energies

MDPI

Article

Potential and Impacts of Cogeneration in Tropical Climate Countries: Ecuador as a Case Study

Manuel Raul Pelaez-Samaniego [1], Juan L. Espinoza [2,*], José Jara-Alvear [3], Pablo Arias-Reyes [4], Fernando Maldonado-Arias [5], Patricia Recalde-Galindo [6], Pablo Rosero [6] and Tsai Garcia-Perez [1]

1 Department of Applied Chemistry and Systems of Production, Faculty of Chemical Sciences, Universidad de Cuenca, Cuenca 010107, Ecuador; manuel.pelaez@ucuenca.edu.ec (M.R.P.-S.); tsai.garcia@ucuenca.edu.ec (T.G.-P.)
2 Faculty of Engineering, DEET, Universidad de Cuenca, Cuenca 010107, Ecuador
3 Corporación Eléctrica del Ecuador CELEC E.P., Cuenca 010109, Ecuador; jose.jara@celec.gob.ec
4 Faculty of Electrical Engineering, Smart Grid Energy Lab., Universidad Católica de Cuenca, Cuenca 010107, Ecuador; pariasr@ucacue.edu.ec
5 Faculty of Economic Sciences, Universidad de Cuenca, Cuenca 010107, Ecuador; fernando.maldonado@ucuenca.edu.ec
6 Ministry of Energy and Natural Non-Renewable Resources, Quito 170135, Ecuador; patricia.recalde@recursosyenergia.gob.ec (P.R.-G.); pablo.rosero@recursosyenergia.gob.ec (P.R.)
* Correspondence: juan.espinoza@ucuenca.edu.ec

Received: 29 August 2020; Accepted: 24 September 2020; Published: 10 October 2020

Abstract: High dependency on fossil fuels, low energy efficiency, poor diversification of energy sources, and a low rate of access to electricity are challenges that need to be solved in many developing countries to make their energy systems more sustainable. Cogeneration has been identified as a key strategy for increasing energy generation capacity, reducing greenhouse gas (GHG) emissions, and improving energy efficiency in industry, one of the most energy-demanding sectors worldwide. However, more studies are necessary to define approaches for implementing cogeneration, particularly in countries with tropical climates (such as Ecuador). In Ecuador, the National Plan of Energy Efficiency includes cogeneration as one of the four routes for making energy use more sustainable in the industrial sector. The objective of this paper is two-fold: (1) to identify the potential of cogeneration in the Ecuadorian industry, and (2) to show the positive impacts of cogeneration on power generation capacity, GHG emissions reduction, energy efficiency, and the economy of the country. The study uses methodologies from works in specific types of industrial processes and puts them together to evaluate the potential and analyze the impacts of cogeneration at national level. The potential of cogeneration in Ecuador is ~600 MW_{el}, which is 12% of Ecuador's electricity generation capacity. This potential could save ~18.6×10^6 L/month of oil-derived fuels, avoiding up to 576,800 tCO_2/year, and creating around 2600 direct jobs. Cogeneration could increase energy efficiency in the Ecuadorian industry by up to 40%.

Keywords: cogeneration; trigeneration; sustainability; industrial energy efficiency; tropical climate country; biomass

1. Introduction and Literature Review

Energy is key for people's well-being and for a countries' development. Still, current global energy use and production heavily relies on fossil derived fuels and electricity produced using this type of fuel. For instance, in 2018, 85% of the worldwide fuel consumption had its origin in fossil fuels. The total petroleum, coal, and natural gas consumption reached 4714 MTOE/year (Million tons of oil equivalent per year), 3744 MTOE/year, and 3328 MTOE/year, respectively [1]. One of the negative consequences of the large consumption of fossil fuels is the raising of greenhouse gas (GHG) emissions that are responsible for global warming. In addition, for several developing countries (especially tropical climate countries), there are pending tasks to fully meet energy needs and make energy generation and use more sustainable. Low energy efficiency, poor diversification of energy sources, low rate of access to electricity service, and necessity to make the energy systems less dependent on fossil fuels are among those pending tasks. The necessity of reducing the use of fossil fuels is critical as these countries may suffer the impact of climate change more intensively (in part due to energy-related activities). The associated costs to mitigate such impacts are very high [2–4]. Although tropical climate countries possess a benign weather and a diversity of energy resources, balancing electricity generation with weather conditions and the reduction of energy sources (e.g., hydropower) are forcing those countries to look for new options for electricity generation and management. This is the case for Ecuador.

The Ecuadorian energy matrix highly depends on oil and oil-derived fuels, which are used in the transportation and industrial sectors, as well as in households (mainly as fuel for cooking) and for electricity generation (in smaller amounts) [5–7]. The transportation and the industrial sectors are responsible for 42% and 18% of the total fuel consumption, respectively [8,9]. Lack of natural gas (NG) sources and insufficient oil refining capacity force the country to import part of the fuels used. The high expenses to import these fuels and the resulting negative environmental consequences are driving Ecuador to look for alternatives to imported fuels and to make the energy sector more sustainable. The Ecuador's GHG inventory shows that the energy sector in the country is responsible for 46.6% of the total of CO_{2eq} emissions [10]. Heat for running industrial processes is produced mostly by burning subsidized oil-derived fuels, especially diesel and fuel oil [5,7,9] and only a few companies use renewable energies (particularly biomass) to produce heat and power. Recent attempts made by the Ecuadorian government to reduce or eliminate subsidies to fuels have failed due to political and social pressure.

The electricity generation in Ecuador, on the other hand, is almost entirely based on hydropower. The current hydropower installed capacity in the country is ~5000 MW, from which 88% corresponds to power plants located in rivers that discharge into the Amazonian river basin, while the rest corresponds to plants located in rivers that discharge into the Pacific Ocean. Hydropower generation, however, has problems to adjust to the country's seasonal rains, which negatively impacts electricity production. Locating hydropower plants on both sides of the Andes Mountains has been a strategy for partially balancing the seasonality of rains. Figure 1 shows the variation of water inflow in hydropower plants located in the Amazonian River and the Pacific Ocean basins in Ecuador. The power generation is proportional to water inflow in the plants. It is seen that from October to January, the water inflow is reduced as a consequence of lower rainfalls [11,12]. Since the seasonality of hydropower generation could jeopardize the electricity supply and its sustainability in the mid-term, Ecuador is currently looking for options to ensure electricity generation in coming years, especially during the dry season. The adoption of the National Plan of Energy Efficiency 2016–2035 (known as PLANEE 2016–2035) is expected to have a positive impact on the energy demand and use [7,8]. In addition, the Ecuadorian State aims to increase the incipient participation of other renewable energy sources (i.e., wind, solar, and biomass) in the electricity sector [7]. In 2017, hydroelectricity contributed with more than 80% of the total electricity generated in the country, but the share of other renewable energy sources was only 0.5% (16.5 MW wind, 24 MW photovoltaic) [13], whereas in 2019, the hydropower share was 85% [14]. In the following years, wind farms (160 MW total) and solar photovoltaic (200 MW) projects will start operating. Nevertheless, although the electricity generation capacity in Ecuador has shown improvements, the negative effects of rains seasonality are unavoidable in coming years, and new electricity generation methods are sought. The PLANEE 2016–2035 foresees that the industry can play an important role by becoming more energy efficient and by generating its own electricity (at least partially) through cogeneration [8]. Besides, the substitution and/or better use of fossil fuels to produce heat in the industrial sector is a pending task.

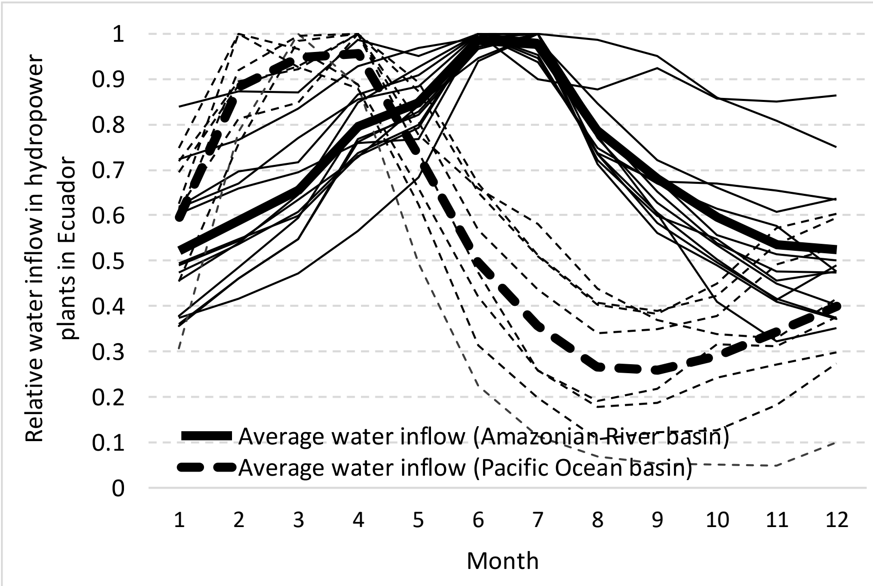


Figure 1. Monthly variation of water inflow in hydropower plants located in the Amazonian River and the Pacific Ocean basins in Ecuador. Thick lines show mean values from 1964 to 2016 [14,15].

Cogeneration has been recognized as a key element for the diversification of the electricity generation matrix (to help balancing the seasonal hydropower generation), for the reduction of the costs of subsidies to energy in the Ecuadorian industry (by making a better use of fuels for heat production), for the increase in energy efficiency, and for reducing GHG emissions [8]. However, further work is required to determine how much the potential of cogeneration in the Ecuadorian industry is and to define strategies for implementing cogeneration in this sector. Year-round tropical climate, subsidies of the state to fossil fuels and electricity, and insufficient energy policies to promote investments in the energy sector are factors that have hindered the penetration of cogeneration in the country. Because of the relatively constant year-round temperature conditions, indoor heating is not required, even in the Andean highlands (where temperature normally varies between 7 and 23 °C). Thus, cogeneration has been adopted only marginally in the industrial sector. Our field work (see Section 2.1.2 for details) and [8,9] have identified that Ecuador's current installed cogeneration capacity is 172 MW_{el}, which represents only 2% of the total (nominal) electricity generation capacity (i.e., 7361 MW_{el}) [7]. Lignocellulosic biomass is the main fuel employed for cogeneration due to the utilization of bagasse in the sugarcane industry (Table 1). Although there are abundant lignocellulosic biomass resources in the country (e.g., oil palm, rice, banana, and wood residues), the use of these energy sources for cogeneration in the country is very low [7]. For example, in Ecuador, there are currently 35 companies that process oil palm fruit and 4 companies that produce oil from oil palm kernel, of which only 2 currently use cogeneration. Because of the positive impacts of biomass for cogeneration [16], the use of this fuel deserves more attention in the country. In addition to the existing installed cogeneration capacity in the country, there is a thermal power plant (Termogas Machala, 132 MW_{el} of installed capacity) [15] that is currently being retrofitted for operating as a combined cycle (CC) plant by adding heat recovery steam generators (HRSG) and steam turbines. This plant runs with natural gas—NG (obtained from the Gulf of Guayaquil) and gas turbines.

Despite the positive reputation and the extended use of cogeneration worldwide (especially in temperate climate countries), there are not enough studies showing the potential of cogeneration of whole industrial sectors or how cogeneration, in the conditions of tropical climate countries, could contribute to meet energy requirements, help to increase energy efficiency, reduce national GHG emissions, and, thus, contribute to sustainable development. For some tropical climate countries, there exists some studies focused on cogeneration in specific industrial sectors, such as the sugarcane industry [17–25], the oil palm industry [26–28], and the wood processing industry [16,29–33]. The methodologies and learnings from those works can be used to conduct a wider analysis on the impacts of cogeneration in a whole country or geographic region, although more research overall is necessary. Thus, the objective of this paper is two-fold: first, to compute the potential of cogeneration in the Ecuadorian industry, and, second, to show the positive impacts of cogeneration on power generation capacity, GHG emission reduction, industrial energy efficiency, and the economy of the country. The presence of subsidies from the state to both electricity and fuels in Ecuador, the seasonality of rains to run hydropower plants, and its year-round tropical weather are particular challenges considered in the study.

Table 1. Ecuador's current cogeneration installed capacity.

Type of Industry	Technology /Process	Type of Fuel	Year Operation Started	Installed Capacity (MW_{el})	Electricity Generation (GWh/year)
Sugarcane industry	Rankine cycle (3 plants)	Sugarcane bagasse	2004	136.6	408.3
Food industry	Diesel engine (1 plant)	Diesel	2007	1.0	N/A
Oil palm industry	Rankine cycle (2 plants)	Oil palm solid residues	1983	2.2	N/A
Wood industry	Rankine cycle (1 plant)	Wood residues	2003	1.0	N/A
Oil refining	Rankine cycle (1 plant)	Fuel oil	N/A	30.75	N/A
Ethanol production	Rankine cycle (1 plant)	Fuel oil	N/A	0.3	N/A
	TOTAL:			172 MW_{el}	

N/A—information is not available.

