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# A Technical-economic Analysis of Wood Gasification for Decentralized Power Generation in Colombian Forest Cores

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## Abstract

This work presents a technical-economic analysis of several biomass gasification-based power plants for decentralized generation. The major aim is to make a preliminary evaluation of their feasibility in the Colombian context by means of the cost of electricity (COE). The analysis was conducted using information provided directly by power plant manufacturers from four continents (Africa, America, Asia, and Europe). A silvicultural analysis of the major commercial forest plantations in Colombia allowed to determine suitable forest crops for energy projects, with energy potentials ranging from 500 kWe to 2000 kWe. Results from the study show that COE varies from 10.2 cUSD/kWe-h to 40.8 cUSD/kWe-h, depending on the technology used. For lower cost plants, the share of investment cost in COE is of 45-50%, whereas for more expensive technologies it is of 63-67%. The methodology used provides technical, economic, and energy support to make informed decisions regarding the best technology for small-medium power applications using biomass.

**Keywords:** biomass gasification; decentralized power; electricity generation cost; forest commercial crops; forest residual biomass.

## 1. Introduction

About 80% of world energy consumption is supplied by coal, oil and natural gas [1–3], which makes energy-related carbon emissions a significant contribution to the global warming effect. Consequences of this environmental problem on climate and society can be severe if no measures are taken to mitigate $CO_2$ emissions [4, 5]. In this context, renewable and hybrid renewable-fossil energy systems appear as a suitable alternative, given that they are the low-carbon option per excellence [6, 7].

Electricity generation from biomass has become a renewable alternative worldwide [8, 9]. For developing countries, the use of biomass in fixed bed downdraft gasifiers has the potential to become a valuable route to supply electricity in regions that are not connected to the electrical grid [10, 11]. It promotes the economic development of these regions and improves the quality of life of their inhabitants [12]. Furthermore, biomass has been one of the most promoted renewable energy sources due to its versatility (solid, liquid, and gaseous biofuels) [13] and widespread geographical distribution [14–16]. Biomass can also support changes of load and power demand in power systems due to its availability for storing. The targets that must be reached to use biomass as feedstock for bioenergy projects are to reduce capital investment cost of technology, and to ensure availability, quality and low cost of the solid biofuel [17].

Technical-economic analysis of biomass-based electricity generation is an important tool in decision making [18]. Several researchers have used such models to assess the feasibility of bioenergy projects. Mc. Gowan [19] considers the cost of technology, operating costs, fuel cost, importation and taxes. Moreover, for financial evaluation, he analyzed the local market conditions, sale price of electricity, taxes on income, and the existence of subsidies or tax incentives. This information allows obtaining the cost of generation, as well as typical indicators such as net present value (NPV), internal rate of return on investment (IRR), and cash flows, among others.

Several studies have performed feasibility analyses of bioenergy projects by means of the estimation of generation cost (USD/kWe-h). Coronado *et al.* [20] conducted a technical-economic analysis of a cogeneration system based on gasification coupled to an internal combustion engine to produce electricity (15 kWe), and hot/cold water. The generation cost reached values between 4.1 and 10 cUSD/kWe-h. Yagi and Nakata [21] studied the economic feasibility of combined heat and power systems (CHP) in a rural area of Japan. Feasibility was defined by four optimal conditions: plant size, location, number of plants and lower generation cost. The optimal gasification plant could produce 180 kWe with a generation cost of 19.1 cUSD/kWe-h.

Gasification is a suitable alternative for small power plants (< 1000 kWe) due to its higher energy efficiency in regard to combustion, among other factors [21]. When considering biomass gasifiers coupled to internal combustion engines, three cost categories stand out by their impact on the cost of electricity (COE), they are the investment, fuel, and operation and maintenance.

Investment cost of the power plant is determined by the commercial value of the plant. It can be taken as total plant cost [14, 22], or it can be divided according to the units that make up the system: gasifier, engines, and additional components [23]. In order to get a detailed break up of this cost, it can be divided into specific sub costs, such as civil works, piping, controls, etc. When detailed information is not available, the usual approach is to use a factor to obtain total plant cost from the cost of equipment, which varies between 1.5 and 2.3 for fixed bed gasification at atmospheric pressure [24].

Fuel cost is a determinant factor for the COE, given that it is the feedstock of the power plant, and because it is used in large amounts, especially at higher power outputs. This cost depends on the origin of biomass, as well as transport and processing needed to set it ready for use on site. The cost of wood planted in Colombia is between 60 and 90 USD/ton, depending on the species and silvicultural management [12]. The cost of waste wood resulting from commercial wood shaping varies between 0 and 30 USD/ton, depending on pretreatments (drying and chipping) needed for its energy use [12]. It is important to highlight the lower cost of waste wood with regard to harvested wood.

The operation and maintenance costs include labor costs, maintenance procedures, replacement parts, and minor consumables such as lubricants and refrigerants. This information is known in detail for existing plants, and can be estimated as a fraction of commercial plant cost in feasibility analyses. A typical figure is 5% [22], although it depends on plant size and its level of complexity [22, 25].

Some works report that investment cost of the plant may represent about 40% of COE, fuel cost may range from 35% to 45%, and operation and maintenance costs between 15% and 25% [23, 24]. Additional factors that affect generation costs are taxes, depreciation, legal and logistic aspects, and subsidies. These kind of variables affect the financial analysis and allow obtaining NPV and IRR [19, 26–29]. These factors are not included in the present feasibility study, which focuses on providing a selection tool for bioenergy projects using as main indicator the cost of electricity (USD/kWe-h), based on technical and energy criteria, as well as on commercial prices of technology.

