August 2016].

[48] Christian Krotscheck and Michael Narodoslawsky, "The Sustainable Process Index. A new dimension in ecological evaluation," *Ecological Engineering,* no. 6, pp. 241-258, 1996.

[49] CONELEC, "Regulacion No. CONELEC - 004/11," 2011.

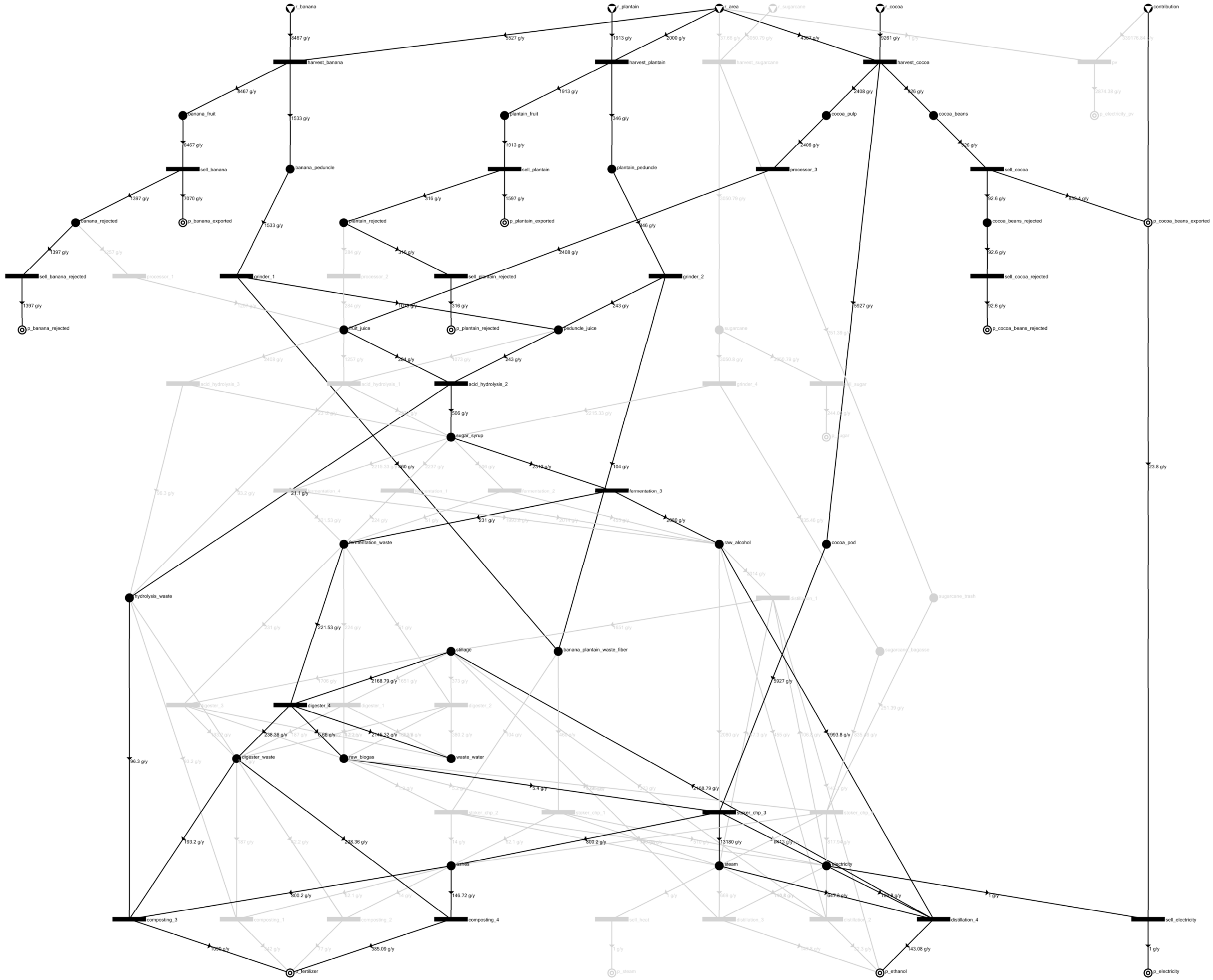
VII. Appendices

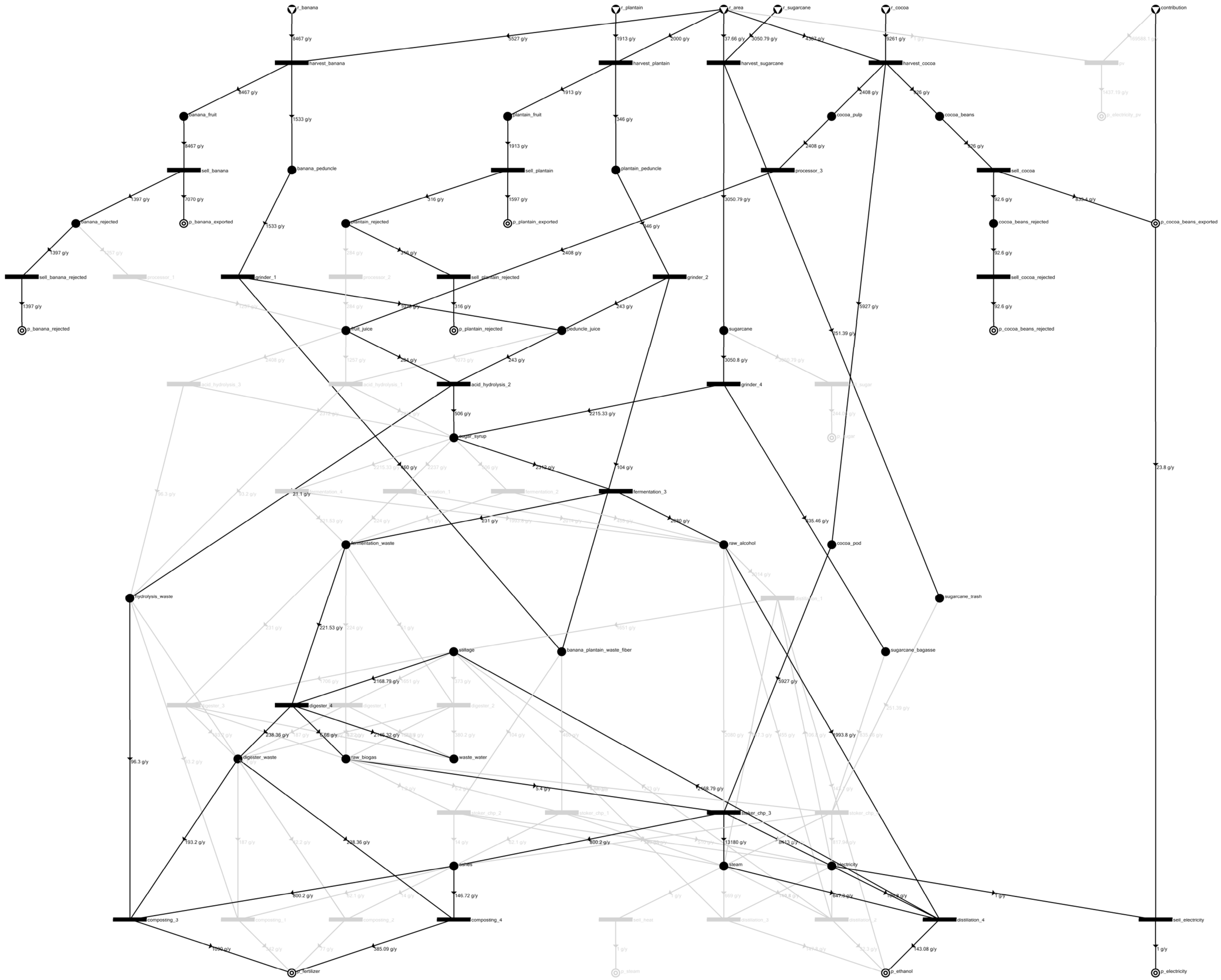
Appendix 1: Maximum Structure



r_banana
r_plantain
r_area
r_sugarcane
r_cocoa
contribution
harvest_banana
harvest_plantain
harvest_sugarcane
harvest_cocoa
pv
banana_fruit
plantain_fruit
cocoa_pulp
cocoa_beans
p_electricity_pv
sell_banana
banana_peduncle
sell_plantain
plantain_peduncle
processor_3
sell_cocoa
banana_rejected
p_banana_exported
plantain_rejected
p_plantain_exported
cocoa_beans_rejected
p_cocoa_beans_exported
sell_banana_rejected
processor_1
grinder_1
processor_2
sell_plantain_rejected
grinder_2
sell_cocoa_rejected
p_banana_rejected
fruit_juice
p_plantain_rejected
peduncle_juice
sugarcane
p_cocoa_beans_rejected
acid_hydrolysis_3
acid_hydrolysis_1
acid_hydrolysis_2
grinder_4
sell_sugar
p_sugar
sugar_syrup
fermentation_4
fermentation_1
fermentation_2
fermentation_3
fermentation_waste
raw_alcohol
cocoa_pod
hydrolysis_waste
distillation_1
sugarcane_trash
stillage
banana_plantain_waste_fiber
sugarcane_bagasse
digester_3
digester_1
digester_2
digester_waste
raw_biogas
waste_water
stoker_chp_2
stoker_chp_1
stoker_chp_3
stoker_chp_4
steam
electricity
composting_3
composting_1
composting_2
composting_4
sell_heat
distillation_3
distillation_2
distillation_4
sell_electricity
p_fertilizer
p_steam
p_ethanol
p_electricity