2. Materials and Methods

Our literature review suggests that there are not standardized methods for computing the potential of cogeneration/trigeneration in a specific geographical region or country, which is understandable since each country and its industrial sector have specific conditions that need to be taken into account. There are different aspects that need to be analyzed to determine the most suitable methodology to compute cogeneration potential at a country level (e.g., weather, types of energy sources available, altitude above the sea level, energy policies and incentives). In tropical climate countries such as Ecuador, the weather is an important factor that determines specific types of cogeneration schemes because, as previously mentioned, there is no need for indoor heating (an important energy requirement in tempered climate countries), but air conditioning is required instead [34–36]. Consequently, cogeneration projects are more suitable in the industrial sector and in other places where hot and cold fluids are used (e.g., hospitals, hotels, airports, shopping malls). These are the target places for cogeneration projects in tropical climate countries.

Another factor to consider for computing the potential of cogeneration is the pattern of energy consumption in the industrial sector, which in Ecuador is relatively constant throughout the year, reflecting a common feature of energy consumption in the industry of tropical countries. For Ecuador, and to illustrate this important point, Figure 2 shows two examples of energy consumption curves (both electricity and fuel) corresponding to two large Ecuadorian industrial companies (herein referred to as companies M and N) devoted to the production of tires (M) and pulp and paper (N). This energy consumption pattern of the industrial sector in Ecuador suggests that cogeneration plants in tropical climate countries could operate at approximately constant capacity year-round, which makes the sizing process of the cogeneration plants easier. The methodology adopted herein considers these elements.

2.1. Methodology

The potential of cogeneration in the whole industrial sector of a country can be obtained if the potential of cogeneration of each industrial plant in which cogeneration can be adopted is determined. The methods for sizing cogeneration plants for specific types of industries are based on their annual energy requirements (normally, heat for the industrial process and/or plant operation, since producing surplus heat will otherwise be wasted). Furthermore, producing electricity is not a priority in the industrial plants in the country due to its relatively low cost (i.e., due to subsidies). Table 2 presents a list of works devoted to determining the cogeneration capacity in specific types of industrial plants. These works served as the basis to compute the potential cogeneration capacity in industrial plants in

Ecuador. In addition, a report on the potential of cogeneration in Spain [37] and a report by the Office of Environment and Heritage New South Wales [38] were used. Moreover, for sizing cogeneration plants, it is necessary to define the cogeneration schemes suitable to specific types of industries and the respective fuels available. In this study, such schemes are shown in Appendix A, while the main equations used are provided in Appendix B. Then, the potential of each industrial plant was added to obtain the potential of cogeneration by cluster of industries and the whole country's potential. The methodology adopted consisted of five stages (summarized in Figure 3) that are detailed in the following subsections.

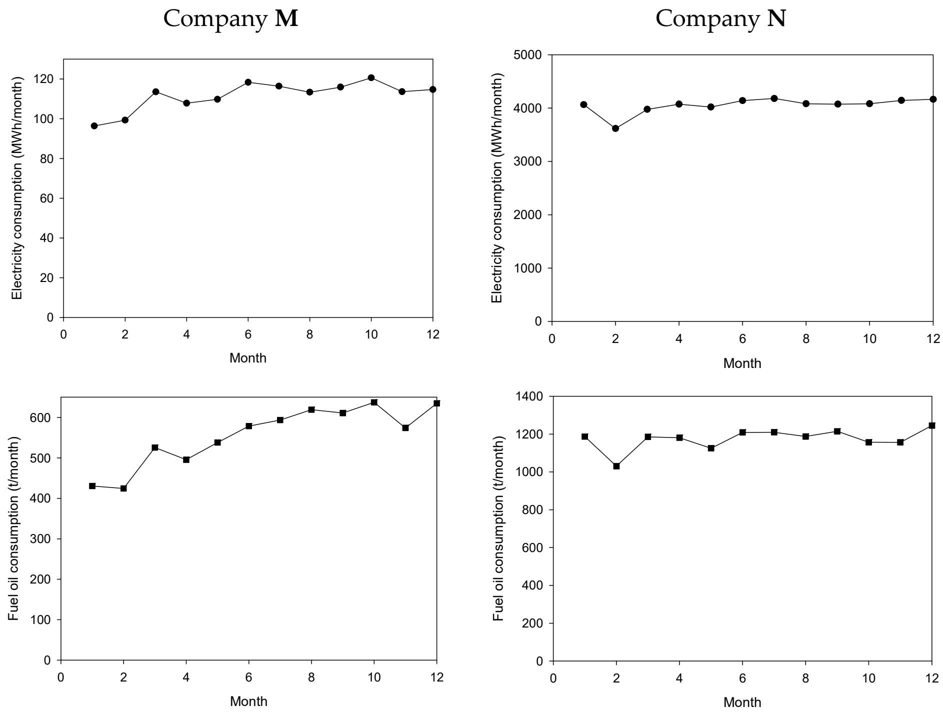


Figure 2. Typical curves of electricity (above) and fuel (below) consumption of two industrial companies (**M** and **N**), taken as examples of yearly (approximately constant) energy demand in most Ecuadorian industrial plants.

Table 2. Some works on cogeneration computing methods for different types of industries.

Type of Industry/Plant	Reference(s)
Hospitals	[39–41]
Small- and medium-sized industries and services	[42–44]
Large-sized industry and commercial sector	[45–47]
Sugarcane/ethanol	[17–19,21–25,48–50]
Oil palm	[27,28,31,51–54]
Wood and wood-derived products	[16,29–33]
Pulp and paper	[32]
Cement industry	[55]
Hotels	[56]
Chemical industry	[57]
Breweries	[58]
Food industry	[59]
Greenhouse gas emissions from cogeneration	[60]
Biogas/renewable energy	[61,62]
Others	[63–71]

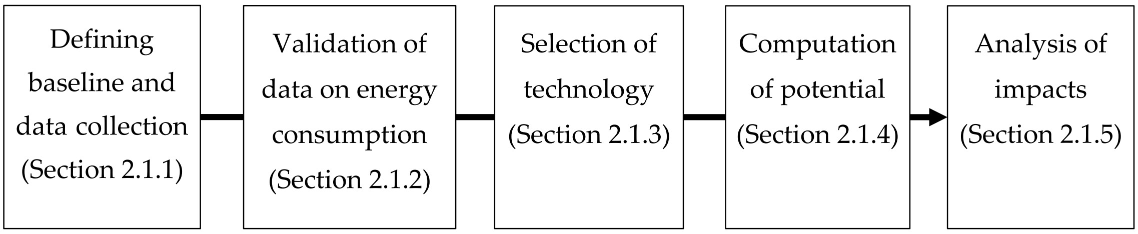


Figure 3. Methodology framework to compute the potential of cogeneration and the resulting impacts in Ecuador.

2.1.1. Data Collection and Energy Consumption Baseline

The tasks described in Sections 2.1.1.1 and 2.1.1.2 aimed to determine which industrial plants could adopt cogeneration (or trigeneration) in the country. For this, information on electricity and fuel consumption was used to define a baseline that allows selecting prospective industrial companies. This information was obtained from two official sources, the Agency of Regulation and Control of Electricity—ARCONEL (in Spanish Agencia de Regulación y Control de Electricidad) and the Agency of Regulation and Control of Hydrocarbon Fuels—ARCH (in Spanish Agencia de Regulación y Control de Hidrocarburos), which are the institutions in charge of regulating and controlling the distribution and use of electricity and fossil-derived fuels, respectively. The data used corresponded to 2015 and were the information available at the time that this study was conducted (2017 and 2018).

2.1.1.1. Electricity Consumption Baseline

The initial list on electricity consumption from the ARCONEL contained clients/consumers reporting electricity consumption above 20,000 kWh/month. This electricity consumption baseline was established after analyzing the energy demand of a small food processing company with installed capacity of approximately 30 kW_{el}, working 24 h/day the year-round (i.e., with electricity consumption of ~20,000 kWh/month). The company is located in the city of Cuenca, and herein it is referred to as Company A. The number of companies/consumers in the initial list was ~41,800. Next, the resulting list was analyzed and filtered again to remove companies and/or institutions (both public and private) in which, although their electricity consumption was >20,000 kWh/month, no fuels are required for their operation, except diesel for transportation and LPG (Liquid Petroleum Gas) for cooking at a small scale. This is the case of:

(1) Elementary schools, high schools, colleges/universities, government buildings and offices at a national or municipal level where, as previously mentioned, due to climate conditions in Ecuador, there is no necessity of cogeneration intending, for example, indoor heating (which is common in temperate places) or water heating.
(2) Construction and civil engineering companies (e.g., roads construction companies) that report high electricity consumption (for example for reducing the particle size of rocks).

It was also observed that the possibilities of cogeneration in a few companies that process polymers/plastics (e.g., High Density Polyethylene-HDPE, Polypropylene-PP, Polyvinyl Chloride-PVC) for producing plastic toys, plastic bags and/or plastic furniture for both domestic and industrial use (with electricity consumption > 20,000 kWh/month) should be verified in situ. Thus, these companies were kept in the list. The amount of companies after this filtering process was approximately 2000.

2.1.1.2. Fuel Consumption Baseline

The fuel consumption baseline started by analyzing the possibilities of cogeneration in the representative Company A (Section 2.1.1.1), which uses heat (produced by burning diesel) for its manufacturing process. The fuel consumption of this company served as the basis to start filtering the data provided by the ARCH. The company uses a typical small boiler (186 kW_{th}) that produces saturated steam at 140–150 °C, working ~6 h/day, 5 days/week, and employing up to 7570 L/month (i.e., 90,840 L/year) of diesel. A preliminary computation (following works of [43,44,47] and energy balances) showed that, if the company was interested in adopting cogeneration, the size of the cogeneration plant would be close to 300 kW_{el}. This cogeneration unit could operate, for instance, on a diesel or a gas engine (depending on the fuel available) and use the waste heat for producing the steam for the process (in a HRSG). However, according to a study conducted in the industrial sector in Mexico (with weather conditions somehow similar to those in Ecuador), the projects on cogeneration that offer better prospective, from an economic viewpoint, are those larger than 500 kW_{el} [72]. Therefore, the minimum capacity of the cogeneration plants in the Ecuadorian industry, in all cases and at this level of the study, should be 500 kW_{el}, which corresponds to a cogeneration plant that demands ~90,800 L/year of diesel (or any diesel equivalent fuel) Consequently, the fuel consumption data filtering process started by considering a baseline of diesel or fuel oil consumption of 90,800 L/year (76.19 t/year).

The information on fossil fuel consumption provided by the ARCH included data on type of fuel, amount, company's name, location and information on the main products of the company. This information was used to identify the location of each industrial plant. The types of fuels consumed in the country are as follows: fuel oil, diesel fuel (for both industry and transportation), gasoline (both regular and premium), liquefied petroleum gas (LPG), and NG in a smaller amount (all fuels were converted to diesel equivalent fuel). The initial list included ~500,000 companies and institutions. An initial filtering process removed from the list companies that a) reported LPG consumption, since in the country LPG is not used for industrial processes, except some hotels, hospitals, and shopping malls that have centralized LPG supply in relatively small amounts, and b) companies that sell diesel and gasoline for transportation (i.e., gas stations). The resulting list was filtered again by removing institutions that reported large amounts of diesel consumption for transportation only (e.g., municipal governments; ministries from the Ecuadorian government; and civil engineering companies that use diesel for transport/operation of heavy machinery for the construction of roads, bridges, and large buildings in the country). After a quantitative analysis, similar to that conducted for company A, it was found that the cogeneration capacity in companies consuming <151,400 L/year of fuel-oil or diesel will be <500 kW_{el}. Thus, the final fuel consumption baseline for selecting the companies where cogeneration could potentially be adopted was 151,400 L/year of diesel and/or fuel oil (both with approximately similar high heating value—HHV). Therefore, the list was reduced to ~1000 companies.

2.1.1.3. Final List of Industrial Companies That Could Adopt Cogeneration

The resulting lists (after filtering the ARCONEL and the ARCH data) were put together to prepare a final list of industrial companies (including hotels and hospitals) at a national level. Although the majority of the companies from the filtered ARCH list were also present in the filtered ARCONEL list, some companies were present in one list only since they reported high electricity consumption but low fuel consumption (e.g., plastics processing and ice making companies) and vice versa (e.g., fishing companies). After a case by case analysis, the final list was comprised of 555 companies (See Figure 4). All the 555 companies from the list, except 2 (from the oil palm industry, which are located in the Amazonian region), are located in the coast (~57%) and in the Andean highlands (~43%) regions. Among this list, there were sixteen companies working on shrimp growing/processing and eight ice making plants. These companies reported both high electricity and diesel consumption, but the chances of cogeneration were apparently negligible, since it was identified that the fuels were used for water pumping using internal combustion (diesel) engines in places where no electricity grids were available for shrimp pools operation and/or for land transport (using trucks). Thus, we decided to keep these companies in the final list to confirm the possibilities of cogeneration after visiting some of those plants.