In this work we develop a comparative technical and economic analysis of several biomass gasification-based power plants for decentralized generation. The most promising forest species for energy use in Colombia are identified by analyzing the main commercial wood plantations. The analysis includes power plants from manufacturers of four continents, using reliable technical and economic information provided directly by them. This work combines silvicultural analysis, energy potential of waste biomass, and a technical-economic analysis with the aim of providing reliable preliminary information to assess the feasibility of small-medium scale bioenergy projects in the Colombian context, which can also be useful to assess future projects worldwide.

## 2. Materials and Methods

### *2.1. Forest commercial crops (FCC) and waste wood in Colombia*

The use of biofuels has raised controversy because of the resulting pressure on native forests in tropical regions. This pressure comes from deforestation or degradation caused by overexploitation for energy use, or by the conversion of wild vegetation areas to food or energy crops [30–32]. This phenomenon is a driver for deforestation and may compromise food supply of nations [33]. An alternative to mitigate these adverse effects is to establish energy crops in areas with poor soil conditions, which are not apt for agriculture.

There are about 50 million hectares of forest in Colombia, but these are not feasible for sustainable energy generation, given the risk of deforestation and loss of biodiversity. For this reason, this study is focused on commercial, sustainable and legal forest plantations [12]. In Colombia there is a potential of about 16 million hectares not covered with wild forests, which are apt for bioenergy forest crops [34]. Location of the most relevant forest cores with planted areas above 1000 ha is presented in Figure 1, showing not interconnected zones to the electrical grid (NIZ) [35]. In Figure 1, the commercial forest crops are classified as a function of their size and their planted wood species, using capital letters from A to M, as follows: *Pinus patula* (A), *Tectona grandis* (B), *Pinus sp.* (C), *Pinus oocarpa* (D), *Pinus tecunumanii* (E), *Pinus caribaea* (F), *Eucalyptus sp.* (G), *Acacia mangium* (H), *Tectona grandis* and *Acacia mangium* (I), *Pinus patula* and *Cupressus lusitanica* (J), *Gmelina aroborea* and *Pachira quinata* (K), *Pinus caribaea*, *Eucalyptus sp.*, *Acacia mangium* (L), and *Pinus sp.* and *Eucalyptus sp.* (M).

The information from this map shows that practically no raw or waste wood from commercial plantations can be used for electricity generation at NIZ under current conditions. This is because of the location of commercial plantations, which in general are near big cities. Wood from those plantations is used in the paper industry, furniture production, and for exportation.

**Figure 1.** Location of forest commercial crops and not interconnected zones in Colombia.

Nevertheless, the results from the present study are useful for decentralized generation and energy production from biomass gasification in the forest industry, agriculture, and textile or food industries, among others. According to Colombian regulation, biomass is one of the major renewable energy sources [36]. Therefore, it is necessary to develop methodologies to assess and compare technological alternatives for bioenergy projects, based on reliable regional and commercial information.

Forest crops were analyzed considering the following variables: 1) Extension (ha): Power generation potential is proportional to crop size and therefore depends on the production of raw or waste wood. 2) Mean annual increment (MAI, $m^3$/ha/year): Growth rate is relevant, given it guarantees the renovation of forest resources and therefore the sustainability of the project in the long run. Higher values of MAI allow developing bioenergy projects in smaller areas, with higher power scales, or with lower rotation ages. 3) Mean age (years): This is a fundamental criterion for energy generation from biomass. It is preferred that crop age be equal or higher to the biological turn in order to regulate forest mass, and to guarantee the sustainability of the resource. 4) Density of roads (m/ha): The existence of roads inside forest plantations to extract wood is determinant for economic success. A minimum value of this parameter for a viable exploitation is 40 m/ha [12]. 5) Waste biomass production (ton/day): It allows energy production with a resource that is not being used. Waste wood that is concentrated in one place is significantly cheaper than raw wood, and requires less transport [21]. The social impact of forest projects is positive, with an average of 10.3 jobs per 100 ha of plantation [12].

### *2.2. Main woods planted in Colombia*

This section presents the information regarding plantation size and growth rate of planted species in the main forest crops. Silvicultural information allowed determining the species with greater potential for the development of bioenergy projects in Colombia, as shown in Table 1.

Fast growing rate woods with greater potential are *Acacia mangium* (Aca), *Eucalyptus sp.* (Euc), *Pinus sp.* (Max), *Pinus patula* (Pat), and *Gmelina arborea* (Gme). Representative samples of these woods were characterized to determine their heating value, and proximate and ultimate analyzes (see Table 2), this information is used to estimate the primary energy potential of forest cores (see section 2.3).

### *2.3. Energy potential from waste wood*

Existing commercial forest plantations in Colombia were conceived for purposes different to bioenergy projects. Therefore, the most suitable option is to use waste biomass resulting from wood processing (sawmill of crops). These waste represent a logistic problem in some plantations, making its energy use a feasible alternative [37].

**Table 1.** Silvicultural characteristics of the main fast growing forest species planted in Colombia.

| Species | Area (ha) | MAI ($m^3$/ha/year) | Harvest time turn (years) |
|---|---|---|---|
| *Acacia mangium* (Aca) | 11 300 | 28 | 4 |
| *Cupressus lusitánica* (Clu) | 4278 | 23 | 10 |
| *Eucalyptus sp.* (Euc) | 46 115 | 25 | 7 |
| *Gmelina arborea* (Gme) | 4972 | 23 | 7 |
| *Pinus patula* (Pat) | 38 495 | 20 | 13 |
| *Pinus sp.* (Max) | 59 811 | 20 | 13 |