Appendix 2: Optimum Structure for scenario A1 and B1


r_banana
r_plantain
r_area
r_cocoa
contribution
harvest_banana
harvest_plantain
harvest_cocoa
banana_fruit
banana_peduncle
plantain_fruit
plantain_peduncle
cocoa_pulp
cocoa_beans
sell_banana
sell_plantain
processor_3
sell_cocoa
banana_rejected
p_banana_exported
plantain_rejected
p_plantain_exported
cocoa_beans_rejected
p_cocoa_beans_exported
sell_banana_rejected
grinder_1
sell_plantain_rejected
grinder_2
sell_cocoa_rejected
p_banana_rejected
fruit_juice
p_plantain_rejected
peduncle_juice
p_cocoa_beans_rejected
acid_hydrolysis_2
sugar_syrup
fermentation_3
fermentation_waste
raw_alcohol
cocoa_pod
hydrolysis_waste
stillage
banana_plantain_waste_fiber
digester_4
digester_waste
raw_biogas
waste_water
stoker_chp_3
ashes
steam
electricity
composting_3
composting_4
distillation_4
sell_electricity
p_fertilizer
p_ethanol
p_electricity
8467 g/y
5527 g/y
1913 g/y
2000 g/y
4367 g/y
9261 g/y
1533 g/y
346 g/y
2408 g/y
926 g/y
7070 g/y
1397 g/y
316 g/y
1597 g/y
92.6 g/y
835.4 g/y
243 g/y
5927 g/y
264 g/y
506 g/y
2312 g/y
104 g/y
21.1 g/y
231 g/y
2080 g/y
23.8 g/y
221.53 g/y
2168.79 g/y
238.36 g/y
1.66 g/y
2146.32 g/y
96.3 g/y
5.4 g/y
1993.8 g/y
193.2 g/y
800.2 g/y
13180 g/y
8413 g/y
146.72 g/y
847.8 g/y
1 g/y
1090 g/y
385.09 g/y
143.08 g/y



r_banana
r_plantain
r_area
r_sugarcane
r_cocoa
contribution
8467 g/y
5527 g/y
1913 g/y
2000 g/y
37.66 g/y
3050.79 g/y
4387 g/y
9261 g/y
23.8 g/y
harvest_banana
harvest_plantain
harvest_sugarcane
harvest_cocoa
banana_fruit
banana_peduncle
plantain_fruit
plantain_peduncle
cocoa_pulp
cocoa_beans
1533 g/y
346 g/y
2408 g/y
926 g/y
sell_banana
sell_plantain
processor_3
sell_cocoa
1397 g/y
7070 g/y
316 g/y
1597 g/y
92.6 g/y
833.4 g/y
banana_rejected
p_banana_exported
plantain_rejected
p_plantain_exported
cocoa_beans_rejected
p_cocoa_beans_exported
sell_banana_rejected
grinder_1
sell_plantain_rejected
grinder_2
sell_cocoa_rejected
p_banana_rejected
fruit_juice
p_plantain_rejected
peduncle_juice
sugarcane
p_cocoa_beans_rejected
5927 g/y
251.39 g/y
243 g/y
3050.8 g/y
acid_hydrolysis_2
grinder_4
506 g/y
2215.33 g/y
sugar_syrup
2312 g/y
104 g/y
fermentation_3
21.1 g/y
231 g/y
2080 g/y
835.46 g/y
fermentation_waste
raw_alcohol
cocoa_pod
hydrolysis_waste
sugarcane_trash
221.53 g/y
stillage
banana_plantain_waste_fiber
sugarcane_bagasse
2168.79 g/y
digester_4
238.36 g/y
5.86 g/y
2145.32 g/y
1993.8 g/y
digester_waste
raw_biogas
waste_water
96.3 g/y
5.4 g/y
boiler_chp_3
193.2 g/y
13180 g/y
8613 g/y
800.2 g/y
ashes
steam
electricity
146.72 g/y
1 g/y
composting_3
composting_4
distillation_4
sell_electricity
1030 g/y
585.09 g/y
143.08 g/y
p_fertilizer
p_ethanol
p_electricity

Appendix 3: Scenarios Detailed Solutions

Scenarios Rates, Materials, and Operating units data in the following excel files:

A0.xls
A1.xls
A2.xls
A3.xls
A4.xls
B1.xls
B2.xls
C1.xls
C2.xls
C3.xls
C4.xls
D1.xls
D2.xls
D3.xls
D4.xls
E1.xls
E2.xls