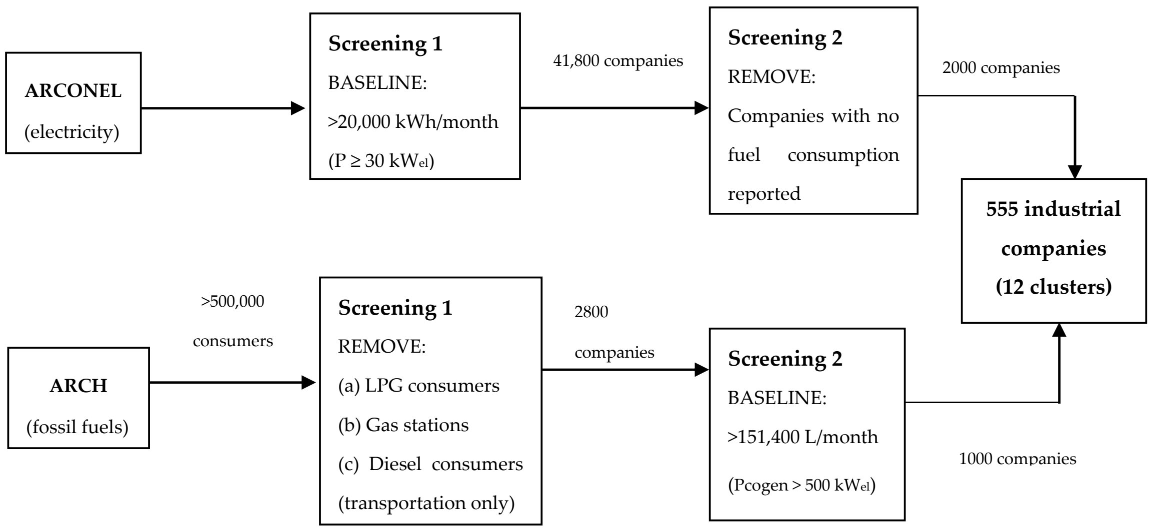


Figure 4. Flow diagram showing the selection of the companies where cogeneration is proposed.

2.1.2. Classification of Companies by Clusters and Validation of Data

The 555 companies in the final list were classified by clusters, which helped to organize visits to confirm the energy consumption data and to identify and record the corresponding industrial processes, including the identification of hot/cold fluids and their characteristics. The companies were grouped into twelve categories or clusters of industries, following the International Standard Industrial Classification of All Economic Activities (ISIC) [73,74]. Airports, shopping malls, and oil refineries were included in the cluster "others". Table 3 shows the list of clusters and the number of companies in each cluster. The information provided by the ARCONEL and the ARCH was validated by visiting 162 companies (~30% of the total), as detailed in Table 3. The selection of the companies to visit considered the amount of companies per cluster, the sizes, location, and the types of manufacturing processes to guarantee that all types of industries were visited. Interview survey formats (asking about energy consumption, types and amounts of fuels, industrial process, types and conditions of industrial fluids, if cogeneration has been adopted in the plant and the corresponding conditions, and other aspects to determine cogeneration potential) were used to collect the information provided by the industrial companies.

Table 3. Classification of industrial companies into clusters, types of industries in each cluster, amount of industrial plants visited, and types of predominant cold/hot fluids identified.

No.	Classification ISIC	Cluster Name	Number of Companies	Number (and %) of Companies Visited	Predominant Work Fluid(s)
1	C13	Textile industry	56	15 (27%)	Steam, Hot gases
2	C23	Construction materials (cement, ceramics/tiles)	23	17 (74%)	Hot gases, Steam
3	C10	Food industry (grain mills, fruit processing/juice, dairy, seafood, etc.)	132	36 (27%)	Steam, Hot water, Cold water
4	C11	Alcoholic and no-alcoholic beverages	35	18 (51%)	Steam, Hot water, Cold water
5	C16	Wood and wood composites	5	2 (40%)	Steam, Hot gases
6	C17	Pulp and paper	22	6 (27%)	Steam, Hot gases
7	C24 y C25	Metal processing industry	29	10 (34%)	Hot gases
8	C20	Agroindustry (includes oil palm industry)	58	14 (24%)	Steam, Hot water
9	Q86	Hospitals	47	17 (36%)	Steam, Hot water, A/C ***
10	I55	Hotels	17	9 (53%)	Steam, Hot water, A/C
11	-	Others (chemical products, tires, glass, shopping malls, airports *, refineries **)	63	15 (24%)	Steam, Hot water, A/C, Hot gases
12	C22	Plastics	68	3 (4.8%)	Hot water
		TOTAL:	555	162 (~30%)	

* Three airports were included in the study: Guayaquil, Quito, and Cuenca. The rest of airports in the country operate only sporadically and are not candidates for cogeneration. ** The three main oil refineries in the country [6] were included. *** Air conditioning.

2.1.3. Selection of Cogeneration Technologies

The following considerations were made for selecting the cogeneration technology that fits into the industrial plants' requirements:

(1) The proposed cogeneration/trigeneration system must fit into the current plant's requirements of heat (e.g., steam and/or hot water necessities) or cold fluids (including A/C) to guarantee cogeneration plants with high capacity factors. Therefore, the plant requirement of thermal energy with heating and/or cooling effect defined the cogeneration/trigeneration capacity of the plant.
(2) The prime mover selected will allow one to cover the electricity requirements totally or partially. In the case of deficit of electricity, and as long as the thermal energy production is met, it is preferred to import electricity from the national grid. If the cogeneration system produces electricity surplus, then it can be sold to the national grid. No sell or purchase of hot/cold fluids (i.e., transport of these fluids from or to the plant) were considered.
(3) The type of fuel (e.g., biomass, biogas, NG, diesel, heavy oil) proposed for cogeneration should be readily available in the place the cogeneration plant will be located. Therefore, fuel availability is a key component for deciding on the technology proposed.
(4) The yearly average thermal energy requirements (not the peak requirements) were used for sizing the cogeneration/trigeneration plant.
(5) No indoor heating and/or district heating are required. This is expected due to geographical location [75].
(6) The selection of the prime movers considered the limitations imposed by geographical conditions, specifically altitude. For the case study, industrial plants in the Ecuadorian Andes highlands are located at approximately 2500 m above the sea level (m.a.s.l.); thus, in these places, it is preferred to use diesel engines, gas engines, or boiler and steam turbines instead of gas turbines to guarantee adequate levels of efficiency of the cogeneration plant [76–78].
(7) The selection of the prime movers also considered possible partial loads requirements (i.e., the ability to vary thermal and electrical output depending on hourly requirements, or the necessity for frequent stopping and starting). Consequently, diesel and/or gas engines are preferable for cogeneration instead of gas turbines or steam turbines coupled with boilers in companies that do not operate 24/7. Diesel and gas engines, additionally, are able to run with renewable fuels (biodiesel and biogas, respectively), which are expected to be available in the country in the future [79] (See Section 3.2).
(8) Trigeneration can be projected only in industrial plants where air conditioning and/or process cooling fluids (above the water freezing temperature) for the industrial process are required. In this case, both air conditioning and/or cold fluids will be produced by using residual heat from the prime mover. The trigeneration system will mostly work on LiBr (lithium bromide) absorption equipment for air conditioning in the Coastal region and, in some cases, hotels, hospitals, and airports in the Andean highlands. Ammonia (NH_3) absorption systems are proposed only when fluids with low temperatures are required for the industrial process (e.g., for pasteurization in the beverages, food, and dairy industries). Freezing is not part of the proposed trigeneration systems.

2.1.4. Computation of the Potential of Cogeneration of Ecuador

The potential of cogeneration of Ecuador was determined in two steps. First, the sum of the potential of cogeneration of all industries by each cluster was conducted. Then, the potential of each cluster was added to obtain the potential at a national level. Regarding cogeneration sizing at the industry level, the computations were first conducted for the industrial plants that were visited (see Section 2.1.2), and computations were carried out for the rest of the plants, using the information on the fuels and electricity consumption, as well as its location, working conditions, and size in a case by case basis. The main steps for computing the potential of cogeneration of a specific company were as follows (see Appendix B for equations used):

1. Identify the location of the industrial plant and the availability of electricity grids to ensure interconnection to import/export electricity when electricity deficit/surplus exists.
2. Collect/verify data on electrical and thermal loads and types of fuels used. This information was compared with the data from the ARCONEL and the ARCH (Section 2.1.1).
3. Gather data on the company's process: types of products, heat requirements (e.g., steam or hot gases) and other fluids used (e.g., cold fluids, air conditioning, hot water).
4. Identify types of fuels that are or could be available in the company (or plant) location place.
5. Select the appropriate cogeneration prime mover and the corresponding fuel.
6. Compute the cogeneration plant capacity, based on the necessities of thermal energy. Table 4 presents equipment parameters used for the computations.
7. Standardize the size of the equipment suggested for a specific company by using catalogues from companies that provide equipment for cogeneration/trigeneration (e.g., boilers, diesel engines, gas engines, steam turbines, HRSGs, and absorption chillers).
8. Compute the amount of fuel that the cogeneration/trigeneration plant will require (Appendix B).
9. Compute the amount of electricity that will be produced by the prime movers in the operating conditions of the cogeneration plant and how much of this electricity will be available for exporting to the national grid (if surplus electricity is available).

Table 4. Parameters corresponding to the equipment used in the computations.

Equipment and Type	Efficiency	Comments
Diesel engine	Up to 40% electric efficiency [78])	Expected heat recovery: up to 86% from the total heat released by the engine (i.e., heat from exhaust gases and heat from jacket coolant), depending on the size of the engine.
Gas engine (working with biogas)	Up to 45% electric efficiency [78]	Expected heat recovery: up to 88% from the total heat released by the engine (i.e., heat from exhaust gases and heat from jacket coolant), depending on the size of the engine.
Steam turbine (back pressure)	~55% [78]	
Heat recovery steam generator (HRSG)	82% [80]	
Absorption chillers (single effect in all cases) *	Coefficient of performance, COP = 0.7	LiBr absorption chillers for air conditioning and for producing cold fluids, except for low temperature fluids (close to 4 °C, where NH_3 absorption chillers are suggested).
Biomass boilers	75–80%	Depends on the capacity of the boiler.

* Single effect chillers are more convenient for diesel (and gas) engines [71].

2.1.5. Assessment of Impacts of Cogeneration in Ecuador

2.1.5.1. Environmental Impacts

The computation of the environmental impacts of cogeneration considered two types of impacts: (a) the GHG emissions resulting from the fuel burned in each cogeneration plant, and (b) the avoided GHG emissions resulting from the possible replacement of large thermal power plants in the country (that use fossil-derived fuels for electricity production) by cogeneration plants in the industry. It is expected that the availability of cogeneration plants could remove the necessity of installing a thermal power plant (that uses oil-derived fuels to run) with capacity equal to that corresponding to the total cogeneration potential. Both results were added to obtain the net GHG emissions.

(a) Emissions in cogeneration plants

The fuels required for cogeneration depend on the prime mover selected. Cogeneration in Ecuador will use diesel, biogas, and lignocellulosic biomass, which are the fuels available currently in the country (See Section 3.2). The GHG emissions were estimated for each type of fuel. The computations followed the concept of conservation of carbon, from the fuel combusted into CO_2, according to the guidelines from the International Energy Agency [81]. For biogas, GHG emissions also considered the release of methane to the environment that can be avoided by using effluents in palm oil mills to produce biogas via anaerobic digestion [28].

(b) Emissions avoided by replacing thermal power plants

This computation consisted of determining how much fossil-derived fuels could save the country due to the substitution of existing or expected thermal power plants for electricity production (which could be a necessity to offset hydropower generation capacity in the country, especially during the dry season of the year) by cogeneration in industrial plants. To make easier the computations, it was assumed that the efficiency of large thermal power plants is ~35% [80] (although the efficiency of some existing thermal power plants in Ecuador is lower). The expected efficiency of the cogeneration plants taken as a reference was calculated in five representative companies (including a hospital and a hotel, where trigeneration is possible). Results showed efficiencies >70% in all cases. Thus, the difference in efficiency in a scenario without cogeneration and a scenario with cogeneration was conservatively taken as 30%.

2.1.5.2. Economic Impacts

Economic analysis was carried out to understand the convenience of cogeneration in the country from an economic point of view. The analysis consisted of (a) estimating the costs avoided if cogeneration is used instead of large thermal power plants that operate on fossil fuels, and (b) computing the cost of generating electricity in cogeneration plants if the whole potential of cogeneration calculated is installed. Table 5 summarizes the parameters employed for conducting the economic analysis. Some of these parameters are in agreement with the work of [42]. The prices of fuels and electricity are similar in all regions of the country.

Table 5. Parameters used for the economic analysis.