| | | | |
|---|---|---|---|
| *Tectona grandis* (Tecg) | 6341 | 18 | 7 |

**Table 2.** Physical-chemical characterization of main wood fuels.

| Property | Wood fuel (biomass) | | | | |
|---|---|---|---|---|---|
| | Max | Pat | Euc | Aca | Gme |
| Bulk density of chips (kg/m$^3$) | 175.60 | 164.09 | 281.30 | 186.04 | 151.52 |
| Ultimate analysis (% wt d.b.) | | | | | |
| Volatile matter | 74.32 | 72.57 | 67.35 | 73.25 | 72.00 |
| Fixed carbon | 25.46 | 27.17 | 32.34 | 26.46 | 27.23 |
| Ash | 0.22 | 0.26 | 0.31 | 0.29 | 0.77 |
| Proximate analysis (% wt d.b.) | | | | | |
| C | 54.43 | 54.99 | 53.28 | 53.00 | 52.66 |
| H | 7.04 | 7.21 | 6.74 | 6.71 | 6.96 |
| O | 37.79 | 36.72 | 39.26 | 39.65 | 39.12 |
| N | 0.52 | 0.81 | 0.39 | 0.33 | 0.47 |
| S | 0 | 0.01 | 0.02 | 0.02 | 0.02 |
| Ash | 0.22 | 0.26 | 0.31 | 0.29 | 0.77 |
| LHV$_{db}$ (kJ/kg) | 18 990 | 18 948 | 18 489 | 18 694 | 18 582 |

According to this approach, only forest crops of relative large size would produce enough residual biomass to make an energy project feasible. Four forest crops with the highest energy potential were selected. The complete methodology for the selection of these forest nuclei is described in the work by Pérez and Osorio [12].

Table 3 presents the amount of biomass resource that can be supplied in a sustainable fashion by the forest plantations. Expected power generation is also presented for each energy core (see equation 1). Sawmill waste is free of charge if it is used at the same place where it is produced, which is an advantage for bioenergy projects [17].

Generated power depends on the efficiency of each of the energy transformation processes, which may vary among providers of technology. As an illustration, it can be expected that the efficiency of the different processes of a generation plant be as follows: 60% for the gasification process, 25% for engine-generator set, and global plant efficiency of 16% [38]. Primary power values are estimated by means of equation (1).

$$P_{primary}[MW] = \dot{m}_{wet,bms} \cdot LHV_{wet,bms} \times \frac{1\,year}{8765.8\,h} \times \frac{1\,h}{3600\,s} \quad (1)$$

Where $\dot{m}_{wet,bms}$ (kg/year) is the annual production of wood for bioenergy with 20% of moisture content, and $LHV_{wet,bms}$ (MJ/kg) is the lower heating value of wet biomass with 20% of moisture content. This moisture content is assumed considering typical drying levels for gasification applications [39]. Annual time is setup at 8765.8 h because forest crops provide waste biomass during the whole year.

### *2.4. Thermochemical processes and technologies for bioenergy projects*

Technology used for electricity generation from biomass gasification is different from that used for coal-based generation. The reason is that biomass is more reactive and fibrous, aside from having lower ash fusion points and lower density. There are specialized manufacturers for the different biomass gasification technologies.

**Table 3.** Residual biomass resource availability and useful power for potential forest crops.

| Forest commercial crop | Species | Annual biomass production [ton/year]* | Primary energy [GJ/year] | Estimated electric power [kWe] |
|---|---|---|---|---|
| FCC1 | Aca | 28 800 | 432 217 | 2084 |
| FCC2 | Gme | 7200 | 108 841 | 525 |
| FCC3 | Pat | 7200 | 110 329 | 532 |
| FCC4 | Pat | 11 880 | 182 043 | 878 |

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[*] Residual wood, air-dried (20% moisture content)

Fixed bed downdraft and fluidized bed gasifiers are the most common alternatives for electric power in the range 500 – 2000 kWe [22, 25, 40, 41]. For the lower power range, fixed bed downdraft technology is more suitable, because of its lower tar production [21, 25, 42]. Fluidized bed technologies are used in larger power facilities, given their higher reaction rates, cost and complexity [43]. Knoef [44] made an inventory of gasifier manufacturers and facilities in the US, Canada and Europe, showing that 75% of commercial designs were of fixed bed downdraft type, 20% were fluidized beds, 2.5% were counter flow designs, and 2.5% other types of design.

There are technology providers with experience and presence in several continents. Generation plants for power levels below 5 MWe are made up by internal combustion engines as prime movers. Gasifiers could be of downdraft or updraft fixed-bed type [45–47].

### *2.5. Technical-economic mathematical model*

There are commercial tools to calculate electricity generation cost with biomass technologies, one of which is developed by the National Energy Laboratory, NREL [48]. The approach used here for technical and economic analysis is also valid, and it has been used by other authors to compare alternatives for bioenergy projects. Some of them are Quaak *et al.* [22] in a work for the World Bank, Wu *et al.* [23] in China, Buragohain *et al.* [14] in India, Wei *et al.* [49] in the United States, and Coronado *et al.* [20] in Brazil, among others. Input variables to the model are the type of technology, investment and operation costs, lifetime of technology, type (physical chemical properties) and specific cost of biomass, and annual operation time. The aim of the model is to obtain the base generation cost of electrical energy (Cost of Electricity – COE). The COE (USD/kWe-h) is a suitable indicator for selecting technology providers from a technical and energy perspective [22, 23]. Nevertheless, it is not the only economic factor for the financial assessment of a project. This figure considers only technical and energy variables, as well as plant setup cost, operation and maintenance costs (O&M), and fuel cost. Complimentary parameters for financial analysis are installation costs for an electrical substation, the required electrical network for electric power transport, taxes, governmental regulations that affect costs, and salvage cost of equipment, among others. Financial variables depend more on local market conditions and specific national regulations. COE is chosen as the target output variable, looking for independence from financial analysis when performing a technical-economic analysis to assess and compare technological alternatives. This way it is possible to evaluate the cost/benefit relationship associated to different options, based on technical, energy and economic criteria (commercial cost of the plant).

Model input is made up by plant power and efficiency, biomass LHV on dry basis and price per ton, as well as several costs: investment, operation and maintenance, and civil works. The main result of the model is the COE, which specifies how much it costs to produce a unit of electrical energy in the plant. The model also offers the possibility to perform a sensitivity analysis of COE to several input variables, such as the specific cost of the plant (USD/kWe), biomass cost (USD/ton), and number of operating hours per year. The relationship among technical, energy and economic variables is presented in the following description of the model [14, 22, 23].

The starting point is the electric power output from the plant. In this work, this variable was determined from the energy potential of each forest crop. The plant is defined mainly by its nominal power. Nevertheless, this value differs from the net available power output, because of self-power consumption of the auxiliary equipment (see equation 2). For a gasification power plant self-consumption is about 10-15% of nominal power [29, 50–53]. The next input is the amount of biomass required to produce a unit of energy, which is called specific fuel consumption – *sfc* ($kg_{bms}$/kWe-h), see equation (3).

$$\dot{N}_e = \dot{N}_{e,nom} - \dot{N}_{e,sc} \tag{2}$$

$$sfc = \frac{\dot{m}_f}{\dot{N}_e} \tag{3}$$

Data needed so far are usually provided by plant manufacturers, and it can be calculated in the case it is not known. All the technical and economic information of the plants used in this work has been provided by the respective manufacturers. These parameters are the base for the reference COE ($COE_{ref}$) analyzed in the section 3.

Power generation efficiency ($E$) is calculated as the ratio of the net electric power produced by the plant and the power input to the system with the biomass resource (equation 4).

$$E = \frac{\dot{N}_e}{\dot{m}_f \cdot LHV_{bms}} = \frac{1}{sfc \cdot LHV_{bms}} \tag{4}$$

Plant-related costs are included in the generation cost through the capital cost ($C_c$) distributed along the lifetime of the plant ($n$ years) with a given effective annual interest rate ($i$). Therefore, the fixed annual payment ($A$) is calculated according to equation (5).

$$A = C_c \cdot \left( \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right) \tag{5}$$

Interest rate is fixed for all the plants in a value of 8% [22], aiming at avoiding any financial fluctuation to affect the comparison among plants. Although it is not used here, an alternative calculation of the fixed annual payment can be obtained as the ratio of the capital cost of the plant and its lifetime period in years, which is valid in the situation that the investor does not need to incur in debt [49].

The specific energy cost associated to the annual payment of the investment in the plant is obtained by relating the annuity $A$ (USD/year) with the amount of energy produced in a year (kWe-h), which involves the net electric power output and the operating hours per year, as shown in equation (6).

$$C_{A,e} = \frac{A}{\dot{N}_e \cdot t_{op,year}} \tag{6}$$

Annual cost of fuel is obtained from the product of biomass consumption rate (ton/h), its specific cost, and annual operation time (equation 7).

$$C_{f,a} = \dot{m}_f \cdot C_{f,ton} \cdot t_{op,year} \tag{7}$$

Annual specific cost of fuel comes from relating annual cost of fuel with the energy generated during a year (equation 8).

$$C_{f,e} = \frac{C_{f,a}}{\dot{N}_e \cdot t_{op,year}} \tag{8}$$

Labor cost depends on average income of a country. In the Colombian case, an annual salary of 15500 USD can be used [22, 54]. For three shifts per day, one worker per shift, the labor cost is 46500 USD/year (equation 9).

$$C_{Lab,a} = C_{Lab,op} \cdot n_{op} \cdot n_{ws} \tag{9}$$

The annual salary considered in this study is similar to the amount used in reference [22] (50000 USD/year) with one worker per shift. The specific labor cost is calculated according to equation (10).

$$C_{Lab,e} = \frac{C_{Lab,a}}{\dot{N}_e \cdot t_{op,year}} \tag{10}$$

Adequate maintenance according to manufacturer specifications is necessary for reliable operation of the plant along is lifetime period. This includes maintenance personnel, as well as replacement or repair of parts. In addition, projected maintenance periods determine how many hours per year the plant is available for power generation. A detailed calculation of these parameters requires very specific information for a given plant, which is not easily known or estimated. Nevertheless, scientific literature suggests to use an annual maintenance cost of 5% of the total equipment cost [22], as presented in equation (11).

$$C_{M,a} = 0.05 \cdot C_C \tag{11}$$

The specific cost of maintenance is obtained from equation (12).

$$C_{M,e} = \frac{C_{M,a}}{\dot{N}_e \cdot t_{op,year}} \tag{12}$$

Technology providers are usually reluctant to give detail about specific infrastructure requirements for plant setup. Despite some detailed information is not available, the analysis is performed using similar values for all the parameters not available, using the respective values from the scientific literature.

The reference cost of electricity generation ($COE_{ref}$) is the sum of all the specific costs described before (equation 13), and it represents the base cost associated to the generation of a unit of net electrical energy. This parameter is useful and versatile for the comparison of a set of power plants, even if they are based on different gasification technologies and thermal engines [48].

$$COE_{ref} = C_{A,e} + C_{f,e} + C_{Lab,e} + C_{M,e} \tag{13}$$

## 3. Results and Discussion

### *3.1. COE for reference case*

A comparative analysis of the COE for the reference case was performed as a function of the power potential for the several FCC described in section 2.1, using technical and economic data obtained directly from manufacturers from Africa (AFR), North America (AME), Asia (AS), and Europe (EU). This kind of information is not usually available, and it gives reliability to the results of this work, by avoiding estimation and the corresponding uncertainties. The model described in section 2.5 is used with the collected data, as well as with the information gathered from forest plantations.