Parameter	Details
Cost of both diesel and gas engines for cogeneration	USD 1,000,000/MW_{el} * installed
Cost of equipment for Rankine cycle (boiler + steam turbine)	USD 3,000,000/MW_{el} installed, from which, approximately 15% corresponds to the cost of the steam turbine and the rest to the boiler and auxiliary equipment and accessories [78,82,83]
Cost of HRSG	USD 300,000 per MW_{el} of cogeneration capacity installed (this value is above that in [80], Ch. 24).
Cost of LiBr absorption chiller	USD 500/TR ** installed [80,84].
Cost of NH_3+H_2O absorption chiller	USD 700/TR installed [84].
Operation and maintenance costs	Value varies from 2% of the investment during the first years of the projects to up to 7% after year 10. Values are in the range of those reported by [85], although a little higher after year 5 due to the necessity of importing parts.
Expected capacity factor	95% to 60%, depending on the type of industry (see Table 6).
discount rate (includes financial cost and financial risk)	12% (rate currently used for electricity projects in Ecuador).
Reinvestment	25% of the initial investment will be required on year 10.
Projects lifetime	15 years.
Plant location and land requirements	No land will be bought for cogeneration plants since the plant will be installed at existing companies' facilities.
Substation and transmission facilities	Cost is included in the cost of prime movers.
Insurance	0.5% of the investment per year
Cost of diesel and natural gas	USD 2.12/gallon (USD ~0.57 US/L) and USD 0.45/kg, respectively (without subsidies) [86].
Cost of biomass ***	USD 20/t, which is in the range of or above the costs of residues from the agroindustry (e.g., oil palm residues) in the Ecuadorian coast region (resulting from a field study).
Workforce salaries	Each cogeneration plant will require one employee per MW_{el} installed per every 8 h of operation, with salaries of USD 1250/month (in the conditions of Ecuador), plus one supervisor and one person in charge of maintenance.

* Includes project management and design engineering as well as construction and start-up. This is a referential cost due to discrepancy of values in the literature. The authors of [78] show higher values, but [87] and [85] report values in the range of USD 1000/kW. However, the cost of a gas engine (1 MW) operating at a landfill in Cuenca was USD 450/kW. The value considered in this work could be adequate due to economy of scale when contracting and installing several cogeneration plants. ** TR refers to ton of refrigeration (equivalent to 3.52 kW). *** Electricity to be sold to the national electricity grid after operation of the plant and service loads are met. *** To operate cogeneration plants based on Rankine cycle.

Table 6. Summary of prime movers selected for cogeneration/trigeneration in Ecuador, range of sizes, and expected capacity factor for each type of industry.

Type of Industry (Cluster)	Location of Company	Prime Mover Suggested	Range of Sizes	Expected Average Capacity Factor
Food industry: Dairy	Coastal region and Andean highlands	Internal combustion engine (diesel engine)	0.75 to 2 MW_{el}, using one or more engines	75%
Food industry	Coastal region and Andean highlands	Internal combustion engine (diesel engine) or steam turbine (biomass fired boiler)	0.5 to 5 MW_{el}, using 1 or more engines	80%
Textile industry	Andean highlands	Internal combustion engine (diesel engine)	1 to 5 MW_{el}, using normally more than 1 engine	80%
Agroindustry (except oil palm industry)	Coastal region	Internal combustion engine (biogas or diesel engine) (4)	0.5 to 3 MW_{el}, using normally more than 1 engine	80%
Agroindustry: Oil palm industry	Coastal region	Internal combustion engine (gas engine) (1)	1 to 5 MW_{el}, using normally more than 1 engine	85%
Beverage industry	Coastal region and Andean highlands	Internal combustion engine (diesel engine)	0.5 to 5 MW_{el}, using 1 or more engines	80%
Wood and wood composites industry	Andean highlands	Boiler (biomass fired) and steam turbine (Rankine cycle) (2)	2 to 7 MW_{el}	85%
Cement and ceramic tiles	Coastal region and Andean highlands	Organic Rankine cycle	Up to 3 MW_{el}	80%
Pulp and paper	Coastal region and Andean highlands	Internal combustion engine (diesel engine) or biomass fired boiler (steam turbine) (3)	0.5 to 3 MW_{el}	90%
Metals	Coastal region and Andean highlands	Organic Rankine cycle	0.9 to 1.25 MW_{el}	80%
Hospitals	Coastal region and Andean highlands	Internal combustion engine (diesel engine)	0.5 to 5 MW_{el}, using normally more than 1 engine	60%
Hotels	Coastal region and Andean highlands	Internal combustion engine (diesel engine)	0.5 to 3.75 MW_{el}, using normally more than 1 engine	60%
Other: Airports	Coastal region and Andean highlands	Internal combustion engine (diesel engine)	0.6 to 3 MW_{el}, using normally more than 1 engine	65%
Other: Shopping malls	Coastal region and Andean highlands	Internal combustion engine (diesel engine)	2 MW_{el}	65%
Other: Tires	Andean highlands	Rankine cycle	~1.2 MW_{el}	95%

(1) Using only gas engines running with biogas. (2) Using biomass from the same plant. (3) Depending on the size of the company. (4) Further study is required to analyze the possibility of using biomass.

2.1.5.3. Social Impacts

According to [88] (p. 43), social impacts are the 'consequences of social relations (interactions) weaved in the context of an activity (production, consumption or disposal) and/or engendered by it and/or by preventive or reinforcing actions taken by stakeholders (ex. enforcing safety measures in a facility)'. A social life cycle analysis (SLCA) should consider the potential social impacts on local communities, workers, and consumers [89]. However, the literature shows that the social implications of projects related, for instance, with the use of lignocellulosic natural resources for energy [90] or wood-based products [91] are hard to estimate due to the difficulty of correlating cause–effect chains with regards to production activities and their potential social effects. Therefore, the computation of the social impacts of adopting cogeneration in a whole country is even more difficult. For this reason, in this work, the social impacts of cogeneration are focused on a preliminary estimation of such impacts on the creation of new jobs in the places where cogeneration plants could be installed. Such jobs are required, generally, for operating the cogeneration plants. Each plant will require at least five people: three for operation, one for maintenance, and one for management/supervision.

3. Results and Discussion

3.1. Current Electricity Demand and Fuel Consumption in the Industrial Sector of Ecuador

The electricity demand (from de National Interconnected System—SNI) and the fuel consumption in the 555 companies are 409,199 MWh/month and 61.73×10^6 L/month (51,773 t/month) of diesel equivalent, respectively. Figure 5 shows the electricity demand and fuel consumption by each type of cluster of companies (See Table 3). It is seen that the electricity consumption (Figure 5a) is higher in the clusters of food and construction materials industries, with 19% and 17% of the total, respectively. The fuel consumption, as seen in Figure 5b, is higher, again, in the cluster of companies of construction materials and in the cluster of food industries, with 17% and 16% of the total, respectively. The large amount of companies in the food industry cluster and the presence of energy intensive industries in the construction materials cluster (e.g., cement and ceramic tiles) explain these results.

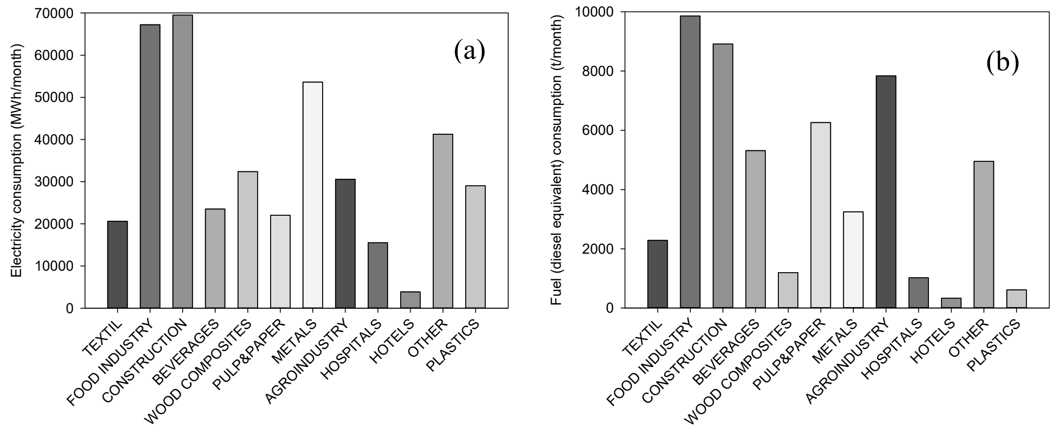


Figure 5. (**a**) Electricity and (**b**) fuel (diesel equivalent) consumption by industrial clusters in the list of the companies analyzed.

3.2. Cogeneration Technology by Type of Industry

Table 6 presents the technologies suggested for cogeneration schemes in each type of industry in Ecuador. The table also shows the geographic location of each cluster of industries. Internal combustion engines (diesel and gas engines) are the most prominent prime movers suggested due to their advantages, as discussed in Section 2.1.3. In addition, these engines offer the possibility of working with biodiesel and biogas, in substitution of diesel and NG, respectively, which is of interest in Ecuador. Currently the country produces only ~30 t/year of biodiesel from *Jatropha curcas* to operate diesel engines in thermal power plants the Galapagos Islands [92]. The program to produce biodiesel from this plant is in its infancy, but it is expected that the biodiesel production capacity will increase in coming years. The use of gas engines deserves further study since it is expected that the agroindustrial sector in Ecuador will start producing biogas using their residues via anaerobic digestion. However, this topic is out of the scope of this paper.

3.3. Potential of Cogeneration/Trigeneration

The estimated potential of cogeneration in Ecuador is 598 MW_{el}, which, as mentioned in Section 2.1, consists of the potential of cogeneration of industries with expected installed cogeneration capacity above 0.5 MW_{el}. The value excludes the existing cogeneration capacity shown in Table 1. This potential is ~7% of the current electricity generation installed capacity in Ecuador and could produce up to 17% of the total electricity consumed in 2017 in the country. This last value is, interestingly, in the range of percentages of the cogeneration share (respect to the total electricity produced) in countries such as Germany (17%), Brazil (18%), Spain (12%), or the United States (12%) [58,93–95]. Even though in the case of Ecuador this amount refers to potential cogeneration (i.e., not installed cogeneration capacity), such value is important because of the possibility of using cogeneration during the driest season of the year, when hydropower generation is negatively affected by weather conditions (See Section 1). For this reason, cogeneration has been seen in the country as an important strategy for electricity production in the near future, and new laws and regulations are under study to promote cogeneration/trigeneration.

Figure 6 summarizes the potential of cogeneration in Ecuador by type of prime mover selected. Diesel engines are the predominant prime movers suggested for cogeneration (Section 3.2). These engines can run with biodiesel (mixed with diesel) when available. Figure 7 presents the potential of cogeneration by cluster, showing that the textile, food, and agroindustry industries are the clusters with higher potential. Moreover, the potential of trigeneration in the country is 212 MW_{el}. Approximately 17% of the 555 companies identified in Section 2.1 could adopt trigeneration, especially in the food and beverages industries, as well as in hotels and hospitals (Figure 8).

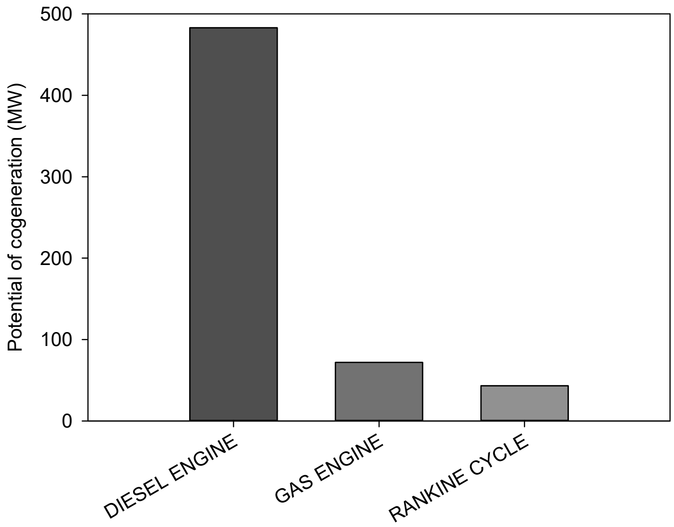


Figure 6. Potential of cogeneration in Ecuador by type of prime mover suggested (MW_{el}).

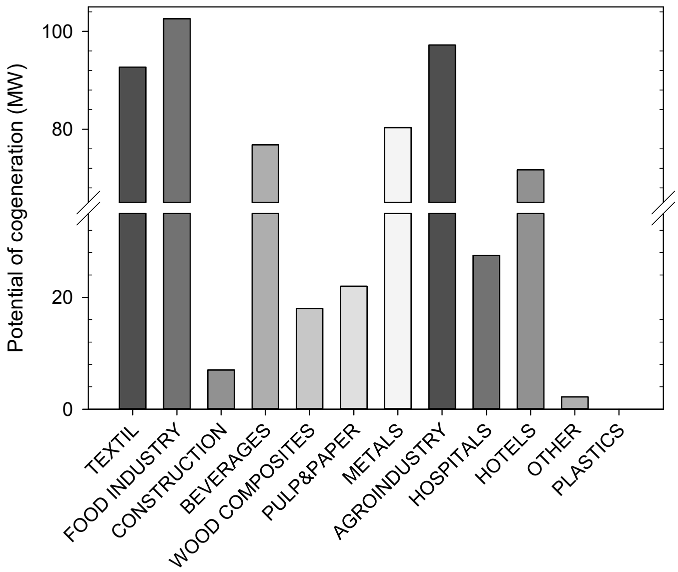
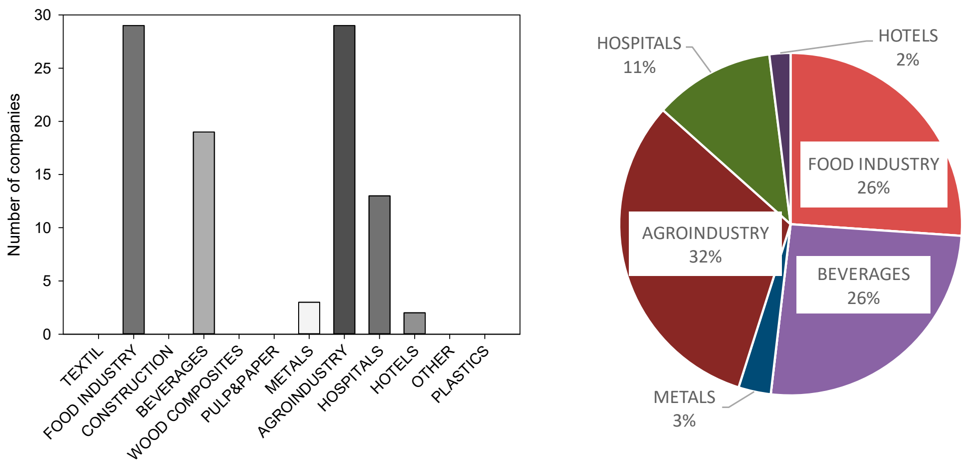


Figure 7. Potential of cogeneration by cluster of industries (MW_{el}).