The ratio of capital cost to equipment cost was taken as 2.0 [22, 24, 49]. Biomass cost was taken as 30 USD/ton, considering tansport and conditioning (drying, chipping, storage, etc.) [24, 49]. These values, as well as labor cost, were considered as constant for the calculations of the reference case, given that the aim of the COE is not to compare financial, but technical and energy aspects of the different alternatives. Additionally, for the reference case, the annual operation time was considered constant for all power plants at 7500 h/year.

Manufacturers are presented according to their continent of origin (see Table 4). It can be observed that some manufacturers provide power plants for several power capacities.

Results for the reference cost of electricity generation ($COE_{ref}$), calculated with the information of Table 4 are presented in Table 5, showing the share of the different cost units that make it up. According to the model used, it is concluded that results depend mainly on the information provided by the manufacturers.

The effect of economy of scale is verified by the results of Table 5, given that $COE_{ref}$ increases as the nominal power of the plant decreases [55–57]. The reference generation cost for medium-low power plants is affected in higher proportion by the capital cost. The relative share of capital cost is 45-50% for plants from Asia, which have the lower commercial price. For the most expensive power plants (EU and AME), this share rises to 63-67%. This result reveals that the feasibility of bioenergy-based projects requires to reduce technology-associated costs, as has been suggested in previous investigations [49].

The cost of fuel (waste wood) contributes from 32% to 37% to the cost of generation for the Asian plants, while its contribution drops to 10-16% for those of Europe and America, which offer higher efficiency. The remaining cost contribution is attributed to operation and maintenance of the plants. This cost rises as the power output of the plant decreases.

By comparing the results of the model with the average price of electricity in Colombia (12 cUSD/kWe-h), it is clear that such bioenergy-based projects are not feasible for plants connected to the national electrical grid.

**Table 4.** Technical and economic information of different suppliers of biomass gasification power plants classified by continents.

| Parameters | Global suppliers of power gasification plants (low-medium power range) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AFR | AME | | | AS1 | | | | AS2 | | AS3 | | EU1 | | EU2 |
| Nominal power (kWe) | 500 | 500 | 1000 | 1945 | 500 | 1000 | 1250 | 2250 | 500 | 1000 | 1000 | 2000 | 750 | 2000 | 500 |
| Self-consumption (% nom. power) | 20 (approx.) | Net generation | | | 20 (approx.) | | | | 15 | 15 | 15 (approx.) | | 10 (approx.) | | 10 (approx.) |
| Plant investment cost (USD x1000) | 1936 | 11 000 | 17 200 | 26 300 | 1760 | 3102 | 3146 | 6270 | 1100 | 2200 | 3190 | 6380 | 6960 | 16 700 | 4470 |
| Efficiency (%) | 25.9 | 19.5 | | | 19.5 | | | | 23 | 23 | 14.3 | | 24 | | 16.3 |
| Fuel consumption (kg/kWe-h) | 0.88 | 1.36 | | | 1.3 | | | | 1.1 | 1.1 | 1.6 | | 1 | | 1.3 |
| Gasification technology | Down-draft | Updraft | | | Downdraft | | | | Fluidized bed | | Fluidized bed | | Downdraft | | Down-draft |
| Annual operation time (h/year) | NS | 7200 (approx.) | | | 7000 (max.) | | | | 7500 (max.) | | NS | | 7000 (approx.) | | NS |
| Lifetime (years) | 15 | 25 | | | 15 | | | | 10 | | 15 | | 20 | | 15 |
| Required labor (# workers) | NS | 2 | | | NS | | | | NS | | NS | | 2 | | 2 |

NS: Not specified.

This can be explained by the hydroelectric share in the Colombian electricity market, which is predominant and offers facilities with nominal power that are significantly greater than those studied here. The following aspects will contribute to the feasibility of bioenergy projects:

- To use waste biomass, given the relevance of fuel cost, and to set the plant as near to the forest plantation as possible, in order to reduce significantly the cost associated with biomass transport [55].
- To implement tax and market incentives for bioenergy projects. There are some measures in this direction in Colombia (Law 1715 of renewable energies, 2014), but more effort is needed [36].
- To develop local technology for biomass-based power generation. Capital investment cost is the most important contribution to generation costs for this power range. Therefore, local developments could reduce significantly the cost of technology, as well as to avoid costs associated with importation. The experiences in Asian countries suggest that this alternative is worth exploring [23].

The feasibility of an energy project is determined in great proportion by the difference between the cost of generation and the price of electricity sale in the local market. This is the driver for the profitability of the project. Current electricity prices in Colombia range from 6 to 12 cUSD/kWe-h [58]. However, when the share of hydroelectricity decreases because of low reservoir levels caused by climatic phenomena, electricity prices increase considerably. Price may increase from an average value of 6-12 cUSD/kWe-h to values up to 30-100 cUSD/kWe-h [58]. Therefore, the considered alternatives are feasible to be connected to the national electrical grid in function of reservoir levels of hydroelectric power plants. On the other hand, at regions not connected to the grid (NIZ), where about 95% of electricity is generated with diesel power plants, generation costs are about 52 cUSD/kWe-h. This cost is associated mainly to high costs for fuel transportation [59], given that these regions often lack roads and infrastructure.

According to the results of this work, the $COE_{ref}$ is in the range of 10-41 cUSD/kWe-h, depending on nominal power and technology provider. This result is in agreement with reported values for biomass electricity generation in the small-medium scale power range [60, 61]. It is clear that bioenergy projects have a high potential when climate phenomena such as "El Niño" (periods of drought) cause reduction of reservoir levels of hydroelectric plants. Moreover, bioenergy would be feasible at NIZ, which amount to about 52% of the total Colombian area, and in which there are about two million people living with a population density of about 2 people/km$^2$. About 80% of these people do not have their basic needs fulfilled, among which is electricity [62]. The additional advantages of bioenergy are to contribute to the national goal of renewable energy share in energy generation for NIZ [63], and to bring social and environmental improvement opportunities to the people who need it the most.

**Table 5.** Contribution of capital, fuel and O&M costs to COE$_{ref}$.

| Manufacturer | Nominal power (kWe) | Capital investment cost (%) | Fuel cost (%) | O&M cost (%) | COE$_{ref}$ (cUSD/kWe-h) |
|---|---|---|---|---|---|
| AFR | 500 | 54.2 | 17.7 | 28.1 | 16.6 |
| AME | 500 | 67.4 | 10.0 | 22.6 | 40.8 |
| | 1000 | 66.0 | 12.5 | 21.4 | 32.5 |
| | 2000 | 64.1 | 15.5 | 20.4 | 26.3 |
| AS1 | 500 | 46.8 | 31.1 | 22.1 | 15.7 |
| | 1000 | 47.0 | 35.4 | 17.6 | 13.8 |
| | 1250 | 43.5 | 40.4 | 16.2 | 12.1 |
| | 2250 | 45.2 | 37.9 | 16.9 | 12.9 |
| AS2 | 500 | 44.8 | 33.8 | 21.4 | 10.8 |
| | 1000 | 47.8 | 36.1 | 16.0 | 10.2 |
| AS3 | 1000 | 50.1 | 35.4 | 14.6 | 15.1 |
| | 2000 | 51.3 | 36.3 | 12.4 | 14.7 |
| EU1 | 750 | 64.5 | 14.5 | 21.0 | 23.0 |
| | 2000 | 64.7 | 16.0 | 19.3 | 20.9 |
| EU2 | 500 | 63.0 | 17.7 | 19.2 | 26.3 |

### *3.2. Sensitivity analysis of COE*

Regarding the result of the cost of electricity generation, it is interesting to explore the effect of three important variables for decentralized biomass-based electricity generation: power plant investment cost, number or operating hours per year, and biomass cost. Each of these variables is modified independently to find how sensitive the COE is to their variation.

#### *3.2.1. Effect of specific investment cost (SIC)*

Plant investment cost is in general the most relevant contribution to the COE for the power levels of interest here. The commercial price of a biomass-based power generation plant is highly variable, depending on the experience of the manufacturer, the type of technology employed, and the country of origin, among other factors [55].

Plant cost has been represented by the specific investment, which is the ratio of total cost of the plant and the power produced by it (USD/kWe). Total plant cost is determined by the manufacturer according to the cost of the equipment that make it up. To start up the operation of the plant it is necessary to incur in transport, civil works, and required supplies, among other costs. These additional expenditures may raise the cost of the plant by a factor of about 2.0 [22, 23, 29, 64].

Figure 2 shows the sensitivity of COE to a change in the SIC of plants. This analysis was made by varying the SIC reported by manufacturers by a factor from 1.0 to 2.5 (see Table 4). Results are shown as a percentage of the respective COE$_{ref}$ for each technology in order to facilitate their interpretation. For instance, for the plant from AFR, an increase in SIC of 1000 US$/kWe leads to a rise of 17% in COE respect to its reference generation cost (see Table 5).

It is observed that plants with SIC in the range of 2000-4000 USD/kWe (shown below the label of the manufacturer) exhibit a similar behavior, having a sensitivity of 17-25% to an increase of 1000 USD/kWe. The most expensive plants, with a SIC in the range 9000-22000 USD/kWe, have a sensitivity below 10% to the same change in SIC. This result is explained by the fact that an increase of 1000 USD/kWe in SIC represents a rise of 25-45% in total plant cost for the former group of plants, while it represents a lower 4.5-11% rise for the latter. The relevance of SIC is confirmed by this analysis, representing a key parameter for the feasibility of this kind of bioenergy projects [49].

#### *3.2.2. Effect of annual operating time*

In general, reported annual operating time for the plants analyzed ranges from 7000 h/year to 7500 h/year (see Table 4). Nevertheless, the effective working time depends on technical and operative availability and on local power demand or its transmission to an interconnected network. It also requires to count on the resources needed for operation, among which the main is residual biomass. For this analysis, the working time of the plant is varied from 4500 h/year to 7500 h/year, in order to cover a broader scenario that includes pessimistic and optimistic conditions.

Figure 3 shows that annual working time significantly affects the value of COE, according to equation (13). This increases as working time is reduced. It is observed that the effect of working time is not uniform for all the plants, which is indicated by the different slope of the curves. The COE in the most expensive plants is more sensitive to a change in working time.

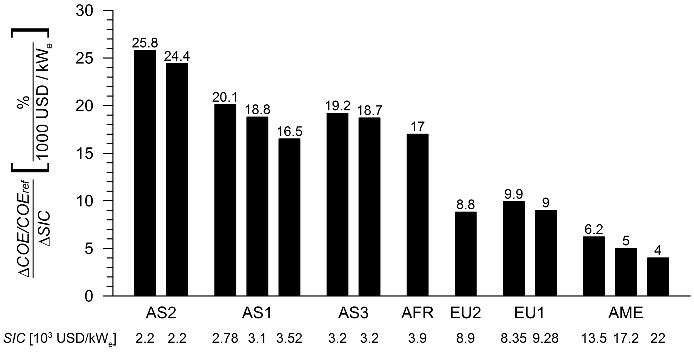


**Figure 2.** Sensitivity of COE to the change in SIC.

The behavior just described is observed in more detail when plotting the proportional increase in the COE respect its reference value for every 1000 h/year of change in working time, as a function of SIC (see Figure 4). It is observed that plants with a SIC between 2000 and 4000 USD/kWe have an increase in COE that ranges from 12.5% to 15% per 1000 h/year of reduction in working time. On the other hand, plants with higher SIC (between 9000-22000 USD/kWe) exhibit a higher sensitivity to a reduction of 1000 h/year in working time, which goes from 17% to 20%. This behavior is a consequence of the higher contribution of SIC to $COE_{ref}$, as presented in Table 5. This means that SIC affects significantly fixed costs, and therefore the increasing adverse effect of stop times. This result points out that it is fundamental to have the highest possible working time, in particular for the most expensive plants [22].