(**a**) (**b**)

Figure 8. (**a**) Amount of companies that could adopt trigeneration, and (**b**) contribution (in %) of each cluster to trigeneration (based on a trigeneration potential of 212 MW_{el}).

3.4. Impacts of Cogeneration in Ecuador

3.4.1. Fuel Consumption, Improvement of Energy Efficiency, and GHG Emissions Reduction

The adoption of cogeneration in Ecuador will require different types of fuels. Due to the lack of NG in the country (the preferred fuel for cogeneration in most countries from tempered regions), in the conditions of this study and considering current fuel availability in Ecuador (See Section 3.2), diesel has been selected. Diesel could comprise approximately 81% of the fuel requirements for cogeneration (if the whole potential of 598 MW_{el} is installed), while biogas and biomass could, together, cover approximately 17% (as shown in Table 7). Biomass fuel is constituted by solid residues generated by the agroindustry (e.g., oil palm and rice), which are abundant biomass resources in the coast region. Although the potential of biomass for cogeneration can be higher than this value, its use deserves more analysis due to the difficulty of hauling and burning this fuel in industrial plants located in urban areas far away from biomass sources. The potential use of NG for cogeneration is very low (~2%). Because of NG is an important fuel for cogeneration in most countries (due to availability, competitive prices, and cleanliness during burning), Ecuador urgently needs to look for NG as an alternative (at least partially) to diesel. For this purpose, two options are being analyzed in the country: (a) importing NG from neighbor countries such as Peru, which, in addition to its high potential production [45], could also import it from Bolivia, as part of the so-called Latin America Energy Integration [96–98], and (b) exploring the Gulf of Guayaquil for more NG, since there is no certainty about the NG reserves in this part of the country.

Table 7. Types and quantities of fuels required for cogeneration in Ecuador and potential contribution to greenhouse gas (GHG) generation/reduction.

Type of Fuel	Potential of Cogeneration (MW_{el}) and Share in the Total (%)	Amount of Fuel	Expected Electricity Generation (GWh/year)	Potential GHG Emissions (tCO_2/year)
Diesel	482.9 (81%)	368,950,000 kg/year	4231.3	+1,150,500 (a)
Biogas	60.0 (10%)	100,126,800 kg/year	525.7	−704,147 (b)
Biomass	43.0 (7%)	71,781,943 kg/year	376.9	−227,770
Natural Gas	11.9 (2%)	19,772,571 kg/year	102.9	+62,210
TOTAL:	598		5236.8	280,793 (Total 1)
			Emissions in the SNI	−576,800
			Net GHG (reduction)	−296,007 (Total 2)

Table 7 also shows the electricity that could be produced by type of fuel (column four) and the corresponding potential contribution to GHG emissions (Table 7, column five). The negative sign in the Table indicates avoided GHG emissions, which results from (1) burning biomass and biogas instead of oil-derived fuels to produce electricity (in cogeneration plants), and (2) the avoided methane formation from liquid effluents from the oil palm industry. Currently, although the majority of the 35 oil palm companies in the country (See Section 1) are aware about the necessity of using liquid effluents for biogas production, these effluents are discharged to pools for stabilization prior to final disposal due to the lack of incentives/regulations from the State to use them for energy.

The adoption of cogeneration could promote a reduction 18.55 million L/month (15,556 t/month) of diesel (and/or heavy fuel oil) and avoid up to 576,800 tCO_2/year. This value results from considering that the country would need to install and operate a 600 MW_{el} power plant (or several plants with equivalent total capacity) to offset the reduction of hydropower during the dry season and that, instead of installing such thermal power plant, cogeneration in the industry will be adopted. The positive impact of cogeneration in the industrial sector's energy efficiency of the country is proportional to the amount of fuels saved. Thus, in the conditions of this study, the increase in energy efficiency, if the whole cogeneration potential was installed, could reach between 35% and 40%.

The net GHG emissions (i.e., total 1 in Table 7 minus 576,800) could be −296,007 tCO_2/year (total 2), showing that installing cogeneration/trigeneration in the industry can be an important strategy to avoid GHG emissions in Ecuador. Figure 9 shows that the clusters in which fuel savings could be higher are the food industry, the beverage industry, and the agroindustry. Further study is necessary for analyzing the environmental positive impacts of changing diesel and natural gas by biodiesel and biogas, respectively. However, Table 7 shows that potential GHG emissions are reduced even using diesel and NG, as a consequence of higher efficiency on burning these fuels in cogeneration plants.

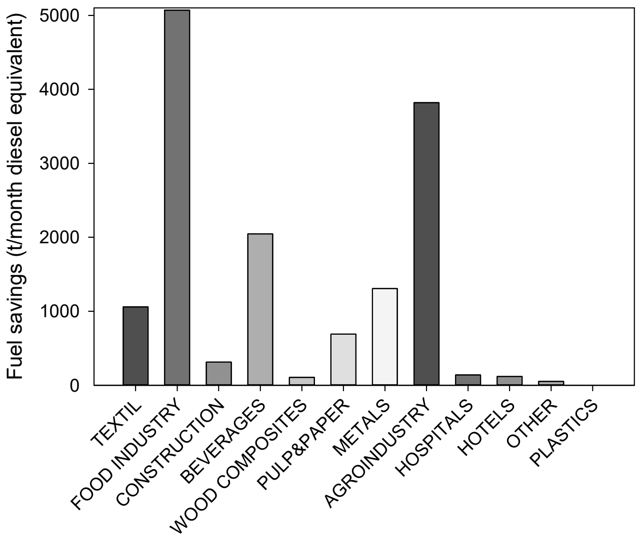


Figure 9. Expected fuel savings (by cluster) resulting from the possible adoption of cogeneration.

3.4.2. Economic Analysis

The economic analysis showed that an important consequence for Ecuador is that, if cogeneration is installed instead of a large thermal power plant to offset the future lack of hydroelectricity, the country could save up to USD 125 million per year by avoiding the use of oil-derived fuels for electricity generation. The cost of the electricity produced in cogeneration plants will depend on the type of cogeneration scheme and the type of fuel used, as seen in Table 8. The cost for electricity produced in cogeneration plants (considering the cost of fuels shown in Table 5, but excluding NG), will vary from USD 0.09/kWh to USD0.17/kWh for electricity produced in the oil palm industry (using lignocellulosic biomass) and in hospitals (using diesel), respectively. Table 8 also shows that some types of cogeneration plants, even using diesel, could produce electricity at costs lower than USD 0.17/kWh. For instance, the hotels industry and the textile industry could produce electricity at USD 0.12/kWh and USD 0.13/kWh (using diesel as fuel), respectively. Although these values are higher than the cost of generating electricity in hydropower plants in Ecuador (up to 0.08 USD/kWh), cogeneration in these conditions is still of interest for Ecuador due to the necessity of diversification of electricity generation and the opportunity of having installed capacity for electricity generation during the dry season of the year. Because of insufficient electricity generation (especially before 2016), Ecuador has often required to import electricity from both Colombia and Peru at prices up to USD 0.28/kWh or to produce electricity using thermal power plants at even higher costs (up to USD 0.50/kWh in old thermal power plants).

An analysis of sensitivity was carried out to understand the effect of using NG (when available in the future) instead of diesel for cogeneration in the country. Results showed that NG could promote a substantial reduction of the costs of electricity production in cogeneration plants. For instance, the dairy industry could produce electricity at around USD 0.06/kWh, hotels at USD 0.08/kWh, and hospitals at USD 0.05/kWh (Table 8). These results reinforce the notion that the country must look for options for buying NG overseas, especially in neighboring countries (see Section 3.4.1). The production and use of biofuels for cogeneration requires further analysis.

Table 8. Examples of costs of electricity generated in some types of clusters of industries in the conditions of the study (including the potential use of NG).

Type of Cluster of Industries	Type of Fuel Suggested	Type of Plant	Expected Cost of Electricity Generated (USD/kWh)
Oil palm industry	Biomass	Cogeneration	0.09
Oil palm industry	Biogas	Cogeneration	0.02
Dairy industry	Diesel	Trigeneration	0.14
Dairy industry	NG	Trigeneration	0.06
Textile industry	Diesel	Cogeneration	0.13
Textile industry	Biomass	Cogeneration	0.10
Hotels	Diesel	Trigeneration	0.12
Hotels	NG	Trigeneration	0.08
Hospitals	Diesel	Trigeneration	0.17
Hospitals	NG	Trigeneration	0.05

3.4.3. Social Impacts of Cogeneration

The adoption of cogeneration/trigeneration in Ecuador could promote more than 2600 new jobs. As mentioned in Section 2.1.5.3, these direct jobs are required for operating, managing, and maintaining the cogeneration plants. There is evidence showing positive impacts of energy efficiency measures on GDP, employment, economic structure, and welfare [99]. In addition, there is an important element that was not included in the economic analysis: the benefit to the state of avoiding the release of CO_2 by installing cogeneration plants, which is related to the "social cost of carbon" or marginal damage caused by an additional ton of carbon dioxide emissions [2–4,100]. Therefore, these and other benefits that are not considered at this level of the study (e.g., the impact on rural areas where some cogeneration will be installed, the benefits on health due to better air quality or the creation of indirect jobs) deserve further study.

4. Conclusions

In tropical climate countries, the potential of cogeneration (and as such, its calculation) of the industrial sector is dependent on particular climate conditions, consumption behavior, cogeneration schemes, and fuel availability. Tropical countries such as Ecuador do not necessitate indoor heating (an important energy requirement in tempered climate countries), although air conditioning is prominently used. Thus, large cogeneration projects are more suitable in the industrial sector and in places where hot and cold fluids are used (e.g., hospitals, hotels, airports, and shopping malls). This study has shown that the adoption of cogeneration at a large scale promotes environmental, economic, and social benefits to countries by reducing GHG emissions, promoting fuel savings and energy efficiency, and by creating new jobs, respectively. In the case of Ecuador, the potential of cogeneration in the industrial sector (including hospitals, hotels, shopping malls and two airports) is approximately 600 MW_{el}, which is around 7% of the total electricity generation installed capacity in the country. If this cogeneration potential is implemented, the energy efficiency in the Ecuadorian industry could be increased by 35–40%. This potential could save up to 18.6 × 106 L/month of oil-derived fuels, avoiding up to 576,800 tCO_2/year, and creating more than 2600 direct jobs. Lack of NG for cogeneration is seen as a problem that needs to be addressed in the future to reduce the cost of electricity generation in cogeneration plants. The use of diesel and gas engines (the main types of prime movers in the conditions of the industry in Ecuador) presents opportunities to easily move from fossil-derived fuels to renewable fuels, i.e., to use biodiesel and biogas in substitution of diesel and NG, respectively. This topic deserves further analysis, especially in identifying options for producing biofuels. Further studies should also address the logistics of integration of cogeneration with other electricity generation sources such as hydropower, or the logistics of biomass for cogeneration, to mention two aspects. Distributed generation through cogeneration offers opportunities to diversify local (small scale) electricity generation to optimize the use of the national grid and offset one of the problems of the Ecuadorian electricity sector: its high dependency on hydropower that has large seasonal variations due to water flow reductions.

Author Contributions: Conceptualization, M.R.P.-S., J.L.E., J.J.-A., P.R.-G. and P.R.; methodology, M.R.P.-S., J.L.E., J.J.-A., F.M.-A., P.A.-R.; validation, M.R.P.-S., J.L.E., J.J.-A., P.A.-R.; data curation, M.R.P.-S., J.L.E. and T.G.-P.; writing—original draft preparation, M.R.P.-S. and J.L.E.; writing—review and editing, M.R.P.-S., J.L.E., J.J.-A., F.M.-A. and T.G.-P.; supervision, J.L.E. and M.R.P.-S.; project administration, J.J.-A.; funding acquisition, J.J.-A., P.R.-G. and P.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the former Ministry of Electricity and Renewable Energy—MEER (currently Ministry of Energy and Natural Non-renewable Resources) and the Corporación Eléctrica del Ecuador—CELEC EP (Contract No. 042-2016).

Acknowledgments: To the former Ministry of Electricity and Renewable Energy—MEER (currently Ministry of Energy and Natural Non-renewable Resources) and the Corporación Eléctrica del Ecuador—CELEC EP, institutions that have authorized this publication. Thanks to Stalin Vaca, Diego Suárez, Jaime Alvarado, Ricardo Álvarez, Robinson Machuca, Guillermo Pérez, Tamara Serrano, Rommel Vargas, and Fernanda Orellana for their support in conducting field research; to all the Ecuadorian industrial facilities that contributed information to conduct this study; to the ARCH and the ARCONEL for providing information on energy consumption in Ecuador; to Paul Martinez and Jorge Ortiz (CELEC EP) for their constructive comments on the results of the study; and to Raul Pelaez-Garcia for revising the English in the text.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Schematics of Proposed Cogeneration Systems

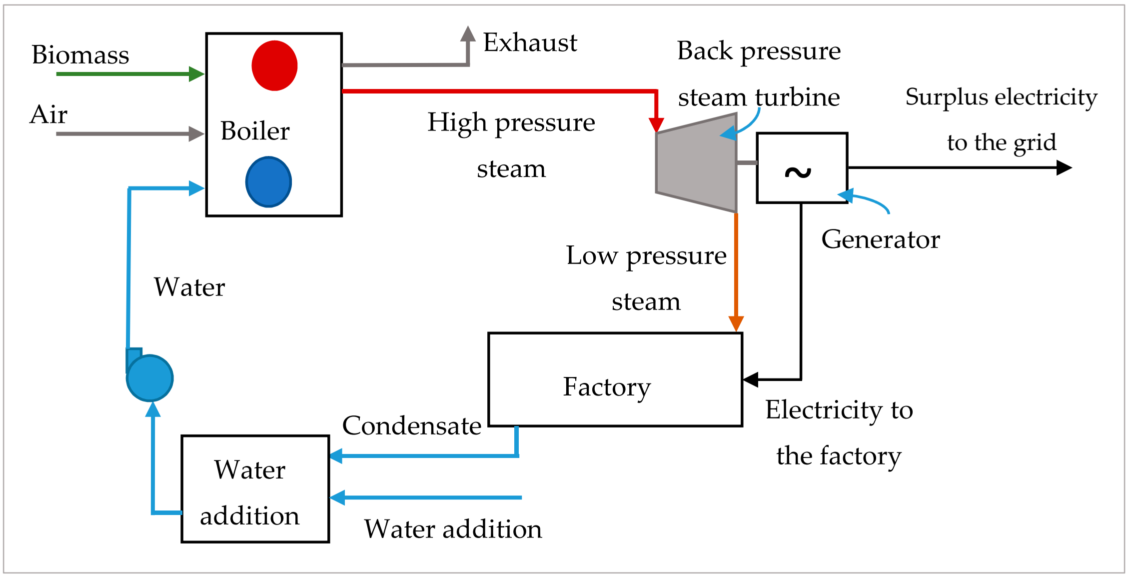


Figure A1. Schematic of cogeneration system based on Rankine cycle for companies that can use biomass as fuel (e.g., sugarcane, pulp and paper, oil palm industries) and back pressure steam turbines. Adapted from [18,19,23,28,32,49,51].

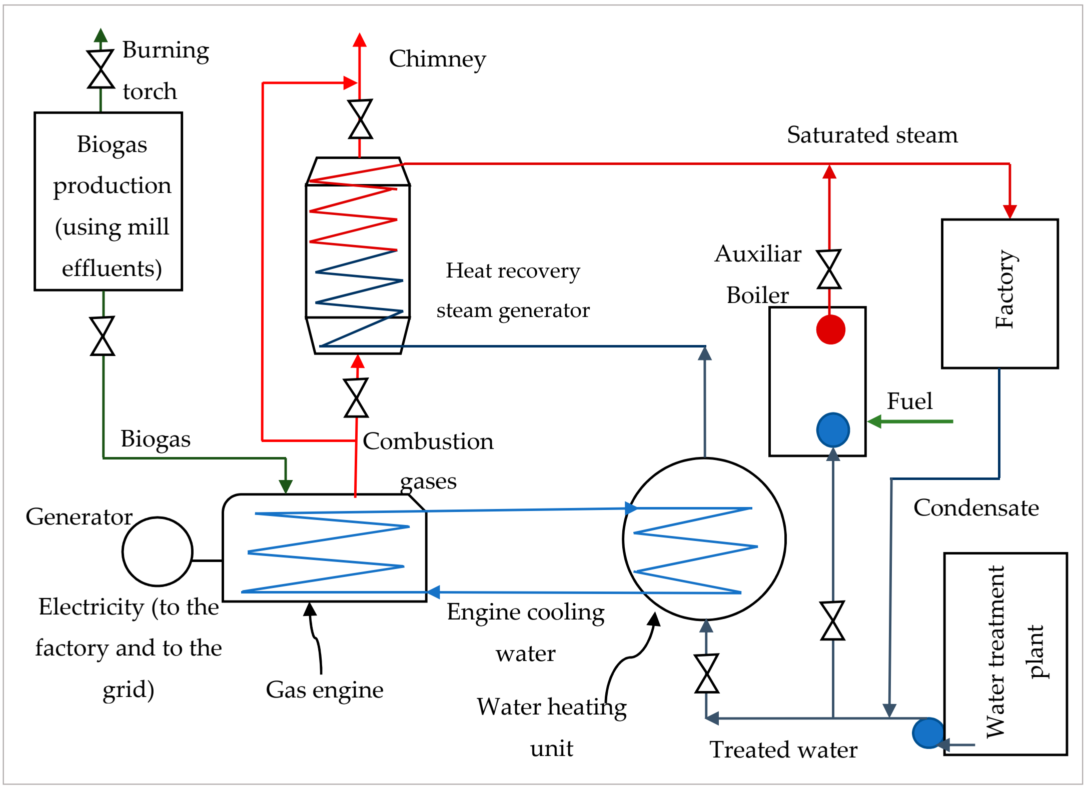


Figure A2. Schematic of a cogeneration system using gas engines for the oil palm industry.

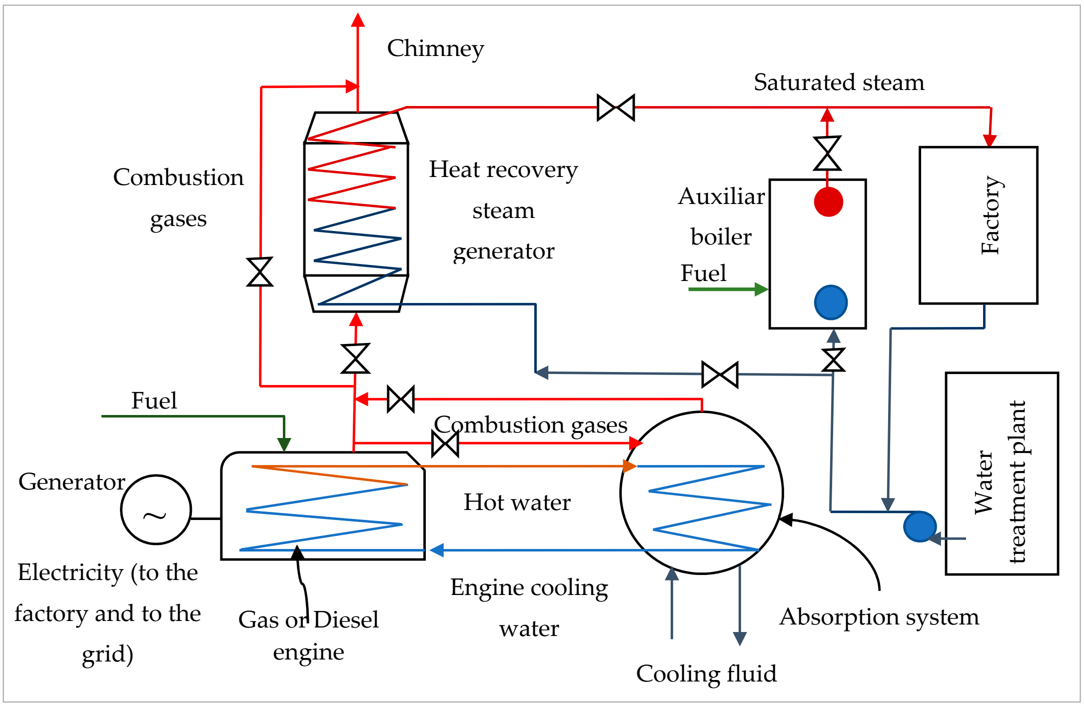


Figure A3. Schematic of a proposed trigeneration system using gas engines or diesel engines for the beverage industry, dairy industry, and food industry.

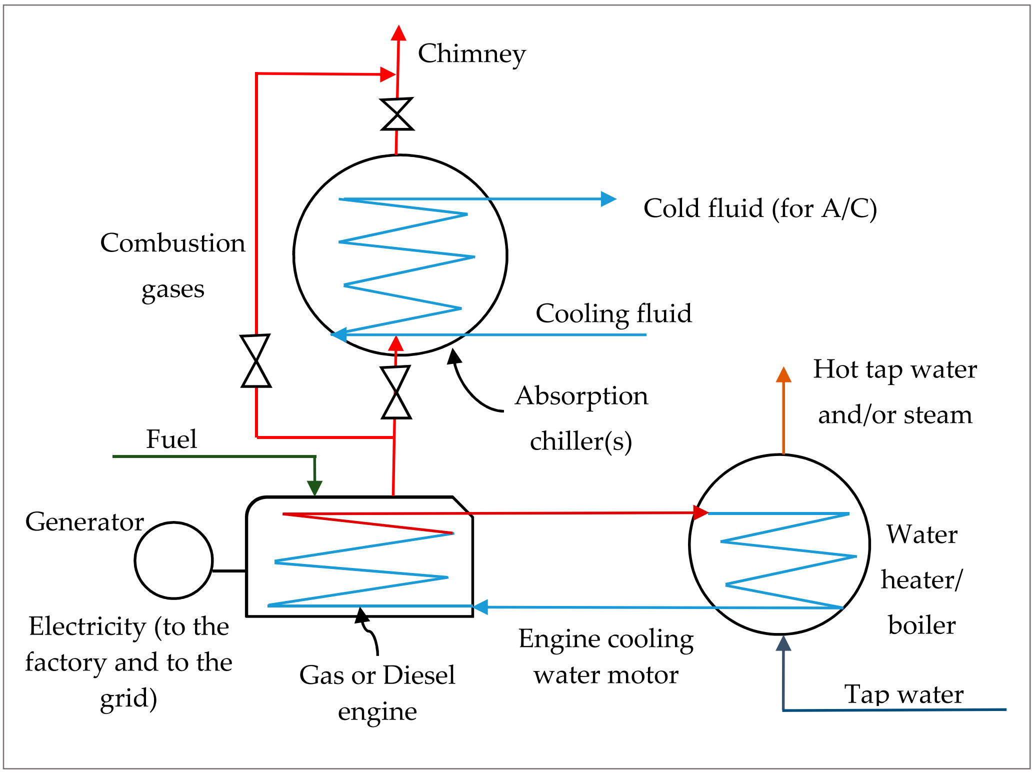


Figure A4. Schematic of a proposed trigeneration system using gas engines or diesel engines for service industries (e.g., hotels, hospitals). Adapted from [46].

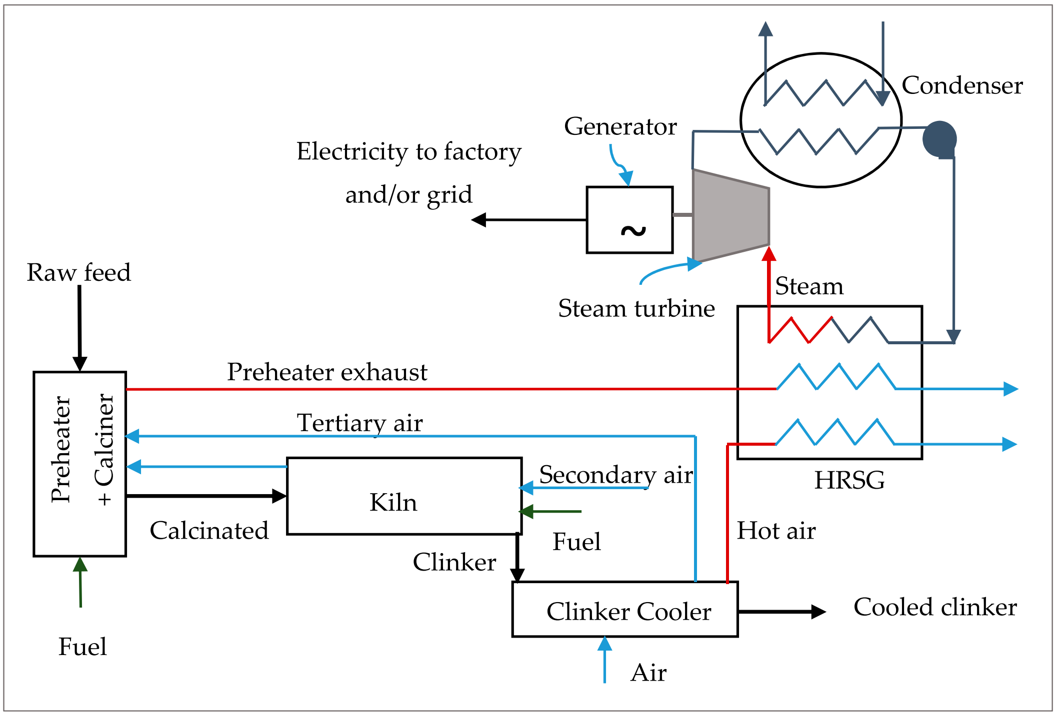


Figure A5. Schematic of a proposed bottom cogeneration system used in cement industry. HRSG—heat recovery steam generator (adapted from [55,101]).