### *3.2.3. Effect of biomass cost*

Waste wood is the feedstock of the power plant, which makes its cost strongly related to the COE. The cost of biomass may vary significantly due to several external reasons, such as wood availability, transportation costs, and specific processing costs among others [43]. This cost factor has been identified as the most important after the SIC of the plant, for biomass-based decentralized electricity generation in this power range in Colombia.

Installation of the power plant in the forest crop itself is among the most effective alternatives to reduce fuel cost, by means of avoiding transportation charges [17]. Another option, as mentioned earlier, is to use residual wood, which usually does not have commercial value and has lower conditioning requirements for gasification processes [21]. It is also possible to reduce fuel cost through natural air-drying of biomass, where ambient conditions and storage capacity allows it. If this is not the case, it is still possible to use hot air from producer gas cooling in the power plant, as well as from waste heat from the thermal engine. These cogeneration schemes also lead to higher overall plant efficiency [20, 21].

Figure 5a shows the sensitivity of COE to fuel cost, emphasizing the effect of the global efficiency reported by each technology provider. This analysis was carried out by changing the cost of biomass from 0 to 80 USD/ton. The higher limit is the price that harvested wood may reach in Colombian forest plantations [12]. It was found that all the plants offered by a given manufacturer were affected the same way by a change in fuel cost. Therefore, only one value is reported here for each technology provider. The increase in COE is reported for an increment in 10 USD/ton in biomass cost, because it has a linear behavior with this cost.

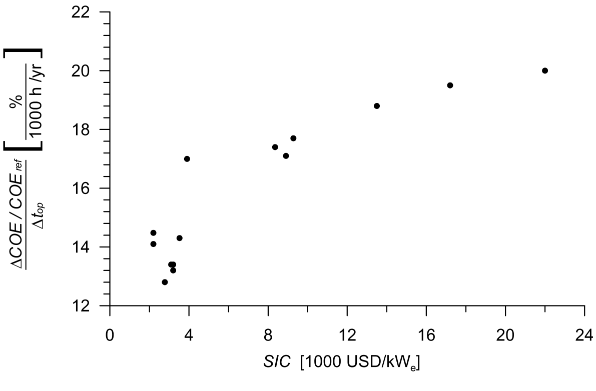


**Figure 3.** Effect of annual working hours on COE.

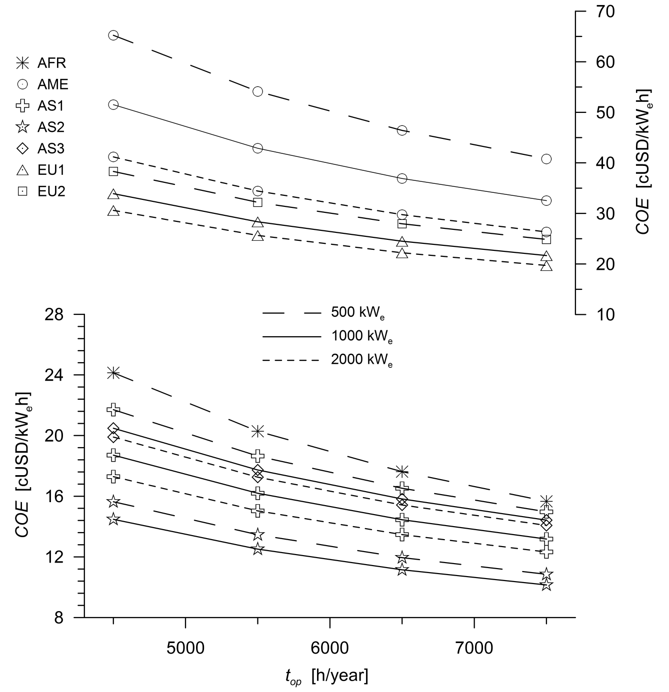


**Figure 4.** Effect of SIC on the sensitivity of COE to a change in working time.

The effect of thermal efficiency of the plants is determinant in the sensitivity of COE to a change in biomass cost. Plants with lower global efficiency (14-20%) exhibit a higher impact of this parameter on generation costs (1.56-1.76 cUSD/kWe-h), while higher efficiency plants (20-26%) have a sensitivity of 0.98-1.36 cUSD/kWe-h to a change of 10 USD/ton in fuel cost. This is because more electrical power is generated by a unit of power supplied by the fuel at higher global efficiency of the plant.

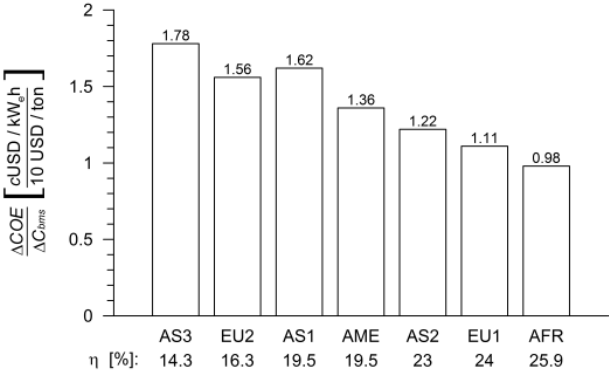
One of the main findings of the analysis is the significant effect that the SIC has on the COE. For this reason it is interesting to analyze the results of Figure 5a in relation to the $COE_{ref}$ for each technological alternative (see Figure 5b). Again, results are shown as a percentage of the respective $COE_{ref}$ for each technology in order to facilitate their interpretation. It is clear how the SIC has a determinant effect on results, even more significant than that of energy efficiency. The group of plants with lower SIC (2000-4000 USD/kWe) is more sensitive to a change in biomass cost, due to their lower value of $COE_{ref}$. The manufacturer from Africa (AFR) shows an atypical behavior, given that it has low sensitivity to a change in biomass cost, and at the same time it belongs to the group of lower SIC. The reason for this is that this plant has the highest efficiency, which diminishes its sensitivity to fuel cost.

## 4. Conclusions

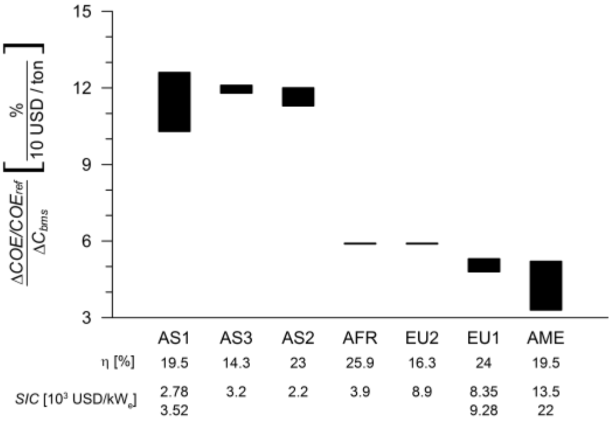
The most important parameters to assess forest plantations for biomass-based electricity generation are their size (ha), mean annual index (MAI, $m^3$/ha/year), average age (years), road density (m/ha), and residual biomass production (ton/year). Wood species with the highest potential to be used as fuel in electricity generation projects in Colombia are *Acacia Mangium*, *Eucalyptus grandis*, *Pinus sp.*, *Pinus patula*, and *Gmelina arborea*, with an average energy content of 18.7 MJ/kg. Waste wood availability from forest commercial crops in Colombia allows net power generation in the range 500-2000 kWe. According to commercial supply, the suitable technology for this low power scale is based on gasifiers coupled to internal combustion engines.

Results from the technical-economic model show that the reference generation cost varies from 10.2 to 40.8 cUSD/kWe-h, depending on the commercial plant used. For lower cost plants (manufacturers from Asia and Africa), the proportional contribution of investment cost is of 45-50%, and that of fuel cost is of 32-37%, while for more expensive plants (coming from North America and Europe), this figures are of 63-67% and 10-16%, respectively. The remaining contribution to generation cost (15-22%) is associated with operation and maintenance of the plant.

The sensitivity analysis of generation cost showed that an increase of 1000 USD/kWe in SIC may rise the COE by about 20% for lower cost plants, and less than 10% for more expensive plants. Regarding annual operation time, the COE rises as it is reduced, showing higher sensitivity for higher cost plants (10-20%) and lower for those with a lesser commercial price (about 14%). Finally, fuel cost has a greater effect on plants with lower global efficiency. An increase of 10 USD/ton in the cost of fuel rises the COE of lower efficiency plants by about 1.5 cUSD/kWe-h, while for higher efficiency plants the rise is about 1 cUSD/kWe-h. The cost of fuel has an effect on the COE that depends significantly on the SIC of plants. For higher cost plants, an increase of 10 USD/ton in fuel cost rises the COE about 5%, while for lower cost plants, the rise is about 11%.



a) As a function of global efficiency



b) As a function of SIC

**Figure 5.** Sensitivity of COE to biomass cost.

**Nomenclature**

| | |
|---|---|
| $A$ | Fixed annual payment [USD/year] |
| AFR | African power plant manufacturers |
| AME | American power plant manufacturers |
| AS1, 2, 3 | Asian power plant manufacturers |
| $C_{A,e}$ | Specific cost of annual investment payment [USD/kWe-h] |
| $C_c$ | Capital cost [USD] |
| $C_{f,a}$ | Annual fuel cost [USD/year] |
| $C_{f,e}$ | Specific fuel cost [USD/kWe-h] |
| $C_{f,ton}$ | Fuel cost [USD/ton] |
| $C_{Lab,a}$ | Annual labor cost per person [USD/year] |
| $C_{Lab,e}$ | Annual labor specific cost [USD/kWe-h] |
| $C_{Lab,op}$ | Labor cost per person [USD] |
| $C_{M,a}$ | Maintenance cost [USD/year] |
| $C_{M,e}$ | Maintenance specific cost [USD/kWe-h] |
| $C_{total,e}$ | Total specific cost [USD/kWe-h] |
| *COE* | Cost of electricity [USD/ kWe-h] |
| $E$ | Global generation efficiency [%] |
| EU1,2 | European power plant manufacturers |
| *FCC* | Forest commercial crops |
| *i* | Effective annual interest rate [%] |
| *LHV* | Lower heating value [MJ/kg] |
| $\dot{m}_f$ | Fuel consumption [kg/h or ton/h] |
| $n_{op}$ | Number of operators in the power plant [-] |
| $n_{ws}$ | Number work shifts [-] |
| $\dot{N}_e$ | Net electric power generation [kWe] |
| $\dot{N}_{e,nom}$ | Nominal electric power [kWe] |
| $\dot{N}_{e,sc}$ | Self-power consumption [kWe] |
| *SIC* | Specific investment cost [USD/kWe] |
| *sfc* | Specific fuel consumption [kg/kWe-h] |
| $t_{op,year}$ | Operating hours of plant per year [h/year] |
| *Subscripts* | |
| *a* | Parameters in specific terms of time [year] |
| *bms* | Biomass |
| *db* | Dry basis |
| *e* | Specific terms of energy [kWe-h]. Electricity basis |
| *f* | Fuel |
| *ref* | Reference case for the analysis |
| *th* | Thermal energy basis |
| *Superscripts* | |
| *N* | Lifetime of the plant [years] |

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