Appendix B. Main Equations Used for the Computation of Cogeneration Systems (Units Are Presented in Brackets)

(a) Cogeneration plant efficiency (CHP_{eff})

CHP_{eff} = (power output + useful heat recovered)/energy in fuel

(b) Energy in fuel (Q_{fuel})

$Q_{fuel} = m_{fuel}*LHV_{fuel}$ [kW]

m_{fuel}—fuel rate [kg/s]

LHV_{fuel}—fuel lower heating value [kJ/kg]

(c) Energy in steam (Q_{steam})

$Q_{steam} = m_{steam}*(h_{steam} - h_{water})$ [kW]

m_{steam}—flow rate (production) of steam [kg/s]

h_{steam}—enthalpy of steam at the boiler exit [kJ/kg]

h_{water}—enthalpy of water at the entrance of boiler [kJ/kg]

(d) Efficiency of boiler [η_{boiler}]

$\eta_{boiler} = Q_{steam}/Q_{fuel}$

(e) Energy in combustion gases (Q_{cgas}) that is used, for instance, in a heat recovery steam generator (HRSG)

$Q_{cgas} = m_{cgas}*(h_{hotgas} - h_{coldgas})$ [kW]

m_{cgas}—flow rate of combustion gases [kg/s] (e.g., gases from gas engine)

h_{hotgas}—enthalpy of combustion gases at the entrance of heat recovery unit [kJ/kg]

h_{oldgas}—enthalpy of combustion gases after passing through the heat recovery equipment [kJ/kg]

(f) Electric energy efficiency of prime movers (motors) (η_{EE})

$\eta_{EE} = W_{elec}/Q_{fuel}$

W_{elec}—electric power (useful energy output) [kW]

(g) Heat recovery unit (HRU) efficiency (η_{HRU}) for water heating

$\eta_{HRU} = Q_{HRUactual}/Q_{HRUtheor}$

$Q_{HRUactual}$—actual heat transfer rate [kJ/s]

$Q_{HRUtheor}$—maximum possible heat transfer rate [kJ/s]

$Q_{HRUactual} = m_{waterHRU} * (h_{waterHRUent} - h_{waterHRUexit})$

$m_{waterHRU}$—water flow rate in the HRU [kg/s]

$h_{waterHRUexit}$—enthalpy of water at the entrance of the HRU [kJ/kg]

$h_{waterHRUent}$—enthalpy of water at the exit of the HRU [kJ/kg]

(h) Heat recovery steam generator efficiency (η_{HRSG}) (for steam production)

$\eta_{HRSG} = Q_{HRSGactual}/Q_{HRSGtheor}$

$Q_{HRSGactual}$—actual heat transfer rate [kJ/s]

$Q_{HRSGheor}$—maximum possible heat transfer rate [kJ/s]

$Q_{HRSGactual} = m_{steamHRSG} * (h_{steamHRSGent} - h_{waterHRSGexit})$

$m_{waterHRU}$—steam (or water) flow rate in the HRSG [kg/s]

$h_{waterHRUexit}$—enthalpy of water at the entrance of the HRSG [kJ/kg]

$h_{steamHRUent}$—enthalpy of steam at the exit of the HRSG [kJ/kg]

(i) Efficiency of absorption chiller (COP_{Achill})

$COP_{Achill} = Q_{evap}/Q_{in}$

Q_{evap}—rate at which water is cooled by the evaporator [kJ/s]

Q_{in}—heat input (rate of heat loss from exhaust gas or steam that are used by the absorption unit) [kJ/s]

(j) Electricity produced by steam turbine-generator (E_{gen}) [kWh/month]

$E_{gen} = Q_{steam}*\eta_{turb}*\eta_{gen}*T_{oper}*p_f$ [kWh/month]

η_{turb}—steam turbine efficiency

η_{gen}—generator efficiency

T_{oper}—time generator operates [h/month]

(k) Present worth (present value) (C_t) of C monetary units

$C_t = C/(1+i)^t$;

i—discount rate; t—number of time periods

(l) Net present value (NPV)

$NPV = (C_1+C_2+C_3+ \ldots + C_n)$

$C_1, C_2, C_3, \ldots, C_n$ – Present worth of anticipated cash flows

References

1. BP STATS. *Statistical Review of World Energy Statistical Review of World*, 68th ed.; BP: London, UK, 2019.
2. Ackerman, F.; Stanton, E.A. Climate risks and carbon prices: Revising the social cost of carbon. *Economics* **2012**. [CrossRef]
3. Moore, F.C.; Diaz, D.B. Erratum: Temperature impacts on economic growth warrant stringent mitigation policy. *Nat. Clim. Chang.* **2015**, *5*, 280. [CrossRef]
4. Dell, M.; Jones, B.F.; Olken, B.A. Temperature shocks and economic growth: Evidence from the last half century. *Am. Econ. J. Macroecon.* **2012**. [CrossRef]
5. Peláez-Samaniego, M.R.; Garcia-Perez, M.; Cortez, L.A.B.; Oscullo, J.; Olmedo, G. Energy sector in Ecuador: Current status. *Energy Policy* **2007**. [CrossRef]
6. Pelaez-Samaniego, M.R.; Riveros-Godoy, G.; Torres-Contreras, S.; Garcia-Perez, T.; Albornoz-Vintimilla, E. Production and use of electrolytic hydrogen in Ecuador towards a low carbon economy. *Energy* **2014**, *64*, 626–631. [CrossRef]
7. Ponce-Jara, M.A.; Castro, M.; Pelaez-Samaniego, M.R.; Espinoza-Abad, J.L.; Ruiz, E. Electricity sector in Ecuador: An overview of the 2007–2017 decade. *Energy Policy* **2018**, *113*. [CrossRef]
8. BID; Ministerio de Electricidad y Energía Renovable; MEER. *Plan Nacional de Eficiencia Energética 2016–2035*; Ministerio de Electricidad y Energía Renovable: Quito, Ecuador, 2017.
9. Insituto de Investigación Geológico y Energético (IIGE). *Balance Energético Nacional 2018*; Ministerio de Energía y Recursos Naturales no Renovables: Quito, Ecuador, 2019.
10. MAE. Resumen del Inventario Nacional de Gases de Efecto Invernadero del Ecuador. Available online: https://info.undp.org/docs/pdc/Documents/ECU/06%20Resumen%20Ejecutivo%20INGEI%20de%20Ecuador.%20Serie%20Temporal%201994-2012.pdf (accessed on 20 May 2019).
11. MEER; BID. *Plan Nacional de Eficiencia Energética*; Ministerio de Electricidad y Energía Renovable: Quito, Ecuador, 2016.

12. Posso, F.; Sánchez, J.; Espinoza, J.L.; Siguencia, J. Preliminary estimation of electrolytic hydrogen production potential from renewable energies in Ecuador. *Int. J. Hydrogen Energy* **2016**, *41*, 2326–2344. [CrossRef]
13. ARCONEL. Balance Nacional de Energía Eléctrica. Available online: https://www.regulacionelectrica.gob.ec/balance-nacional/ (accessed on 20 December 2019).
14. CENACE. Energía Neta Producida por las Centrales de Generación. Available online: http://www.cenace.org.ec/docs/Produci{\protect\edefT1{T5}\let\enc@update\relaxó}n-de-Energ{\protect\edefT1{T5}\let\enc@update\relaxí}a-(GWh)-mensual.htm (accessed on 12 March 2020).
15. MEER; ARCONEL. *Plan Maestro de Electrificación 2016–2025*; Ministerio de Electricidad y Energía Renovable: Quito, Ecuador, 2017.
16. Nzotcha, U.; Kenfack, J. Contribution of the wood-processing industry for sustainable power generation: Viability of biomass-fuelled cogeneration in Sub-Saharan Africa. *Biomass Bioenergy* **2019**. [CrossRef]
17. Arshad, M.; Ahmed, S. Cogeneration through bagasse: A renewable strategy to meet the future energy needs. *Renew. Sustain. Energy Rev.* **2016**. [CrossRef]
18. Deshmukh, R.; Jacobson, A.; Chamberlin, C.; Kammen, D. Thermal gasification or direct combustion? Comparison of advanced cogeneration systems in the sugarcane industry. *Biomass Bioenergy* **2013**. [CrossRef]
19. Dias, M.O.S.; Modesto, M.; Ensinas, A.V.; Nebra, S.A.; Filho, R.M.; Rossell, C.E.V. Improving bioethanol production from sugarcane: Evaluation of distillation, thermal integration and cogeneration systems. *Energy* **2011**. [CrossRef]
20. Salem Szklo, A.; Soares, J.B.; Tolmasquim, M.T. Energy consumption indicators and CHP technical potential in the Brazilian hospital sector. *Energy Convers. Manag.* **2004**. [CrossRef]
21. Restuti, D.; Michaelowa, A. The economic potential of bagasse cogeneration as CDM projects in Indonesia. *Energy Policy* **2007**. [CrossRef]
22. To, L.S.; Seebaluck, V.; Leach, M. Future energy transitions for bagasse cogeneration: Lessons from multi-level and policy innovations in Mauritius. *Energy Res. Soc. Sci.* **2018**. [CrossRef]
23. Gongora, A.; Villafranco, D. Sugarcane bagasse cogeneration in Belize: A review. *Renew. Sustain. Energy Rev.* **2018**. [CrossRef]
24. Deepchand, K. Commercial scale cogeneration of bagasse energy in Mauritius. *Energy Sustain. Dev.* **2001**. [CrossRef]
25. Rincón, L.E.; Becerra, L.A.; Moncada, J.; Cardona, C.A. Techno-economic analysis of the use of fired cogeneration systems based on sugar cane bagasse in south eastern and mid-western regions of Mexico. *Waste Biomass Valoriz.* **2014**. [CrossRef]
26. Booneimsri, P.; Kubaha, K.; Chullabodhi, C. Increasing power generation with enhanced cogeneration using waste energy in palm oil mills. *Energy Sci. Eng.* **2018**. [CrossRef]
27. Nasution, M.A.; Herawan, T.; Rivani, M. Analysis of palm biomass as electricity from palm oil mills in north sumatera. *Energy Procedia* **2014**, *47*, 166–172. [CrossRef]
28. Garcia-Nunez, J.A.; Rodriguez, D.T.; Fontanilla, C.A.; Ramirez, N.E.; Silva Lora, E.E.; Frear, C.S.; Stockle, C.; Amonette, J.; Garcia-Perez, M. Evaluation of alternatives for the evolution of palm oil mills into biorefineries. *Biomass Bioenergy* **2016**. [CrossRef]
29. Simo, A.; Siyam Siwe, S. Availability and conversion to energy potentials of wood-based industry residues in Cameroon. *Renew. Energy* **2000**. [CrossRef]
30. Mujeebu, M.A.; Jayaraj, S.; Ashok, S.; Abdullah, M.Z.; Khalil, M. Feasibility study of cogeneration in a plywood industry with power export to grid. *Appl. Energy* **2009**. [CrossRef]
31. Duval, Y. Environmental impact of modern biomass cogeneration in Southeast Asia. *Biomass Bioenergy* **2001**. [CrossRef]
32. Coelho, S.T.; Velázquez, S.G.; Zylbersztajn, D. Cogeneration in Brazilian Pulp and Paper Industry from Biomass-Origin to Reduce CO_2 Emissions. In *Developments in Thermochemical Biomass Conversion*; Bridgwater, A.V., Boocock, D.G.B., Eds.; Springer: Dordrecht, The Netherlands, 1997.
33. Coronado, C.R.; Yoshioka, J.T.; Silveira, J.L. Electricity, hot water and cold water production from biomass. Energetic and economical analysis of the compact system of cogeneration run with woodgas from a small downdraft gasifier. *Renew. Energy* **2011**. [CrossRef]
34. Udomsri, S.; Martin, A.R.; Martin, V. Thermally driven cooling coupled with municipal solid waste-fired power plant: Application of combined heat, cooling and power in tropical urban areas. *Appl. Energy* **2011**. [CrossRef]

35. Mahlia, T.M.I.; Chan, P.L. Life cycle cost analysis of fuel cell based cogeneration system for residential application in Malaysia. *Renew. Sustain. Energy Rev.* **2011**, *15*, 416–426. [CrossRef]
36. Silva, H.C.N.; Dutra, J.C.C.; Costa, J.A.P.; Ochoa, A.A.V.; dos Santos, C.A.C.; Araújo, M.M.D. Modeling and simulation of cogeneration systems for buildings on a university campus in Northeast Brazil—A case study. *Energy Convers. Manag.* **2019**. [CrossRef]
37. IDEA. *Análisis del Potencial Cogeneración de Alta Eficiencia en España 2010–2015–2020*; Instituto para la Diversificación y Ahorro de la Energía: Madrid, Spain, 2016.
38. NSW. Office of Environment and Heritage NSW, Cogeneration Feasibility Guide; Sidney, 2014. Available online: https://www.environment.nsw.gov.au/resources/business/140685-cogeneration-feasibility-guide.pdf (accessed on 20 January 2018).
39. Alexis, G.K.; Liakos, P. A case study of a cogeneration system for a hospital in Greece. Economic and environmental impacts. *Appl. Therm. Eng.* **2013**. [CrossRef]
40. Renedo, C.J.; Ortiz, A.; Mañana, M.; Silió, D.; Pérez, S. Study of different cogeneration alternatives for a Spanish hospital center. *Energy Build.* **2006**. [CrossRef]
41. Fabrizio, E. Feasibility of polygeneration in energy supply systems for health-care facilities under the Italian climate and boundary conditions. *Energy Sustain. Dev.* **2011**. [CrossRef]
42. Armanasco, F.; Colombo, L.P.M.; Lucchini, A.; Rossetti, A. Techno-economic evaluation of commercial cogeneration plants for small and medium size companies in the Italian industrial and service sector. *Appl. Therm. Eng.* **2012**. [CrossRef]
43. Sugiartha, N.; Chaer, I.; Marriott, D.; Tassou, S.A. Combined heating refrigeration and power system in food industry. *J. Energy Inst.* **2008**. [CrossRef]
44. Bianco, V.; De Rosa, M.; Scarpa, F.; Tagliafico, L.A. Implementation of a cogeneration plant for a food processing facility. A case study. *Appl. Therm. Eng.* **2016**. [CrossRef]
45. Gonzales Palomino, R.; Nebra, S.A. The potential of natural gas use including cogeneration in large-sized industry and commercial sector in Peru. *Energy Policy* **2012**. [CrossRef]
46. Arteconi, A.; Brandoni, C.; Polonara, F. Distributed generation and trigeneration: Energy saving opportunities in Italian supermarket sector. *Appl. Therm. Eng.* **2009**. [CrossRef]
47. Fantozzi, F.; Ferico, S.D.; Desideri, U. Study of a cogeneration plant for agro-food industry. *Appl. Therm. Eng.* **2000**. [CrossRef]
48. Szklo, A.S.; Tolmasquim, M.T. Strategic cogeneration-Fresh horizons for the development of cogeneration in Brazil. *Appl. Energy* **2001**. [CrossRef]
49. Bechara, R.; Gomez, A.; Saint-Antonin, V.; Schweitzer, J.M.; Maréchal, F. Methodology for the optimal design of an integrated sugarcane distillery and cogeneration process for ethanol and power production. *Energy* **2016**. [CrossRef]
50. Jenjariyakosoln, S.; Gheewala, S.H.; Sajjakulnukit, B.; Garivait, S. Energy and GHG emission reduction potential of power generation from sugarcane residues in Thailand. *Energy Sustain. Dev.* **2014**. [CrossRef]
51. Husain, Z.; Zainal, Z.A.; Abdullah, M.Z. Analysis of biomass-residue-based cogeneration system in palm oil mills. *Biomass Bioenergy* **2003**. [CrossRef]
52. Oliveira, R.C.d.; Silva, R.D.d.S.e; Tostes, M.E.D.L. A methodology for analysis of cogeneration projects using oil palm biomass wastes as an energy source in the Amazon. *DYNA* **2015**. [CrossRef]
53. Wu, Q.; Qiang, T.C.; Zeng, G.; Zhang, H.; Huang, Y.; Wang, Y. Sustainable and renewable energy from biomass wastes in palm oil industry: A case study in Malaysia. *Int. J. Hydrogen Energy* **2017**. [CrossRef]
54. Arrieta, F.R.P.; Teixeira, F.N.; Yáñez, E.; Lora, E.; Castillo, E. Cogeneration potential in the Columbian palm oil industry: Three case studies. *Biomass Bioenergy* **2007**, *31*, 503–511. [CrossRef]
55. Pradeep Varma, G.V.; Srinivas, T. Design and analysis of a cogeneration plant using heat recovery of a cement factory. *Case Stud. Therm. Eng.* **2015**, *5*, 24–31. [CrossRef]
56. Cardona, E.; Piacentino, A. A methodology for sizing a trigeneration plant in mediterranean areas. *Appl. Therm. Eng.* **2003**, *23*, 1665–1680. [CrossRef]
57. Costa, M.H.A.; Balestieri, J.A.P. Comparative study of cogeneration systems in a chemical industry. *Appl. Therm. Eng.* **2001**. [CrossRef]
58. Dillingham, G. *Combined Heat and Power (CHP) in Breweries—Better Beer at Lower Costs*; U.S. Department of Energy: Washington, DC, USA, 2016; pp. 1–37.

59. Freschi, F.; Giaccone, L.; Lazzeroni, P.; Repetto, M. Economic and environmental analysis of a trigeneration system for food-industry: A case study. *Appl. Energy* **2013**. [CrossRef]
60. Chicco, G.; Mancarella, P. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators. *Energy* **2008**. [CrossRef]
61. Darabadi Zareh, A.; Khoshbakhti Saray, R.; Mirmasoumi, S.; Bahlouli, K. Extensive thermodynamic and economic analysis of the cogeneration of heat and power system fueled by the blend of natural gas and biogas. *Energy Convers. Manag.* **2018**. [CrossRef]
62. Su, B.; Han, W.; Chen, Y.; Wang, Z.; Qu, W.; Jin, H. Performance optimization of a solar assisted CCHP based on biogas reforming. *Energy Convers. Manag.* **2018**. [CrossRef]
63. CEN-CENELC. *Manual for Determination of Combined Heat and Power (CHP)*; CEN: Brussels, Belgium, 2004.
64. Cho, W.; Lee, K.S. A simple sizing method for combined heat and power units. *Energy* **2014**. [CrossRef]
65. Howard, B.; Saba, A.; Gerrard, M.; Modi, V. Combined heat and power's potential to meet New York city's sustainability goals. *Energy Policy* **2014**. [CrossRef]
66. Gambini, M.; Vellini, M. High efficiency cogeneration: Performance assessment of industrial cogeneration power plants. *Energy Procedia* **2014**. [CrossRef]
67. Kavvadias, K.C.; Tosios, A.P.; Maroulis, Z.B. Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis. *Energy Convers. Manag.* **2010**. [CrossRef]
68. Liu, M.; Shi, Y.; Fang, F. Combined cooling, heating and power systems: A survey. *Renew. Sustain. Energy Rev.* **2014**. [CrossRef]
69. Al Moussawi, H.; Fardoun, F.; Louahlia-Gualous, H. Review of tri-generation technologies: Design evaluation, optimization, decision-making, and selection approach. *Energy Convers. Manag.* **2016**. [CrossRef]
70. Sanaye, S.; Meybodi, M.A.; Shokrollahi, S. Selecting the prime movers and nominal powers in combined heat and power systems. *Appl. Therm. Eng.* **2008**. [CrossRef]
71. Shelar, M.N.; Bagade, S.D.; Kulkarni, G.N. Energy and Exergy Analysis of Diesel Engine Powered Trigeneration Systems. *Energy Procedia* **2016**. [CrossRef]
72. GIZ; BMZ. *Micro y Pequeña Cogeneración y Trigeneración en México*; GIZ Mexico: Mexico City, Mexico, 2013.
73. United Nations. *United Nations Statistical Division International Standard Industrial Classification of All Economic Activities (ISIC)*; Rev.4; United Nations: New York, NY, USA, 2008; ISBN 9789211615180.
74. INE. *Clasificación Nacional de Actividades Económicas*; Instituto Nacional de Estadistica: Madrid, Spain, 2012.
75. Carvalho, M.; Serra, L.M.; Lozano, M.A. Geographic evaluation of trigeneration systems in the tertiary sector. Effect of climatic and electricity supply conditions. *Energy* **2011**. [CrossRef]
76. Chaker, M.; Meher-Homji, C.B.; Mee, T.; Nicolson, A. Inlet Fogging of Gas Turbine Engines-Detailed Climatic Analysis of Gas Turbine Evaporative Cooling Potential. In Proceedings of the ASME Turbo Expo, New Orleans, LA, USA, 4–7 June 2001.
77. Santoianni, D. Power plant performance under extreme ambient conditions. *WÄRTSILÄ Tech. J.* **2015**, *1*, 22–27.
78. USEPA. Catalogue of CHP Technologies. U.S. Environmental Protection Agency Combined Heat and Power Partnership. Available online: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf (accessed on 14 December 2017).
79. MAGAP. Ecuador Marca su Rumbo en la Industria de los Agrocombustibles. Available online: https://www.agricultura.gob.ec/ecuador-marca-su-rumbo-en-la-industria-de-los-agrocombustibles/ (accessed on 15 May 2020).
80. Hyman, L.B.; Meckel, M. *Sustainable On-Site CHP Systems*; Meckler, M., Hyan, L., Eds.; McGraw Hill: New York, NY, USA, 2010.
81. IEA. *CO2 Emissions from Fuel Combustion. Statistics*; OCD Publishing: Paris, France, 2017. [CrossRef]
82. Black & Vetch. *Cost and Performance Data for Power Generation Technologies*; Black & Vetch: Overland Park, KS, USA, 2012.
83. IRENA. Renewable Power Generation Costs in 2014. Available online: www.irena.org/publications (accessed on 20 June 2017).
84. Midwest Application CHP Center; Avalon Consulting. *Combined Heat and Power (CHP) Resource Guide*, 2nd ed.; University of Illinois at Chicago–Energy Resource Center: Chicago, IL, USA, 2005.
85. GIZ. *Cogeneration & Trigeneration—How to Produce Energy Efficiently*; GIZ: Bonn, Germany, 2016.
86. Petroecuador Subsidio Proyectado Por Producto Del 11 De Septiembre Al 10 De Octubre De 2020. Available online: https://www.eppetroecuador.ec/wp-content/uploads/downloads/2020/09/PRODUCTOS-SUBSIDIADOS-SEPTIEMBRE-2020-COMERCIAL-11-AL-10.pdf (accessed on 18 September 2020).

87. Arne, O.; Schlag, N.; Patel, K.; Kwok, G. *Capital Cost Review of Generation Technologies*; Energy and Environmental Economics Inc.: San Francisco, CA, USA, 2014.
88. UNEP; SETAC. *Guidelines for Social Life Cycle Assesment of Products*; Benoît, C., Mazijn, B., Eds.; UNEP/SETAC: Druk in de weer, Belgium, 2009; ISBN 978-92-807-3021-0.
89. Rafiaani, P.; Kuppens, T.; Dael, M.V.; Azadi, H.; Lebailly, P.; Passel, S.V. Social sustainability assessments in the biobased economy: Towards a systemic approach. *Renew. Sustain. Energy Rev.* **2018**. [CrossRef]
90. Contreras-Lisperguer, R.; Batuecas, E.; Mayo, C.; Díaz, R.; Pérez, F.J.; Springer, C. Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica. *J. Clean. Prod.* **2018**. [CrossRef]
91. Siebert, A.; Bezama, A.; O'Keeffe, S.; Thrän, D. Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. *J. Clean. Prod.* **2018**. [CrossRef]
92. Salgado Torres, R. *Plan Maestro de Electricidad 2019–2027*; Ministerio de Electricidad y Energía Renovable: Quito, Ecuador, 2019.
93. COGEN Europe. *Cogeneration Country Fact Sheet GERMANY*; COGEN Europe: Brussels, Belgium, 2014.
94. Mercados, E. *Análisis de la Industria de Cogeneración en España*; COGEN Espana: Madrid, Spain, 2010.
95. DOE; EPA. *Combined Heat and Power: A Clean Energy Solution*; United States Environmental Protection Agency: Washington, DC, USA, 2012.
96. Raineri, R.; Dyner, I.; Goñi, J.; Castro, N.; Olaya, Y.; Franco, C. Latin America Energy Integration: An Outstanding Dilemma. In *Evolution of Global Electricity Markets: New Paradigms, New Challenges, New Approaches*; Elsevier: Amsterdam, The Netherlands, 2013; ISBN 9780123978912.
97. Corneille, F. Energy Integration in Latin America: The Connecting the Americas 2022 Initiative. Available online: http://www.ecpamericas.org/Blog/Default.aspx?id=134 (accessed on 3 January 2018).
98. The Atlantic Council Regional Energy Integration: The Growing Role of LNG in Latin America. Available online: http://www.atlanticcouncil.org/events/webcasts/regional-energy-integration-the-growing-role-of-lng-in-latin-america (accessed on 22 January 2018).
99. Bataille, C.; Melton, N. Energy efficiency and economic growth: A retrospective CGE analysis for Canada from 2002 to 2012. *Energy Econ.* **2017**. [CrossRef]
100. Tol, R.S. *The Private Benefit of Carbon and Its Social Cost*; Working Paper Series; Department of Economics, University of Sussex Business School: Sussex, UK, 2017.
101. Khurana, S.; Banerjee, R.; Gaitonde, U. Energy balance and cogeneration for a cement plant. *Appl. Therm. Eng.* **2002**, *22*, 485–494. [CrossRef]